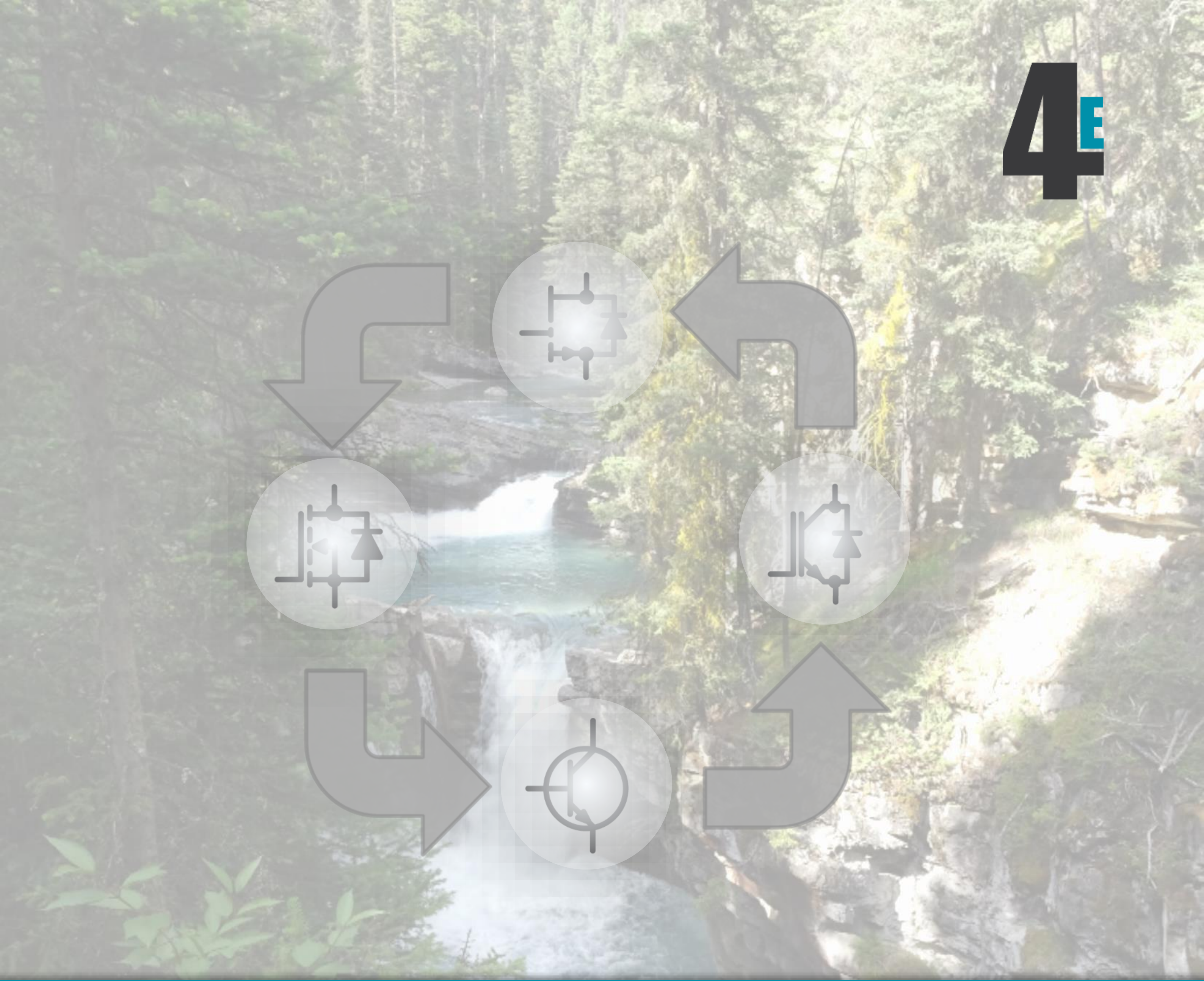

# Wide Band Gap Technology: Timing of most beneficial policy measures

## 4E Power Electronic Conversion Technology Platform (PECTA)

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The report was commissioned by the IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E) – Power Electronic Conversion Technology Platform (PECTA). It was authored by Bjarke Spliid Hansen, Tek-Info.

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## Abstract:

This report reflects a special working result of the first term of PECTA, the Power Electronic Conversion Technology Platform. It contains suggestions for possible policy measures and mapping with applications over a timeline. The work is based on previous PECTA activities and results including the analysis presented in the Application Readiness Map for WBG technologies, on interviews with representatives from industry, policy, and research. The work evaluates product application specific policies as well as horizontal and vertical regulatory approaches of policies.

### About the IEA 4E Power Electronic Conversion Technology Platform (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 devices develop, and engages with research, government, and industry stakeholders worldwide to lay the base for suitable policies in this area.

Further information on PECTA is available at: https://pecta.iea-4e.org.

### About the IEA Implementing Agreement on Energy Efficient End-Use Equipment (4E):

The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP) has been supporting governments to co-ordinate 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 range of projects designed to meet the policy needs of participating governments. Members of 4E find this to be 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.

Current members of 4E TCP are: Australia, Austria, Canada, China, Denmark, European Commission, France, Japan, Korea, Netherlands, New Zealand, Switzerland, Sweden, UK, and USA.

The main collaborative research and development activities under 4E include the:

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

Further information on the 4E TCP is available from: www.iea-4e.org.

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# Executive Summary

This work has analysed different potential policy measures to support the uptake of efficient wide band gap (WBG) power electronic for end-use equipment for improved energy efficiency. The measures considered spans over standardisation, in various fields (test methods for reliability and efficiency, rules for environmental footprint, modules and package architecture), research areas, economic support for creating a WBG ecosystem, and to product specific regulatory measures.

Implementation drivers and barriers are identified through stakeholder interviews highlighting specifically two barriers: knowledge gaps on reliability of WBG and lack of standardised components and product platforms for WBG.

Four main product applications; PV inverters, external power supplies (EPS), uninterruptable power suppliers (UPS) and electric vehicle (EV) chargers were analysed more in details.

PV inverters have currently no requirements on energy efficiency, but various label and endorsement schemes exist based on the Euro efficiency or the similar CEC (Californian Energy Commission's) metric. MEPS on PV inverters therefore could be introduced relatively unproblematically and quickly. The MEPS could be introduced in two tiers, the second with an improved efficiency up to 98 %, to allow for a possible energy label for PV inverters. That in turn presumes an optimised test method and narrow verification tolerances or else it will be difficult to distinguish between the energy classes.

EPS are covered by MEPS, but current regulations could be improved with stricter MEPS at 91-92 % efficiency and phased in with two tiers. For multi voltage EPS the regulations could cover different voltage modes, and not only the lower one, as is the case for the European ecodesign. Verification tolerances could be optimised (currently they are very lenient compared with other products), and a label could be considered since the development seems to go towards fewer but multi-functional EPS that are used for many appliances. That means the performance of the individual EPS is more important for the consumer and environment. Material consumption is a particularly relevant environmental aspect for this product.

UPS are currently not covered by MEPS, but existing voluntary requirements could be transformed into mandatory requirements. Therefore, mandatory requirements could be established relatively quickly. MEPS on around 98 % for double conversion mode UPS (VFI UPS) are realistic in a near future considering the potential of WPG based products. The market of UPS, as well as the use time of each individual UPS, is foreseen to increase significantly. In the future, UPS will develop from being just emergency backup to be used for peak balancing to optimize the energy economy. UPS with double conversion mode can do that and is expected to be the common product in the future.

EV chargers are currently not covered by MEPS. For EV chargers the number one priority and an urgent task is to define and decide on one or more charging efficiency metrics. Currently no metric exists, which effectively stops any kind of comparison or regulation to ensure efficient EV charging. The present work considers off-board chargers, but on-board chargers may have same problem.

Lifting the head up from vertical product applications to horizontal and perspective stands one issue back:

A paradigm shift is on its way, with the potential to reshape the industry and supplier landscape, and those suppliers or even regions that grasp this development successfully, will control the future electric power consumption on all levels of the society. The current cupper and silicon based world of power electronics is quickly changing into a WBG world, where gallium nitride and silicon carbide will rule.

Having said that, then it is recommended not only to focus on the first generations of WBG materials, but also coming and new materials.

To get the full benefit, education and development of skilled labour force including technicians, engineers and university scientists is essential. Particularly the market all over the world needs people that understand both practical electrotechnics and it and control.

# Contents

# Glossary and Abbreviation

| | |
|---|---|
| 4e | IEA Technical Cooperation Programme: Energy Efficient End-use Equipment |
| AC | Attenuating current |
| CDM | Complete drive module (defined in IEC 61800-9-2) |
| CSC | Current Source Converters |
| DC | Direct current |
| CoC | Code of Conduct |
| DC/AC converter | Power converter (aka inverter) converting from DC a DC source to AC e.g., between PV modules and utility grid, or battery and AC-motor |
| DC/DC converter | Power converter converting from one voltage to another) |
| EDEL | Ecodesign and Energy Labelling |
| EPS | External Power Supply |
| EV | Electric vehicle |
| EVSE | Electric Vehicle Supply Equipment |
| GaN | GalliumNitride |
| HEMT | High-electron-mobility transistor |
| HEV | Hybrid electric vehicle |
| IGBT | Insulated-gate bipolar transistor |
| IGCT | Integrated Gate-Commutated Thyristor |
| MEPS | Minimum Energy Performance Standards |
| MOSFETs | Metal–Oxide–Semiconductor Field-Effect Transistor |
| MPPT | Maximum Power Point Tracking; maximizing power extraction from the PV cells to the grid |
| MV/LV converter | Power converter from medium voltage to low voltage, e.g. for grid connection of large-scale PV systems |
| OBC | On Board Charger (on an EV) |
| PV | Photo Voltaic |
| SiC | SiliconCarbide |
| SOC | State-of-charge |
| UPS | Uninterruptible Power Supply |
| VSC | Voltage Source Converter |
| | |

## Other definitions

Commonly used Voltage Ranges in different Application areas. The voltage classification as specified in the table is proposed for the PECTA report of Makoschitz 2020 [2] and as such not valid generally but only in the present report and in the source report.

| Voltage Range Applications | Low | Medium | High |
|---|---|---|---|
| **Automotive** | <12 $V_{DC}$ | 12 $V_{DC}$ – 60 $V_{DC}$ | >60 $V_{DC}$ |
| **Industrial** | <1000 $V_{AC}$/1500 $V_{DC}$ | 1 $kV_{AC}$ – 52 $kV_{AC}$ | >52 $kV_{AC}$ |
| **Energy Distribution** | <1000 $V_{AC}$ | 1 $kV_{AC}$ – 52 $kV_{AC}$ | >52 $kV_{AC}$ |

# 1. Introduction

## 1.1. Overview and Objectives of PECTA

The emerging Wide Band Gap (WBG) offers significant opportunities for improved energy efficiency from the rapidly maturing technologies of power electronic devices that are incorporating WBG technologies. PECTA assesses the efficiency benefit of utilizing the WBG technology for power electronics, to harvest these opportunities.

The work presented below assesses possible policy measures in relation to the development of WBG technology to suggest ambitious policy measures for selected product applications and within a reasonable timeline. Policies, spanning from guidance and knowledge building, to targeted product policies with minimum requirements like the European ecodesign are evaluated. The evaluation is based on current technological state and foreseen development as presented in the "Application Readiness Map" (ARM) which is developed by Thoben and Phost as part of the PECTA work [32].

## 1.2. General approach and methodology

The present work was split in three tasks that explore the potential policy measures, possible product applications, and the timeline for the chosen measures and applications:

- Task 1 Categorisation and evaluation of policy measures.
- Task 2 Implementation barriers and drivers.
- Task 3 Timing of and most beneficial policy measures.

The project categorises and investigates potential policy measures according to the IEA Policy Classification for energy efficiency [2], and the points below:

- Horizontal measures and initiatives, such as requirements on component level for many applications or detailed research in WBG materials and devices.
- Vertical measures and initiatives, such as efficiency and material requirements, with a focus on a specific application.
- Other aspects or specific concerns that could be considered relevant for WBG based products.

The development of WBG related standards and adaptation of standards to new requirements and potentials is ongoing and the development of these is also an important factor for applicability of potential policies. Therefore, some effort has also been put into finding relevant standards for selected product applications and updating some of the work that was already performed by other PECTA activities at earlier stages. Standards are mentioned in relevant sections and in Annex 1. There might however be other relevant standards that are not mentioned in the present work.

## 1.3. Interviews and sources

Policy implementation barriers and drivers are also identified through and discussed with eight selected stakeholders from industry, policy makers, test laboratories and universities during individual in-depth interviews. The interview frame is presented in Appendix 3. The inputs from interviews are presented and discussed in relevant sections together with some of the key conclusions from PECTA work packages.

Finally, the timing of most relevant requirements, their applicability, potential benefits, and limitations are evaluated. Particularly requirements that could be relevant in the ecodesign framework are considered.

# 2. Applications in Focus

It has been found that WBG power electronics enables a significant global energy saving potential. The annual global energy savings potentials for the considered applications have been elaborated in a PECTA-report by Spejo et al [48]. Table 1: Overview of products and their annual saving potentials globally by 2021 (Sources: [48]):Table 1 presents some main results.

Table 1: Overview of products and their annual saving potentials globally by 2021 (Sources: [48]):

| **Characteristics**<br>**Application** | **Savings [TWh/year]** |
|---|---|
| Photovoltaic inverters (SiC): | 20.7 |
| Laptop chargers (GaN): | 3.2 |
| Data center / server power supplies (SiC): | 4.6 – 6.7 |
| Electric vehicle charging stations (SiC): | 0.8 |
| Low-voltage motor drives (SiC): | 103 |
| This value includes HVAC systems: | |
| fans | 20 |
| pumps | 20 |
| compressors | 33 |
| Inverters for grid-connected battery storage systems (SiC): | 0.4 |

The same report has performed estimates of the potential energy savings of specific applications for the year 2050 based on the estimates of the annual consumption/generation in the same year. Photovoltaics is expected to generate electricity of about 13’000 TWh/year in 2050. The global electrical vehicle fleet may achieve a value of 672 million vehicles in 2050. Considering the assumptions performed in previous sections (PV power generation and E-vehicle fast chargers), potential energy savings of 270 TWh/year and 33 TWh/year for the PV and EV charger applications in 2050 have been calculated, respectively.

The product category data centers / server power supplies include uninterruptible power supplies (UPS) for that application. For all data centers considered in the report is it assumed that the input power passes through uninterruptible power supplies (UPS). So, UPS are a central power conversion component for that product group.

The saving potentials from several product groups overlapping the above mentioned cases were analysed for the European Union Ecodesign and Energy Labelling Working Plan, (see [14], [19], [64], [48]) and in the preparatory study for PV modules and inverters [7]). Table 2 provides an overview of estimated saving potentials for four technologies according to the EU studies mentioned above, estimated by 2023. The estimations are based on improvement from current typical to best available technologies and do as such not specifically consider WBG technologies. This means that WBG technologies would increase the saving potential even more but nevertheless, the studies provide interesting information, and the calculated saving potentials supplements the PECTA report mentioned above.

Table 2: Overview of products and their annual saving potentials in the EU by 2023 (Sources: PV inverter preparatory study: [7], EPS: Current regulation. UPS and EV chargers: The 2021 EELWP studies [14], [19] and [64])

| **Characteristics** / **Application** | **Savings [TWh/year]** | **Comparison with products considered in** Table 1 |
|---|---|---|
| PV Energy generation | 11 – 14 | Similar |
| EPS (External Power Supplies, AC/DC) | 260 | EPS for laptops (as in table 1), but also for other applications |
| UPS (Uninterruptable Power Supplies) | 7 | UPS for servers (as in table 1), but also for other applications |
| EV Charging Stations | 1.4 | Similar |

For the present study are four end-use product applications found to be particularly promising for WBG technologies:

- PV inverters.
- External power supplies (EPS).
- EV charging stations/DC chargers.
- Uninterruptible power supplies (UPS) including for data centres.

The motivation for selecting these product groups despite they were not all with the highest potential saving also comes from looking at future foreseen developments as well. The product application low-voltage motor drives is well covered in IEA 4E regie by the EMSA work.

PV inverters are chosen as the highest prioritised product application for the present work. The motivation is firstly the high potential loss savings, secondly, the fact an efficiency metric is already established and widely accepted, and thirdly, because the European commission is currently assessing and preparing requirement for solar panels and inverters, meaning there could be a "window of opportunity" to impact European policy requirements for this application area.

Generally, it now seems to be a good time for (re)considering product policies due to the ongoing maturation of the WBG industry. An industry source informs that *50 % growth of GaN market is foreseen from 2023 to 2024. We are "just behind the hockey stick" and 5 – 8 years behind SiC which has an extreme market growth now. We can see that during the last three years the GaN community has gotten adult, and now we know what we can get out of the materials. Many products have gone from predevelopment to pilot production phase, and the first products are entering the market. So now we see a very high growth, and a clearer picture of which applications GaN is being used for. By 2028 it is expected that around 20 % of the power semiconductor market will be WBG based. But Si product will have their place on the market in the future as well. Below 10 kW you will take SiC, and we have no customers with plans for exploration of SiC for higher than 10 kW* [20]f.

Particularly applications where part load is a significant share of operating time like PV inverters, could benefit from WBG based power electronics due to its potentially higher part load efficiency [32].

Technological state, market development, test methods, and policy potentials for the four mentioned product applications are reviewed and presented in the four subsequent sections.

## 2.1. PV inverters

Photovoltaic inverters (PV inverters) are electric energy converters that change direct electric current (DC) to single-phase or poly-phase alternating current (AC).

The JRC preparatory study [7] reported that average efficiency of marketed PV inverters from the kW range up to the MW range span from 96 to 97 %. For typical products available on the market the variation spans from 94 to 98.6 %. The PECTA report by Spejo et al [48] finds that typical SiC-based PV inverter may present a peak efficiency in the range of 98.2 up to 99.2 %.

The path from conversion of solar energy to a voltage level which can be fed into the electric grid, load, or storage system, involves two different main stages:

- The solar cell with conversion of solar energy into electrical energy.
- The internal link between cell and grid or consumer and the associated electrical energy conversion facilitated by power electronic circuits.

There are different "topologies" for application of inverters for PV systems with each their pros and cons. The four most relevant topologies for small and medium-scale systems are:

- Microinverter or module inverter: one inverter per one or two PV modules.
- String inverter: One inverter per array, or string, of e.g. 10 or 20 interconnected PV modules, and with input power typically ranging from 0.5 kW to 5 kW. The more modules that are connected in one string, the higher the voltage, and power, delivered to the inverter.
- Multistring inverter: One inverter can handle several strings by multiple gates, and with input power typically ranging from 3 kW to 30 kW.
- Central inverter: One central inverter for all PV modules in larger PV systems with input typically ranging from a higher two-digit kW and up to 1 MW.

Microinverters enable power management from each individual PV module giving a higher system efficiency in case of varying shadows (typical smaller systems like domestic). On the other hand, the individual inverter efficiency is normally slightly lower in micro inverters than in string inverters.

String inverters give the simplest control and traditionally they enable higher efficiency of the inverter itself compared with micro inverters. String inverters have higher DC cable loss since the current is higher and the voltage is lower in the cables from the PV modules than when the power has been converted (and inverted) already at module level.

Systems with module inverters (microinverters) are more flexible in terms of expansion if the power requirement should change at a later stage. This is because it should not be necessary to replace the old string inverter, but just new PV modules with additional microinverters could just be plugged in.

Both for small and large-scale PV systems and inverters, are lower losses expected from inverters with WBG devices than in traditional Si based inverters. For micro inverters and perhaps small string inverters are GaN based devices relevant, while SiC devices are relevant for string and central inverters.

