



Wide Band Gap Technology: Efficiency Potential and Application Readiness Map

4E Power Electronic Conversion Technology Annex (PECTA)

May 2020

Power Electronic Conversion Technology Annex - 2020

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

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Acknowledgements to contributors and reviewers:

The authors are very much indebted to the following experts and organizations, who generously supported the elaboration of the report with their significant technical knowledge, text and review contributions.

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Industrial representatives from the following industry and associations:

ECPE European Center for Power Electronics e.V., ABB Power Grids Switzerland Ltd., BLOCK Transformatoren-Elektronik GmbH, Infineon Technologies AG, KSB SE & Co., Wolfspeed Inc.

Abstract:

This report reflects the working result of the first phase of PECTA, the Power Electronic Conversion Technology Annex. It contains a first estimation of the energy saving potential of different applications, shows the predicted technology readiness of different devices and does lay out first, preliminary ways of possible regulations expediting the market entrance of Wide Band Gap based applications. By summarizing key findings, it leads to an outlook and discusses the next steps.

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About the IEA 4E Power Electronic Conversion Technology Annex (PECTA):

Power electronic devices incorporating Wide Band Gap (WBG) technologies are maturing rapidly and offer enormous opportunities for improved energy efficiency. 4E's PECTA assesses the efficiency benefit of utilizing the emerging WBG technology, keeps participating countries informed as markets for Wide Band Gap technologies 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 a range of projects designed to meet the policy needs of participating governments. Members of 4E find this an efficient use of scarce funds which results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions. The 4E TCP is established under the auspices of the International Energy Agency (IEA) as a functionally and legally autonomous body.

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)
- Monitoring, Verification and Enforcement (MV&E)
- Solid State Lighting (SSL) Annex
- Electronic Devices and Networks Annex (EDNA)
- Power Electronic Conversion Technology Annex (PECTA)

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Executive Summary

Technologies, systems and applications incorporating power electronic conversion devices and modules are defining many aspects of our modern society, making possible higher living standards and sophisticated industrial activities, as well as enabling the reduction of GHG emissions. Power electronics condition and control the conversion and flow of electricity and are handling a wide range of power levels, from milliwatts to gigawatts. Power electronic conversion is the focus of the 4E Annex PECTA - Power Electronic Conversion Technology Annex. The overall goal of the PECTA includes collecting and analyzing information about new Wide Band Gap (WBG) based power electronic devices, coordinating internationally acceptable approaches that promote WBG-based power electronics, and developing greater understanding and action amongst governments and policy makers.

This report examines the use of power electronic circuits across a vast list of applications. Even though power electronics are mature in different applications, further development towards higher quality may be triggered, for example, by advances in component technology and by economic driven optimization. Increased awareness of energy efficiency and environmental impacts is expanding the focus to exploring the reduction of energy consumption, the minimization of the environmental impacts by considering the resources needed for production, during operation and for recycling. As pointed out in this report, increasing the efficiency, reducing the size of passive components as well as reducing the cooling may be improved by the use of devices with new WBG technology.

This report investigates the potential energy savings from the use of WBG in important end-use applications, e.g., energy savings for data centers would be in the range of 28'000 GWh/year worldwide, for PV inverters savings would be around 10'000 GWh/year, and for laptops, tablets and cellular phones energy savings would be in the range of 7'700 GWh/year. It is as well estimated, that WBG technology could reduce the losses in the worldwide installed wind power generators by around 35'000 GWh/year. The energy savings presented are intended to inform policy makers about the merits of emerging WBG technologies incorporated in power conversion for relevant applications. These figures confirm that it is worth communicating this potential to policy makers, and to explore mechanisms and measures supporting the adoption and market penetration of WBG technologies.

PECTA developed an "Application Readiness Map" (ARM), estimating the time horizon for various sorts of WBG technologies being incorporated in corresponding applications as well as their market availability. This ARM is based on various existing roadmaps of renowned organizations, with a strong contribution of the WBG Roadmap of the European Center for Power Electronics e.V. (ECPE), and covers different applications and sectors, such as transport (automotive and railway), industry, automation, robotics, drives, ICT and data centers, PV inverter, wind generation, and grid converters. The ARM shows that without policy making support, a large amount of WBG devices will reach significant market share only in 2030 or later.

Finally, this report studied existing measures for promoting energy efficiency according to the type of measure (e.g. regulatory, voluntary, information based, etc.) to identify possible policies applicable to WBG technology. The report describes the kinds of measures that are available, and those which could be developed in the near future. The interactions with and within the industrial value chain, and the market actors are important considerations for deciding which policy instruments could be applied. It will also depend on the applications, as they might be in different maturity states, e.g., "before commercialization", "during initial commercialization", and "after initial commercialization".

The elaborated results (i.e. saving potential, applications readiness map, draft path for policy measures, summarizing observations) are - just as phase 1 of PECTA - a first step of the Annex work. Additional work is needed to continue this assessment process and to come to in-depth results. PECTA and its member countries will continue the work initiated in phase 1 to comprehensively elaborate further background information and to deduct adequate recommendations for policy makers.

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1. Introduction

1.1. Overview and Objectives of PECTA

The field of Power Electronic Conversion Technology deals with the use of solid-state electrical devices for the conversion, control and processing of electric power. With the requirements for handling a wide range of powers, from milliwatts to gigawatts, with minimized energy waste, power electronics systems have a huge impact on modern society in many aspects from the living standard, industrial revolution, to the reduction of greenhouse gas emission.

For illustration, a common example is the battery in a cell phone, which might provide a voltage between 3.6 and 4.2 Volts. The processor, performing all the essential tasks, might need a voltage in the range of 0.7 and 1.5 Volts (depending on its actual workload). Thus, the shape of electricity – the voltage in this case – needs to be changed by some circuitry, ideally with minimum losses. This circuitry is called power electronic circuit, and performs its task by combining electronic switches, passive components for (short-term) energy storage and filtering, as well as some sensing and control functionality. The control influences the action sequence of the individual switches, based on the sensed output voltage and the voltage demand for the processor.

As determined by the laws of physics (conservation of energy), the average power supplied to the load is lower than the power drawn from the energy source. The difference between input and output power is the amount of losses, dissipated as heat due to imperfections of the power electronic circuitry. These losses might be reduced by further developments in power electronics and related components.

Silicon (Si) is by far the most widely used semiconductor material at present and will most likely remain in the foreseeable future. The currently commercially used power electronic systems all are built upon the usage of one or the other silicon device¹. As awareness is rising for the need of energy savings, the development of power semiconductors which minimize losses has been increasing too. Power semiconductors with Wide Band Gap (WBG) technology are being developed, to allow for a broad application in industry, while ensuring energy efficiency.

WBG-based semiconductors allow higher blocking voltages, faster switching speeds and increased operating temperatures, which enable smaller and lighter systems by a reduction of the size of active and passive components and cooling equipment. Moreover, WBG integrated power electronic systems come with an improved efficiency if operated with the same switching frequency as Si-based devices. It has been estimated that a wide-spread adaptation in excess of 90% of such emerging power electronic systems utilizing WBG semiconductor devices would lead to a substantial annual decrease in electricity use worldwide. Thus, WBG power devices have a potential to provide a paradigm shift in performance and energy efficiency over the well-established and mature Si power devices. Silicon carbide (SiC) and gallium nitride (GaN) are the most mature WBG materials so far.

Policy makers are hardly aware of the efficiency benefits of WBG semiconductor devices and governments do normally not have access to an independent and well-founded source of expertise in this field. Therefore, it is difficult for policy makers to foresee and judge the future impact of this technology. Only based on profound knowledge it is possible to apply appropriate policy measures.

¹ There are two general categories of power electronic (PE) devices, **discretes**, and **modules**. When referring to **discretes** are power semiconductor devices that are not arranged and packaged together in a module. **Discretes** include rectifiers (diodes), thyristors and transistors, including bipolar junction (BJTs), metal-oxide semiconductor field-effect (MOSFETs), and insulated gate bipolar (IGBTs) transistors. **Modules** are often composed of several bare semiconductor dies, packaged together, sometimes with the control and protection circuitry included (Amstrong et al., "Wide Bandgap Semiconductor Opportunities in Power Electronics", 2017. Oak Ridge National Laboratory).

The Power Electronic Conversion Technology Annex (PECTA) has therefore been initiated as a new Annex to the International Energy Agency (IEA), under the Technology Collaboration Program (TCP) on Energy Efficient End-Use Equipment (IEA - 4E)². PECTA is assessing the efficiency benefit of utilizing the emerging WBG technology, by monitoring potential near-term and long-term devices and application of Wide Band Gap (WBG) Power Electronics, considering the areas with significant market and potential for adoption. With these results PECTA does assist policy makers with guidance on suitable policies to expedite the market entrance and does thereby as well eliminate hurdles and obstacles. At the same time PECTA serves as an independent knowledge platform and assures access to an independent source of knowledge in this particular cross-sectional technology.

1.2. Content of this report

This report reflects the first working result of PECTA. In the first part the report explores and explains the use and purpose of power electronics within various applications, as well as why and how further developments in power electronics and related components may reduce energy consumption within these applications. In consultation with industry experts, the potential efficiency gain in electrical energy conversion has been estimated.

The second part discusses and shows the foreseen technology readiness of different applications and devices, presented on the basis of so-called Applications Readiness Maps (ARMs).

The third part does lay out possible regulations to expedite the market entrance of Wide Band Gap-based applications. Summary of observations and key findings are included at the end of the report.

Even though the focus of IEA 4E is end-use equipment, in this first stage of PECTA the applications investigated were not constrained to end-use equipment. This gives an impression of the many existing applications and the associated possible saving potentials enabled by WBG power electronics. This approach also shows that power electronics have an undisputable position of relevant cross sectoral technology. It is clear that the presented results have to be considered as initial findings. Further work is needed to obtain more detailed results and to elaborate in-depth conclusions. With this report the basic direction is given, as it is evident that further work is needed specifically when considering the large energy savings potential.

² <https://pecta.iea-4e.org/>

2. Applications in Focus

2.1. Overview of Voltage ranges

In the various fields of applications, different definitions regarding voltage levels, such as low, medium and high voltage, are in use. Table 1 provides an overview of the most common used definitions in the respected area. The voltage classification as specified in Table 1 is proposed by the authors and contributors of this report and only valid for this specific document. It allows the authors and contributors to express a range of voltage levels by using modest linguistic and stylistic expressions without to need of specifying and denoting a concrete voltage each time within the text for various applications, devices and components. The voltage range classification of a device is in general only of minor relevance for the actual design of a power electronics converter as this is neither of precise nor of technical information. Instead, the blocking voltage of a semiconductor device is amongst others the parameter that is relevant during a converters design phase which is precisely specified and defined according to datasheet information.

Table 1: Commonly used Voltage Ranges in different Application areas.

Voltage Range	Low	Medium	High
Applications			
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}

2.2. Road Transport Electrification

Transport Electrification is a broad term that encompasses various kinds of vehicles (including Passenger Car, Commercial Road Vehicle, Scooters and Motorcycles, High Performance Motorcycles). Considerations provided here are restricted to Electric Vehicles where the main energy source is the battery, installed on the vehicle itself, charged while vehicles are stationary or during recuperation (deceleration and braking) and discharged while vehicles are in the use. Thus, prime source of energy (from the battery) is DC by nature, of certain voltage characteristics that are related to the state-of-charge (SOC) and must be adapted for various consumers inside the vehicle. Considering the limited amount of energy installed in the battery, it is of high importance to perform electrical energy conversion, by means of power electronics, as efficiently as possible.

Extending the operation range of such a vehicle can be achieved by adding a fuel cell into the system, transforming the energy, stored in the fuel (e.g. Hydrogen) chemically, into electricity that is then used for charging the battery and powering the driving cycle. This way, a further degree of freedom is added to the system for optimisation of battery size, vehicle performance, range, weight and overall energy consumption. The battery is still needed for storing regenerated energy while braking and for increasing the power supply dynamics. Hybrid storage systems that also include some form of ultra-capacitor to manage short term transient behaviour are also feasible.