It would be logical to think, that for large systems therefore the economy of scale as well as higher professionality automatically would result in a development towards WBG technologies, which is also to some extend correct. The market drive – and failure – is presented below in section 2.1.5

### 2.1.1. Market and technology development

The PV installation market can be split into the following power ranges inspired by the JRC study [7]:

- Residential and small-scale commercial applications with a rated capacity from 0.3 up to a few kW. Here are microinverters, string and multistring inverters typically applied.
- Medium-scale PV systems for commercial application, public and municipal institutions, agroindustry, small and middle-sized industry and with a typical power range from 10s of kW up to 100-200 of kW peak power.
- Utility-scale central inverters with a rated capacity up to 4 MW.

The market development of PV inverters in terms of peak capacity must logically mirror the development of solar power installations and production. The development of PV energy production is presented below:

- The global amount of PV energy production was approximately 1250 TWh in 2022 (500 TWh in 2018) [18].
- Nearly 220 GW additional net PV capacity during 2022. 310 GW additions are expected in 2024 [14].
- Total net production capacity reaching 1.1 TW by 2022 (500 GW in 2018), illustrated in Figure 1 [16].

As similar PV inverter capacities are needed, the inverter characteristics should also match the mentioned relevant market categories.

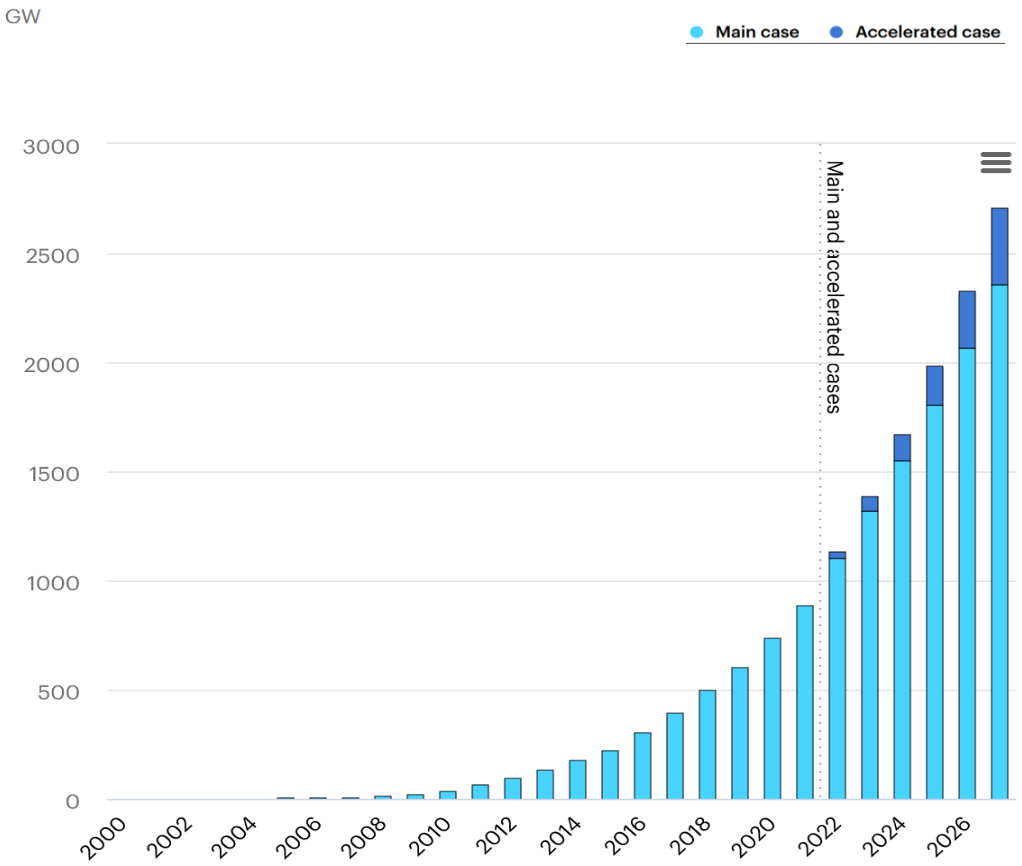

Figure 1. World total PV peak production capacity 2000-2027 (source: IEA 2023, CC BY 4.0 [16])

As could be seen from these developments and estimates on future additions then each 0.1 %-point lower efficiency of the around 1500 GW PV inverters already installed worldwide in 2023 will result in 1.5 TWh lost electricity production every year the next 5 – 10 – 25 years. With the tremendous growth foreseen ambitious requirements would as quickly as possible save significant lost production.

### 2.1.2. Efficiency metric including Euro efficiency

One crucial factor in the dissemination of efficient products and to enable labelling schemes and MEPS, is that test standards and an efficiency metric is defined and adapted. For PV inverters, one such metric is defined in the EU as the Euro efficiency. The Euro efficiency is defined and tested according to the standards EN 50530 and EN 61683. It was proposed by the Joint Research Centre (JRC/Ispra) and is well established and accepted as the efficiency metric for PV inverters for more than a decade [35],[36],[7].

The Euro efficiency is a measure based on a test method incorporating several part load modes to simulate average yearly power distribution in “middle Europe”. The development of test standards being able to show “real life” operation is important to demonstrate the benefits of most WBG converter/inverter technologies. The calculation form is given below, where e.g. Eff5 % means efficiency at 5 % load [7]:

Euro efficiency

= 0.03 x Eff5 % + 0.06 x Eff10 % + 0.13 x Eff 20% + 0.1 x Eff30 % + 0.48 x Eff50 % + 0.2 x Eff100 %

Other metrics on similar principles are used worldwide, e.g. the Californian Energy Commission’s (CEC’s) which also include a weighting of the efficiency at six different power levels, but slightly different, adapted to the Californian climate, e.g. with 10 % being the lowest part load [37],[38].

### 2.1.3. Test methods and accuracy

Accuracy of tests and tolerances for verification are essential factors when setting up realistic requirements that could also be enforced.

For solar inverters the measuring accuracy is defined by IEC 61683 ([35] as max deviation on the conversion efficiency and it is calculated as follows: Max deviation = $\pm 0.2 \cdot (1 - \eta) \cdot \eta$[%]. Hence the measuring accuracy is +/- 0.39 % of the efficiency at 98 % efficiency and +/- 0.2 % at 99 % efficiency. Among others, Valentini et al (in a cooperation between Sera at Queensland University, Australia and Aalborg University, Denmark) have tested and confirmed that it this is also a realistic measuring accuracy in a test laboratory [34]. To decide verification tolerances, also the interlaboratory variation should be added to the accuracy. Assuming that the interlaboratory variation (conservative estimate) is in the same range, a verification tolerance on around or up to 1 %-point efficiency could be suggested – having in mind a more detailed tests and analysis need to be performed. This at a similar level as for other power electronics like power transformers and VSDs (see section 6.3.3).

Assuming a minimum requirement of 96 % efficiency of PV inverters, there are 4 %-points up to 100 %. Based on the above assumed 1 % verification tolerance would four efficiency classes be possible in a label or efficiency class scheme, leaving no room for an A to G efficiency label. Should better analysis and test methods with a lower verification tolerance, be developed, could the traditional A to G label potentially be relevant. Alternatively, an A, B and C or IE1, IE2 and IE3 efficiency class declaration would enable and motivate consumers to select PV inverters that decrease the losses by 25 - 50 %.

### 2.1.4. Readiness of WBG based PV inverters and efficiency

For PV inverters the energy efficiency depends on technology, and the efficiency and the different technologies’ representation on the market depend on the specific market category. The JRC preparatory study [7] finds the following span of Euro efficiency for various market categories:

- Micro inverters for residential and commercial applications: Euro efficiency 94 – 97.5 %.
- String inverters for residential, commercial, or utility-scale: Euro efficiency 95 – 98.2 %.
- Utility-scale central inverters: Euro efficiency 97.5 – 98.6 %.

The preparatory study further defined three so-called base cases with average products for different sectors. For each of the base cases the study also found improvement potential from the best available technology (BAT) and best not-available technology (BNAT). The BAT is defined by the best products that are relatively widely available on the market. BNAT is defined by WBG technology. Table 3 shows the Euro efficiency of the different cases and thereby the potential for improvement.

Table 3: Euro efficiency of PV inverters for different applications (extracted from [7]).

| **Type**<br>**Application** | **Average** | **Better EE** | **WBG** |
|---|---|---|---|
| 2.5 kW transformer-less single-phase string inverter | 96 % | 98 % | 99 % |
| 20 kW transformer-less three-phase string inverter | 97 % | 98 % | 99 % |
| 1500 kW utility-scale central inverter | 97 % | 98 % | 99 % |

In a PECTA report of Phost and Thoben [32] is the market readiness of WBG technologies for various applications mapped and as Figure 2 shows, basically all categories of WBG inverter products have now entered the market.

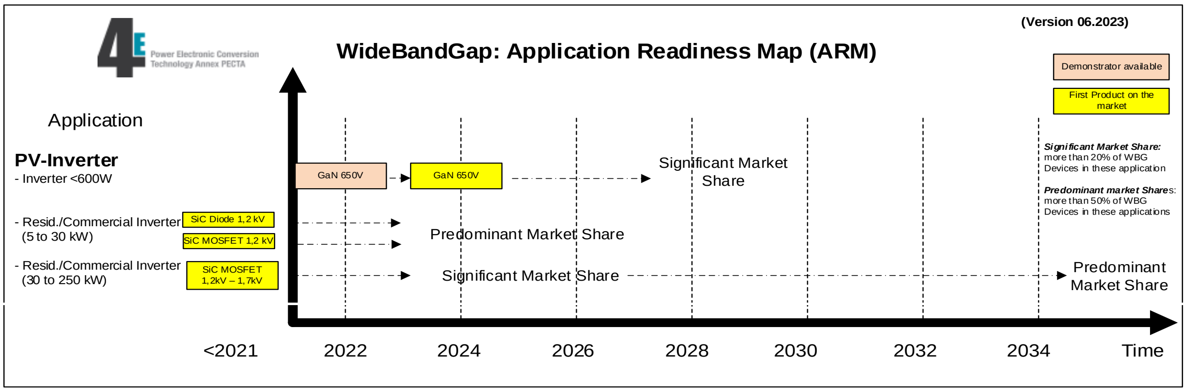

Figure 2. Extract of 6th version of the PECTA application readiness map shows that WBG based devices have entered the market for all categories of PV inverters [32].

Some of the main points from the ARM [32], the performed interviews [20], and desk studies of announced products launched during first half 2023 [17] are that:

- SiC products are available now for larger power ranges [32].
- GaN products available now for small inverters for residential application, e.g. PV micro inverter products with 650V GaN devices [32].
- *Exponential growth (50 % yearly) for GaN products from now and coming years is foreseen. This includes potentially GaN for small PV inverters too*[20]f.
- Review of product launches confirms that the WBG technology is approaching the market with product launches accelerating during first half of 2023 [17].

In a PECTA project by Jehle et al [40] the potential improvement by changing from Si (IGBT) devices to SiC (MOSFET) devices for PV inverter applications is analysed. A product with a boost function which can increase the voltage level at low power was analysed. The project found that SiC devices improved the efficiency particularly for higher power levels and lower input voltages (requiring a greater boost in voltage). The efficiency gain of the energy generated annually, taking into account the varying PV input power has been calculated to 2.66% [40].

The current proposal (2022) for minimum requirements for PV inverters is a minimum Euro efficiency of 96 % across technologies and capacities. The result from such approach is an estimated saving (as increased yield from PV modules) at around 3.5 TWh by 2040 according to JRC. The preparatory study mentions that this is probably underestimated [7].

The conclusion from the current review is that WBG technologies, which in 2020 was defined as BNAT, has now entered the market and could within a few years – if promoted by policies – reach a significant or even predominant market share.

### 2.1.5. Market failure

Often energy efficient products are, in-spite of their apparent obvious benefits, not finding their way into the market due to market failures. The reason could be that the market fails to recognize the products perhaps from missing knowledge, short-term focused on purchase price and not on lifecycle price/total cost of ownership (TCO), or lacking trust in the long-term benefits compared with short-term added cost.

However, the case may be that the extra energy you can feed into the grid due to lower losses, cannot yet pay back the extra investment. So even for these large-scale systems the market may not by itself introduce the more efficient technology, at least not before learning curve effect has been taken in. And this is a barrier for the development.

For PV inverters the picture is mixed.

One manufacturer of PV inverters stated that *when products are compared in tests e.g. at HWT Berlin* [10]*, for small and medium-scale PV, only the top products have a chance of success on the market afterwards*. So here the conclusion is that market presses for efficiency.

On the other hand, an interviewee from a major European whole sales company informed that efficiency is generally ignored among their customers. The important factors are price, easy handling (max weight of 25 kg), and quick and easy installation. This company supply the professional installer market for households, small and medium-scale commercial and industrial energy installations, which adds to the conclusion that these markets are subject to a market failure.

So there seems to be a push for the benchmark products from high-end customer segments, and a price focus with no TCO considerations from the general market. And this combination has the drawback, that either the top or the cheap products are requested, while the “almost top product” seem to be challenged; not requested by front-runners, nor by ordinary price hunting customers.

The efficiencies’ dependence on application and installation size, presented in section 2.1.4 for inverters seem to support this mixed picture, indicating that more professional purchasers have higher focus on efficiency than less professional (utility vs. residential sector).

This underlines the need for appropriate minimum requirements, which when set at a higher level than the current proposal will be able to promote WBG technology to avoid market failure. Alternatively, labelling may be a measure to differentiate the best and the average products and pull market towards products including WBG.

An interviewee from policy side noted that *for PV inverters a label could be the solution "to give the WBG products a chance to shine", but he also noted that an energy label was found not feasible as the test tolerance was conflicting with the steps on the label scale*[20]e. *The measuring tolerances would result in a low number of energy efficiency classes,* since products could be overdeclared by more than one efficiency class without the MSAs being able to enforce the classes.

Two models for labels were suggested in the JRC study, either a label on PV module level or at system level. The latter is counting inefficiency from PV module, inverter, and other system losses, but no label for the inverter alone was suggested.

### 2.1.6. Environmental and life cycle impact

Being an energy related product, a power converter is expected to have the highest environmental impact during the use phase. As examples Glaser et al [28] have looked at the LCA information about two PV inverters. The PV inverter A with 98.3 % Euro efficiency shows that 72 % of the total product carbon footprint (PCF) relates to the use phase, and for the PV inverter B with 97.8 % Euro efficiency, 44 % of the total PCF occurs in the use phase".

Further, for PV inverters the challenge is to compare designs on lifetime (above 10 years) and humidity resistance. As an interviewee from research noted, *are PV inverters warm during daytime and cold during nighttime with risk of condensation and humidity problems. It is important to understand the lifetime efficiency* [20]c.

### 2.1.7. Choice of technology

The preferred technology depends on operating conditions. Potential savings from different WBG components depend on load profiles. *Is the product e.g. operating at full or part load mainly? In automotive, the product is mainly operating at part load*[20]c.

Interviewees from both research and industry noted that for PV inverters it is more important to have high efficiency at part load, than full load. *The increasing PV and wind power production capacity means that the PV will more often produce more power than needed. During summertime this is already the case. In the future full load production of PVs will more often overlap with situations of ample (renewable) energy in the grid. Part load situations for PV inverters are on the other hand overlapping with the times when there are less renewables than needed, e.g. late afternoon, or winter. Consequently, the part load performance of PV inverters is increasingly relevant*[20]a. Yet, the high load efficiency is also important for solar inverters as *another aspect becomes apparent, that the higher efficiency brings with it both higher production and less heat, and therefore less demand of cooling*[20]c.

*SiC have better efficiency at full load, and SiC are for higher power applications*. *The choice of technology depends on the energy levels in the device, but for smaller solar inverters like residential rooftop PV inverters the business should be focusing on GaN, especially for micro inverters* [20]c, [20]g. Therefore, products operated at part load can gain from GaN potentially higher efficiency at part load.

There was consensus among the interviewees that product regulations should not base product policies on specific materials or technologies. This is relevant for PV inverters but also for other WBG related products. Some pointed out that policies, or PECTA work, could help improving knowledge about which technologies like WBG in general, or more specifically GaN or SiC, are relevant for which situations and applications.

## 2.2. External power supplies (EPS)

External power supplies (EPS) are power adaptors used to convert electricity from household power mains into lower voltages, i.e. from AC to DC, and to protect the devices they supply from the potentially harmful mains voltage. EPSs power for instance shavers, smartphones, loudspeakers, and laptops.

Universal external power supplies are EPS's that can be used for different products and brands by using a harmonized common charging port such as USB Type-C [14].

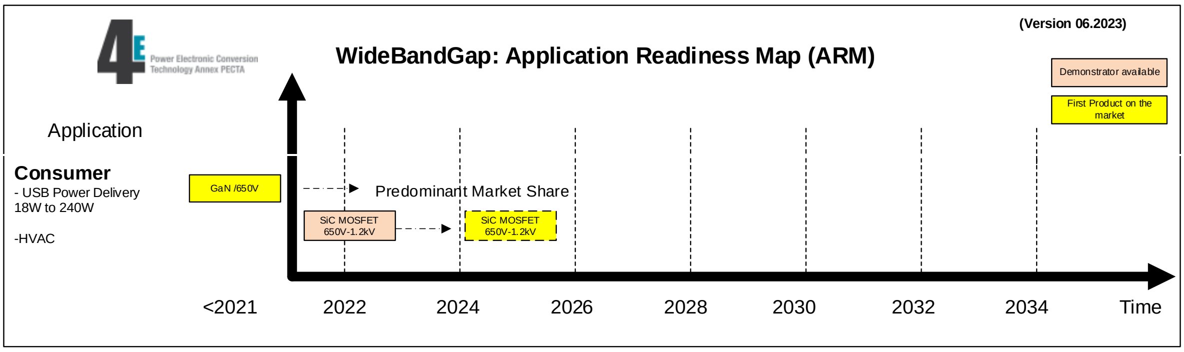

Figure 3. Extract of 6th version of the PECTA application readiness map illustrates that WBG based devices already are reaching a high market share for USB power delivery 18 W to 240 W (extracted from Fehler! Verweisquelle konnte nicht gefunden werden.).

The energy being shaped by a single adapter throughout its operational life is low (i.e., in the range of 10 kWh), but efficiency still plays an important role, because of the high number of devices in use. Aside from efficiency improvements at full and partial load operation, volume and weight reduction is an important direction of development. This Economy of materials perspective may be supported using WBG devices, enabling higher switching frequencies and thereby allowing for size reduction of passive components and reduced consumption of resources during production and recycling.

### 2.2.1. Current efficiency requirements

External chargers for AC/DC and AC/AC conversion are covered by the ecodesign regulation (EU) 2019/1782 for external power supplies [27]. The regulation covers EPSs for output up to 250 W for typical residential and commercial consumer electronics. Out of the scope are e.g. EPSs placed on the market before 1 April 2025 solely as a service part or spare part for replacing an identical external power supply placed on the market before 1 April 2020.

Minimum efficiency requirements in the regulation go up to 88 % for EPS with a capacity above 49 W, and less for smaller chargers. The efficiency metric covers full load (100 %) and three-part load (75 %, 50 %, and 25 %) by arithmetical means.

### 2.2.2. Market and technology development

For EPSs, GaN HEMT is expected to be the dominant power electronic device in applications at lower voltages (100 V – 650 V), DC/DC converters and power supplies during the coming 10 years [2].

Universal EPS will at an even higher level be subject to part load operation than EPSs and internal power supplies which are dedicated for a specific product application and operating condition. WBG devices for EPS will be able to meet stricter requirements for combined full and part load operation.

Until now, chargers have generally been included with the product they serve, and even if they are not, consumers are probably not willing to pay more for chargers, as expressed by Ulrike Grossner, Swiss Federal Institute of Energy SFOE: "(…) but who is prepared today to spend money on a charger at all?" (2020, [22]).