2.2.1. Traction Drive

In an electric vehicle, a large power DC/AC power electronic converter serves as main interface between battery (DC) and electric machine (AC). This is by far the largest power electronic converter on the vehicle, with power ratings in the range from 50 kW to 500+ kW (e.g. 53 kW in Toyota Prius,

581 kW max. in TESLA Model S). Its role is to supply electric machines with appropriate voltage and currents, in order to generate appropriate torque on the wheels and achieve desired speed of the vehicle.

2.2.2. Charging

There are various ways to charge the battery on the electric vehicle. Depending on the location of the charger, one can distinguish on-board battery chargers which are integrated into the vehicle itself, requiring users to provide external AC power from the utility grid, or off-board battery chargers, realized outside the vehicles as parts of static charging infrastructure.

In any case, a battery charger is some kind of power electronic converter topology, performing the role of electrical energy conversion from an AC utility grid for the adequately shaped DC voltage and current suitable for the battery. Depending on the power ratings of the charger, different speed of charging (levels) can be achieved, and one can differentiate between:

- 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

2.2.3. Rapid Charging

Rapid charging has the goal to achieve very short time at charging station, during which significant range can be added to the electric vehicle. While Level 1 charging adds around 5-8 km per hour of charging, and Level 2 charging around 16-32 km per hour, Level 3 charging is expected to add around 80 % of charge below 10-30 minutes. Such an approach requires high power rated converters to be used inside the charging stations (off-board charging), considering that very high powers are expected in a very short time.

This also creates additional stresses to the utility infrastructure and often some kind of peak shaving technique is used; e.g. stationary batteries are installed as part of charging station infrastructure and are charged slowly respecting grid capacity, while discharged rapidly into electric vehicle batteries using charging station converters. Interfacing (charging) the stationary batteries again, involves AC to DC conversion, while with the fast charging itself a DC to DC converter is controlled according to the voltage and current needs of the battery in the vehicle.

2.2.4. Wireless Charging

Connecting the car (i.e. the battery) with the charger – for fast charging – or the on-board charger to some power outlet – for moderate charging speed – involves parking the car close to a charging outlet at the charging station and handling heavy connectors and cables, which is seen as cumbersome.

Thus, several research activities elaborate devices for transmitting the energy, required for charging the battery over an air gap between two respective parts, usually integrated in the bottom of the car and the surface of the parking lot (much like it is done for electric toothbrushes or smart phones). The energy is transmitted by means of magnetic fields, which is built up by magnetic coils in both, the stationary and the vehicle side, being supplied with high frequency currents, again generated by means of power electronic circuitry. Some effort needs to be spent on achieving sufficient efficiency and power density as well as safety, e.g. detection of obstacles, debris, waste or animals which might be moved or move close to or in between the two coils and get exposed to the high frequency magnetic fields.

2.3. Railway Transport

In contrast to previously described electric vehicles, railway vehicles are predominantly always connected to the power supply line, which can be either AC or DC. Typical AC supply grid is 1-phase and rated either as 15 kV, 16.7 Hz or 25 kV, 50 Hz. On the other hand, DC supply lines may be 750 V (trolley buses, metros), 1.5 kV or 3 kV [1]. Due to the fact that railway vehicle is always connected to the supply line of relatively high voltages various power electronics converters are needed on-board to perform electrical energy conversion functions.

2.3.1. Traction drive

Main traction propulsion converters are with high power ratings and serve as interface between primary supply line and propulsion motors. Most of them provide bidirectional power flow and return energy back to the supply grid during train braking operation. As the contact between catenary wire and pantograph is not constant and even lost for short time intervals, braking resistors need to be provided, dissipating the regenerated energy in recuperative braking mode, if it cannot be supplied back into the grid. Again, power electronic converters shape the electric energy according to the needs of the electric propulsion motor and the primary supply line and control and stabilise the power flow, both in driving and braking operation.

2.3.2. Battery chargers

In public transport systems, batteries serve two main purposes:

- On one hand, batteries are used to provide the energy for the traction drive, on routes, where the installation of catenary wires is not feasible economically. Thus, these batteries have to be charged as long as the vehicle is connected to a power supply, e.g. at the stations and line segments with overhead lines.
- On the other hand, batteries are needed to supply auxiliary devices when the main power supply is not present or fails. Such auxiliaries include (emergency) lighting, power supply for vehicle control, and the like.

In any case, the energy stored into the battery during charging and taken from the battery while discharging is shaped by power electronic circuitry according to the power supply and the loads with higher power in the first and lower power in the second case.

2.4. Lighting

2.4.1. General Lighting

While the incandescent lighting was simple and operated without any power electronics, it was also very inefficient. Modern LED light relies completely on power electronic converters (drivers) and provides significantly improved energy efficiency.

In addition, the migration from fluorescent and incandescent lighting to LED lighting is leading to the need for careful management of flicker and light quality [2]. The health risks of flicker are an active area of concern and new products using WBG technology must ensure that they do not contribute to adverse health effects on the consumer.

According to various purposes of illumination, there might be different demands regarding colour (temperature), intensity and spectral composition. In any case, power electronic circuits provide efficient supply with electric power. In some cases, dimming function may be needed, in some domestic applications, integration into the bulbs may be desired, in automotive head lights, a dot-matrix may be driven for precise control of the areas to be illuminated.

2.4.2. Street Lighting

With emergence of LED lighting, various public places are being illuminated using this kind of technology. This requires presence of large number of power electronic drivers. At the same time, there are examples from Netherland, where power distribution for street lightning is done using DC, rather than commonly used AC lines. Such an approach modifies the overall system layout, requires power electronics converters at both end of DC line and improves the overall system efficiency due to use of DC cables.

Autonomous LED lighting for public areas can avoid the need for power distribution and the related investment at all. This can be achieved by collecting energy with photovoltaic panels during the day, storing it in batteries and use the energy for illumination during the night on demand only, in an intelligent manner. All the power flow (i.e. from the photovoltaic panels to the battery while charging and from the battery to the LED while illuminating) is controlled by power electronic circuits, possibly taking advantage of Wide Band Gap technology [3] [4].

2.5. Heating/Cooling

Heating, ventilation, air conditioning and refrigeration (HVACR) systems usually use some sort of heat transport medium (e.g. water) which needs to be circulated by pumps as well as heat pumps for shifting thermal energy from lower to higher temperature levels. These heat pumps typically involve compression of a working medium, condensation at higher pressure and temperature and expansion and evaporation at lower pressure and temperature. The process is powered by a compressor drive.

The role of power electronics in the majority of these applications is to provide variable speed operation for the sake of improved efficiency and better control of the thermodynamic process.

These systems are available in various sizes; e.g. domestic heating/cooling, refrigerators for household application up to HVACR of office buildings or industrial sites and cooling devices for professional use in grocery stores and cold storage houses.

2.6. Energy Storage (battery)

2.6.1. General remarks

While battery energy storage systems (BESS) are increasingly being deployed for various domestic, industrial and utility applications, they always require power electronic converters at different system levels. Battery cell voltages are low (e.g. 2.7 V) and to achieve higher voltages required by majority of applications, multiple of battery cells are normally connected in series, effectively increasing the voltage at the terminal of the battery pack.

Due to differences in internal properties of each battery cell, equal voltage distribution cannot be guaranteed across each cell and some kind of voltage balancing circuits are needed. This is often realized using power electronic converters, ensuring that deviations of the voltages among different cells are within allowed limits and thus ensuring long reliable operation and longevity. Charge balancing is the main reason, the battery has to be charged at a much slower rate above 90-95 % of its capacity, so that the balancing circuits do not dissipate excessive heat and over-heat the battery pack as a result. Once desired voltage ratings are achieved, further paralleling of multiple battery packs is needed to increase energy storage capacity.

On the other hand, once aggregation of multiple battery packs is achieved and a large battery is created, its connection to applications, irrespectively being it AC or DC, requires power electronic converters of some sort. In addition, Battery Management System (BMS) is deployed as combination of hardware circuitry and software functions, allowing for continuous monitoring of state-of-charge and health of battery cells, their temperature and any other deviations that are considered relevant.

Energy storage systems should also consider the use of hybrid storage systems, including supercapacitors, inductive storage and grid integration to provide effective and efficient support for energy systems and consumers.

2.6.2. Hybrid Energy Storage Systems

There are three main topologies of battery-supercapacitor hybrid energy storage systems (HESS): passive, semi-active and active. The passive HESS is the simplest and lowest-cost topology, however supercapacitor cannot be used effectively alone because the voltage of the supercapacitor must be equal to that of the battery and cannot be varied over a wide range [5].

The semi-active topology adds a power electronic converter between the supercapacitor and the DC bus, while the battery is directly connected to the DC bus. This topology decouples the supercapacitor and the battery, but the current of the battery cannot be conditioned directly, which may have a negative effect on the lifetime of the battery [6].

The active HESS uses dedicated converters for the supercapacitor and the battery and is the most commonly used configuration. The advantage of this configuration is that both the current from the battery and the current from the supercapacitor can be actively controlled [7].

2.6.3. Domestic Energy Storage Systems

Domestic, small-scale BESS are popular additions to household photovoltaic (PV) installations, especially when there is desired to achieve energy autonomy or standalone mode of operation without dependency from the utility grid. In such a scenario, provided that PV generation is sufficiently large, energy stored in the BESS is used to supply loads (overnight) when there is no PV generation. Off-grid storage is particularly important in isolated communities which are far away from grid infrastructure.

2.6.4. Medium Scale Energy Storage Systems

At utility level, medium-scale BESS are used to provide various supporting roles and ancillary services to the grid (e.g. peak shaving, frequency support, voltage support). Ratings of these systems are in the range of tens of MW and high-power converters are used to provide interfaces to the utility networks (normally AC today).

2.6.5. Large Scale Energy Storage Systems

When it comes down to the large-scale energy storage installations, hydropower energy storage constitutes around 95% of all combined electrical energy storage installed worldwide. For those reasons it is very often omitted from charts and graphs, as it significantly overshadows new popular storage means, e.g. batteries. The principles of operation are relatively simple and rely on:

- Storing the energy from the electrical network in form of potential energy of water in the upper reservoir (lake) by means of electrical machine operated as a motor (pump);
- Releasing the energy in form of kinetic energy of moving mass of water impacting the turbine driven electrical machine operated as generator connected to the electrical network.

Large amount of hydropower installations has been built more than 50 years ago, without any power electronics components, relying on previously described principles and operated at fixed speed with round trip efficiency of around 70% - 80%. It is worth mentioning that this is truly renewable energy storage system. Nowadays, trend is to retrofit old installations with variable speed units. The most dominant variable speed technology is based on use of doubly fed induction machine, where rotor side power electronics converters is normally rated around 10% of the machine rated power, providing reduced range of speed variation. Another emerging solution is based on use of converter fed synchronous machines, where power converter ratings are matching those of the synchronous machine. It is worth mentioning that in these large installations, the medium voltage motor/generator

units is in the range of 100-200 MW, and typically there are several units inside the plant, easily leading to near or over 1 GW of rated power.

Considering changing power system requirements and need for a variety of ancillary services to be provided, hydro pumped storage plants are increasingly being improved. This is made possible thanks to advancements in power semiconductors and power converter topologies. Being very critical applications, it is believed that future developments of high voltage semiconductor devices would enable realization of more reliable converter structures that would continue to serve these applications.

The main thrust for battery development over recent years has been for transport applications, particularly for the automotive market. These batteries are at present the biggest component both physically and in the bill of materials for a vehicle and so need to be carefully managed in order to maximise their lifetime. However, the capacity of such packs does reduce over time due to the physical degradation of the cells inside the pack. Once the cell capacity is reduced to 60% of their initial value (corresponding to 60% of their range), they are no longer considered viable for automotive applications. At this point they can be reused for other purposes such as energy storage; this is also known as *second life usage*. At this point, it may be desirable to disassemble the battery pack and reassemble with known good cells. This reuse extends the value of this expensive component, before it needs to be recycled. Usually, energy storage is a less demanding use of the battery as many of the high frequency charge/discharge cycles are reduced. The BMS is an essential integral power electronics part of the battery.