This is confirmed by a major power chip supplier, who however also notes that *"the charger and adapter market has undergone a paradigm shift recently as chargers/adapters are no longer delivered with the* *devices. Therefore, the end-user demand for separate power supplies has increased. This also means that the market is changing to multiport power supplies*[20]f.

Phost and Thoben [32] conclude that only size and not efficiency is prioritised by customers - efficiency of USB power adapters of 91 % is normal which means that the full potential from WBG is not gained.

Grossner [22] considers that an energy label for EPSs for small consumer electronics would help environmentally conscious consumers to decide in favour of efficient WBG based chargers [22].

### 2.2.3. Environmental and life cycle impact

As mentioned above, materials savings are probably the most important aspect to consider in the EPSs' life cycle. PECTA work performed by Machtinger et al [39] has investigated this aspect in a study of consumer chargers (i.e., EPSs). Typical GWP savings due to smaller components are shown in Table 4 (from [28]).

Table 4: Impact of adopting WBG on design and on Global Warming Potential [28].

| Component | Typical application[1] (g) | Reduction in weight (g) | Global Warming Potential savings (kg $CO_2$-eq) |
|---|---|---|---|
| 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 |

[1] 65W USB-C charger based on conventional Si technology.

The study 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 laptop, using the electricity. Table 5 shows selected results for the laptop chargers, including the energy and GHG emissions savings.

Table 5: Impact of adopting WBG on the energy consumption, energy efficiency and Global Warming Potential of chargers in the use phase. [28]

| 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 |

Phost and Thoben [32] conclude that for the consumer market, GaN-HEMTs will already soon reach a predominant market share for USB power delivery. High power density can be achieved with GaN-HEMT devices due to their high possible switching frequencies.

Test performed by Machtinger et al [39] on Si and GaN based power supplies showed some interesting results in relation to the ecodesign regulation on external power supplies. The tests found indications that the power supplies are more efficient in lower voltage mode than in the higher voltage mode in the nominal output power for the chargers which could supply the rated output power at multiple voltage output modes. The explanation might be, that the efficiency requirements of the ecodesign regulation (EU) 2019/1782 only apply to the lowest voltage mode if multiple output voltages are available for providing the nominal out-put power. If a charger e.g. has two modes e.g., a 15 V mode and 20 V mode that can provide a nominal 30 W output power, then it should only meet the requirements in the 15 V mode. Such a charger was tested, and the 20 V mode was found to be less efficient than the 15 V mode.

The authors suggest that ecodesign regulation (EU) 2019/1782 on external power supplies could be improved by including a voltage mode other than just the lowest voltage rate at which the converter is declared for use to ensure further energy saving. than the current requirements of regulation 2019/1782 for external power supplies.

A rough estimate of total losses from mobile phone chargers for the global stock of 6.26 billion mobile phones would be calculated to 5.5 TWh/year. An increase in efficiency from 86.5 % as was measured for the typical Si-charger, to 91.5 % as measured for a typical GaN device would lead to savings of 40 % of the energy lost, or 2.2 TWh per year [39].

Another potential issue is the verification tolerance according to regulation (EU) 2019/1782. The tolerance is max 5 % compared to the declared *efficiency.* That is a huge variation on the losses, e.g. 100 % compared to an EPS with 95 % efficiency. The measurements from before mentioned article suggests that a verification tolerance in that scale is not necessary and other related product regulations have lower verifications tolerances (see section 6.3.3)

## 2.3. Uninterruptible Power Supplies (UPS) including for data centres

An Uninterruptible Power Supply (UPS) is a combination of an electronic power converter, switches, and an energy storage device (such as batteries) forming a power system. Its purpose is to maintain the power to a load in the case that the input power (the grid) fails. The present work concerns the power conversion steps but not the battery or potential improvements from battery technology shift.

UPSs are used in data centres, in hospitals, in the tertiary sector for power backup in offices, and in the production sector, when reliable power supply is critical to some degree e.g., for controlled closedown procedures.

In a UPS the AC utility power is first converted to DC for charging the battery and then, when the load comes from the battery due to power interruption, it is converted back again from DC to AC utility levels. Therefore at least two converters are necessary where WBG components could be relevant. For some special applications, only a DC supply is required, and the DC/AC converter can be replaced by a cheaper and more efficient DC/DC converter. This does not depend on WBG devices [2], although WBG devices may increase the efficiency further.

There are two fundamentally different system architectures of UPSs, depending on the specific applications' tolerance of short power breaks. For some applications, a power supply interruption range of 10 ms can be tolerated, for others the supply needs to be completely steady.

Short interruptions are allowed: Power can be supplied directly from grid by means of bypass switches, until it is interrupted. This means the losses from the AC/DC and DC/AC converters are only relevant in the few cases where the mains is interrupted, and for recharging the battery to compensate for the general discharging [2]. These UPSs are found in two main classes; Voltage and Frequency Dependent

(VFD) UPS or Voltage Independent (VI) UPS, where the VI class provides a little higher protection grade than the VFD class.

No interruptions are allowed: The UPS will continuously supply the power, even when power is available from the grid. In this operation mode, the load power flows through two conversion stages (or double conversion mode; AC to DC and DC to AC) continuously, with the resulting power losses [2]. Consequently, loss minimization is particularly important for this type of UPS. This type is also classified as Voltage and Frequency Independent (VFI) UPS.

### 2.3.1. Efficiency of UPS

UPSs for data centres in double conversion mode are on the market with peak efficiencies up to 97 – 98 %, but the efficiency decreases at part load. SiC MOSFET devices can increase the peak energy efficiency by more than 0,5 %-points and SiC devises enable efficiencies above 98 % even at part load down to 30 % [45].

Spejo et. al, [48], estimated improvement potential for UPSs for data centres by assuming that the efficiency is improved from silicon-based UPSs operating with an average efficiency of 96 % to SiC-based UPSs with an average efficiency of around 98.3 %. By assuming that the global yearly energy consumption of IT equipment in data centres is 201 TWH (without including data centres for cryptocurrencies) a global energy-saving potential by implementing SiC technology could be estimated at 4.6 TWh/year final electricity consumption for data centres. This is however only for UPSs for data centres.

Task 3 of the 2021 EELWP study [64] estimates potential savings for all the three UPS topologies VFI, VI, and VFD as well as all rated power classes and purposes – except the largest data centres and other above 200 kVA. This study reaches a savings potential at 7.2 TWh electricity consumption in the EU by 2030 by going from standard efficiency to BAT levels (as defined in the preparatory study [65]) and without changing battery technology. The EELWP study notes that generally, “*large UPSs in the range between 50 and 200 kVA are used in larger data centres and server rooms, as well as back-up for nonIT applications.*” The study’s base cases are separated in the four power ratings: UPS below 1.5 KVA, UPS from 1.5 to 5 KVA, UPS from 5 to 10 KVA, and UPSs from 10 to 200 KVA. The highest power class is assumed to contribute with 1.6 of the 7.2 TWh of final electric energy consumptions savings potential.

If the savings potential on a global scale for all applications of UPSs and not just for data centers, could be correlated with the EU potentials, would a conservative estimate be that a little less than the 1.6 TWh for UPSs from 10 to 200 KVA is consumed by data centers and similar applications. Hereof is it seen that maximum 20 % of the savings are from data centers, whereby the total saving potential will be at least five times larger. Extrapolating from the 4.6 TWh/year from Spejo et. al, [48] on a global scale would provide a conservative indication that 23 TWh could be saved globally for UPSs by changing to more efficient converter technologies.

The higher efficiency is a driver to get WBG-device based UPSs into large data centres, but perhaps a bigger driver is their potentially higher power density. The output power could increase by more than 25 % in double conversion mode at the same unit volume. It means that UPS systems can be integrated in medium voltage power distribution cabinets allowing more server racks to be installed in the same space [45].

The 2023 IEC White Paper [45] also refers that in average about 10 % of the power consumption in data centres is used for the power distribution system incl. for transformers and uninterruptible power supply (UPS) systems). Another 30 – 35 % is consumed by the cooling system according to the paper. Lower energy waste due to more efficient power electronics would also result in lower need for cooling, although the cooling power is also (or mainly) used for cooling the processors.

### 2.3.2. Current efficiency policies

No mandatory efficiency requirements have been found for UPSs, but voluntary policies exist with the *Energy Star* label in the USA and the *Code of Conduct* (CoC) in the EU. EU CoC has been issued by JRC in a second version for one and three phase UPSs for delivering uninterruptible AC power above 0.05 kW at 240/400 V [58]. Also, Energy star has established a set of minimum requirements to UPS and is now in second edition [61]. The specifications and tests of the EU CoC are based on EN IEC 62040-3 Ed.3, 2021 [59] while the Energy Star refers to the 2011 version of the IEC 62040 part -3, IEC 62040 -5-3:2016, ATIS-0600015.04.2010 and ATIS-0600015:2013 depending on the UPS category and rated power.

The efficiency of a UPS in a specific load point is simply defined as the power output/power input [62]. Several sources including the 4E EDNA 2023 policy report [60] observe that data centres are rarely operating at maximum capacity, and UPSs are therefore also most of the time operating at part load, which gives lower efficiency. For the same reason is the efficiency definition of UPSs based on average load profiles. The average efficiency of UPS according to the two schemes is calculated as a weighted average based on a load profile with the calculation [62]:

$$Eff_{AVG} = t_{25\%} \times Eff_{25\%} + t_{50\%} \times Eff_{50\%} + t_{75\%} \times Eff_{75\%} + t_{100\%} \times Eff_{100\%}$$

Where:

- $Eff_{AVG}$ is the average loading-adjusted efficiency,
- $t_{n\%}$ is the proportion of time spent at the particular n % of the Reference Test Load.
- $Eff_{n\%}$ is the efficiency at the particular n % of the Reference Test Load.

The average load profiles are defined in the standard and as regards Energy Star they depend on the classification of the UPS. EU CoC only considers UPS for AC output while Energy Star also considers DC-output UPSs. For both efficiency schemes depend the efficiency requirements on the rated power [61], [62].

The minimum efficiency requirements for UPSs for AC-output of respectively the EU CoC and the Energy Star are presented in Table 6 respectively Table 7.

Table 6. Efficiency requirements for EU CoC AC-UPS, elite requirements [58].

| Power Range, *P* (kW) | Performance Classification | | |
|---|---|---|---|
| | VFD | VI | VFI |
| $0,05 < P \leq 0,3$ | 91.0 % | 90.0 % | 85.5 % |
| $0,3 < P \leq 3,5$ | 94.0 % | 93.0 % | 87.5 % |
| $3,5 < P \leq 10$ | 95.7 % | 94.4 % | 90.0 % |
| $10 < P \leq 200$ | 97.0 % | 95.0 % | 91.5 % |
| > 200 | 98.0 % | 96.0 % | 93.5 % |

Table 7. Minimum Average Efficiency Requirement for AC-output UPS according for Energy Star [62].

| Rated output Power Range, $P$ (W) | Performance Classification | | | |
|---|---|---|---|---|
| | VFD | VI | VFI | Example* |
| $P \leq 350$ | $5.71 \times 10^{-5} \times P + 0.962$ | $5.71 \times 10^{-5} \times P + 0.964$ | $0.011 \times \ln(P) + 0.824$ | 350 W => $Eff_{avg} \geq 0.889$<br>1500 W => $Eff_{avg} \geq 0.904$ |
| $350 < P \leq 1500$ | 0.982 | 0.984 | | |
| $1500 < P \leq 10000$ | 0.981 - $E_{MOD}$ | 0.980 - $E_{MOD}$ | $0.0145 \times \ln(P) + 0.800 - E_{MOD}$ | 1500 W => $Eff_{avg} \geq 0.919$ |
| $10000 < P$ | 0.970 | 0.940 | $0.0058 \times \ln(P) + 0.886$ | 15000 W => $Eff_{avg} \geq 0.942$ |

$E_{MOD}$ is an allowance of 0.004 for Modular UPSs applicable in the commercial 1500–10000 W range. *Own calculations.

### 2.3.3. Market and technology development

The 2023 IEC White Paper [45] mentions a new development, that future data centres probably will utilise higher shares of renewable energy and more fluctuating prices to use the UPS units more actively for peak shaving. UPSs for data centres would be integrated into power systems rather than just serving as backup emergency power. At the same time the coming years might increase the risk of unbalances and fallouts of the grid, at least locally due to the current transformation of the power system, and the need for back-up power could be foreseen to increase.

Both developments could expand the usage and installation rate of UPSs including for smaller installations, and for commercial and industrial consumers generally. For smaller consumers including business consumers, where the efficient operation of servers is not key business, the awareness of energy efficiency would typically be less prominent than for large data centres. Again, from a policy perspective this shows the importance of reviewing the development, as a more extensive use could also lead to higher installation rate.

Task 3 of the 2021 EELWP study [64] finds an adverse effect for smaller UPS, where the increased use of laptops with own batteries instead of desktops means that power pass outs are less critical. Still, the EELWP study finds increasing numbers of UPS at all product application levels in the EU with an estimated growth in the UPS stock from 2020 to 2030 at 37 % - 39 % depending on product category. The annual sales volume is expected to double from 1.5 million units in 2015 to 3 million by 2040.

SiC is starting now to be used in ICT and data centres for HV DC, power supplies and UPS system. SiC will dominate in high voltage applications, while GaN will be the dominant power electronic device in applications at lower voltages (100 V – 650 V), DC/DC converters and power supplies [2].

As the ARM (Figure 4) shows, both SiC and GaN based UPS are available and for higher voltage rates, 1.2 kW SiC actually already has a predominant market share. Both SiC and GaN are relevant for UPSs and SiC MOSFET (650 V – 1.2 kV) and GaN HEMT (650 V) are expected to be the dominant devices for ITC and large data centres in the coming ten years.

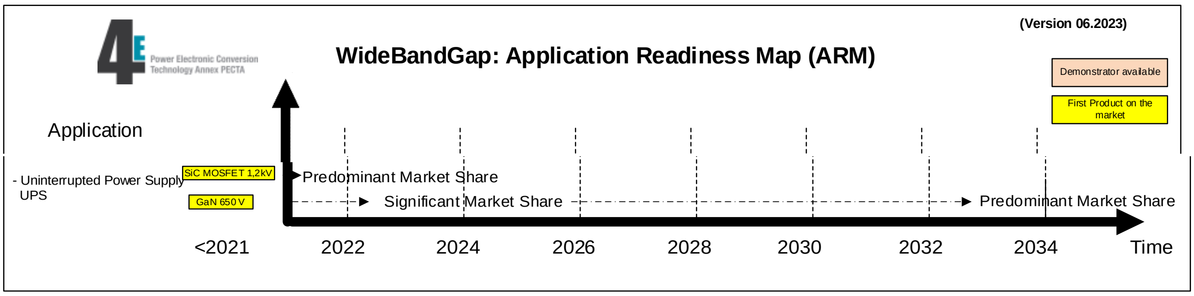

Figure 4. Extract of 6th version of the PECTA application readiness map for UPS illustrating that WBG based devices already have a predominant market share for higher voltage rates (1.2 kV, [32]).

## 2.4. EV charging stations / DC chargers

Electric Vehicle Supply Equipment (EVSE) are charging stations supplying power to Electric Vehicles (EVs). The chargers could supply AC or DC electricity power. If the EVSE provides an AC power source to the vehicle, then the vehicle’s on-board-charger (OBC) must convert the AC power to DC power for the vehicle’s battery. If the EVSE provide a DC power source for charging, then EVSE contains power electronic that converts the AC from the grid source to DC. Some DC OBCs are bidirectional and can thus facilitate supplying power from the EV to the ESVE as well.

The charging of BEVs is performed via AC wall boxes - typically private – or DC charging stations. The chargers are defined below according to [2]:

- Level 1: Charging from a 1-phase AC outlet and power normally below 3.7 kW.
- Level 2: Charging from a 3-phase AC outlet and powers between 3.7 kW and 22 kW.
- Level 3: Charging from a 3-phase AC outlet and powers between 22 kW and 43.5 kW.
- Level 3: Charging from a DC station with power in excess of 150 kW.

The EELWP EV pre study [19] defines the charger and connector types like this:

- Simple AC wall box connector (corresponds to Level 1 and 2 above).
- Smart AC wall box connector (corresponds to Level 1 and 2 above).
- Public “low” speed DC charger.
- Public “high” speed DC charger (corresponds to level 3 from DC above).

The DC chargers performs AC/DC conversion and are within the scope of PECTA.

AC chargers (AC source EVSEs) are not relevant for the current study and for PECTA since they do not convert the power and therefore do not use power electronics. It should however be noted that there are improvement potentials for those as well. It is related to e.g., off mode and idle mode operations. Energy Star set requirements to these modes, and the saving potentials roughly estimated in the EELWP EV pre study are based on these as well, as regards the AC charging.

EV on-board DC-chargers are not considered for this study since PECTA focuses on non-automotive applications. A note to this concerns losses in bidirectional charging. There is high interest in bidirectional charging where the battery of the EV can serve as part of a home power management system, levelling out peak prices or perhaps storing electricity from the consumers’ own PV installations. In this case the transportation unit is used for stationary applications as well but does not fall under potential efficiency requirements for stationary power electronics. However, as illustrated by the application readiness map (ARM) for automotive applications then WBG based and efficient vehicle to grid converters are on the market (Figure 5, [32]).

The materials used for EV chargers varies if it is an EV OBC or for wall boxes and charging stations. For bidirectional charging integrated into the vehicle as OBC is SiC being introduced, but also wall-mountable are introduced with SiC MOSFETs [15]. GaN HEMT devices are used in automotive backup DC/DC converters for OBC. For high power DC/DC converters, SiC MOSFET solutions are used now, and GaN is expected to be used later, when reliable 1200V devices are available as also illustrated by the application readiness map for automotive applications (Figure 5 and Figure 6,[32]).

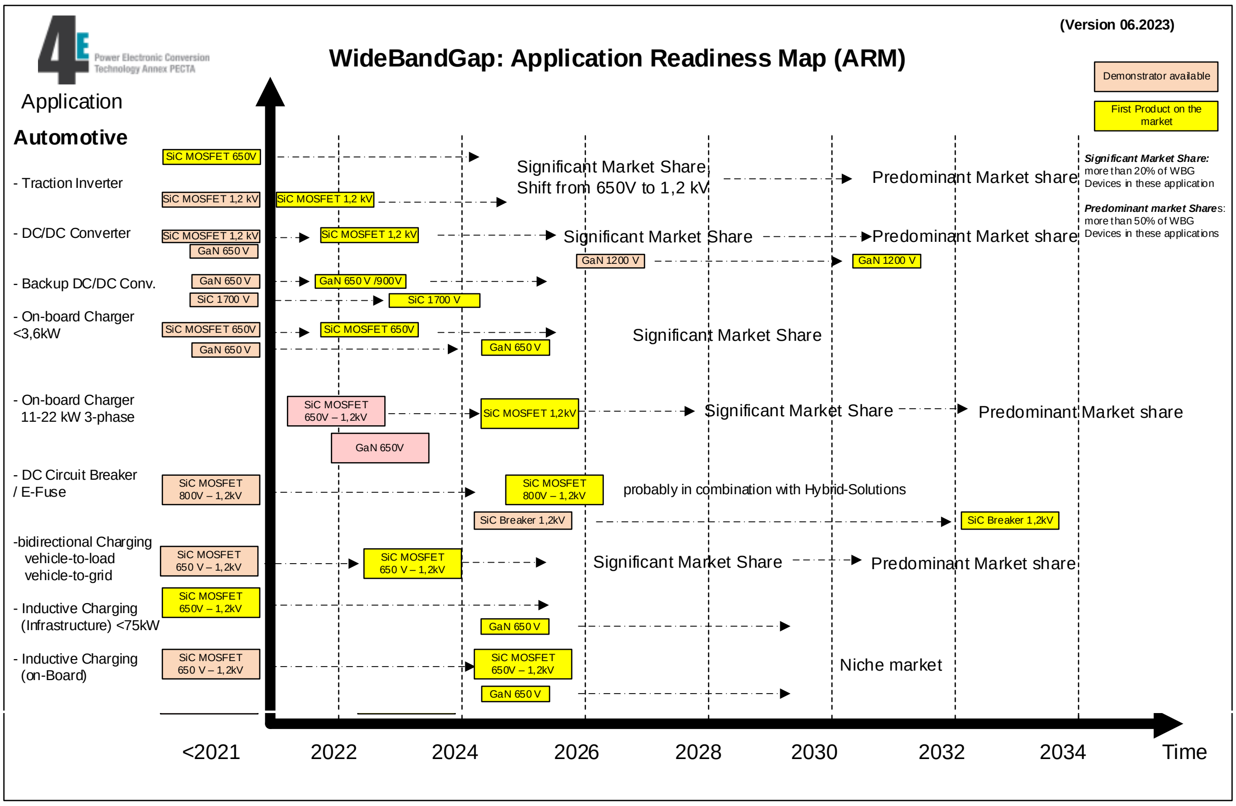

Figure 5. Application readiness map of WBG for automotive (extracted from [32]).