2.7. Wind Energy Generation

In contrast to renewable PV generation, which naturally produces power in DC form, wind turbines are using principles of electromechanical energy conversion relying on AC machines, and thus producing the power in AC form. For the sake of efficiency and controllability, modern wind turbine systems (type 3 and type 4) are completely relying on use of power electronic converters to achieve interface towards the AC grids. In this way frequency decoupling can be achieved, between fixed frequency of the AC network on one side, and wind speed defined turbine frequency on the other side. For those reasons, these kinds of converters are often termed frequency converters.

The amount of global installed wind energy has been increasing rapidly, with total installed capacity jumping from 23.9 GW in 2001 to 539.123 GW by 2017, as Figure 1 presents. The reasons for the increase of wind energy penetration for electricity generation are the maturing of the industry and the reduction in wind turbine price. Power electronics are widely used for wind energy conversion systems to improve the overall system performance in terms of efficiency, reliability and reduced cost. Wind turbines equipped with a squirrel cage induction generator (SCIG) connected directly to the grid, were very common in the 1980's with a maximum capacity of 50 kW. By developing power converter technology in the 1990's and 2000's, the rating and size of wind turbines have been growing fast, to reach 7.5 MW capacity in 2011 and 10 MW wind turbine by the year 2018, as Figure 2 shows.

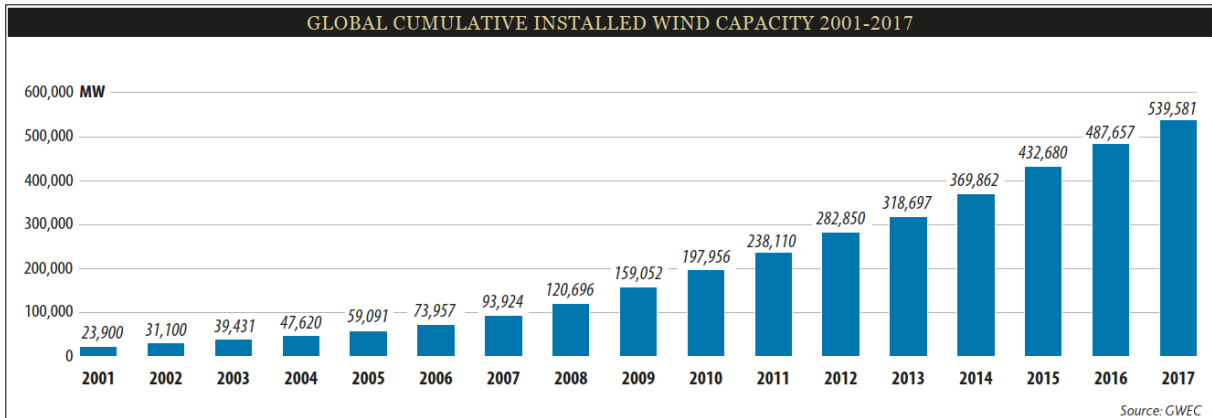


Figure 1: Installed wind power capacity [8].

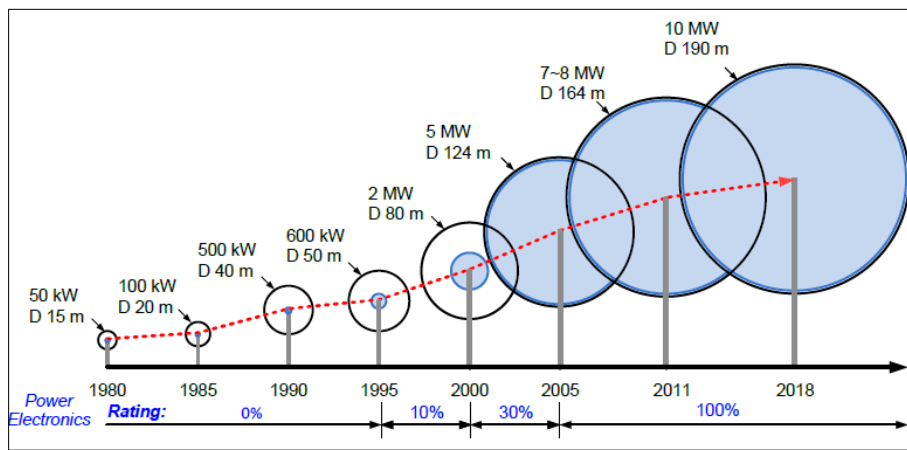


Figure 2: Development of wind power size from 1980 to 2018 including the share of power electronics for interface between generator and grid [9].

2.8. PV Energy Generation

In the field of renewable energy systems such as wind power, hydropower, biomass or geothermal energy, solar energy plays a key role in CO₂ free energy generation. Compared to traditional fossil resources/fuels, CO₂ is only generated during the manufacturing and disposal process itself (e.g. processing/disposal of electronic components, solar modules etc.). Energy generation from renewable energy sources such as solar is therefore much more environmental or eco-friendly and comes with a lower sustainability and environmental footprint than fossil resources such as coal, natural gas or liquid fuels.

One of the current weaknesses of photovoltaic solutions is their still relatively low overall system efficiency, which mostly originates from the solar cells. However, since 1976 the technology has strongly improved and cell efficiency highly increased for various PV cell types. Currently, the highest ever recorded and measured conversion efficiency value in a test laboratory is close to 50 % (e.g. 46 %, III-V Multijunction Concentrated Solar Cell, Fraunhofer 2019, standard test conditions).

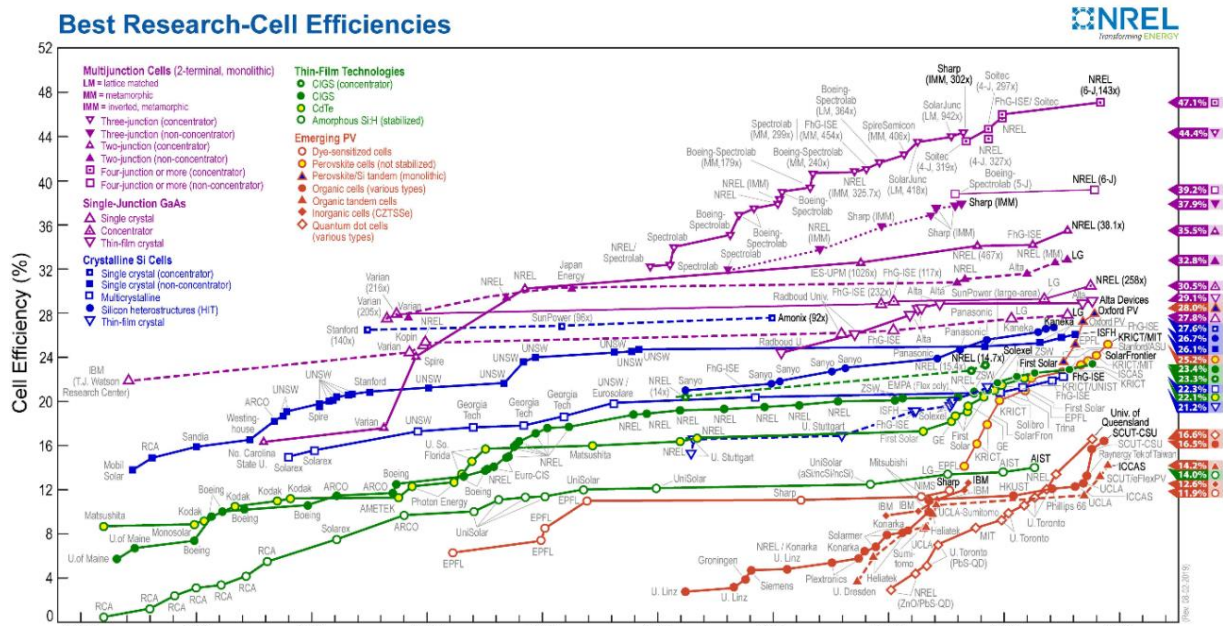


Figure 3: PV cell efficiency development. [10] (This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO.)

Despite its relatively low overall efficiency, PV offers one of the most attractive options in the very competitive field of solutions in renewable energy systems. It is possible to offer PV systems for a wide variety of power levels and reasonable cost. Due to the rather unpredictable development of energy cost per hour in the near future a lot of private customers show interest in low power home PV systems. Thus, compared to wind or hydropower, solar energy is also attractive for private households and hence offers a much broader market compared to other renewable energy technologies. The power range of these home PV systems will not change much in the near future as the household connected load limits of the grid will not increase and irradiated power is limited by the roof area.

In 2017, PV had the highest added power generating capacity (~ 100 GW) worldwide (2018 and 2019 not included), compared to other electricity generation technology, such as wind power, gas, coal, etc. Furthermore, an increase in installed capacity to slightly above 1 TW is forecast by 2022 (medium scenario) [11](page 7, 10).

The share of PV systems in the grid will therefore continue to proliferate in the near future. China in particular (new installations 2022; estimated high: 283 GW, estimated low: 148 GW) is playing a significant role in this scenario, alongside with India (new installations 2022; estimated high: 105 GW, estimated low: 53 GW) as these two countries will be among the main drivers for the integration and a push of PV power plants [11](page 20).

Due to the vast increase of PV and strongly fluctuating energy generators in general (as e.g. wind power), the availability of local storage systems (e.g. battery storage) is becoming more and more relevant. Thus, an increase in local installed battery storage systems is necessary to guarantee grid stability as it becomes indispensable to store excessive energy in the short, medium and/or long term and utilize it whenever the short-term energy production is not able to cover the instantaneous energy demand (see Section 2.6).

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

- the solar cell (conversion of solar energy into electrical energy) and
- the interlink between cell and grid or consumer and the associated electrical energy conversion facilitated by power electronic circuits.

In contrast to renewable wind generation, which naturally produces power in AC form, PV panels generate power in DC form. Similar to batteries, PV panels are made out of large numbers of PV cells of relatively low voltage and can be further aggregated into strings. Various power electronic converters are used to interface these systems with utility networks, and actual configurations or topologies depend on several factors. A brief classification is given here and shown in a historical overview of PV systems development in Figure 3.

PV Inverter: The inverter performs DC-AC electrical energy conversion from a DC source (one or many aggregated PV panel systems) and AC utility network. It can be 1-phase or 3-phase.

- **DC-DC Booster:** It is often used between PV panel and common DC collection power distribution network and provides the function of maximum power point tracking (MPPT), maximizing the extraction of power from the panel, under varying environmental conditions (e.g. illumination, temperature).
- **Central Inverter:** The advantage of this solution is the simplicity of the overall system. Only one inverter is required which is connected to the AC mains. An additional DC/DC converter for setting the MPP of each individual string is not required and hence omitted. Further advantages of this system are the simplified control, reduced effort in grid monitoring, and a minimum number of current and voltage sensors compared to other solutions such as string inverter or micro inverter. If isolation between grid and generator is mandatory, either a line-frequency or a high-frequency transformer (increased power density) can be utilized. Disadvantages of a central inverter are the additional string diode losses and the fact that only one global MPP controller can be in operation.
- **String Inverter:** As the name already indicates, each PV string is equipped with one bidirectional inverter. Thus, string diodes can be optionally omitted for such a solution. An additional DC/DC converter is only required if the total string voltage is lower than the minimum DC-link bus voltage for proper grid-connected operation. As each string has its own inverter they can be operated in MPP-mode individually. Furthermore, the topology is easily extendable by paralleling additional String Inverter building blocks. However, it has to be noted that paralleling of multiple non-synchronized inverters can lead to increased system losses due to circulating currents. Due to the high number of inverters, however, the total system cost increases, as the number of components (semiconductors, sensors, transformers, etc.) is also ramping up.
- **Multi-String Inverter:** The multi-string inverter is a combination of a central inverter and a string inverter. The inverter which has been used in the string inverter setup is replaced by a conventional or a more sophisticated DC/DC converter (full-load, partial load converters) and each of the individual DC/DC converters are then coupled via a common DC voltage bus. This DC bus is then connected to the AC grid via a central DC/AC converter. The multi-string inverter therefore requires fewer sensors than the SI. Furthermore, each string can be operated in its MPP. In addition, the system efficiency can be improved while omitting the string diode. Due to the common and distributed DC bus, however, this topology results in higher DC cable losses.
- **Micro inverter:** These low power converters are normally attached to the backside of single PV panels and perform local MPPT function on the single panel itself. Their outputs are con-

nected to the power distribution network. Modules with low voltage also require a DC/DC converter and thus a high number of components per PV cell. Therefore, this solution results in lower efficiency and higher relative cost compared to other solutions in a similar power range.

- **New Approaches:** Research has been performed to overcome the disadvantages of the DC/DC converters inside Micro Inverters or the effect of partial shading in string or multi string inverters. Mitigating the reduced energy production caused by partial shading can be achieved by connecting the PV modules in parallel instead of series. To avoid the high current due to directly paralleling the modules, a highly efficient and compact nX converter is proposed to transform the generated energy to a higher voltage level with a fixed voltage ratio and perform the parallel connection, as well as the MPP tracking at that higher voltage level [4].

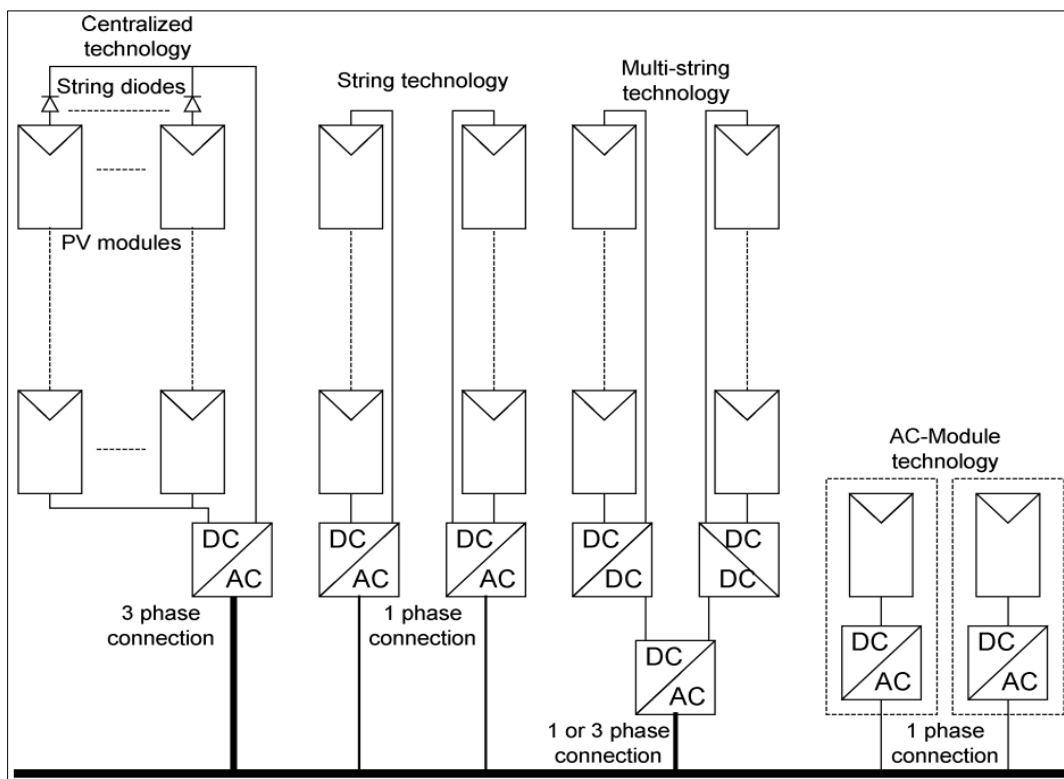


Figure 4: Historical overview of PV systems development [12].

2.8.1. Domestic PV-Converter

Domestic PV power converters typically operate at input voltage levels between 400 V and 700 V and are rated for a power delivery of few kW's (2.5 kW-10 kW). They are designed both in single- and three-phase versions, where the three-phase version usually has the main benefit of relieving input DC link capacitive filter requirements. A number of topologies have been proposed during the past years, for both stand-alone and grid-connected operation, and some specifically aiming at containing the common-mode currents associated with the specific characteristics of the input power source. The benefits of replacing Si technology with WBG in this particular application domain have been amply demonstrated and consist mainly in:

- Higher efficiency in an energy critical application;

- Reduction of components count, with important savings on the assembly and testing phases of the industrial manufacturing process;
- Reduction of filter elements sizes and volumes, with important spin-out benefits on storage/delivery phases of the commercialization process;
- Better EMI signature and easier filtering (the high switching speed demands for careful selection and design of passive filter components);
- Reduction of cooling and thermal-management needs, with the possibility to reach better reliability of operation even in harsher environments (see Figure 5).

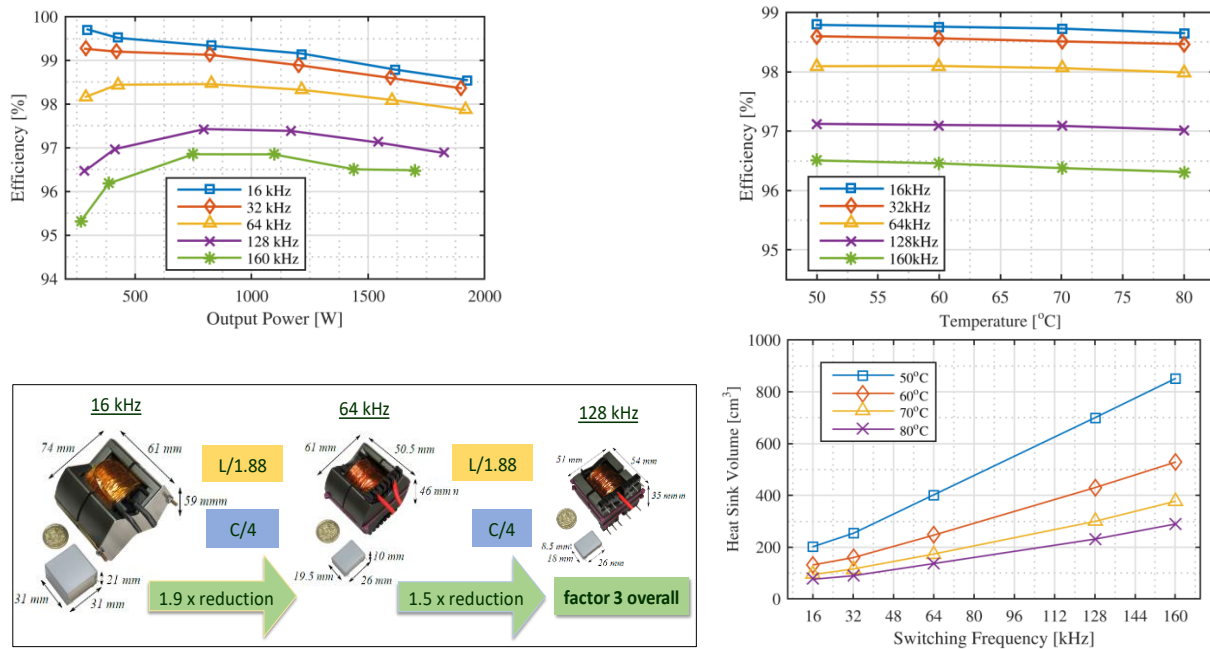


Figure 5: Trade-off between switching frequency, efficiency and volume for a GaN HEMT based single-phase three-level active neutral point clamped (ANPC) inverter; Single prototype measurement results: Efficiency over output power at constant heat sink temperature (upper left), efficiency over heat sink temperature at constant output power (upper right); Computed results: Minimum heat sink volume over switching frequency at maximum output power with the allowed temperature as a parameter (lower right), illustration of filter component volume (lower left) [13].

2.8.2. Medium Scale PV Converter

These systems are typically in the range from 10s of kW up to 100s of kW peak power. Most relevant topologies are as aforementioned the central inverter, string inverter or multi-string topology. In order to increase the peak power of the overall system all types of inverters and converters can come in parallel configuration. However, if those inverters are paralleled, a synchronized operation should be considered in order to omit circulating currents which can highly decrease the efficiency of each leg and also the total system.

The main benefit expected from using WBG devices, aside from efficiency gains, is the increase of power density and reduction of weight, reducing the effort of transport and installation.

2.8.3. Large Scale Systems

One example for a large-scale PV power plant is Canada's 97 MWp "Sarnia Solar Plant". The system consists of several *central inverters* (800 kW each) including a LV/MV transformer. Each LV/MV transformer is connected to the electrical grid via one common MV/HV transformer. Alternatively, an implementation would be possible using a dual-central inverter (2 x 800 kW) and a 12-pulse transformer

combining two stages, which results in lower volume. If transformers are not required for isolation, a multi-cell inverter can be utilized for each mains phase (virtual star point). The low voltage DC output of each switching cell can be used to gather one or more PV strings and their dedicated DC/DC converters.

When 10 kV+ SiC MOSFETs with distinct lower switching losses than their Si-IGBT counterparts become available, Multicell solutions for MV grid connected power electronics can be simplified. Further component savings could be achieved when directly feeding all PV cells into a MV DC-bus.

Furthermore, it can be shown that lower losses can be expected than in established Si solutions systems, but due to the low electricity prices, the extra energy you can feed into the grid due to lower losses cannot pay back the extra investment.

2.9. Aviation

Future hybrid and all-electric avionic propulsion will – as of today – be largely based on series hybrid drive architectures (see Figure 6 for example), in which the fuel turbine is used as a prime mover for an electrical generator; power electronics will then be used to interface generator and motor. Such approach offers the possibility to easily include energy storage devices or the introduction of advanced energy management and usage concepts, such as regenerative energy storage, integrated starter/generator functionalities and added safety for contingency situations. To ensure, sufficient power can be made available with realistically contained additional harness burden, which would adversely affect the vehicle overall efficiency, very high DC voltage buses are required, ranging from possibly a few kVs for a small light type of vehicle up to the MV range for airliners (for reference, the highest nominal DC voltage in the More Electric Aircraft architecture today is 540 V). The capability to accept higher DC voltage bus values further offers the potential to enable the use of permanent magnet synchronous machines as generators, with reduced circulation of reactive power (e.g., field-weakening), which, in turn, has a beneficial impact onto the rating of the power electronics, which comes much closer to that of the active power that needs to be circulated. Because of the desirably high rotational speed of the generator, high switching frequency of the semiconductor devices within the power converters is also a very important asset and one which also enables an important reduction of filter elements sizes and weights.

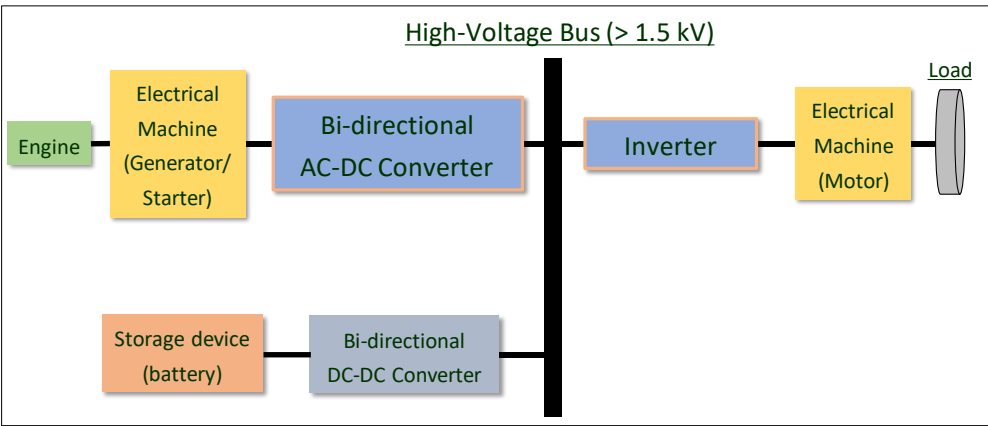


Figure 6: Series hybrid drive architecture (PECTA).

Silicon carbide is the most promising semiconductor device technology to jointly satisfy all of the requirements, while still guaranteeing high conversion efficiency. Recently developed 3.3 kV and 6.5 kV SiC MOSFET devices are of great interest for the lower power range aircraft and can also be used within modular power converter architectures to reach the higher voltage/power demands of larger aircrafts.

2.10. Ship

Marine industry has been benefiting from power electronics technologies, for many years already. Most of modern ships today are true electrical island networks on their own. Electricity generated from the synchronous generators driven by diesel engines, is distributed at medium voltage AC level to a variety of loads or consumers on the ship. These predominantly include propulsion drives (combination of AC-DC and DC-AC converters), and all the other hotel type of loads.