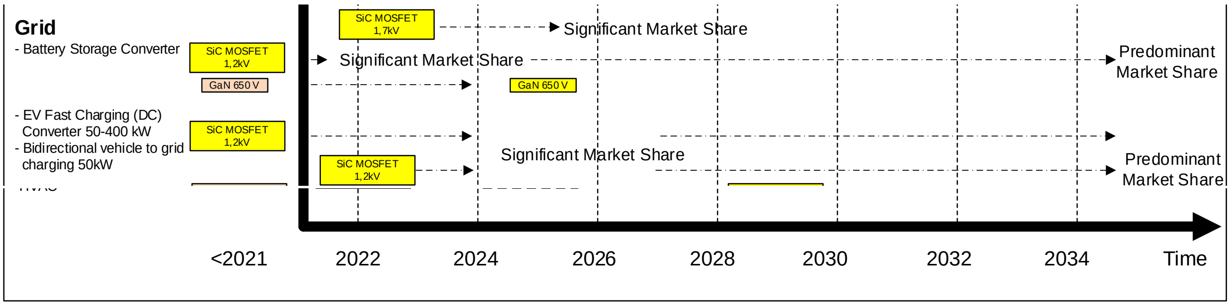

Figure 6. Application readiness map of WBG for grid/vehicle applications (extracted from [32]).

### 2.4.1. Market and technology development

Globally, IEA Global EV Outlook estimated that nearly 14 million electric cars were sold in 2023 and that from 2021 to 2022 the stock of public EV slow chargers (i.e., ≤22 kW) increased by 55 % to 2.7 million. Additionally, 850 – 900,000 public fast EV chargers are installed globally by the end of 2022 [49], [50]. On top of this is an even larger number of private slow chargers installed. The EELWP pre study on electric vehicle chargers estimate that around 47 million wall box chargers (home chargers) will be installed by 2030, compared to around 2 million in 2020. This number is assuming that there is one wall box charger installed per EV [19].

Most of the chargers are currently AC chargers, but for bidirectional charging or Vehicle-to-Grid (V2G) is DC conversion necessary also in small wall boxes < 22 kW. The recently released standard on EVSE communication EN ISO 15118-20:2022 will pave the way for widespread application of V2G [21]. This may point towards market expectations that EV batteries and thereby EV chargers and wall boxes will develop into a "power management hub". DC chargers for public and commercial chargers will be more common due to the quicker charging.

As regards test standards and efficiency for EV chargers' efficiency, the Energy Star has an efficiency program for EV chargers [51]. Energy Star only considers AC wall box chargers' idle mode and no-load losses, and not DC chargers and their conversion losses.

### 2.4.2. Efficiency of small EV chargers and savings potential

The PECTA report of Spejo et. al, [48] estimates the potential efficiency savings from off-board charging stations by comparing a SiC based EV chargers with 97 % charging efficiency with a Si based chargers with a charging efficiency of 95 %. A rough estimate finds potential energy savings of 0.8 TWh globally per year from EV chargers in 2021. This is based on the 16.5 million EV stock worldwide estimated in 2021.

The EDEL Working plan 2020-2024 study assumed the average efficiency of DC public chargers would increase from 85 % to 95 % [19]. Based on this is the potential saving from the EU stock of 46,6 million EVs estimated at 1,44 TWh final electricity consumption by 2030.

One interviewee, a researcher with particular knowledge of the general energy system[20]g, stated that *the main applications to focus on for power electronics are hydrogen conversions, converters for charging of electric vehicles and generally the HVDC distribution transformers. The latter DC/DC transformers are increasingly relevant to optimize due to the plans to convert a major part of the European energy supply to electricity and are already relatively efficient. However, the most important thing to work on is the DC/DC transformers and AC/DC inverters for EVs. Basically, all transportation energy will in the future be converted via these appliances, except potentially a smaller share as hydrogen*[20]g.

So, having the already high numbers and the exponential growth rates in mind sets some pressure on the implementation of efficient technologies for the charging infrastructure as quickly as possible.

One barrier for more efficient DC chargers is, however, that standards so far has been developed for safety and for communication protocols (e.g., ISO 15118 Road vehicles -- Vehicle to grid communication interface or plug and charge), but it seems that no metric or standard for testing and declaring energy efficiency of EV chargers are developed and published. This calls for the development of a test metric considering full and part load time, load classes, test conditions etc.

Charin, The Charging Interface Initiative (CharIN) e.V., published in 2023 a Whitepaper on DC bidirectional chargers that also considers efficiency of DC chargers [57]. The White paper covers the efficiency of the process from vehicle to grid, not AC/DC chargers' efficiency, but the group might be considering the other part as well.

## 2.5. Discussion

### 2.5.1. PV inverters

Overall, PV inverters are selected as a specific case for in-depth analysis due to the potential significant gains on decreased losses (20 TWh/year globally by 2021 increasing to potentially 270 TWh/year according to [48]), and there could be a “window of opportunity” to impact EU product policy for this application since the European commission is currently preparing requirements for PV inverters.

Further, PV inverters are an important product from an efficiency and environmental perspective due to the foreseen high market growth rates now and over the coming years, hereof for residential consumers and small-scale commercial and industrial customers which are not professional power producers. Since WBG based products in this area are BAT technologies that are rapidly maturing, and WBG device-based PV inverters are entering the market perhaps quicker than foreseen, both GaN and SiC product policies are recommended to reflect this.

As mentioned in section 2.1.5 the EU preparatory study for PV modules and inverters suggested two label approaches on PV system level, that were not possible for PV inverters. A third model could be a label or efficiency classification based on A, B, and C or IE1, IE2, and IE3 efficiency classes for the PV inverter alone. This is a model also know from the EU ecodesign regulation No. 2019/1781 on motors and variable speed drives [66]. The motor regulation defines the efficiency threshold values for motors based on three IE classes (IE2, IE3, and IE4), and requires that the IE class must be informed in various written materials, AND on the rating plate which is physically attached to the product.

For PV inverters, it could further be considered whether the different topologies mean that there should be different requirements for different inverter types.

### 2.5.2. EPS

For universal EPS energy labels could be considered as there might be a chance now to make consumers aware of efficiency of EPS. The shift that chargers are not being supplied per default with the electronics might end up with people having fewer chargers. In this case, consumers will be more actively involved in the purchase decision of EPS, and a focus on efficiency could be a more prominent decision factor if it is supported by relevant information.

The verification tolerance for market surveillance seems large and if they could be tightened this could lead to increased savings, from current more efficient EPS technologies.

It is suggested that:

- The requirements of chargers’ minimum efficiency could be tightened.
- Regulations for efficiency of different voltage modes could be included to ensure further energy savings.
- The potential for smaller verification tolerances is investigated.

### 2.5.3. UPS

UPS are most of the time operating at part load would they benefit from WBG devices and requirements. There are established voluntary efficiency labels and CoC and WBG products has already entered the market and are in the process of establishing a predominant market position. However, both efficiency programs, especially the EU CoC, request efficiency levels well below the current BAT products.

At the same time the market for usage of UPS could be foreseen, especially of with double conversion mode for peak balancing which gives high operating times, could be foreseen to increase during the coming years. Therefore, both current voluntary schemes may be relevant to develop further. To ways to go could be:

1. Strengthen the requirements; if the BAT levels could be better reflected the average efficiency could be closer to 98 % for double conversion mode UPS (VFI UPS)

2. Transform voluntary requirements into mandatory requirements. This also means that mandatory requirements could be established relatively quickly, and with future tiers considering WBG-device based UPSs.

Since the two different voluntary efficiency schemes already exist it could be considered to align the product classification and efficiency metrics of the two. This is not the same as requiring the same minimum efficiency level but using the same metric, test method, and classification would make the test regime and marketing based on efficiency development more efficient, thereby increasing the accessibility to the voluntary efficiency schemes and improve the competition.

Test methods for UPS are established, and both the EU CoC and the Energy Star labelling schemes have existed for more than a decade. Both are fully (EU CoC) or partly (Energy Star) based on the EN/ISO 62040-3, although not the same edition. So, this indicates that test lack of standards is not a barrier. However, test tolerances might be a barrier for requiring the efficiency levels going towards 98 %, something that could be investigated further.

It would be relevant to analyse the savings potentials more in depth.

As regards potential PECTA work with UPS, this could be coordinated with the 4E EDNA which works with the efficiency of data centres where UPSs are important components.

### 2.5.4. EV chargers

For EV chargers the technical development of WBG is already progressed enough to count the improvement potential into coming product regulations like the foreseen EU regulation.

On a general level there was consensus among the interviewed that regulations and policies should not select specific materials or technologies. Some pointed out that policies, or PECTA work, could help in improving knowledge about which technologies, like WBG in general or more specifically GaN or SiC, are relevant for which situations and applications.

# 3. Policy measures and initiatives in focus

The current section presents different policy measures, their applicability for different purposes, and timing, both generally and more product specific. The main focus is the regulatory framework of the European union, but relevant policies from other regions are also presented, although more briefly. More detailed presentations of the characteristics of different environmental and energy efficiency related product policies are available in [2] and [23], while Appendix 2 lists some practical examples of implemented WBG related policies and roadmaps.

The feasibility of policy measures depends on the development stage of the products, which could be classified as:

- Before commercialization (Innovation).
- Build-up / initial commercialization (Penetration enhancement).
- After initial commercialization (Consolidation).

Policy measures before commercialization could focus on supporting research and development. In the initial commercialization stage policies could focus on promoting the most efficient products on a voluntary basis. And when the market is more consolidated, mandatory requirements for products could be applied.

Crucially for deciding on potential product policies is to consider the following product levels:

- Device level: The component, semiconductor, itself. The more down to single components, the higher potential for horizontal coverage, but also risk that component efficiency comes at the cost of system losses.
- Module level: Meaning more application specific, allowing also targeted regulations.
- Product application level: Appliances or end-user equipment such as PV inverters, EPSs etc.

Stakeholders were asked to comment on this, and the general approach is that requirements should be on product application level. One interviewed component manufacturer explained that *we have discussed the issue internally. We found that the easiest approach would be requirements on device level but concluded that the impact could be small or non-existing. It is the overall integration of the components that defines how efficient the final product is*[20]c.

This leads to focusing on product policies on the application level, for which a regulatory framework is already in place, as it is in many countries and regions globally. One of the most developed frameworks are the European ecodesign directive and energy labelling framework regulation (see Appendix 2.2). The current report has high focus on these product policies.

## 3.1. Product regulations already in place targeting or covering WBG

Currently no EU ecodesign or energy label (EDEL) regulations has been based on the improvement potentials from WBG technologies, but several EDEL regulations have WBG relevance, as presented below.

### 3.1.1. EU product regulations: Ecodesign and energy labelling

EDEL regulations with high WBG relevance are:

- Power transformers (50 Hz) > 1 kVA, 3-phase however > 5 kVA (ED).
- EPS (ED).
- Electric motors (variable speed drives, ED).
- Air conditioners (SEER and SCOP requirements, ED + EL).
- Heat pumps (SCOP requirements, ED + EL).

- Heat pumps for central air condition (air-air + air-liquid) and high temperature chillers (seasonal EE performance, ED).
- Circulators (ED).
- Pumps (ED revision -> EEI).
- Servers and data storage products incl. for their power supply units (ED, revision).

Where ED means ecodesign and EL means energy labelling. Additionally, some potential new regulations in the pipeline could be targeting WBG technologies, first PV inverters are presented in Table 8.

Table 8: Ecodesign regulations relevant for WBG products and timing of reviews (estimate 2023).

| **Subject and title** | **Planned adaptation date (indicative)** |
|---|---|
| Ecodesign for PV modules, inverters, and systems, new product group | 2025 |
| Ecodesign for external power supplies (EPS, AC/DC), revision | 2024/25 |
| Electric vehicle chargers, new product group | 2026 |
| Ecodesign for electric motors and variable speed drives, revision | 2025 |

### 3.1.2. WBG related product regulations worldwide

Also, outside the EU there are examples of WBG related product regulations that include minimum requirements.

For Australia and New Zealand, in NZ according to Energy Efficiency (Energy Using Products) Regulations 2002, these are e.g.:

- Distribution transformers (MEPS).
- Dry-type distribution transformers (MEPS).
- External power supplies (MEPS).

Japan has regulations on:

- Power transformers (MEPS on avg. yearly energy consumption).

India has regulations on:

- Distribution transformers: Mandatory Star Labelling informing of total losses at no load, 50 % load, and 100 % load, and energy label with star rating (revised 2022). No. BEE/S&L/DT/01/22-23.
- Solid State Inverters (SSIs): Voluntary Star Labelling on SSIs for 12 Volts DC storage batteries. The scope includes rated output between 250 VA to 2000 VA for continuous output. Includes no-load loss test, output power factor (> 0.8), and efficiency at nominal load > 83 % minimum for 1 star and > 91 % for 5 stars.

### 3.1.3. Other examples of product policies worldwide

- Voluntary labels (in contrary to the mandatory labels).
  - Energy: Energy star (CA, CH, JP, TW, US), JIS Energy saving Labelling Program (JP retailers).
  - Other environment: Nordic Swan, EU Ecolabel (EU flower).
  - Average minimum requirement.

  - Weighted average of all products sold on a market should exceed a threshold value
- Japan Energy Conservation Law for a several products.
  - Voluntary minimum requirements.
  - The business commits themselves.
- EU ED for printers and scanners (voluntary ecodesign).
- Product ranking.
  - TopTen (20 countries worldwide).
  - Japan TopRunner: Best product at the time of entry into force is the level for "top runners" until revision. Part of "multistage rating system" with mandatory EE info, MEPS, and minimum average market efficiency (and a label).
- Green Public procurement.
  - LLCC requirements.
  - Environmental minimum requirements.
  - Technology ban.
  - Compliance with voluntary labels, etc.

# 4. Drivers

PECTA a report by Makoschitz [2] points already in 2020 towards some of the main benefits from WBG technology, and these were indeed confirmed during the stakeholder interviews [20].

The main technological driver is obviously the potentially low energy losses with the multiple derived added benefits:

- Less material consumption.
- Smaller devices.
- Less troubles with over-heating.

With smaller devices the material consumption is smaller (although not yet fully harvested due to higher production waste), and handling might be easier. Alternatively, it is possible to get more power in the same standard modules.

Additionally, a component supplier informed [3] that further benefits could be:

- More silent operation, for two reasons. First, the lower (heat) loss means potentially smaller, or no, cooling fans. Secondly, reduction of audible noise in magnetics due to the potential operation at other frequency band at higher – non-audible – frequencies. For power drives for compressors e.g., this could help minimizing noise problems of heat pumps.
- Higher thermal conductivity (SiC) leads to improved heat spread and less risk of hot spots, which improves the lifetime and enables simpler component design.

There was consensus among the interviewed people, that the main technological drivers are potential benefits from low losses, as well as the multiple benefits from less material consumption, smaller devices, and less troubles with over-heating. Consequently, the technologies that are being introduced and taken up by the market most quickly are for applications where the combination of weight, volume, and efficiency is important.

This is primarily the case for mobile and portable applications, ranging from consumer IT (GaN) to automotive (SiC) applications. This is in line with the current PECTA work, although the development seems to be even more than predicted, especially in EVs where several manufacturers has announced or are already using SiC power electronics with significant gains on range.

For applications where only one of the parameters, e.g., efficiency is important, the development will be slower or in need of support. One interviewed industry representative[20]c, however, pointed to PV inverters where (at least for large-scale PV systems) the power production is the most important parameter. Hence the utility market moves towards high-efficiency (SiC) inverters.

So, it seems, that product requirements of the energy efficiency of PV inverters could be expected to have the largest impact on inverters for residential and small-scale commercial PV's, including the replacement at the end of life of the current stock of PV-inverters.

Savings from different WBG components depend on load profiles. An important question for designers as well as legislators therefore is, whether the product operates at full or part load mainly? That means that *in automotive the product is mainly operating at part load and can gain from GaN potentially higher efficiency at part load. In industrial applications the products are typically operated at nearly full load, and the benefit from GaN components is lower or perhaps non existing. They might even provide lower efficiency than Si components if not designed properly. SiC has better efficiency at full load*[20]c.

SiC is becoming increasingly popular, and therefore one of the interviewees concluded that *no pushing is needed* [20]d. However, the same and another interviewee noted, that *it is also very important that the* *industry knows when the different products (Si, SiC, or GaN) should be used. It was therefore suggested that it could be a task for PECTA to support with information about when to use which materials.*[20]g

## 4.1. Refurbishment / retrofitting of power devices

Traditionally refurbishments are considered a barrier for product policies because spare parts including power electronic should be backwards compatible. But power supplies and drives are products with standards specifications regarding power range, frequency, AC/DC, intended environment, etc., so it may not be so difficult to obtain backwards compatibility.

One industry interviewee explained [20] that for most consumer electrical devices it would not be a problem to design new WBG power supplies that could function as spare parts for older power supplies. They are developing standard power electronic packaged (power supplies, drivers) for a range of consumers products, and they fit into old products. This was backed up by a university interviewee who considered it to be *a matter of power, current, and voltage requirements from which products with relative standardised specifications can be matched the application*[20]g.

## 4.2. Prices

For automotive, the properties of WBG itself is a big driver due to lower losses and less expensive passive components and cooling equipment. For consumer products like refrigerators and washing machines there are not the same drivers. The manufacturers get benefit from lower prices from traditional Si based components compared to WBG based components, while the end-user will benefit from less costs for energy consumption. *Overall, we see*, explained an industry representative, *that the market by itself develops towards higher energy efficiency. WBG components have high prices – but in applications where the need for cooling and passive components can be reduced, the drive is bigger*[20]b.

Another explained that *GaN will continue to be more expensive than Si for some years, so clear customer benefits are needed, and these are higher power efficiency and power density. The higher the switching frequency, the less use of material and smaller dimensions at higher capacity. With GaN we can have higher power density and higher switching frequency at lower losses than Si, and we can downsize remarkably* [20]f.

## 4.3. Other technical aspects

### 4.3.1. Audible noise

Audible noise from power converters or inverters depends on the switching frequency. WBG materials have a wider span in switching frequencies than Si components and some interviewees noted that WBG materials could minimise noise. One interviewee explained that *in terms of audible noise these offer new opportunities like using very fast components for which the switch frequency can be modified to eliminate overtones*[20]c. Another interviewee mentioned that *DC/DC converters that are using high frequency transformer can create a "ringing effect", which also create additional losses. So, using correct driver and filters in the drive section is very important for accurate design*[20]g. The case was specifically for EVs but is a general mechanism as well.