Current trends in marine sector are looking to replace AC electrical distribution networks by DC distribution networks. This is motivated by fuel savings, which can be achieved on the diesel-generator sets, provided they can be operated at variable speed. This is possible if the need to synchronize them to the AC power distribution is removed, and instead DC power distribution is used. This on the other hand requires addition of AC-DC converters (rectifiers) between AC generators and the DC power distribution network. This trend is already commercially happening in the LVDC domain with ABB and SIEMENS having many commercial ships outside in the field, whereas it is in the early phase in the MVDC domain, due to the lack of commercially available conversion and protection technologies.

The development of shipboard micro-grid can be traced as long back as to the early 1840s. A historical timeline of the shipboard micro-grid, with some development milestones highlighted, is illustrated in Figure 7. In the late 1830s, a fully battery-powered small boat capable to carry about a dozen passengers was demonstrated. The power used here was approximately 1 kW. The first formally recorded form of a commercially available shipboard electrical system can be dated back to 1880s: a DC system was used in the SS Columbia, a cargo and passenger steamship (1880–1907). The DC power system was used to supply the on-board lighting system, rated at around 6 kW. Between 1920 and 1960, main developments focused on diesel-powered engines for ships. Following the development of AC induction motors, hybrid diesel-electric vessels and turbo-electric propulsion for ships was pursued. A key momentum giver for further development was the availability of solid-state power devices around the 1960s.

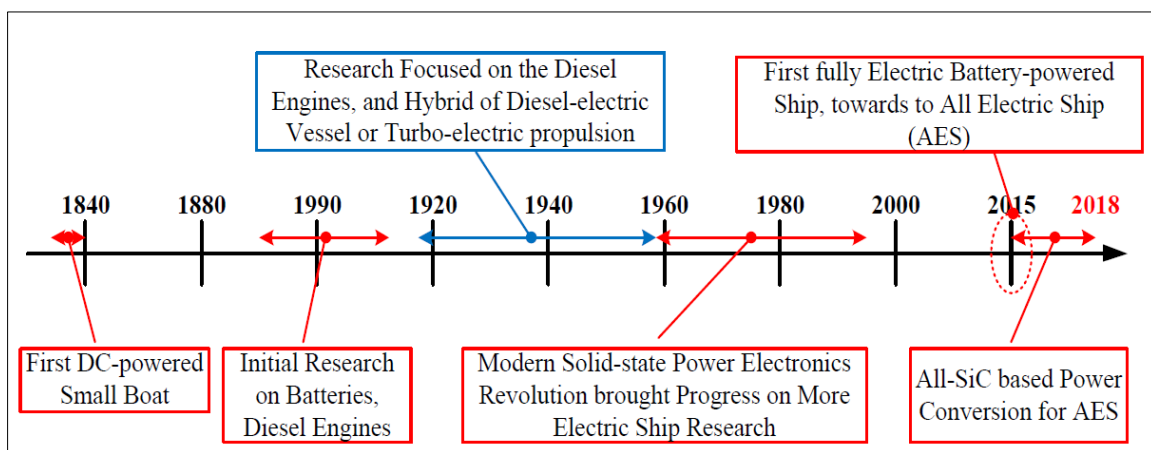


Figure 7: Historical development milestones in ship electrification (based on [14] [15]).

The Queen Elizabeth 2 (QE2) was developed in 1968: its power system was an integrated diesel-electric power grid, where a couple of diesel engines used for propulsion had generators connected. The main AC bus line rated at more than 10 MW and 10kV, and a power electronics-based conversion component was connected to supply the auxiliary loads. The conversion to diesel-electric propulsion of QE2 demonstrated an overall efficiency improvement and it was expected a maximum 12 million British pounds a year savings could be brought due to the reduced fuel requirement. The success of QE2 pushed a big step of the application of power electronics in shipboard micro-grids. In

January 2015 the first fully electric battery-powered ship was introduced. After that, the development of all electric ship (AES) has become a major research and development area.

2.10.1. Propulsion

Marine propulsion variable speed drives are often rated from few to few tens of MW, and represent critical elements of the ship, expected to operate highly reliably. In a modern ship with AC electrical power distribution, these drives normally represent the biggest power conversion block and thus their high efficiency is of high importance. Very often, redundancy concepts are employed (e.g. two standard 3-phase inverters are used to supply a 6-phase propulsion motor). Due to space constraints on the ship, there is strong motivation for compact and optimized solutions, better integrated into the overall ship layout.

2.11. Electric Drives

Whenever physical mass is accelerated or decelerated in a controlled manner by means of electricity (e.g. electric current flow in magnetic field, electric charges in electric field), engineers speak about electric drives. Therein an electro mechanic actuator (e.g. electric machine) transforms electric energy into mechanic movement (or vice versa). In many cases, precise control of the mechanical movement is needed, which is achieved by appropriate supply of the electro mechanic actuators with electrical energy of distinct “shape”. Changing the “shape” of electric power from what is available from the source to what is needed by the actuator is what *Power Electronics* is used for.

Electric drives can be found nearly everywhere:

- Residential appliances;
- Industrial drives (in production sites of nearly any kind, see 2.11.2);
- Traction (see 2.2.1, 2.3.1, 2.9, 2.10.1);
- Auxiliary drives in nearly any application.

Roughly half of the world-wide generated electrical energy is converted to mechanical energy in electrical drives. Half of this power is shaped by power electronic circuits to better suit the needs of the electric machines for supporting the mechanical processes.

2.11.1. Residential Appliances

A vast number of home appliances and household tools can be identified to depend on electric drives. By using power electronics, the performance and efficiency can usually be improved:

- White goods: washing machines (drum drive), dish washers (pump), refrigerators (compressor drive), freezers (compressor drive), etc.
- Tools: Blenders, coffee mill, vacuum cleaner, and others
- Heating system (pumps, fans); heat pump for heating and/or cooling (compressor drive), etc.

2.11.2. Industrial Drives

Industrial robots and conveyors are used to manipulate the geometric position of objects (tools, components, products ...) within production sites. Electric drives in paper mills, rolling mills, stamping machines depend on supply by power electronics as well as the drives for pumps, fans or compressors in chemical industry processes.

The role of power electronics in the majority of these applications is to provide variable speed operation for the sake of improved efficiency and better control of the industrial process.

The basic operating principles of power electronic circuits (i.e. generating the output voltage by switching between discrete input levels) result in the generation of steep voltage transients at the input terminals of the electric machines. These high dv/dt contents in the machine input voltage

pose a challenge for the design of the insulation system with the use of silicon power semiconductors already. Increasing the switching speed, which is enabled by the use of WBG based semiconductor switches, may reduce the losses inside the inverter, but also magnifies the challenge of insulation design, as well as bearing currents and EMI mitigation and dealing with capacitive residual currents. The higher switching speed, enabled by WBG technology may – on the other hand – allow for the integration of dv/dt or even sine filters with small size. By that, the use of cheaper unshielded cabling and cheaper insulation can become possible, resulting in lower cost for those components and even in a reduction of losses, otherwise caused in cables and machine windings by the harmonic content of the machine currents.

2.11.3. Auxiliary Drives

Within the term *auxiliary drives* we summarize all the drives, supporting the main purpose of any application listed.

An electric passenger car, for example, obviously uses an electrical machine as the main (traction) drive (see 2.2.1). Aside from the main drive, there are many additional drives present in a modern passenger car – in the range of 100 auxiliary drives for a medium sized car (even if it is powered by an ICE). These drives range from fuel and coolant pumps over fans for the air conditioning of the passenger cell or cooling of LED headlights to mirror positioning and seat adjustment.

Modern refrigerators may have fans inside and outside the cooling compartment for improved heat exchange and valves and flaps for controlling the coolant and air flow for maintaining the desired temperature distribution.

As with all (auxiliary) equipment, the operating conditions, lifetime, safety demands highly depend on the type of application. E.g. operating life differs between passenger cars and commercial vehicles; temperature ranges differ between industrial components and home appliances.

2.12. Energy Distribution

The power electronics technology base and advancements have opened up a wide range of possibilities in terms of controlling the way electrical energy is transported and distributed. Today, the electrical energy grid system requirements are mainly influenced by the largely increased energy demands especially in heavily populated and industrialised urban areas plus the challenge to deliver power from remote energy generation locations which include alternative energy sources such as wind turbines, solar cells and hydro plants. Furthermore, renewable energy supply is intermittent and unpredictable; hence the requirements on them for network integration/compatibility, grid stability and energy storage have also increased since their impact on the grid is of major importance. “Smart Grids” is often the terminology used for this evolutionary step for modernizing the entire Transmission and Distribution (T&D) network.

At the heart of the advancements in energy distribution power electronics systems lies the power semiconductor device. The very high-power end in grid applications which exceeds today the Gigawatt mark, represents a relatively small but important market sector for power semiconductor components. Their progress in principle is largely dependent on technologies developed initially for lower power applications and then scaled and optimized to enable the components to withstand higher voltages and currents to meet the requirements of higher power ratings.

In addition, many of the different applications in this area can be served by the same principal concept – the Modular Multilevel Converter (MMC) – which utilises identical Power Electronic Building Blocks (PEBB). These PEBB can be standardised and produced in high quantities.

Advances in ultra-high voltage semiconductors have led specifically over the past few decades to tremendous improvements in grid system applications in terms of power handling capability and control. With the recent energy related social, economic and environmental concerns coupled with the continuous progress in electrical power generation and control, the device development trends are set to continue as a major enabler for matching the performance expectations of future grid systems.

2.12.1. HVDC Current (Point to Point)

Today, most of the generated power is transported using 400 kV High-Voltage Alternating Current (HVAC) lines. Nevertheless, over longer distances (> 400 km), HVAC is economically unattractive due to high reactive power consumption rates, higher losses and lower stability of the transmission line. Therefore, for longer distances, High Voltage Direct Current (HVDC) transmission is the system of choice. In principle, for a point to point transmission, an HVDC system consists of two converters or valve stations at both ends of the transmission line. Depending on the direction of power flow, each station can perform the task to convert AC to DC or DC to AC. Different power semiconductor-based circuit topologies such as Current Source Converters (CSC) and Voltage Source Converters (VSC) are employed for the AC/DC conversion process depending largely on the transmission distance and power levels involved.

For long distances and multi-Gigawatt power transmission, classical Phase Controlled Thyristor PCT based CSC topologies are widely applied in what is referred to as line commutated HVDC due to their overall low system losses which are attributed to the very low conduction losses of the thyristor concept. Furthermore, since a large number of PCT press-pack devices are connected in series to achieve the high blocking voltage requirements of the system, PCT voltage ratings up to 8.5 kV have been developed with single device current ratings in excess of 6000 A. Therefore, such systems are reaching transmitted powers in excess of 10 GW using DC-voltages of +/-1100 kV.

2.12.2. HVDC Voltage (grid)

Normally, line commutated HVDC systems require high quality AC-networks on both ends of the transmission line to switch off the thyristor valves. This system limitation can be resolved using VSC based HVDC systems which require turn-off devices such as the IGBT. Additional advantages are achieved for providing a more stable grid with high levels of regenerative power sources. In brief, a VSC based HVDC system can precisely control reactive power for stabilizing any AC networks it connects to. Therefore, for relatively shorter distances and lower power levels, IGBT based VSC conversion is becoming the system of choice due to a number of integration and control features especially when taking into account the introduction of renewable energy into the grid. This is due to the fact that there is no more need for the AC network part and hence VSC HVDC is employed to connect large offshore wind-parks to the mainland.

The first-generation VSC HVDC systems were based on a two-level topology with a large number of power semiconductor switches (mainly IGBT press-pack modules) connected in series to reach the required voltage levels. The operation frequency of such systems was in the range of 1-2 kHz and hence both the conduction and switching losses were strongly determining the system losses. This approach was modified with the introduction of the Modular Multilevel Converter topologies which operated at much lower frequencies below 300Hz. As a result, the IGBTs and diodes were optimised to have low conduction losses. Such topologies enabled the VSC HVDC concept to target power levels approaching those of CSC HVDC systems (3 GW) with similar overall system losses as shown in Figure 8 courtesy of ABB's (HVDC Light © is VSC HVDC).