It could be considered to further investigate audible noise and whether this is a relevant subject for policies. Having in mind that more and more power consumption goes via power electronics, that noise is an issue particularly for some HVAC products, and that good or bad sound design and sound management can influence the sound characteristics of these products. An example is a three-phase high power DC EV charger (360 kW) which has a noise level on up to 75 dB(A), and 95 % efficiency at full load [56].

### 4.3.2. Electric noise and power quality

Another concern is power quality – especially that the characteristics are different from those of traditional Si power electronic devices. Consequently, the interaction with other components in a system might show new problems. An example is motor drives where not all motors are ready for some types of high efficiency drives. Some motors can't handle the high switching frequencies, *but in fact, what they can't handle is the rapid voltage change, the steepness of the dV/dt curve, how quickly it changes from 0 to 1. This can give "common mode noise" and risk of generation of transients*[20]c. It could be considered to declare motors to be "VSD ready", but probably the problem mostly relates to old, already installed motors according to the interviewee.

### 4.3.3. Monitoring for predictive maintenance, diagnosis, and condition control

Several interviewees (including [20]d) and the IEC 2023 White Paper on power electronics [45] also point to the subject of data handling and smart systems. This is particularly relevant for industry products and e.g. trains and other automotives with high operating time. The idea is to bring sensors in power modules or to use the information and feedback gathered from the operation e.g. from gate drivers (integrated circuits), without use of sensors, for smart and predictive maintenance.

One interviewee[20]d explained that, *smart data handling even by getting data on device level goes hand in hand with the use of WBG materials. Interaction and smart systems are topics parallel with the purpose of enabling predictive maintenance and actively controlling the devices for lifetime, optimizing load distributions etc. That could be relevant in a process line or multiple drive lines for a train where it is important to know if redundancy is being removed or if some devices are stressed more than others to balance the system better to create more constant degradation or loading of the devices*.

The PINTA network, a partly EU funded traction market consortium, has worked with future traction systems for trains including SiC and electrical and data interfaces and smart maintenance [44].

In some (industrial) applications is onsite maintenance common, and here the market will also drive the development of new self-diagnosis methods [20]a, [20]d. *Generally online monitoring is becoming the new norm, and self-diagnostics as well are new developments, and it is yet to be seen how they will impact operation of power systems with power electronics, and if policy could also benefit from it*. Perhaps these technologies could change the approach to reliability and repairability requirements, perhaps by minimising the need for very specific spare part requirements? One challenge in such data handling systems is to get access to the relevant data without also getting access to business-critical data that the system owners do not want to share with external parties.

### 4.3.4. Temperature

The subject of temperature resistance and sensitivity is very relevant due to the high energy intensity in the products. Zhang et al [67] mentions temperature as "the most dangerous variable to keep under control".

One of the interviewees stated that on temperature control there WBG has an advantage Compared to silicon*; silicon carbide power semiconductors' device parameters such as the* $R_{DS(on)}$ *increase less with higher temperature. This allows designers to work with tighter margins or at higher temperatures in wide WBG power electronics designs, enabling extra performance*[20]f. Section 5 also concerns overheating.

### 4.3.1. Remember other WBG materials

GaN is logical for all high frequency applications, and GaN is a suitable for many applications. One interviewee recommended to not focus solely on GaN. *GaN is good, but have we really found a solution that is long time stable, or should we look at alternative materials for high frequency? EU policy should be actively supporting research of very high frequency semiconductors. If we* [EU] *don't do that, we are already behind – like on batteries*[20]d.

It could be a relevant further work in PECTA regie to start looking at other WBG high frequency semiconductor materials. Also, policies could support research and development on this subject.

# 5. Barriers

When considering barriers, several interviewees from universities and industries [20] pointed to the historical development of transistors and chips for power electronics and power modules. The Si IGBT based components, which are todays' standard products, have been developed during the last three decades. All power modules today are developed with the properties of Si IGBT in focus. This goes for the transistors and chips themselves; it goes for all other products categories, frames, and applications they are integrated into; and it goes for the production lines. It has led to the development of current standardised lines of components that fit together from a basic geometrical viewpoint, but also when electronic and electrotechnical properties are considered. These components are well known and have through multiple product generations had their real-life performance characteristics, weaknesses, strengths, safety, EMC, durability etc. tested.

From these considerations, two main barriers for the introduction of WBG products and product policies are:

- Reliability and the knowledge gap regarding it (see section 5.1).
- Lack of standardised components and product platforms (see section 5.2).

Other implementation barriers relate to power quality, capacity limits and production costs, resulting in higher prices of WBG components.

Overheating is one of the issues related to WBG products, but this is both an opportunity (potential driver) and a barrier since:

- Less losses give less heating and overheating problems in WBG modules.
- Smaller heat sink gives challenges with internal heat transport in the chip (esp. GaN).
- SIC has higher thermal conductivity.

## 5.1. Reliability

In the WBG community reliability has been discussed a lot, and from a policy point of view this could be a showstopper. These concerns stem partly from known issues, and from potentially unknown long-term behaviour, together leading to uncertainties on long-term performance.

This potential lack of confidence regarding performance makes it difficult to set energy efficiency requirements that phase out Si-based components/products, unless there are means to address this through new lifetime/durability test methods, complementary policies such as warranties, etc. To tackle this, current policies have supported research and development as well as standardisation work for test standards, but on reliability more is needed.

On the other hand, it is worth noting, that products are entering the market, and at high pace depending on the application. One industry source – a supplier of semiconductors – explains that *there were some QA issues with the early SiC devices, but this is not a problem now*. *Now everyone trusts the material, which is also a reason for the market growth.* [20]f.

The current knowledge and trust are to a large extend based on learnings from WBG based consumer electronics and EVs. SiC based power electronic is currently entering the automotive sector with increasing pace and this will continue during the coming years. Several interviewees mentioned that it will be possible to build on the experience and knowledge gained from that, but also that other products have very different operating conditions. Two main differences are that:

- Other appliances and industries have different use pattern and operating conditions.
- Usage time is different from sector to sector.

Products for industrial applications or e.g. PV inverters cannot always be compared in the case of reliability. The main difference is the use time. The use time of a vehicle can be counted in a few thousands of hours during its entire lifetime. PV inverters and power electronic for industrial applications are operated during full days, or even night and day, and their total operating hours can be counted in tenths or hundreds of thousands of hours.

One industrial interviewee noted that *relatively high efficiencies (higher than market standard today) can be achieved and with relatively cheap products. However, the risk is that these low-price high-efficiency products fail on other parameters, especially reliability and robustness*[20]c.

The interviewee further expressed concern that at the same time, *standards to serve as tests for compliance of potential reliability requirements* [specifically] *for WBG components are not yet developed. In the past the devices in the power electronic has just been replaced from Si to SiC, but now a full packaged adapted for SiC* and the standards are not developed to cover this change. *Basically, reliability tests are still done in almost the same way as for silicon-based power electronics. Reliability tests are still under considerations in IEC e.g., who has published a guideline but not yet a standard about which kind of tests that should be done. Other test standards are developed but for automotive applications, and the same tests cannot be used* [for industrial applications] *so we have to get these test standards developed*[20]c.

*Tests for robustness, reliability and repairability must be tailored to the specific application. Some of todays' power electronics will not only be used for the next 5 years but may be used for 25+ years. Regarding robustness, the test regime must consider the system, rather than the WBG device or component alone since it also depends on the control system. If it is configured with a driver that at times gives short power spikes, it might impact the operability of the product*[20]g.

An industry representative expressed some concerns, *that certain strict requirements to efficiency currently isn't possible to combine with high reliability*[20]c.

A researcher specialized in WBG materials expressed parallel concerns regarding reliability and whether the products and test methods are currently ready for testing of the products reliability. One concern is that *Si power conversion equipment builds on several decades of traditions, practical knowledge, product catalogues, assembly methods and component combinations that are tested and developed together.* Again, a message was that reliability concerns must be handled carefully[20]a. Same interviewee also has mentioned that *traditional reliability test can be performed for WBG devices also, but that the manufacturers as it is now will have to* [and are] *adding extra robust designs that will be more optimized in future*[20]a.

### 5.1.1. Reliability – components level vs system level

Robustness validation describes a process how to design, develop, manufacture and test electronic devices, components, and systems. It is a process based on the knowledge of the conditions of use (mission profile), the failure mechanisms as well as of accelerated models needed for accelerated tests. This means that the tests, with ECPEs words [12], are shifting from "test for standards" to "test to fail", which requires new test methods to be developed. Organisations like ECPE and JEDEC has taken this task up, but as an industry representative told there are still challenges: *One of the main challenges for larger industry power electronic products today is that there are not yet developed standards specifically to robustness of SiC for industrial applications. Authorities and organizations should work with these standards and the specific challenge that for industry the products are operating in hundreds of thousands of hours at close to full load. This is compared to automotive and consumer power electronics, that are operating in thousands or tens of thousands of hours and at part load*[20]c.

Same interviewee also explained how reliability and efficiency for WBG sometimes clash. *Generally, to get low resistance a higher number of chips should be parallel coupled. It will use more materials, but still less than compared to cupper. There is however an adverse effect that SiC chips are not yet uniform enough from the production (parameter variation), which in the end risks to decrease the robustness of the product*[20]c.

The European lighting ecodesign regulation has as one of the first ecodesign regulations covered robustness and fail test for semiconductor devices with long lifetime, and potential policy measures might be inspired from this. The regulation requires test of 10 devices. This could be possible for less costly products as lamps, perhaps also the smallest EPSs, but as a general approach for other power electronic appliances it would probably not be realistic.

## 5.2. Standardised components and component packaging

Changing from Si IGBT to SiC MOSFET (and GaN) based components is a goodbye to the Si-age and a welcome to the WBG age. Therefore, it is not just another one-in-one-out component shift but rather a paradigm shift. An interviewee phrased that this change *has the potential to reshape products and even the industry*, and added *To realize the full benefit from WBG based devices, the overall component architecture and geometry changes, everything known about humidity and temperature resistance, EMC etc., is new or uncertain*[20]c.

The current architecture is based on standard modules and packages, e.g. power modules where individual devices and components can be changed 1:1 if a better or cheaper component is developed or in case of supply restrictions.

However, this means it is more difficult to gain the full benefit from WBG components, since they are not by nature fully compatible with the existing components, module, and package architecture.

An example of one important issue explained by a supplier of chip and devices[20]f is that *the thermal path needs to be reconsidered in all packaging. This is due to the very small sizes of GaN devices and higher switching speed. The small dimensions make heat dissipation easier, but at the same time the lower thermal capacity from the small components could results in higher internal temperatures from the switching losses. Additionally, a faster control loop is needed to tackle potential short-circuit failures.*

*SiC components are somewhere in between GaN and Si components on the development state of packaging and integration of SiC devices and could be described as an evolutionary development* [20]f.

A component supplier considered it to be the most urgent task for politicians working with industry to take actions on these problems with compatibility between new and existing components. *In line with the European Chip Act, a WBG act should be developed and implemented, as soon as possible*. *The purpose of such an act should be to develop common standards and product architectures of power modules and systems. At first, the focus could be on SiC products, then later GaN products*[20]c. The motivation is that power electronics are a central part of many electric and electronic products in households as well as industry. So, it is crucial to prepare the industry for the WBG age to ensure competitiveness and local production of central power components.

In Europe, the EU Commission do support the development of WBG production, for example with the Horizon 2020 REACTION project, which aims to develop a European 200 mm (8 inch) SiC production line [4], and with the Important Project of Common European Interest (‘IPCEI'), which supports research, innovation and the first industrial deployment of microelectronics and communication technologies [8]. The support is mainly at the component level, but as explained above, it could be considered to supplement with activities on common standards and architectures of power modules and packages as well as integrated product design.

As regards GaN devices is the newly (2023) initiated All2gan project working with better new solutions for integration for GaN devices. The project is supported with 60 million Euro by the European Union's Chips JU (Joint Undertaking), 12 countries and national granting authorities as well as research, universities, and manufacturers.

In a WBG roadmap from Power America, a similar approach is suggested, called "Strengthening the Power Electronic Ecosystem" [5].

## 5.3. Shortage of materials

Already the 2020 PECTA report[2] mentions the barrier regarding supply of important materials. At that time the SiC base material was in focus mentioning that "shortages may occur when demand explodes", and that supply problems could slow down the development. Also, for GaN is there a potentially critical supply situation, as the world an particularly the EU rely almost on only one country (China). But the raw material Gallium itself is available (see also section 7.3.1).

One Asian (Japanese) manufacturer also mentions that not only raw materials could be problematic. *A barrier has the last years, 2021-23, been the supply situation due to a lack of materials. On SiC materials and devices there are suppliers from all over the world. But they need e.g. special gasses and there are very few suppliers of these*[20]b.

As examples of challenging process components are process gas for SiC: $SiH_4$ and $C_3H_8$ (propane). Gasses for chemical etching are typically various fluorine gasses and additive gasses including argon [46],[47].

Conclusively, is suggested to consider investigating where the weak and vulnerable spots in the production are for the full supply chain, and which helping compounds / gasses that have weak supply chains. This is a proposal for PECTA and for national and regional associations and authorities. National effort could be put into strengthening potential weaknesses in the supply chain for WBG material and device production. Globally, this is also essential for keeping the pace of the transition to more efficient power electronics.

## 5.4. Economy

As with other new technologies being introduced, the cost, in this case financing cost, is a barrier inspite of advantageous long-term economy. *Currently this is worst for GaN products as SiC are MOSFET, which are relatively cheap components, while GaN HEMT transistors are more costly, as it is now*[20]a.

The adaptations of packaging and system architecture as explained in section 5.2 impacts the prices according to an industry interviewee resulting that *the packaging of GaN solutions will be more expensive in the beginning, but in the long run the prices will come down. GaN components have the potential to become cheaper than SiC components*[20]f.

## 5.5. Education

A subject that has not been touched in the PECTA work packages so far, is the lack of WBG relevant competences in engineering and among skilled labour. Nevertheless, this subject was raised independently and unprovoked (i.e., it was not an interview subject) by many of the interviewees. Also, during the PECTA Final panel debate at the EPE'23 conference in Aalborg in September 2023, this subject was raised, and it is highlighted in the 2023 IEC White paper [45]. The general message is that it could be a major showstopper for WBG development and implementation that we need skilled and educated people in this business. I.e. in power electronics generally and even more specifically in WBG power electronics.

It was explained that all over Europe and Asia, there are "huge troubles" in regard to filling out open positions. The semiconductor area has a lack of engineers with electrotechnical skills. One explained that *we really need the people who can all make the links to the physics and the hands-on-work. Someone with a basic knowledge and theory. Energy has a boring reputation but now it has become crucial for our development. It is a side topic that falls in between a lot of other subjects* [in the educations]. *There are a lot of good candidates on the IT part, but we are missing the link to the basic electrical engineer*[20]d.

This lack of experts in power electronics and systems in all branches of the educational system (from technicians to university candidates) would be an(other) important subject for policy to target.

## 5.6. Discussion

Despite expressed concerns regarding reliability, it is worth mentioning, that the manufacturers have already brought products to market, and it is fair to conclude that they rely on them! The manufacturers manage to test the reliability of their products using traditional testing methods, including WBG products, and to produce products that they trust.

So, the standardisation situation regarding reliability could be improved, but we can go with what we have. Products will not fail (generally), but perhaps be over-dimensioned, and as manufacturers and users are gaining confidence in the WBG based product, the limits will be pushed. The following conclusions could be drawn:

- Reliability properties cannot be handled by policy on device level, it must be on product application level – or potentially power module level.
- This could be addressed through improved lifetime/durability test methods – but the current situation is not a showstopper.
- Complementary policies such as warranties are possible and could be considered.

Requirements may have to be adjusted depending on operating conditions due to reliability concerns e.g. based on:

- Operation environment (ambient conditions).
- Industry, automotive, residential, indoor/outdoor, clean/dirty, humid/dry, ATEX etc.

This could be problematic from a regulatory point in the case of product policies involving MEPS and other minimum requirements, since it involves the “taking into use” situation, rather than the “placing on market” situation. But is does not need to be a problem for policy.

# 6. Test standards and methods and their impact on policy

Technical product standards are essential prerequisites for companies to offer products based on compatible, geometric interphases, measuring methods etc. and for authorities to base product policies on.

Standardisation seems based on the input from interviews as well as other PECTA work to be an important measure for WBG in various ways, both globally and on national/regional scale. The identified needs are standards on:

- Reliability and durability test methodologies. Not just on the device level, but also on the product application level.
- Efficiency test methodologies to support the part load benefits of WBG and to cope with uncertainties when efficiencies are getting high/losses low.
- Product architectures of power modules and systems to gain the full benefit from WBG components when not compatible with the existing Si component, module, and package architecture.
- Product categorisation rules (PCR) and material efficiency (ME) aspects of WBG to support the calculation of product environmental footprint (PEF).

Table 9 provides an overview of some of the standardisation aspects. The last item regarding PCR is not considered for the current project. ME and PEF is described later in chapter 7.3, however without analysing the standardisation situation.

Table 9 Overview of standard situation for WBG products. Specific reliability standards for EPS, UPS and EV chargers were not identified, but no in-depth investigation was performed. Not application specific

| Application\Parameter | 6.1 Reliability | 6.2 Efficiency | 6.3 Modularity |
|---|---|---|---|
| PV | EN/IEC and EN/ISO | EN | No specific WBG standards |
| EPS | - | EN | |
| UPS | - | IEC and ATIS | |
| EV Chargers (wall box) | - | Lacking! | |
| Not application specific | JEDEC guidelines on device level | JEDEC guidelines on device level | ALL2GaN-development and existing standards |

The PECTA report of May 2020 report [2] mentions that harmonized approaches to measuring and declaring energy efficiencies are currently lacking, which is making it difficult for users to compare the efficiency of devices based on different technologies.

## 6.1. Background

Three main organisations working with standardisation and guidelines for power electronics including WBG power electronics are ECPE – The European Center for Power Electronics –, IEC – International Electrotechnical Commission -, and JEDEC – Solid-state Technology Association. ECPE is working with information and knowledge building e.g., developing guidelines on WBG technologies, while the two others are standardisation organisations. They are also - especially JEDEC producing guidelines.

The Joint Electron Device Engineering Council (JEDEC) has developed guidelines and standards for SiC and GaN power electronic devices. After the PECTA report from 2020 [2] have the JEDEC subcommittees 70.1 and 70.2 on GaN and SiC launched several new standards and guidelines improving the standardisation framework for WBG devices [11] (listed in Appendix 3). ECPE has published guidelines on SiC. As regards IEC is it the technical committee, TC47 that concerns WBG products.

The WBG related guidelines and standards from the organisations concerns primarily reliability issues. The standards for determine WBG devices energy efficiency are still generally missing, in-spite that the potentials for improved energy efficiency is exactly one of the main parameters for WBG semiconductor devices.

On the other hand, existing standards on application level can also be used for WBG products for the same purpose. Euro efficiency of PV inverters is one example. These efficiencies are both presented on device and on system level. The question is if test standards for energy efficiency of WBG devices already exist, just not being publicly available nor widely approved and accepted. This could be investigated further, as they could serve as starting points for a quick development of officially published and widely accepted standards.

The interviewees had differing views on how the lack of standards impact the development. One of the interviewed manufacturers explained that, *from a power device perspective a lot of the issues are similar* [between Si and WBG]– *especially for SiC devices. The production uses the same processes, except that SiCs are more chemically and mechanically robust.* And added that, *ECPE's guidelines could provide a good start for standards, e.g. to build the current missing link between the electronic that controls the semiconductor and the conductor itself*[20]d.

Specifically, on product application level the test standards need more development, but this is a matter related to the further optimisation of the products to lift them to the next level and should not stop the implementation of WBG products for practical applications. And already now there is well developed set of test guidelines for specific tests on device level which could be developed into standards for some product applications, but not for all.

## 6.2. Reliability

*In future, tests for robustness, reliability and repairability would need to be adapted for the specific application. Some of todays' power electronics is not just used 5 years but could also be used the next 25+ years which also might push for further development of reliability test. Regarding robustness the test regime must consider the full system, rather than the WBG device or component alone since the performance of a device also depends on the control system. If it is configured with a driver that sometimes gives short power spikes, it might impact the operability of the product*[20]g.

One point that needs observation, related to test standards is the temperature set. GaN and SiC can't necessarily be tested at the same temperature set as Si IGBT. This was a message from an industry interviewee who also mentioned the importance of getting a full set of performance parameters of power chips at different conditions[20]f.

The section below mentions reliability related standards for the four product applications.

### 6.2.1. Application specific test standards

**PV Inverters**

For PV inverters specifically, the following reliability standards exist:

- Reliability PV Inverters: EN/IEC 62093:2022 Photovoltaic system power conversion equipment – Design qualification and type approval. Does not cover inverters fully integrated into PV modules.
- Reliability: EN/ISO 62093 Balance-of-system components for photovoltaic systems Design qualification natural environments.

**EPS, UPS, and EV chargers**

No reliability standards were identified for EPSs, UPSs, and EV chargers. However, since PV inverters where the main priority of the present work, a more extensive search might reveal applicable standards.

### 6.2.2. General test methods

The JEDEC guidelines present a number of methods for testing reliability on component and device level. See Appendix 1.

A more detailed review of reliability test challenges is done by Zang, Ianuzzo, and Christiansen [67].

## 6.3. Efficiency

The section below mentions efficiency related standards for the four product applications.

### 6.3.1. Application specific test standards

**PV Inverters**

- Euro efficiency of PV inverters: *EN 50530 /A1:2013 Overall efficiency of grid connected photovoltaic inverters* provides measuring methods for efficiency of MPPT (Maximum Power Point Tracker) inverters. CENELEC. The standard is based on IEC 61683.
- IEC 61683 "Photovoltaic systems – Power conditioners – Procedure for measuring efficiency

**EPS**

For external power supplies (EPS) is the following harmonised standard relevant for energy efficiency:

- EN 50563/A1:2013/A1:2013 External a.c. – d.c. and a.c. – a.c. power supplies – Determination of no-load power and average efficiency of active modes.

**UPS**

For uninterruptable power supplies UPS there exist several standards

- For AC-output UPSs, International Electrotechnical Commission (IEC) standard:
    - *IEC 62040-3:2011, Ed. 2.0, Uninterruptible power systems (UPS) - Part 3: Method of specifying the performance and test requirements*, Section J.2.
- For High-voltage Dc-output Datacentre UPSs (output voltage greater than 60 V), International Electrotechnical Commission (IEC) standard:
    - *IEC 62040-5-3:2016; Uninterruptible power systems (UPS) – Part 5-3: DC output UPS – Performance and test requirements*, Annex F.
- For Low-voltage Dc-output UPSs/Rectifiers (output voltage less than or equal to 60 V), Alliance for Telecommunications Industry Solutions (ATIS) standards:
    - *ATIS-0600015.2013, Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting – General Requirements*.
    - *ATIS-0600015.04.2010, Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting DC Power Plant – Rectifier Requirements*. Used for Energy Star

**EV chargers**

For EV chargers, no test standards regarding energy efficiency were identified (see also section 2.4).

### 6.3.2. General test methods

The JEDEC guidelines present two methods for testing switching losses from SiC respectively GaN devices, and a method to threshold voltage of SiC MOSFET devices. See Appendix 1.

### 6.3.3. Test and verification tolerances

An important part of proficiency testing is obviously accuracy and verification tolerances. An interviewee from policy side stressed the impact of the test tolerances for energy efficiency in deciding requirements. Especially when energy label classes are considered, must the label classes' efficiency span be aligned with test tolerances. For PV inverters e.g., an energy label was found not feasible due to the test tolerance was conflicting with the steps on the label scale[20]e. The low losses of the WBG devices seem to challenge traditional methods for testing of components and more accurate test methods for high-efficient power electronics could be a subject for development.

Test tolerances, variability and reproducibility hinders stricter requirements and energy labels on power electronic products, as exemplified by the PV inverters (section 2.1.3).

Verification test tolerances on different WBG related products could be to see if the levels are aligned. If they are not, there might be basis for investigating why and if the verification tolerances could be decreased. Examples from EU ecodesign are external power supplies (EPS), power transformers, and variable speed drives (VSDs) for motors, from which the verification tolerances for market surveillance purpose are presented below:

- EPS regulated by (EU) 2019/1782: Max 5 % verification tolerance compared to the declared *efficiency.*
- Power transformers regulated by (EU) 548/2014 transformers: Max 5 % verification tolerance compared to the declared *loss* defined as load and no-load losses where both losses are subject to the tolerance.
- VSDs regulated by (EU) 2019/1781: Max 10 % verification tolerance compared to the declared *total loss* [66].
- PV inverters Euro efficiency: Accuracy compared with loss *and* efficiency:

  Max deviation $=\pm 0.2\cdot(1-\eta)\cdot\eta[\%]$.

  This is not a verification tolerance, but a verification tolerance could be based on the same method.

**Zhu** et al [33] present in a PECTA report on loss measurements of WBG-based devices a methods for measuring low losses of WBG components by a calorimetric method. This method was verified for power range from 20 mW to 10 W with an accuracy of 5 % of the measured losses. The method was developed and used for analysing a complete losses breakdown on internal losses of GaN devices but this is not used for efficiency test on product application level. A calorimetric test method however, is also part of IEC 61800-9-2 for efficiency testing of motor power converters.

## 6.4. Modularity

Examples of issues to tackle for GaN devices and components in the integration and packaging are[20]f:

- Cycle to cycle control. Faster switching means more control.
- Minimize parasitic loop-inductances.
- Protection issues.

The interviewees mentioned that there is an urgent need for standardisation of the architecture of power modules to get the full benefit from WBG. Now, the current known architectures and standards are used and apparently slightly adapted for WBG devices, but will this change in future. Manufacturers will waste money on developing own solutions if no common standards are decided. The ALL2GaN project is working with modularity of GaN products.

## 6.5. Discussion

Standardisation seems to be an important measure for WBG in various ways both globally and on national/regional scale. Review of the standardisation situation showed that:

- As regards reliability are standards and guidelines on device level relatively well developed.
- On product application level are the standards currently based on Si devices. They are applicable but not optimal.
- Test standards could be further developed for reliability tests of product applications with WBG components.
- Efficiency tests are available on product application level, except for EV chargers. They are not adapted for WBG products, however.
- Generally, standardisation of efficiency measures and at device level and to some extend also module level at are not defined yet. So, each manufacturer does at his own view measure and declare. Engineers therefore cannot be sure that they compare products based on the same scales when designing products.
- The measuring tolerances in the current regulations and standards are relatively high compared to the low losses of WBG based product applications.
- Efficiency test methodologies to support the part load benefits of WBG and to cope with uncertainties when efficiencies are getting high/losses low.
- Product categorisation rules (PCR) and material efficiency (ME) aspects of WBG to support the calculation of product environmental footprint (PEF).
- Product architectures of power modules and systems to gain the full benefit from WBG components when not compatible with the existing Si component, module, and package architecture.

As section 5.1 showed, it seems fair to conclude that despite the lack of the current test standards on application level regarding reliability as explained in chapter 6, those standards developed for traditional Si devices could be applied for SiC and GaN device-based products as well. They might result in overdimensioning from manufacturers to compensate for uncertainties, but it is not problematic. In the coming years learnings from production and operation will be implemented and the products and standards could be optimized further.

# 7. Environmental, resource criticality, safety, and lifecycle aspects

That material efficiency is the new black in product design, was one of the take-outs from the EPE'23 PECTA final panel discussion, it is underlined by the coming EU regulation on sustainable products [52], and particularly for EPSs this is a main life cycle consideration as explained in section 2.2.3.

The comparison of WBG devices with classic silicon-based technologies on a life cycle perspective has only just started, but WBG-device based products seem to be ahead of Si based. Glaser et al. [28] have thoroughly described and analysed three life cycle stages of WBG technology from an environmental, energy efficiency and resource perspective:

1. Raw material supply and manufacturing of WBG components.
2. The design effects of WBG on applications and their use.
3. The End of life (EoL).

Some main conclusions are presented below.

## 7.1. Production of materials and wafers

Production processes for Si, SiC, and GaN are all energy intensive due to many purification steps of the metals. WBG raw materials are even more energy intensive in production than silicon due to more purification steps and larger production wastes and cassation rates e.g. due to defects from "micro pores" being developed during crystal growth. Also, WBG materials are extremely hard materials and the tools for machining the WBG wafers are subject to more wear due to the hardness of the WBG materials and higher pressures, and more power is necessary.

Processes are being continuously developed, and Glaser et al [28] explains that next generation SiC wafer production process could safe 70 % of the energy compared to the current normal. And the devices could soon be 90 %, compared with pure silicon-based devices with the same performance.

The resource consumption is potentially significantly lower for WBG than for Si components for same applications which is also commented by an interviewee: *With GaN we can have higher power density and higher switching frequency at lower losses than with silicon, and we can remarkably reduce the size*[20]f.

Because of the lower material consumption, WBG based products have a potential to save materials and minimize greenhouse gas emissions during productions. In the PECTA report from Glaser et al [28] compares the impact in the production phase from a typical USB-C charger based on conventional Si technology compared with a WBG based similar design. The transformer weight was cut by 20 % and the heat sink in aluminium by 50 %. All in all, the material consumption was cut down by around 28 %.

## 7.2. Use phase

The use phase concerns energy and for WBG the prominent difference is obviously the lower energy consumption from the improved efficiency of WBG devices. Additionally, the lower energy consumption and other properties of WBG based power devices gives potential reduction of the size of active and passive components and cooling equipment as added benefits as explained throughout the present report.

Glaser et al [28] also showed that approximately 50 % of the total GWP of consumer chargers is caused by the losses in the use phase of a conventional Si based charger for a laptop.

## 7.3. EoL - Recycling of WBG materials and (WEEE, RoHS, REACH)

J. W. Kolar discussed circular economy and electronic waste on the EPE'23 conference [70]. In 2021 52 million tons of electronic waste was produced globally according to *The Global E-waste Monitor 2020*.

By 2030 is it expected to increase to 74 million tons and further to 120 million tons of Global E-Waste by 2050. The challenges according to Kolar are increasingly complex constructions and very low level of repair or recycling (less than 20 % recycled). One solution to this huge problem is to design for "Circular-Economy-Compatible (CEC) Power Electronics". CEC electronics are designed with a multidimensional environmental set of parameters including focus on repairability, reusability, and recyclability combined with minimum consumption of scarce materials and product of toxic waste.

The EoL situation for WBG based power electronics was analysed in PECTA work by Glaser et al [28] basically concluded that SiC and GaN devices are currently not suitable for being recovered. Partly because of the - so far – low material amounts, but also because the materials are even more difficult to recycle than Si based devices. And already now the most of the printed circuit boards ends up in the WEEE waste stream and are considered "not recyclable". Not much work has yet been performed to enable recycling, so it might change in future. According to the finding from Glaser et al are the potential biggest for Gallium. The overall conclusion is that the low foreseen level of recycling of WBG based electronics call for effort on long lifetimes.

### 7.3.1. PEF – product environmental footprint

Customers are starting to require PEF certificates, and now also for scope 3 (supply) while before this was the case only on scope 1 and 2. However there are missing knowledge and data in this for SiC (and GaN too)[20]c.

### 7.3.1. Critical raw materials

The PECTA work from Glaser et al [28] finds based on various sources including [29] and [30] that for Si for SiC there are large quantities available. 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 has overcapacity and could double Si production. However, the Chinese energy is bound to the existing electricity mix of this country, which relies mainly on fossil fuels. Also, it is problematic to be dependent on one single source of raw materials as mentioned by some interviewees and as also concluded in the EU critical raw materials act [31].

For Ga for GaN, the situation is more difficult, however still with abundant Ga resources. In 2016 the annual demand for Ga in the EU was estimated at 40 t and it is expected to grow 17-fold i.e., to 750 – 800 ton by 2050 [31]. It might be worth noting, that GaN is also quickly penetrating the market for radio and Wi-Fi equipment, radar sensors and lidars [53]. Estimates on future GaN demands are obviously uncertain, particularly since it is not clear if the current shift to WBGs including GaN for power electronics is counted in, and the future needs could be significantly higher.

Ga is produced as byproduct from aluminium (primarily) and zinc. There is 210,000 to 700,000 tons Ga available in bauxite ores for aluminium production. Currently China has 80 % of WW production volumes of Ga, and EU's reliance on imported Ga is 97 %, which is why Gallium is rated as critical raw materials (CRM) by the European Union [17].

Gallium is although not a limited resource, still critical to ensure a stable regional supply situation. As a European chip manufacturer explains, *the production is limited. Gallium is a byproduct from aluminium production, so in principle, its criticality should not be high, but it is not produced in EU*[20]f. *We need the wafers to be produced in EU. It is a core topic of our energy and information safety to analyse and decide if we need independent sources for Si, SiC, GaN etc. in EU and how drastic we should regulate to have it. We may have to invest in both the material sources and in the materials processing and production* [of devices and components][20]d.

The EU CRM Impact assessment report points itself to a potential solution by mentioning that increased demand for smaller-volume materials that are byproducts such as Ga “can be satisfied (…) just by introducing an additional processing step on an existing site (…) of aluminium production” [31]. See also section 5.3 on critical materials.

## 7.4. Safety and electromagnetic disturbances

One interviewee noted that *with GaN and SiC we are entering frequency ranges where we will get electromagnetic disturbances, and this is something we should look at. For the power ratings we are looking at and for the switching speed we might be facing multiple risks, spanning from system failure to even health risks. We are entering new markets and environments for products with combinations of higher power and frequencies. High power and high frequency mean that there is a risk of bringing energy to other systems close by where we don’t want it nor expect it*[20]d.

The interviewee noted that this subject needs to be investigated including if perhaps the EMC or other regulations are already fully addressing it. *So far it has not been a necessary concern for industries or regulators, but we move to a new level so we will have to consider changing the rules in the future*[20]d.

It could be suggestion for further work in PECTA regie, and from policy side to support research to review potential health and safety issues related to the combination of high power-density and high-frequency power electronics. As first task, it could be considered to review in the EMC and LVD directives about how they foresee such new situations [68],[69].

## 7.5. Discussion

**Raw materials** (and wafer production). The call for action to minimising the criticality of GaN and SiC materials is urgent according to industry comments, and the EU Commission. This is probably a governmental task and would require financial support.

**E-waste.** It could be suggested as further work to analyse data and methods for data gathering for scope 3 for PEFs for SiC (first) and GaN (later). One specific problem in this respect mentioned by an interviewee is that it is important that there are not e.g. PFAS compounds in the components[20]c.

From a policy perspective this means that focus should be on support for research and development of recycling methods including by providing test facilities.

Another suggestion for further work is to start working on standards for recycling and reuse of materials and components.

The waste streams from WBG products are small compared to other waste streams, but it all adds up. The materials would start to be present in the waste streams within the coming 4-6 years, so from a resource perspective it is not an urgent task, yet still relevant due to the high energy consumption for materials production and with general efforts to minimize waste. It would be timely to initiate more research projects on this subject.

Another suggestion for further work is to start working on standards for recycling and reuse of materials and components.

**Circular Economy Compatibility**. The other side of minimizing e-waste is the design, and here e.g., task B suggest investigating the possibilities of the ESPR and the coming product passport. This is a research and development task that could be initiated immediately.  First by defining the task, e.g. if the CEC principle as presented by Kolar should be the goal. It is also a horizontal task, and the sooner solutions are developed, the less waste in the future.

**Safety**. The combination of electromagnetic disturbances and safety is an aspect that has not been presented previously. This may be part of the LVD and EMC directives scope, but the present author has not evaluated this.

From a policy perspective this means that focus could be on support for research and development of recycling methods including by providing test facilities.

# 8. Policy measures and timing

One of the interviewees[20]a had this message for policy makers: "*Be aware, the shift to WBG will come evidently. The question is how quickly, and who will control the market in the end*".

It could be added that, the quicker the change is coming and the better it is implemented the higher are the gains from improved energy and resource efficiency. The purpose of the present section is to conclude which specific policies could accelerate this development and their timing.

Another of the interviewees did not see any need for specific WBG product regulations. *Customers, manufacturers, and authorities have a common interest in creating standardised solutions e.g. on power modules and packaging structure. This is a subject for the industry and will be solved.* This interviewee did not see that policy has a role to play in this part of the market development, since in the end "*no matter how, it will be the bigger companies that makes the standard"*. On the consumer side, however, *are policies relevant and necessary to develop the market in the right way*[20]d.

On the question if regulatory support is necessary for driving development of power electronics, the answer depends on which improvement should be addressed. One interviewee, a power module supplier, found that *there is no need for regulatory advice in terms of materials use*[20]f. *But the market fails as regards improvements of energy efficiency, and product regulations are necessary to cut the worst* (least efficient) *products out of the market*, referring to experiences with the 10 years old EU minimum efficiency requirements for AC/DC power supplies for PCs (regulation (EU) No 617/2013 [55]). The supplier has customers with power supplies that are only 0.2 % point above minimum requirements to efficiency (e.g. 80 % efficiency at 10 % of rated output for single output (AC/DC) power supplies with rated output of more than 1 000 W]. The interviewee's company *could offer 2 % improvement for only a few cents, but these customers do not want to spend one extra cent. So, in this case the regulatory drive is needed for steady improvements of the products.* [20]f

As regards if product efficiency regulations should be component or application-based measures, there was consensus pro an application-based approach. An industry interviewee I[20]f recommends doing it on application level. *Some requirements on component level will be overshooting for specific applications and for other applications will it be relevant to require more than what would be feasible if the requirement is applied on component level*[20]f.

An interviewee from research considered that *a specific inverter can be used for more than one appliance if requirements to power level, voltage level and current level are comparable. The product requirements should be adapted to that rather than to specific applications, being it power transmission distribution, EV charging, PV inverters, or heat pumps*[20]g. Same person on the other hand also noted that *regulations can't go all the way down on device (power chip) level. For example, the very important aspect of losses is highly dependent on the interaction with the specific driver. For SiC or GaN devices alone, the losses from switching are less than for Si alone, but losses can also be created from the driver if the driver cannot control the turn-on and turn-off. So, drivers also play an important role and a well-designed driver for the power module plays a very important role in reducing switching losses*[20]g.

From policy side concerning product regulations, in the EU the Ecodesign for Sustainable Products Regulation (ESPR) extends the scope of the ecodesign regulation from energy related products to other products, and grants material and resource efficiency a more prominent role.

For product policies, one barrier to define the optimal scope of requirements is knowledge of the power capacity of the products in scope. This definition depends on predictions of the market development, e.g., of new SiC and GaN based power electronic products and transistors. And these estimates require reliable market information.

An interviewee from policy noted that *cost efficiency is to be considered ahead of all new regulations so from a regulatory perspective, the price* [of products and technologies compared with efficiency, ressources, design etc.] *is important knowledge*[20]e.

## 8.1. Policies targeting specific products

Timing:

- For PV inverters, the EU policy development is in its final stage in 2024, which means significant changes to policies, especially MEPS, based on new knowledge are difficult to take up. But on the other hand, these regulations might initiate similar regulations in other regions, that could be impacted.
- For EV chargers – stationary part; wall boxes and stations -, the work is starting up end 2023, and improvement of the efficiency of the power supplies are to be considered.
- For data centres, the work on a revision is starting by the beginning of 2024 and base cases are in the process of being defined.