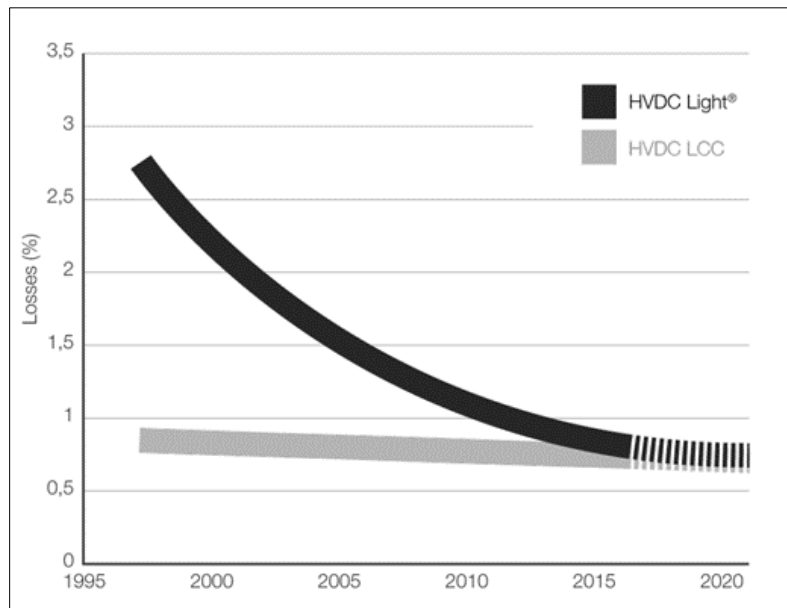


Figure 8: HVDC overall system losses comparison, courtesy of ABB [16].

Furthermore, such systems will enable multi-point grid systems with plans to commission the world first HVDC grid in China in 2020 as shown in Figure 9 courtesy of ABB.

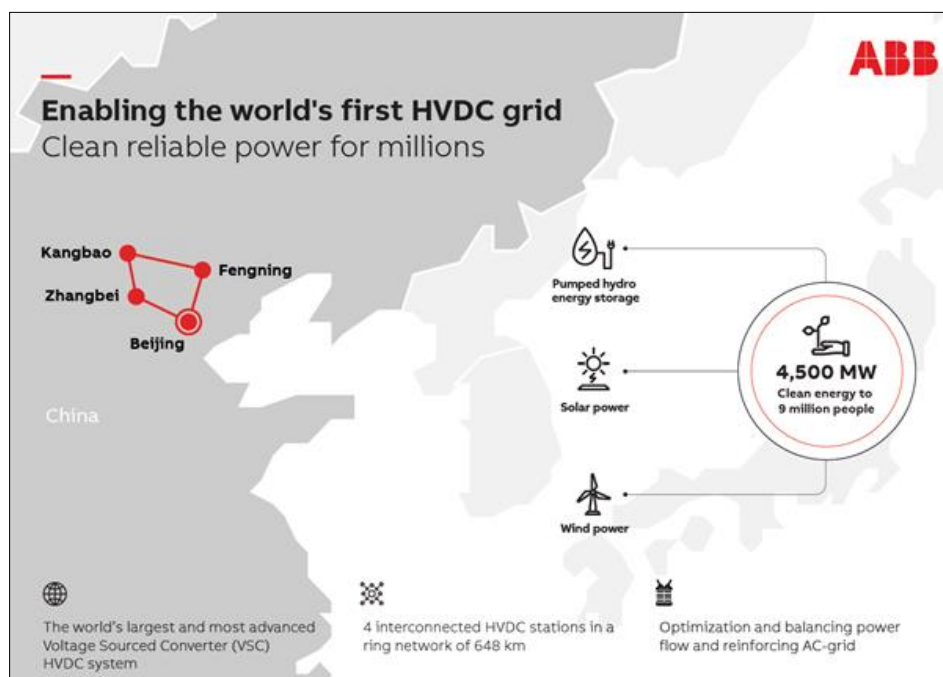


Figure 9: World first HVDC grid, courtesy of ABB [17].

From the power semiconductor prospective, HVDC system main requirements are low system cost, low operational losses, high power ratings and stable and reliable operation. Hence, devices with high voltage and current ratings, low conduction losses, wide Safe-Operating-Area margins and reliable behaviour are a must. Furthermore, they are normally operating under full load conditions and hence the losses under nominal operating power ratings or higher represent the larger portion of the overall losses.

2.12.3. Flexible AC Transmission Systems (FACT)

In addition to HVDC, a number of grid power electronics applications exist predominantly on the AC side which are generally grouped under the heading Flexible AC Transmission Systems (FACTS). These include Static Compensators (STATCOM) for voltage stabilization and load balancing, grid interties, energy storage, and active filters to name a few. Many of these systems, as they are fundamentally AC based, operate at medium voltage and connect to the high voltage grid via transformers. They are mostly based on VSC topologies utilizing turn-off devices such as IGBTs. Similar to modern HVDC systems described above, Modular Multilevel Converter topologies are increasingly employed in modern FACTS systems especially for the higher power range. As for HVDC, the power semiconductor has a huge impact on the levels of performance achieved in FACTS applications with clear focus on reduced cost and losses. However, they differ in the fact that they are more likely to operate under sub-load or idle conditions where the losses under such operational modes represent a more significant portion of the overall losses [18].

Despite the fact that a wide range of high voltage devices with attractive electrical characteristics exist, higher power and superior overall performance remain as the main development trend for satisfying the demands of next generation grid system designs [19].

2.12.4. Smart Transformer resp. Solid-state Transformer

Solid-state Transformer (SST) or Power Electronics Transformer (PET) has been attracting a lot of research attention recently, both in academic and industry. While there is no consensus on the actual topology or implementation details, there are some common features that characterize many proposals made in the literature:

- SST is generally considered to be isolated power electronics conversion structure, where galvanic isolation is achieved by means of single or multiple transformers operated at higher frequencies, e.g. several kHz or tens of kHz.
- SST terminals are normally power electronics based, while galvanic isolation is inherently built inside the converter.
- SST can be adapted (topologically) to perform any conversion of interest, as symbolically illustrated in Figure 10. Inputs and/or outputs can be DC or AC, single-phase or three phase AC, low, medium or high voltage, respectively.
- SST is often considered to be modular conversion structure made out of many modules, allowing reaching high application voltages.

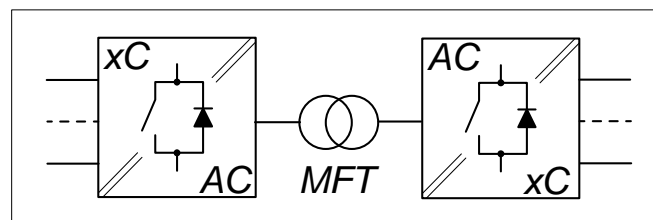


Figure 10: Generalised structure of Solid-state Transformer power conversion (PECTA).

Development of (SST) technology has many different drivers, which are applications specific. In railway AC applications, SST is considered as replacement for bulky line frequency transformer and rectifier, normally found on locomotives. In this case it performs single-phase MVAC to MVDC conversion. Further motivation comes from the fact that transformer size is significantly reduced through operation at higher frequencies, which leads to compact size (volume and weight) of the SST solutions. Power semiconductors enable these high frequencies and new WBG devices offer significant prospects in this domain, over the Si counterparts. Similarly, for other applications, where galvanic isola-

tion combined with need for compact solutions is of paramount importance, SST offers interesting prospects. Examples are: wind turbines, marine on-board installations, urban utility installation, etc.

When it comes to utility and power distribution networks, SST being a power electronics converter, offer full control over the power flow and variety of supporting functions to the power systems operators. Nevertheless, there are challenges associated with SST, the main ones being the reliability and efficiency, which are driving research area forward and will strongly benefit from developments in WBG area. For stationary applications, where weight and volume do not play an important role, the efficiency levels of nowadays Megawatt transformers are not foreseen to be reached by solid-state transformers even using SIC devices. In terms of efficiency, solid-state transformers can become feasible if AC to DC conversion is needed, though.

Considering ongoing and near future changes from centralised to distributed energy generation, overall energy distribution efficiency as well as thermal and stability limitations of the transferable power within low voltage and mid voltage distribution grids may profit from the additional capabilities (i.e. dynamic adjustment of the voltage transfer ratios and injection of reactive power) of hybrid or solid-state transformers, as laid out in [20].

2.13. Power supply (AC-DC)

Switched Mode Power Supplies (SMPS) represent by far the biggest industrial sector and market by number of sold units. These power converters are found inside all consumer electronics (e.g. induction cookers, TV sets, satellite receivers, tuners, DVD players, electric shavers, epilators, electric toothbrushes ...), computers, mobile phones and various industrial applications. As the name says, they are characterized by high frequency operation of semiconductor devices inside the corresponding power electronics topology, irrespectively whether it is galvanically isolated or non-isolated. These kind of power electronic converters are subject to strict power quality, EMI and EMC regulations.

2.13.1. Mobile Devices

Mobile devices, being powered from the battery of a modest capacity, with compact form factor and with severe space constraints, require extremely efficient power electronic converters. Taking a mobile phone as an example, there are dozen SMPS integrated inside, providing voltage regulation for various sub-circuits: WIFI, audio, screen backlighting, processor, etc.

Recharging the battery involves power electronics in reshaping electrical power from AC to DC, reducing the voltage level from the mains to 5 V and especially isolation from the potentially harmful mains voltage.

Even though, the energy being shaped by a single adapter throughout its operational life is rather low (i.e. in the range of 10 kWh), efficiency 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 one of the prominent development directions, which may be supported by the use of WBG devices, enabling higher switching frequencies and thereby allowing for size reduction of passive components. Volume and size reduction should lead to reduced consumption of resources during production and recycling and together with the increased efficiency allow for lower environmental impact.

2.14. Auxiliary Power Supplies

All sorts of DC/DC converters are used for stepping up or stepping down the voltage of the battery for the various loads on vehicles. Considering that battery voltage will normally be reduced as battery is being discharged, these auxiliary converters provide effective voltage regulation at its output from a varying input voltage, and output voltage is adjusted to match the load requirements (e.g. 24 V,

15 V, 12 V, 5 V). In general, there are multiple loads (consumers) present in the vehicle, such as: electronic control unit (ECU), lighting, displays, sensors, actuators, etc.

In Railway applications, aside from the main traction drive, there are various other auxiliary power converters providing power to so-called HVAC (Heating, Ventilation, Air-Conditioning) systems. These converters need to provide well-regulated voltage with high power quality, considering that they supply very sensitive loads. E.g. to charge mobile devices (e.g. laptops, mobile phones) in the train, passengers are using private chargers, designed for domestic use. For those reasons, power quality must be maintained very high, either through high switching frequencies or use of appropriate filtering.

2.15. Uninterruptible Power Supplies

Some applications, such as intensive care units and data centers, demand for continuous power supply. These demands are satisfied by the installation of Uninterruptible Power Supplies (UPS). These utilise a battery, capable of providing the needed energy in case of a grid failure. While the electrical energy provided by the battery comes as DC, the consuming devices, normally powered from the mains, need the energy on form of AC voltages and currents. Therefore, at least one DC to AC conversion is needed during grid failure and another *DC to AC* conversion is needed for (re)charging the battery, when power from the grid is available.

As some loads can tolerate power supply interruption times in the range of 10 ms and others can't tolerate any interruption at all, different topologies for UPS have been developed:

If short interruptions are allowed, bypass switches can be used to supply the load directly from the mains, as long as the voltage does not trip below a certain limit and switching to the battery supply otherwise. Taking the drawback of short supply interruption during switch operation is rewarded by lower system losses and longer lifetime, as the power is only shaped by the DC to AC converter when really needed.

Intolerance to any supply interruption is met by continuous operation of the DC to AC conversion without utilising bypass switches (in regular operation modes) and powering the DC bus by an AC to DC converter at the same time, as long as power is available from the grid, and draining the battery otherwise. Thus, the load power flows through two conversion stages (AC to DC and DC to AC) continuously, resulting in according power losses and component wear out.

Independent of the type of UPS, WBG devices can be expected to increase the efficiency of the conversion stages, which is especially important for the second version.