The following tables presents suggested policy measures and their potential timing for the four product applications in focus of the present report. The suggested timing is the year of potential implementation or upstart of the measure. If it is coordinated with EU regulatory measures the timing is assumed based on best knowledge and expectations of the political process.

The suggested policies are as also presented by [2] are categorised according to:

- "Main type": Information, financial, conformity.
- "Nature": Supportive, voluntary, mandatory.

Table 10 lists suggested policy measures for PV inverters (see also section 2.1). For PV inverters, the policy development is in its final stage in 2024, which means significant changes to policies, particularly regarding MEPS, based on new knowledge are difficult to take up. Input that could easier be considered are e.g. suggestions to information requirements and items for a review clause. However, since other regions often follows the requirements and principles laid out in EU ecodesign and energy labelling regulations, when they are first of their kind, would improvement potentials for the expected regulations still be relevant to work with.

Table 10. Potential policy measures and their timing for PV inverters.

| **Potential policy measure (Action)** | **Explanation** | **Main type and Nature of policy measure** | **Potential action taker** | **Timing**<br>**Explanation on timing** |
|---|---|---|---|---|
| MEPS on PV inverter efficiency in two tiers, the second tier with improved Euro efficiency e.g. 97 % or 98 % | Working document suggests MEPS in one tier. Euro efficiency level at 96 % corresponding to average efficiency or a little below which is a reasonable level based on current market. However, the potential to promote the efficient WBG products is small.<br>Currently the Euro efficiency for the better products is around 98 % and the best WBG based with 99 % Euro efficiency are already now entering the market. | Conformity<br>Mandatory | Legislators | First tier could be implemented quickly (2025, without considering the legislation process). Second tier by 2027-28 |
| MEPS on PV inverter efficiency based on a | PV inverters perform differently depending on how big the loads are. Both part and full load are important. | Conformity<br>Mandatory | Legislators | Quickly (or 2025 with respect to regulatory |

| | | | | |
|---|---|---|---|---|
| full and part load metric | Part load because that typically matches higher needs. Full because low efficiency risk overheating or need for auxiliary equipment and consumption (cooling). Full and part load is already part of the Euro efficiency metric.<br>Two methods exist; Euro efficiency and CEC (California). Applicability depends on climate. | | | processes). Does not depend on MEPS level. |
| Energy label to draw the better solutions forward, or alternative efficiency classes (e.g., IE1-4 or A, B, and C class spanning from 96 to 99 % efficiency) | Energy label with A-G classes seems challenged by measuring tolerances and their impact on the necessary spread in classes on the labelling scale. Hence, the alternative classes, potentially as mandatory information requirement in e.g. ecodesign.<br>Efficiency based on full/part load metric like Euro efficiency or CEC | Information<br>Mandatory | Legislator | Quickly (2025 with respect to regulatory processes) |
| Test and map PV inverter's dependence on temperature regarding efficiency and robustness | Both factors are impacted by materials, design, and ambient conditions | Conformity<br>Supportive | Governments by financial support, test bodies and standardisation organisations, PECTA | 2024 – '25<br>And after, ongoing process. |
| Optimize verification tolerances | Potential verification tolerances depend on test accuracy, repeatability and interlaboratory variations (reproducibility). This could be investigated e.g. by interlaboratory round robin tests | Conformity<br>Supportive | Governments by financial support, test bodies and standardisation organisations, PECTA | Immediately<br>2024 – '25<br>And after, ongoing process |
| Develop test methods for high-efficient PV inverters | 1 %-point variation in efficiency does not seem much, but if we are reaching 98 – 99 % efficiency this corresponds to 50 – 75 % reduction on losses. It matters because the power flows through many conversion steps and it sums up.<br>Includes development of standards | Conformity<br>Supportive | Governments by financial support, research institutions with test lab, test bodies and standardisation organisations, PECTA | 2024 – '26<br>And after, ongoing process |
| Endorsement programs | Financial support to the better products, e.g. first PV inverters with 98 % or higher efficiency, and later, from 2026 – 27 products with 99 % efficiency | Financial<br>Voluntary | Authorities | From 2 H 2024 |
| Public procurement | Require the better products, e.g. first PV inverters with 96 % or higher efficiency, in 2026 98 %, and from 2028 products with 99 % efficiency | Financial<br>Voluntary | Authorities (regional, national, | From 2 H 2024 |

|  |  |  |  |  |
|---|---|---|---|---|
|  |  |  | local communities)<br>PECTA could support with developing requirements |  |
| Knowledge building and dissemination of best WBG practices and materials according to application. | Could improve product development. | Conformity<br>Supportive |  |  |

Table 11 lists suggested policy measures for universal EPSs based on section 2.2.

Table 11. Potential policy measures and their timing for EPSs.

| **Potential policy measure (Action)** | **Explanation** | **Main type and Nature** | **Action taker** | **Timing**<br>**Explanation on timing** |
|---|---|---|---|---|
| Stricter MEPS | Stricter MEPS according to ecodesign could be based on WBG technology, as WBG based products are entering the market, and within a few years they could have a significant share of the market.<br>Test performed under the auspices of PECTA indicates that the current highest limit value could be increased to 90 % from 88. A later second tier on 91-92 % (which seem to be currently a typical efficiency) could be considered. | Conformity<br>Mandatory | Legislators | 2026 – '27<br>The EU ecodesign regulation is under revision. |
| Cover several voltage modes | For multi voltage EPSs only the lower voltage mode is covered in the ED regulations. Tests indicate that EPS therefore only tend to be optimized the efficiency performance for the lower voltage modes. | Conformity<br>Mandatory | Legislators | 2026 – '27<br>The EU ecodesign regulation is under revision. |
| Energy label | The market development seems to go towards that chargers are not per default delivered together with electronics. Consequently, consumers may have fewer chargers and will be more actively involved in the purchase decision and tools for that. WBG based chargers can decrease losses significantly. | Information<br>Mandatory | Legislators | 2026 – '27<br>In the EU a revision of the current ecodesign regulation is going on from 2023 to 2025 (exp). |

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| | However, the current verification tolerance for market surveillance is 5 % which means a label could only have 2 classes | | | |
| Lower verification tolerances | EPS have verification tolerance on 5 % of efficiency according to ecodesign. This seems unnecessarily high, and it could be investigated if this is the correct level or what it should be. | Conformity<br>Mandatory | Legislator, research institutions with test laboratories, or standardisation organisations. | 2024 (1 H 2025).<br>If a larger cooperation and interlaboratory comparisons would be decided first half of 2025 would be necessary as well. |
| Requirements on material consumption | With WBG devices is it possible to reduce material consumptions and for EPS is this aspect particularly relevant. It could be investigated how to and if it is relevant to introduce such requirement and which levels. | Conformity<br>Mandatory | Governments by financial support of research institutions | 2024 – ‘26 |

Table 12 lists suggested policy measures for UPSs (see also section 2.3)

The work on a revision of the regulation for data centres and power supplies is starting by the beginning of 2024 and base cases are in the process of being defined.

Table 12. Potential policy measures and their timing for UPSs.

| **Potential policy measure (Action)** | **Explanation** | **Main type and Nature** | **Action taker** | **Timing<br>Explanation on timing** |
|---|---|---|---|---|
| Introducing MEPS | An increased use of UPS is foreseen.<br>WBG devices are on the market for the products with larger rated power (with SiC). For the smaller products it is in the pipeline (with GaN).<br>MEPS could be based on current EU CoC and Energy Star and with delay for smaller products to enable development of GaN devices. | Conformity<br>Mandatory | Legislator | 2026 – ‘27 |
| Stricter requirements in existing voluntary schemes (EU CoC and Energy Star) | The general UPS market has already developed to the same or higher efficiency levels, especially for the large power capacities because of WBG products entering the market. To stay relevant the voluntary actions must follow up.<br>For the EU CoC the Elite requirements could be increased particularly for the smaller power capacities to speed up the introduction of GaN products. | Information<br>Supportive | Legislator | 2024 – ‘25 |

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| Energy label | Since an extended use and more widespread installation of UPS could be foreseen, consumers that are not professional, even they are using UPS for business, are entering the market. A label could help selecting more efficient products as with professional refrigeration in the EU. Further, a label could help a quicker introduction of GaN products for lower power capacity | Information<br>Mandatory | Legislator | 2025 – '26 |
| Investigate the load profile | Literature informs that some categories of UPS are mainly operating at 20 – 40 % load, but the current load profiles stops at 25 % load, and for some products 50 % is the lowest load. | Information<br>Supportive | Governments by financial support of research., Users, standardisation organisations | 2024 – '26 |

Table 13 lists suggested policy measures for EV DC chargers (see also section 2.4).

Table 13. Potential policy measures and their timing for EV DC chargers.

| **Potential policy measure (Action)** | **Explanation** | **Main type and Nature** | **Action taker** | **Timing**<br>**Explanation on timing** |
|---|---|---|---|---|
| Test method for efficiency with load profile | No test method is established yet. Number 1 priority must be to develop and agree on an efficiency metric and test conditions.<br>Potentially, are some organisations already working on it. | Information<br>Supportive | Legislator, test institutions, standardisation organisations | 2024 – '25<br>Urgent task, but even given high priority this would be difficult to finalize before ultimo 2025 |
| MEPS for wall boxes and stationary commercial chargers | MEPS on charging efficiency stationary DC chargers including part load;<br>MEPS on standby, idle mode, and off mode consumption for wall boxes, both AC and DC chargers, level 1, 2 and 3 (up to 43.5 kW AC charging).<br>Could be based on Energy Star | Conformity<br>Mandatory | Legislator | 2025-26 with requirements coming into force 2026-27. Based on realistic expectations on what is possible in the regulatory systems. |
| Mandatory Efficiency label | Wall boxes level 1 and 2. Millions of private EV owners are installing wall boxes and currently there are no indication on their efficiency in spite of the large energy amounts going through.<br>An efficiency label could help. | Information<br>Mandatory | Legislator | 2025-26 with requirements coming into force 2026-27. Based on realistic expectations on what is possible in the regulatory systems. |
| Voluntary Efficiency label | Could contain standby, idle mode, and off mode consumption for wall boxes, both AC and DC chargers, level 1, 2 | Conformity<br>voluntary | Legislator | 2024-'25 |

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|  | and 3 (up to 43.5 kW AC charging).<br>Energy Star could be promoted more, or a label could be based on Energy Star.<br>Efficiency of charging for commercial stationary DC chargers including at part load.<br>Thiis would be a quicker way to establish a label and to promote the better products |  |  |  |
| CoC | As above, but with more focus on DC charging up to 43.5 kW since these could be expected to be installed at private and public workplaces, companies with transportation need etc.<br><br>Could be part of public procurement | Information<br>Voluntary and mandatory (for public users) | Legislator | 2025-'26 |
| Test and investigate EV DC chargers efficiency and dependence on ambient conditions, load profiles etc. | Important knowledge. High energy levels going through the charger will increase their temperature, and the very changing ambient conditions for EV chargers may also impact charging efficiency. | Information<br>Supportive | Governments (financing), research, test and standard organisations | 2024-'27<br>Both quick results and more long term work is relevant |

## 8.2. Policies targeting horizontal subjects

Financial support for the period of transformation from the old to the new technologies could also be used to help the market, since the new technologies in the beginning will be more expensive in investment cost[20]g.

For future work it could be suggested to analyse cost on capital and operational expenditures. This could be on device level but also by break down on added costs (cooling, filters, size, handling, general horizontal level and application specific.). Table 14 shows potential horizontal policy measures.

Table 14. Suggestions for horizontal policy measures and their timing.

| **Potential policy measure (Action)** | **Explanation** | **Main type and Nature** | **Action taker** | **Timing Explanation on timing** |
|---|---|---|---|---|
| Dissemination of knowledge of WBG technolgies | Continuously support of reliability knowledge building, and dissemination of know-how, best practice of both design/constructions, and measuring of reliability parameters in order to support the different relevant industry branches in gaining confidence. | Information<br>Supportive | Governments, Industry organisations | From now and ongoing |

|  |  |  |  |  |
|---|---|---|---|---|
| Education and competence building | Support and improve education in all levels of power electronic competences. Multiple skills and knowledge are needed, from production, machining, maintenance and repair to specifiers and design and construction. This lack of experts in power electronics and systems – at all levels of the educational system – is a general comment from several interviewees and was also discussed during the EPE2023 PECTA section final debate as well as being highlighted in the IEC White paper "Power semiconductors for an energy-wise society" as a key recommendation for policy makers (2023). | Information Supportive | Governments, technical schools, universities, business organisations | Now |
|  | Technicians and engineers knowing about electrotechnics, and particularly engineers which both understands the semiconductor area and have basic electrotechnical skills are lacking. | Information Supportive | Governments, universities, business organisations | Now, ongoing |
|  | First step from policy and perhaps PECTA side could be to map which competences that is missing and should be promoted. | Information Supportive | PECTA, universities, business organisations | Now |
|  | Next step from policy side could be funding of bachelor, master, and Ph.D. projects in these areas, and to ensure that technical schools in their workshops has funding for the appropriate tools and teaching materials. | Financial Supportive | Governments, technical schools, universities, business organisations | 2H 2024 |
| Financial support of efficient products | Financial support for the period of transformation from the old to the new technologies could also be used to help the market development, since the new technologies in the beginning will be more expensive in investment cost. | Financial Supportive | Governments | 2H 2024 – a few years more depending on product |
| Suppply chain | Investigate the full supply chain – where are the weak and vulnerable spots in the production, which helping compounds / gasses has a weak supply chain? | Information Supportive | Governments, universities, business organisations | 2024-'25 |
|  | Invest in the most critical parts of the supply chain | Financial Supportive | Governments<br>Business | 2025-'28 |
| Support research in WBG devices | Continuously support of reliability research including research and development of best practice of both design / construction and measuring | Information Supportive | National governments and regional | Continue current actions, potentially at increased pace. |

| | | | | |
|---|---|---|---|---|
| | of reliability parameters, and specific observation points. | | research support schemes, | |
| Support development of standards | Standards for recycling and reuse of materials and components. | Information<br>Supportive | Legislator, test institutions, standardisation organisations | 2025-‘28 |
| | Support work with prioritisation, selection, and transformation of most the important JEDEC guidelines to actual standards. | Information<br>Supportive | Legislator, test institutions, standardisation organisations<br>PECTA | 2024-‘26 |

# 9. Conclusion and outlook

The present work categorises and evaluates different policy measures that can support increased uptake of WBG technology in end-use equipment, with the aim of improving the overall energy and resource efficiency. The evaluation points at product regulations as one of the most promising directions and uses the European ecodesign framework and proposed PV inverter minimum requirements to discuss when and how ambitious measures to increase WBG application and help to avoid market failure for efficient product with WBG inside could be applied.

Interviews with stakeholders identified various drivers and barriers for implementation of WBG technology. Besides low energy losses, the drivers include smaller devices and lower material consumption which can be beneficial for WBG technology as product regulations moves towards requirements on product environmental footprint. Among barriers two prominent ones identified are knowledge gaps on reliability of WBG and lack of standardised components and product platforms that can support the WBG ecosystem. Other implementation barriers relate to power quality, capacity limits and production costs, to be investigated further.

At least three main policy areas can support the WBG uptake:

- Product regulation.
- Standardisation.
- Support of research, innovation and first industrial deployment.

For product regulations, both energy efficiency and environmental measures can be set to promote WBG for individual end use equipment such as PV inverters, EV chargers, EPSs, UPSs. Energy efficiency measures must be based on realistic operational profiles, to reflect the advances of WGB technology. For suppliers and end user to gain confidence in new WBG technology, complementary policy measures on lifetime/durability or warranties can be introduced. Energy labelling of products may as well have a role in promoting the most efficient technology.

Standardisation seems to be an important measure for WBG in various ways, both globally and on national/regional scale. The identified needs are standards on:

- Reliability and durability test methodologies. Not just on the device level, but also on the product application level.
- Product categorisation rules (PCR) and material efficiency (ME) aspects of WBG to support the calculation of product environmental footprint (PEF).
- Efficiency test methodologies to support the part load benefits of WBG and to cope with uncertainties when efficiencies are getting high/losses low.
- Product architectures of power modules and systems to gain the full benefit from WBG components when not compatible with the existing Si component, module, and package architecture.

In the field of research, innovation and first industrial deployment, specific economic support could include activities where the whole WBG ecosystem is addressed.

Table 15. Key conclusions

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| Product policy is recommended to focus on:<br>- Firstly, end-user product applications like solar inverters, EPS etc. -and not on horizontal requirements for devices or power modules<br>- Secondly, 2. gen. MEPS which may be developed into a more horizontal approach targeting e.g. power modules based on voltage and power levels – and potentially environmental factors and planned use time |

| |
|---|
| WBG market is in the phase of initial commercialization and approaching consolidation. Market actors confirm increased acceptance among their customers.<br>=> Good timing for mandatory EE requirements |
| Market failures means that the development will not happen automatically for all end-use applications – e.g. residential and middle-sized commercial PV inverters<br>=> Good reason for mandatory EE requirements |
| Legislators could consider the supply situation. Ga and Si metals are on the EU list of critical and strategical raw materials, and industrial interviewees confirmed that it is for a reason and that it is even more relevant for SiC |
| Further work to be done on standards, harmonization is e.g. needed, but generally – with EV chargers as exception - we can work with those we have |

## 9.1. Conclusions on Policy measures:

- A general conclusion from interviews and other work presented in the present report is that there was not found reason for a specific WBG product regulation targeting the WBG technology itself, but for product requirements that benefit from the WBG based components' potentials. For research and knowledge building on the other hand the conclusion is different, see other policy options below.
- For PV inverters would energy classification other than a label be worth considering
- For universal EPSs could energy labels be considered. The shift towards chargers not being per default delivered together with the electronics, might result in consumers having fewer chargers. In this case consumers will be more actively involved in the purchase decision, and a focus on efficiency could be a more prominent decision factor. In the EU the timing is good as a review process is starting up 2023/24, and the technology is ready.
- Continuously support of reliability research including research and development of best practice of both design / construction and measuring of reliability parameters, and specific observation points.
- Continuously support of reliability knowledge building, and dissemination of know-how, best practice of both design/constructions, and measuring of reliability parameters to support the different relevant industry branches in gaining confidence.
- Support and improve education in all levels of power electronic competences. Multiple skills and knowledge are needed, from production, machining, maintenance and repair to specifiers and design and construction. This lack of experts in power electronics and systems – at all levels of the educational system – is a general comment from several interviewees and was also discussed during the EPE2023 PECTA section final debate as well as being highlighted in the IEC White paper "Power semiconductors for an energy-wise society" as a key recommendation for policy makers (2023):
    - Both technicians and engineers knowing about electrotechnics are lacking.
    - Even more are lacking engineers which both understands the semiconductor area and have basic electrotechnical skills.
    - We need the people who can all make the links to the physics and the hands-on-work. Someone with a basic knowledge and theory.
    - First step from policy and perhaps PECTA side could be to map which competences that is missing and should be promoted.

    - Next step from policy side could be funding of bachelor, master, and Ph.D. projects in these areas, and to ensure that technical schools in their workshops has funding for the appropriate tools and teaching materials.
- Financial support for the period of transformation from the old to the new technologies could also be used to help the market development, since the new technologies in the beginning will be more expensive in investment cost.
- Investigate the full supply chain – where are the weak and vulnerable spots in the production, which helping compounds / gasses has a weak supply chain?
    - For electronic production exotic gasses are necessary and there are only a few suppliers of these. Process gas for SiC: $SiH_4$ and $C_3H_8$ (propane). Gasses for chemical etching are typically various fluorine gasses and additive gasses including argon.
    - Could be element in the European chip act to get control of in the supply chain.
- Support development of standards, hereof:
    - Standards for recycling and reuse of materials and components.
    - Support work with prioritisation, selection, and transformation of most the important JEDEC guidelines to actual standards.
    - Support investigations of necessary verification tolerances and accurate and reproducible test methods. Verification tolerances for some of the current regulations hinders ambitious MEPS.