In special cases, when the powered load needs DC supply only, the DC to AC converter can be replaced by a cheaper and more efficient DC to DC converter, adjusting the voltage level only, thus allowing for an additional increase in efficiency, which does not depend on WBG devices, though.

2.16. Data Centers

The increasing amount of digital data, being generated, processed and stored, spawns an increase of energy demand as well. The energy consumed in data centers is used for powering the more obvious loads, such as computers, data storage and network units, but also auxiliary equipment for cooling and ventilation in order to get rid of the waste heat, generated during data processing and the shaping of electrical energy.

Thus, reducing the losses in the AC to DC converters for supplying the data processing and storing units is paid back twofold: First, the amount of power not being dissipated into heat does not need to be supplied and second, the energy needed for the disposal of the waste heat is reduced as well.

Considering the conversion efficiency, one needs to keep typical load cycles in mind. Nominal power might not be drawn continuously, and partial load operation might be the predominant situation. Therefore, efficiency at partial load is of same – if not higher – importance as at nominal load. The introduction of load balancing is attempted for between the data processing units as well.

Together with the integration of UPS (see 2.15) and the introduction of DC distribution of the energy within the data center a reasonable potential for saving energy is opened by combining the increase in conversion efficiency, e.g. by the use of WBG devices, with the reduction of conversion steps by optimising the energy distribution topology, the latter one of which does not depend on WBG technology, though.

3. Advantages of WBG in the Applications

3.1. Introduction

A wide range of power electronics applications were outlined and briefly explained in the previous chapter 2. In this section a short overview of such applications in relation to the different existing power semiconductor devices is presented to provide a platform for addressing the potential advantages brought by WBG devices.

3.1.1. Power Electronics applications

The majority of power electronics conversion applications are based on Voltage Source Converter (VSC) topologies operating at switching frequencies not exceeding 150 kHz for the low power range, 20 kHz to 25 kHz for the medium power range and 2 kHz for the high-power range. With few exemptions such as in GW thyristor based Current Source Converters (CSC) for energy distribution systems, the majority of applications are fully reliant on silicon IGBTs and in few cases on IGCTs such as in medium voltage industrial drives and silicon (Super Junction) MOSFETs for the low power range. Figure 11 shows the different Silicon based power devices in relation to the conversion power and frequency. Furthermore, different power electronics applications are presented in relation to the required current and voltage ratings. The wide range of power electronics applications differ from one another with respect to the technical requirements/specification and economic targets in terms of power handling and efficiency.

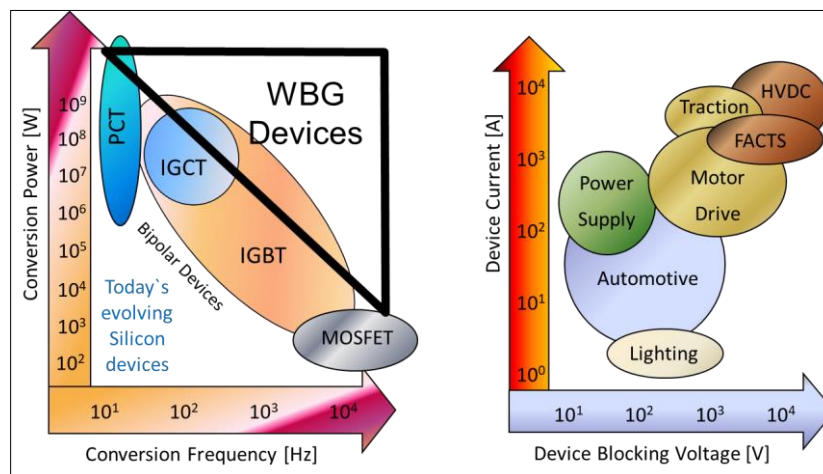


Figure 11: Power Devices and Applications: Conversion power and device classification (based on [18]).

Below, power electronics applications are classified into three sectors:

- **Traditional conversion applications:** Traditionally, VSC based applications such as in Grid Systems (HVDC and FACTS), Rail Traction and Auxiliary Converters, Low Voltage and Medium Voltage Industrial Drives and power supplies adopted mainly 2-level or 3-level circuits depending on the application requirements and optimum performance/cost ratio. Hence, higher voltages were only possible to achieve through the series connection of many devices such as in HVDC systems. Nevertheless, in the past decade, many grid system and industrial drives applications have employed multi-level topologies, which operate at much lower frequencies (<300 Hz) for achieving very low losses and much higher power levels. Such topologies build on the strength of silicon devices for lower conduction losses and large area device manufacturing capabilities (including high power IGBT modules). Mainstream applications have benefited strongly from the evolutionary steps made on device/package technologies and manufacturing capabilities for achieving

large gains in system performance, reliability and cost. Hence, there exist many device and package solutions available to satisfy the different application requirements.

- **Emerging conversion applications:** Based on similar principles to the traditional applications, there is a strong development trend with strong market growth for emerging conversion application such as EV/HEV traction, Marine and Aviation propulsion, Renewable Energy Conversion and Storage, high reliability military and medical applications to mention a few. Depending on the production volume and the mobility of such applications they may show stronger demands to reduce weight, size and cost of the power electronics system when compared to the traditional (stationary) applications. In addition, a stronger drive for system integration meant increased requirements to increase the power semiconductor maximum operating temperatures and operational frequencies.
- **Emerging Solid-State applications:** Advances in power semiconductors and power electronics systems have led to the current research direction for new solid-state applications for replacing traditional mechanical based products, which also require optimized power devices. For example, DC-DC conversion envisioned for future traction and MV grid systems require very fast switching devices for operating at high frequencies >2 kHz with minimum switching losses. On the other side of the operational spectrum, high voltage DC breaker solutions, which are best described as event switching, have a clear target to minimize conduction losses. There exists a wide range of breaker and contactor applications which seek solid-state solutions with improved reliability, better controllability and the potential for digital integration.

3.1.2. Power Semiconductor Devices

Silicon based power semiconductors have established themselves as the devices of choice in the vast majority of power electronics applications. The dominant role of silicon power devices which include MOSFET, IGBT, IGCT, Diode and Thyristor, has been achieved by the tremendous advancements over the years in the starting material quality, advanced process fabrication techniques and evolving device design concepts. In parallel to the silicon device developments, components based on Wide Band Gap (WBG) materials such as Silicon Carbide (SiC) have been intensively researched and developed for power electronics applications due to the substantial advantages their inherent material properties could realize at device level as shown in Table 2 below. For the two main WBG materials SiC and GaN which have been researched and developed extensively over the past two to three decades, the main advantageous properties are the much higher critical electric field and excellent thermal conductivity (especially for SiC). Wide Band Gap refers to the energy bonding atoms together in the semiconductor, these bonds are much stronger than for Silicon and give the WBG materials much superior performance due to the fact that higher electric fields are needed to break the atomic bonds.

Table 2: Si and WBG material properties [21].

Parameter		Silicon	4H-SiC	GaN	Diamond
Band-gap E_g	eV	1.12	3.26	3.39	5.47
Critical Field E_{crit}	MV/cm	0.23	2.2	3.3	5.6
Permittivity ϵ_r	–	11.8	9.7	9.0	5.7
Electron Mobility μ_n	$cm^2/V\cdot s$	1400	950	800/1700*	1800
BFoM: $\epsilon_r \cdot \mu_n \cdot E_{crit}^3$	rel. to Si	1	500	1300/2700*	9000
Intrinsic Conc. n_i	cm^{-3}	$1.4 \cdot 10^{10}$	$8.2 \cdot 10^{-9}$	$1.9 \cdot 10^{-10}$	$1 \cdot 10^{-22}$
Thermal Cond. λ	W/cm-K	1.5	3.8	1.3/3**	20

* significant difference between bulk and 2DEG

** difference between epi and bulk

In brief, such WBG based components can be manufactured on much thinner base regions for realising unipolar type power semiconductors such as MOSFETs for a wider range of voltage ratings beyond their bipolar silicon counterparts and with higher power densities and improved electrical performance in terms of

- low conduction losses during light and partial load due to absence of bipolar junction,
- very low switching losses due to absence of any stored bipolar charge, this will enable a factor of 10 higher operational frequencies.
- higher operating temperature capabilities due to low leakage current
- compact due to switch and diode integration with the available built-in diode in the MOSFET.

These characteristics of the WBG devices (especially SiC and GaN) lead to an extending of the “Silicon Limit” as shown in Figure 12.

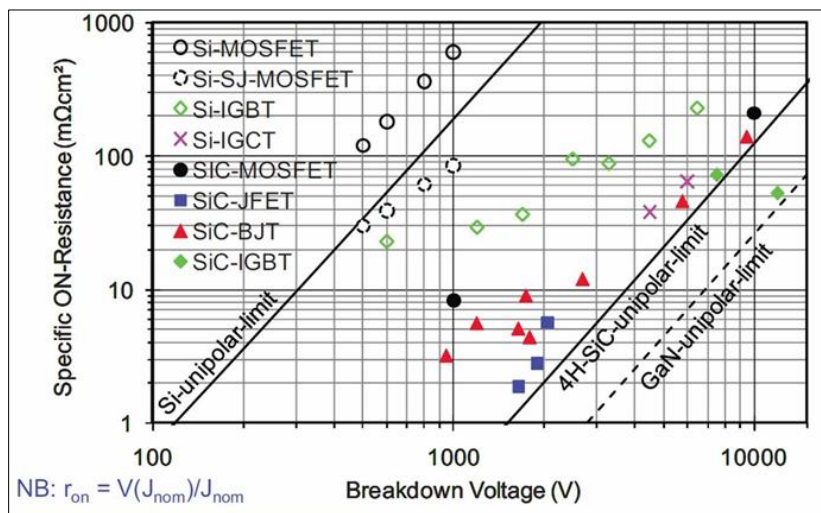


Figure 12: Silicon, Silicon Carbide and Gallium Nitride Specific On-state limits [21].

Such superior performance has a clear impact on almost all power electronics applications for achieving much improved efficiencies while operating at higher current densities, frequencies and temperatures. Substantial reductions in the overall system size and weight due to the potential downsizing of the semiconductor, passive components/magnetics and the cooling system will be gained. In the following paragraphs, the focus will be on Silicon Carbide since the material has provided the most advanced VERTICAL power device concepts suitable for medium to higher power applications.

3.2. Advances of SiC-based Power Semiconductor Devices

As mentioned above, SiC has a clear impact for realising fast switching unipolar type power semiconductor devices with higher voltage ratings than those based on Silicon. The first SiC device product that was introduced to the market in 2001 was the Schottky Barrier Diodes (SBD) with ratings up to 600 V. The SiC diodes are today offered as single discrete components or in Hybrid modules alongside silicon IGBTs with voltage ratings up to 1700 V. Such devices are featured in power factor correction PFC applications and in many low power inverters such as in solar PV applications. In addition, SiC MOSFETs are available today alongside SiC diodes with ratings up to 1700 V where they are also offered as discrete components or in full SiC MOSFET modules. The introduction of the SiC MOSFET shown in Figure 13 is regarded as an important milestone in the development of power semiconductors in general. Hence, a growing number of power electronics applications which require power devices with rating above 600 V are looking today into SiC based devices in order to realise the next generation systems with overall performance specifications superior to those of the older generations based on Silicon power semiconductors.

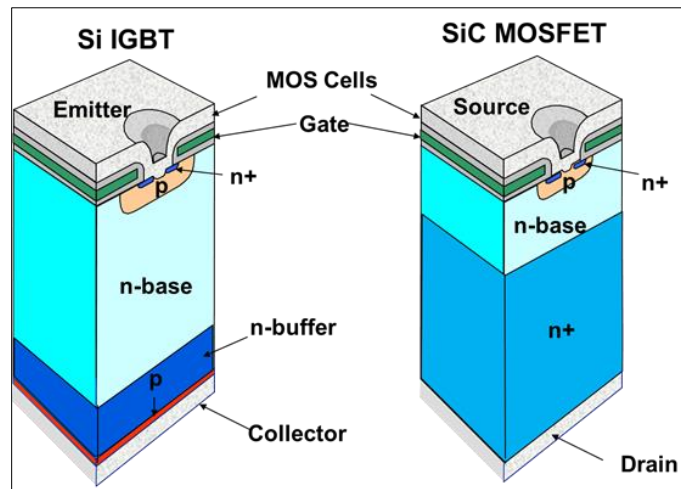


Figure 13: The Silicon IGBT (left) compared to the SiC MOSFET (right) [22].