## 9.2. Suggestions for further work in the frame of PECTA

Based on the report some ideas for potential measures or lack of knowledge to investigate further, has come up. Below are the suggestions for further work:

- Investigate other WBG high frequency semiconductor materials.
    - Other WBG materials enabling even higher switching frequencies and miniaturization are in the pipeline. Important to follow this (this is also a policy suggestion).
- Perform cost analysis on capital and operational expenditures.
    - On device level but also break down on added costs (cooling, filters, size, handling…, general horizontal level and application specific.)
    - Important input for policy development including cost-benefit analysis. Lack of this knowledge could hinder or delay ambitious product policies.
- Push for and support development of EV charger efficiency test.
    - Metrics.
    - Load profiles.
    - Conditions.
- Standardised sets of requirements for various internal power supplies for new products applications.
    - The idea is to investigate if a set of combined parameters like ambient conditions, requirements for lifetime in years or in operating hours, and part and full load power, current and voltage rates could be defined.
    - Could a low number of standard power modules fit the major household appliances from hair dryer vs. washing machine vs. LED driver vs. PV inverter etc.? Could such usage classes serve as basis for more universal requirements in line with the universal EPS regulation but for internal power supplies?
    - Feedback from interviews suggest it could be possible.
    - Inspiration can be drawn from the development explained by one interviewee[20]b. In the past the company had no standards for packages or products and developed or

    adapted power modules for each application and customer need specifically. This resulted in more than 10000 product numbers of power modules. Now a work is going on to standardise power modules and power supplies.

- Standardised power modules for retro fitting and for other products.
    - Consider and investigate which requirements that should be fulfilled for WBG power supplies for retrofitting for replacement of old existing power supplies, and how it could be implemented.
    - An important part would be information about the potential, and `how-to!´ guides.
    - The motivation for this to improve repairability and lifetime of old products and at the same time improve their efficiency with the newest technology.
    - Another motivation for looking at WBG power modules for retrofit is that a solution could enable a quicker introduction of improved product minimum energy performance requirements for new products. Often product regulations contain clauses on spare part availability referring to inefficient spare parts that by new law would not be legal.
- DC chargers and home power systems – relevant from PV inverter perspective as well.
    - Product category under introduction now.
    - Future grid structure and operation – physical as well as economic – with more own production from PV, large batteries including for EVs, and increased fluctuation on grid transport prices could benefit from optimized use of home power system.
- Investigate potentials and risks from solid State Circuit Breakers (SSCB):
    - The potential benefits of SSCB are faster protection capability and lower conduction losses during normal operation compared with electromechanical circuit breakers.
    - These are also potentially integrated in PV inverters and converters and other power electronics.
    - IEC White paper “Power semiconductors for an energy-wise society” (2023) explains it.
- Map data and methods for data gathering for scope 3 for product environmental footprint (PEFs) for SiC (first) and GaN (later)
    - Customers are starting to require PEF certificates, and now also for scope 3 (supply side). However, there are missing knowledge and data in this for SiC and GaN too.
    - The adaption of WBG products could be slowed down if customers cannot get PEF data on WPG components and devices. If this is the case, they may be pushed towards less efficient non-WBG based products if data are available on these.
- Analyse the full supply chain – where are the weak and vulnerable spots in the production, which helping compounds / gasses have weak supply chains?
    - For electronic production exotic gasses are necessary and there are only a few suppliers of these. Process gas for SiC: $SiH_4$ and $C_3H_8$ (propane).
    - Gasses for chemical etching are typically various fluorine gasses (particularly $SF_6$) and additive gasses including argon. Also, a subject to get control of in the supply chain.
- Analyse which ECPE and IEC guidelines that could be relevant as basis for harmonised standards to support product regulations. Standards for recycling and reuse of materials and components could be one subject to consider.
- Test methods for test of efficiency and losses of power electronics and repeatability and accuracy of these test methods.
    - E.g. by round robin tests involving several test laboratories.
    - Investigating actual situation and improvement potential.

# 10. Appendices

## 10.1. Appendix 1: WBG relevant standards and guidelines

This appendix contains an overview of standards for test, declaration, information etc. of WBG devices physical and electrical parameters.

Recently a number of standards has been published from JEDEC and several are available for free download after registration see Table 16

Table 16. List of JEDEC WBG related standards (Source: https://www.jedec.org/committees/jc-70)

| | |
|---|---|
| Guideline for Reverse Bias Reliability Evaluation Procedures for Gallium Nitride Power Conversion Devices. JEP198.<br>This document provides guidelines for evaluating the Time Dependent Breakdown (TDB) reliability of GaN power transistors. It covers suggested stress conditions and related test parameters for both High Temperature Reverse Bias Stress and Application Specific Stress-Testing designed to evaluate the reliability of GaN transistors over their useful lifetime under accelerated stress conditions.<br>Committee: JC-70.1 | Feb 2023 |
| Guideline for Gate Oxide Reliability and Robustness Evaluation Procedures for Silicon Carbide Power MOSFETs<br>This document provides guidelines for evaluating gate reliability and lifetime testing for silicon carbide (SiC) based power devices with a gate oxide or gate dielectric.<br>Committee(s): JC-70, JC-70.2 | |
| Guideline for Evaluating Gate Switching Instability of Silicon Carbide Metal-Oxide-Semiconductor Devices for Power Electronic Conversion<br>This document elaborates on the information given in JEP184 regarding the long-time stability of device parameters under static conditions and under application near switching conditions.<br>Committee(s): JC-70, JC-70.2 | Feb 2023 |
| Guidelines for Measuring the Threshold Voltage (VT) of SiC MOSFETs<br>This publication describes the guidelines for VT measurement methods and conditioning prior to VT testing in SiC power MOSFETs to reduce or eliminate the effect of hysteresis.<br>Committee(s): JC-70.1 | Jan 2023 |
| Guidelines for Gate Charge (QG) Test Method for SiC MOSFET<br>This publication defines a QGS, TOT, QGD and QGS, TH which can be extracted from a measured QG waveform for SiC MOSFETs.<br>Committee(s): JC-70, JC-70.2 | Jan 2023 |
| Guideline for Evaluating dv/dt Robustness of SiC Power Devices, Version 1.0<br>This document provides stress procedures, general failure criteria and documentation guidelines such that the dv/dt robustness can be demonstrated, evaluated and documented. This document gives examples for test setups which can be used and the corresponding test | Aug 2022 |

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| conditions. Additionally, criteria are explained under which device manufacturers can select an appropriate test setup.<br>Committee(s): JC-70.2 | |
| Guideline to Specify a Transient Off-State Withstand Voltage Robustness Indicator in Datasheets for Lateral GaN Power Conversion Devices, Version 1.0<br>This guideline describes different techniques for specifying a Transient Off-state Withstand Voltage Robustness Indicator in datasheets for lateral GaN power conversion devices. This guideline does not convey preferences for any of the specification types presented, nor does the guideline address formatting of datasheets. This guideline does not indicate nor require that the datasheet parameters are used in production tests, nor specify how the values were obtained.<br>Committee(s): JC-70.1 | Dec 2021 |
| Guidelines for Representing Switching Losses of SIC MOSFETs in Datasheets<br>This document describes the impact of measurement and/or setup parameters on switching losses of power semiconductor switches; focusing primarily on SiC MOSFET turn-on losses. In terms of turn-off losses, the behaviour of SiC MOSFET's is similar to that of existing silicon basedpower MOSFET's, and as such are adequately represented in typical datasheets.<br>Committee(s): JC-70.2 | Dec 2021 |
| Guideline For Evaluating Bias Temperature Instability Of Silicon Carbide Metal-Oxide-Semiconductor Devices For Power Electronic Conversion<br>The scope of this document covers SiC-based PECS devices having a gate dielectric region biased to turn devices on and off. This typically refers to MOS devices such as MOSFETs and IGBT's. In this document, only NMOS devices are discussed as these are dominant for power device applications; however, the procedures apply to PMOS devices as well.<br>Committee(s): JC-70.2 | Mar 2021 |
| Guideline For Switching Reliability Evaluation Procedures For Gallium Nitride Power Conversion Devices<br>This document is intended for use by GaN product suppliers and related power electronic industries. It provides guidelines for evaluating the switching reliability of GaN power switches and assuring their reliable use in power conversion applications. It is applicable to planar enhancement-mode, depletion-mode, GaN integrated power solutions and cascode GaN power switches.<br>Committee(s): JC-70.1 | Jan 2021 |
| Test Method For Continuous-Switching Evaluation Of Gallium Nitride Power Conversion Devices<br>This document is intended for use in the GaN power semiconductor and related power electronic industries and provides guidelines for test methods and circuits to be used for continuous-switching tests of GaN power conversion devices. | Jan 2021 |

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| Committee(s): JC-70.1 | |
| Dynamic on-Resistance Test Method Guidelines For GaN HEMT Based Power Conversion Devices, Version 1.0<br>This document is intended for use in the GaN power semiconductor and related power electronic industries and provides guidelines for measuring the dynamic ON-resistance of GaN power devices.<br>Committee(s): JC-70.1 | Jan 2019 |

Table 17 contains examples on vertical (product specific) standards relevant for the WBG products in focus of the present report.

Table 17. List of WBG related product specific standards

| | |
|---|---|
| EN 50530 /A1:2013 Overall efficiency of grid connected photovoltaic inverters provides measuring methods for efficiency of MPPT (Maximum Power Point Tracker) inverters. CENELEC. Note: This is the standard for Euro efficiency on PV inverters<br>Committee(s): CLC/TC 82 | 2013 |
| EN IEC 61683:2001 "Photovoltaic systems – Power conditioners – Procedure for measuring efficiency" Provides guidelines for measuring the efficiency of power conditioners used in stand-alone and utility-interactive photovoltaic systems, where the output of the power conditioners is a stable AC voltage of constant frequency or a stable DC voltage. | |
| EN IEC 62093:2022 Photovoltaic system power conversion equipment – Design qualification and type approval<br>IEC requirements for type approval of power conversion equipment (PCE) suitable for terrestrial photovoltaic (PV) systems in respect of EMC and safety testing, including resistance to environmental impacts. The standard concerns PCE which is connected to PV arrays that do not nominally exceed a maximum circuit voltage of 1500 V DC. The standard does not address power electronic conversion equipment fully integrated into photovoltaic modules.<br>Committee(s): CLC/TC 82, IEC/TC 82 | 2022 |
| EN ISO 15118-20:2022 Road vehicles – Vehicle to grid communication interface – Part 20: 2nd generation network layer and application layer requirements<br>Specifications of the communication between the electric vehicle (EV), including battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV), and the electric vehicle supply equipment (EVSE).<br>Committee(s): CEN/TC 301 and ISO/TC 22/SC 31 | 2022 |
| EN 50563/A1:2013 External a.c. – d.c. and a.c. – a.c. power supplies – Determination of no-load power and average efficiency of active modes<br>Harmonized for (EC) No 278/2009 on external power supplies. This standard is applicable to external power supplies with a rated input voltage within the range 100 V ac to 250 V ac having a single output with a rated output power not exceeding 250 W and a rated output voltage not exceeding 230 V a.c. or 325 V d.c. The output voltage may be either at a fixed | 2013 |

| | |
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| voltage, or at a voltage which is user selectable, or at a voltage that is automatically selectable by the external power supply so as to be compatible with one or more product-loads.<br>Committee(s): CLC/TC 100X | |
| EN IEC 62040-3:2021 Uninterruptible power systems (UPS) - Part 3: Method of specifying the performance and test requirements, IEC, 2021 | |
| ATIS-0600015.2013, Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting – General Requirements;<br>For Low-voltage Dc-output UPSs/Rectifiers (output voltage less than or equal to 60 V), Alliance for Telecommunications Industry Solutions (ATIS) standards (used for Energy Star) | 2013 |
| ATIS-0600015.04.2010, Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting DC Power Plant – Rectifier Requirements.<br>For Low-voltage Dc-output UPSs/Rectifiers (output voltage less than or equal to 60 V), Alliance for Telecommunications Industry Solutions (ATIS) standards (used for Energy Star) | 2013 |

## 10.2. Appendix 2: Review of WBG policies

The following appendix concerns already existing WBG relevant product policies and non-policy measures that are supporting the innovation and enhancing the market penetration of efficient WBG products.

### 10.2.1. Supporting policies

#### Showing the way – Roadmaps

One way to support policy as well as guide industry is to develop roadmaps pinpointing technological trends, challenges and opportunities.

Roadmap with a technology focus could help by pedagogically describing WBG components and challenges as well as the current state of the art. Baes on this information the roadmap typically looks forward to the WBG power electronics future. It could further, like the roadmap mentioned below from IEEE show potentials for commercial realisation in short term (< 5 years), medium term (5-15 years) and long term (> 15 years). Examples of such roadmaps are given below and further described in the PECTA May 2020 report.

The roadmaps are good examples are examples of a horizontal measure as explained in the IEA classification system (see [2] and [54]), but road maps on specific products could also be developed which would be a vertical measure. IEA roadmap on heat pumps is an example of such a more vertical product roadmap.

IEEE Power Electronic Society developed such a roadmap in 2019 named ITRW: "International Technology Roadmap on Wide Band Gap Semiconductors" which looks at short, middle and long term (presented more detailed below) [24].

ECPE, European Center for Power Electronics, has developed the "Roadmap Lead Applications for SiC and GaN" in 2018 on railways, PV inverters, wind, industry automation, large drives, grid and ICT and data centres. The roadmap from ECPE contains an overview of applications and benefits with WBG power electronics. It also contains a roadmap and expected status of different WBG components in different applications at the year 2018, 2025 and 2035 [12].

Power America: has developed a roadmap that outlines key markets, performance targets, and application areas for SiC and GaN technologies, technical barriers to achieving those targets, and the activities needed to overcome those barriers. Power America made this with the "Strategic Roadmap for Next Generation Wide Band Gap Power Electronics" in 2019. Power America is an institute and a network of public and private partners committed to increasing U.S. manufacturing competitiveness. It contains strategies for a 5-year roadmap to:

- Reduce Cost
- Improve Reliability and Quality
- Enhance Performance Capabilities
- Strengthening the Power Electronics Ecosystem [5]

CASA China Advanced Semiconductor Industry Innovation Alliance, *Technology Roadmap for Wide Band Gap Power Electronics 2018,* contains 150 pages well explained analysis on more or less all relevant aspects in relation to the development and market maturing of WBG technologies. CASA consists of research institutes, universities and enterprises related to Wide Band Gap semiconductors and is supported by the Ministry of Science and Technology, Ministry of Industry and Information Technology and the Beijing Municipal Government [25].

The ITRW, “International Technology Roadmap on Wide Band Gap Semiconductors”, is a part of the IEEE Power Electronic Society and produced in 2019 a roadmap to:

- Share R&D progress and identify opportunities and bottlenecks.
- Identify most effective paths for technology development.
- Develop technology specific content within working groups.
- Create a reference framework for regional roadmaps [24].

SiC alliance Roadmap with the aim to guide the R&D plan of the Japanese SiC Alliance members in the seven areas: vision, automobile, super express train, industrial inverter, switching device, parts, and wafer [26].

#### Shaping the industry

Another example of policy support which transcends RD&D is This is the EU funded REACTION project with the ambition to develop a European 200 mm (8 inch) SiC production line. The change to 200 mm will reduce the cost due to size and volume increase, and also give the SiC technology access to most recent processing production [3].

#### Standardisation

Active involvement in increased standardisation in the entire production chain for WBG power electronics is needed. This includes standardisation of wafer and material, device, modules and packaging as well as of electrical parameters, efficiency measurements, power measurements and developing on accelerated reliability tests and expected module lifetime This could take place via existing frameworks and organisations for standardisation such as SEMI, IEEE, JEDEC, IEC, and ISO. See also section 6 on Standardisation.

#### Research, development, and deployment (RD&D)

In principle, all identified WBG-technology challenges (chapter 6 in the PECTA report of May 2020) are potential subjects for support and fundings for RD&D projects. This is not a subject that will be covered in the precent study.

### 10.2.2. Product regulation – Ecodesign regulations as WBG driver

The European ecodesign regulations are considered as one of the most important vertical measures, which historically has provided around half of the realized European energy savings and 10 % improved energy efficiency of the products covered by regulations. Ecodesign often apply in tandem with energy label requirements. Where ecodesign applies mandatory minimum energy efficiency requirements aimed for suppliers, energy labelling mandatory information requirements through an easy understandable energy label, will inform consumers and nudge them towards the most efficient products.

The latest development is the extension of the current Ecodesign directive to the new Ecodesign for Sustainable Products Regulation (ESPR) initiative, which will increase the possibilities of ecodesign to handle other resource aspects, to introduce calculations of product environmental footprints (PEF) of products, and potentially an environmental digital product passport (DPP) [11]. This will require development of product specific standards on product categorisation rules (PCR) and material efficiency (ME) aspects. Considering other PECTA studies, the environmental focus and policy measures could be beneficial for WBG products.

No ecodesign measures targets WBG technologies specifically, and no ecodesign regulations has so far been written or reviewed to promote the potential benefits from WBG technologies. But ecodesign regulations do cover WBG products in various regulations, including some of the products that are considered for the present work.

## 10.3. Appendix 3: Interviews

Task 2 of the present project aims to identify implementation barriers and drivers for policies to promote and facilitate efficient wide band gap technologies generally and for specific application areas, where the latter primarily concerns PV inverters.

The method was a series of interview with relevant, primarily industrial, stakeholders. The interviews collected views and considerations on the drivers and barriers they see, potential policies to overcome barriers, and the timing of those.

The various policy measures identified in the present project as most relevant formed the basis for the interviews.

### 10.3.1. Presentation of interviewees

Eight in-depth interviews targeting different stakeholders were performed. The following groups were represented in the interviews:

- Industry and business (main weight, both manufacturer and trade)
- Universities (research and test)
- Policy

Representatives from NGOs were also approached but they did not find they had the capacity to participate.

The full list is presented below anonymised. All interviewees were at high organisational and technical level:

a. Researcher at European university working with failure mechanisms and reliability test.
b. Representing a manufacturer of industrial and consumer electrotechnical products, home appliances, high and low voltage. Work with both SiC and GaN WBG devices. Main business focused on power modules, not the transistor itself.
c. European manufacturer supplying power modules for motor drives and inverter builders or the semiconductors themself.
d. European manufacturer of high-voltage equipment, transformers, grid integration. Representative of research department.
e. Representative of European Commission, in section working with policies for power electronics.
f. Representing manufacturer and supplier of semiconductors and semiconductor products.
g. Researcher at European University working with renewable energy and power electronics including with work on hydrogen conversion.
h. Representing central and south European wholesales company supplying technical installers. The interviewee had particular knowledge of the solar power market from residential to medium scale.

The purpose of this study is a more qualitative evaluation of and input to potential measures and policies and not e.g., to collect market data. Therefore the interviews were performed as semi structured interviews. Some stricter questions regarding potential threshold levels were included, depending on the people interviewed.

Main conclusions and extracts are included and discussed in the report in relevant sections and referred to by reference to the reference list as reference [20]a to [20]g.

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b. Representing a manufacturer of industrial and consumer electrotechnical products, home appliances, high and low voltage.
c. European manufacturer supplying power modules for motor drives and inverter builders or the semiconductors themself.
d. European manufacturer of high-voltage equipment, transformers, grid integration. Representative of research department.
e. Representative of European Commission, working with policies for power electronics
f. Representing manufacturer and supplier of semiconductors and semiconductor products.
g. Researcher at European University working with renewable energy and power electronics including hydrogen conversion.
h. Representative of wholesales company supplying technical installers in several countries in central and southern Europe.

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