Furthermore, SiC device development has extended to higher voltage ratings ranging from 3300 V and up to 10 kV. Remarkably, bipolar device concepts were also demonstrated as prototypes with breakdown voltages exceeding 20 kV. In principle, such HV devices have the potential to provide further improvements with respect to lowering the overall losses to those in the lower power range.

With some of SiC based devices, a high level of maturity has been achieved, including the overall device ruggedness as well. In many applications the fast switching characteristic in forward and reverse operation can be utilised. In reverse operation the same chip size is available.

It is important to note that Silicon devices will continue to serve the market for power electronics applications in the lower power end which require device ratings below 600 V. This has led to the focus on developing SiC devices with ratings beyond 600 V for the medium power range (600 V-1700 V) and high-power range (>2500 V). Today, the short to medium term target for SiC market penetration remains in the medium power range due the wide variety of power electronics applications and related market and potential growth.

3.3. Advantages of SiC-based Power Electronics Applications

The traditional trend for power devices in general is to reduce both conduction and switching losses in order to increase the power density handling capability and/or to achieve an improved system efficiency. Therefore, almost all applications will benefit from these features regardless of the operational switching frequency. Silicon device concepts are always developing towards improvements with respect to lower losses, higher operating temperatures and increased robustness and reliability for satisfying requirements in new converter designs.

Hence, in order to challenge silicon devices in this power range, while SiC devices bring many advantages, they will still need to overcome a number of challenges (depending on the application) that will be faced when compared to the well-established silicon devices such as IGBTs and diodes. This also applies if a new approach at converter level is being adopted to accommodate the benefits of SiC devices. The focus in the next section will be on the SiC Power MOSFET where the main advantages can be summarised in four aspects when compared to Silicon IGBTs:

- **Low Conduction Losses:** Compared to the Bipolar Silicon IGBT, the SiC MOSFET is a unipolar device which means it does not suffer from a built-in voltage drop as for Si IGBTs and diodes. Silicon IGBTs and diodes exhibit a built-in voltage of around 0.7 V which means regardless of the IGBT or diode technology and /or device total area, the conduction losses cannot achieve voltage drops below that value. The MOSFET, when it is gated on, on the other hand behaves like a resistor and

the losses can be reduced with improved technology steps and with increased active areas. Figure 14 shows the IV characteristics representing the conduction losses (as a product of voltage drop and current) of a Silicon IGBT and SiC MOSFET in both switch and diode modes for a 3300 V rated device with an active area of 1 cm^2 . The diode mode shows both the channel diode and PIN diode of the SiC MOSFET.

Hence, the potentials for reducing losses with SiC MOSFETs is beyond the reach of Si devices in light-load or partial-load operation and until the break-even point between both, IGBT and SiC MOSFET output characteristic is reached. Thus, against the current perception, this aspect makes SiC MOSFETs very attractive for those applications (including modern multi-level topologies) which require primarily low conduction losses due to the low operating switching frequencies for such systems and despite the fact that the benefits from the lower switching losses will be minimal. Furthermore, the SiC MOSFET resistive like IV characteristic can provide low conduction losses over a wide current range due to absence of bipolar junction. This will result in much lower losses at low current below 10% of the nominal current. Many power electronics applications can hugely benefit from the low conduction losses at low currents such as in FACTS/STATCOM or Urban Traction where a large percentage of the losses are dissipated in partial-load or idle conditions. Furthermore, solid-state breakers can benefit hugely from the SiC MOSFET's low conduction losses to compete with the very low voltage drop in mechanical breakers.

- **Low Switching Losses:** Again, compared to the bipolar Silicon IGBT, the SiC MOSFET is a unipolar device which means it will exhibit very low switching losses due to absence of stored charge during turn-off. Figure 15 shows the current and voltage waveforms of a Silicon IGBT and SiC MOSFET in both switch and diode modes for a 3300 V rated device with an active area of 1 cm^2 . The turn-on losses will also be low due to the low diode recovery charge. Overall, the SiC MOSFET offer more than 80% reduction in switch mode losses with negligible diode recovery losses (despite the MOSFET PIN diode charge) when compared to silicon diodes. This will enable higher switching operational frequencies with lower losses and also allow systems to adopt less passive components/magnetics.

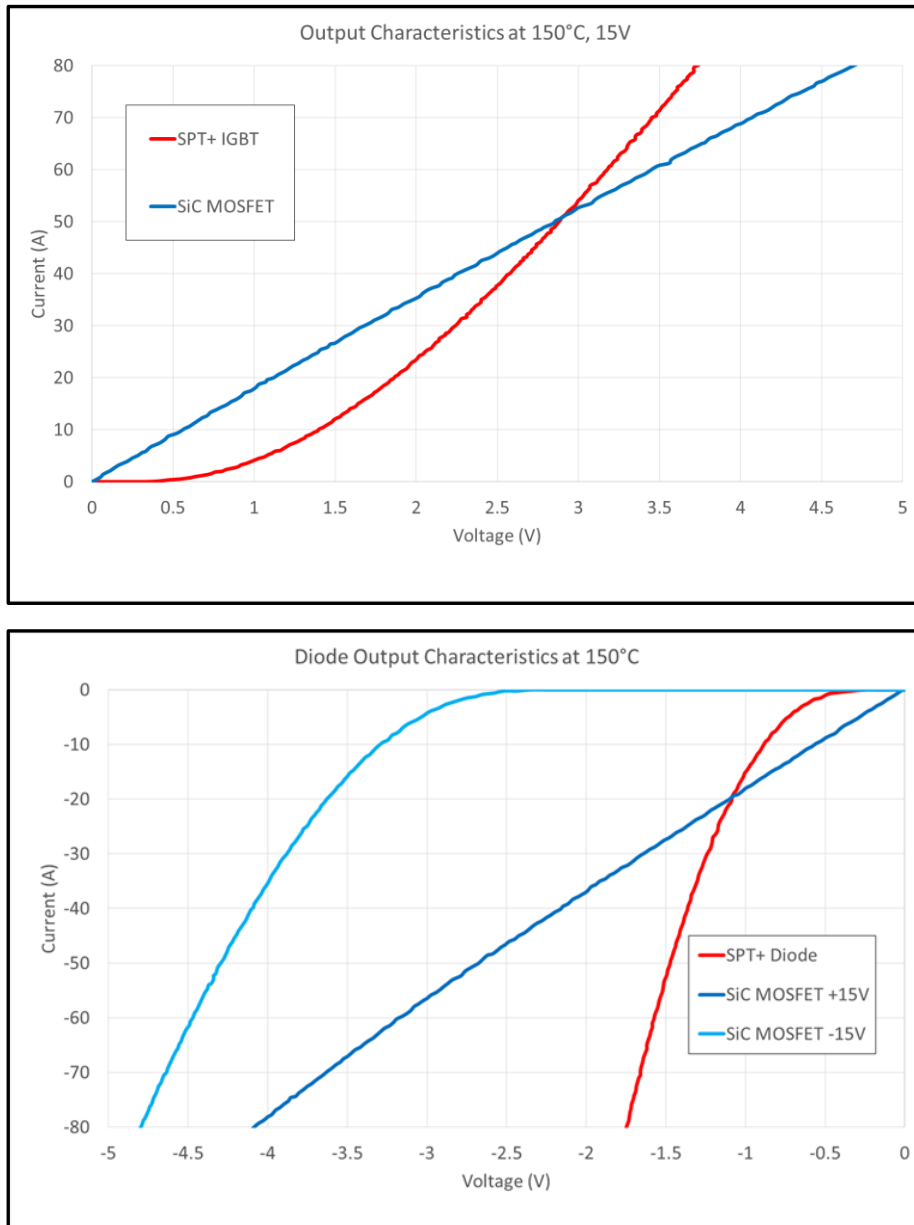


Figure 14: The Switch (top) and Diode (bottom) IV Characteristics of a 3300 V 1 cm² ABB SPT+ IGBT and Rohm SiC MOSFET at 150°C [22].

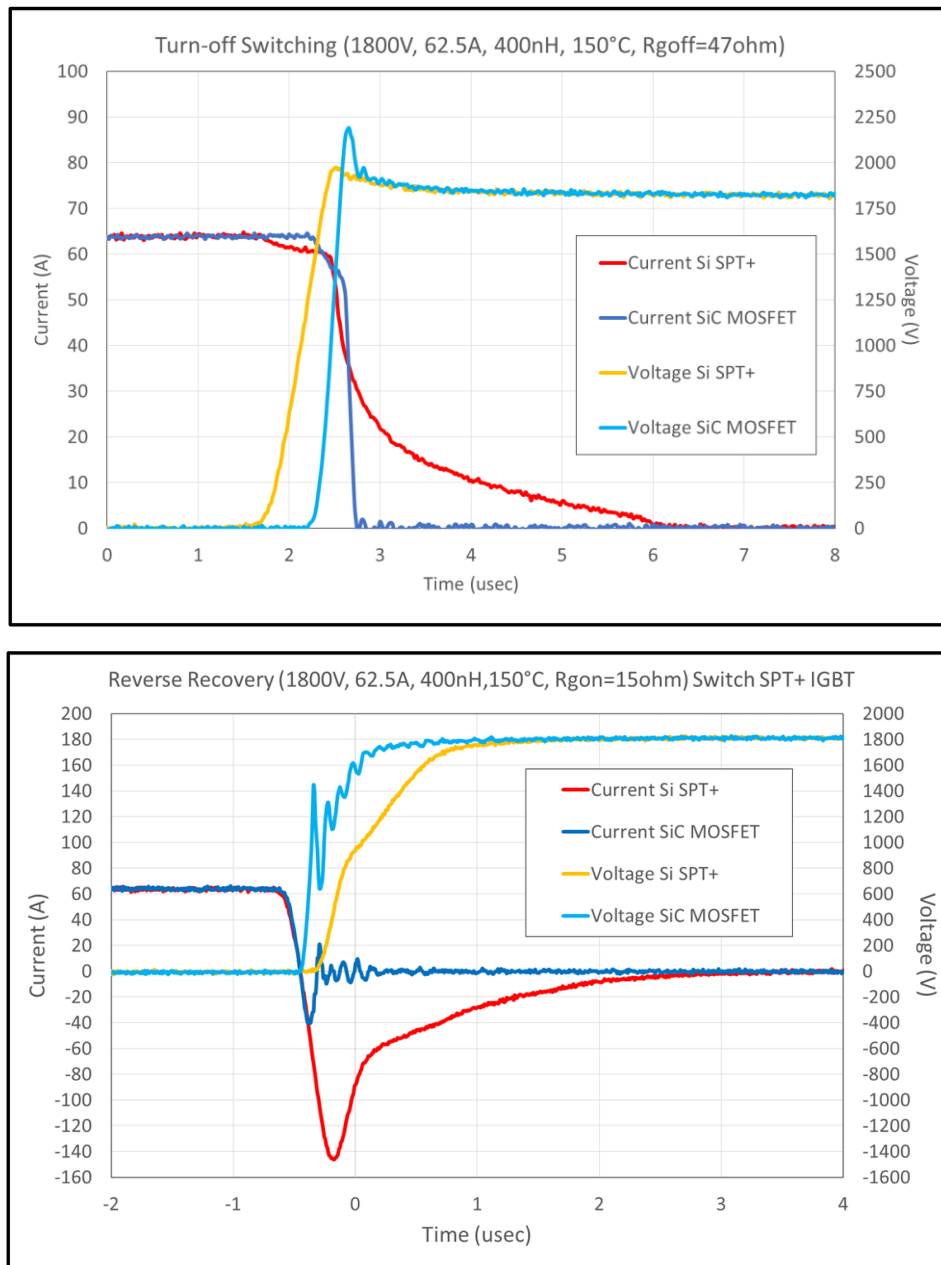


Figure 15: The Switch (top) and Diode (bottom) current and voltage waveforms of a 3300 V 1 cm² ABB SPT+ IGBT and Rohm SiC MOSFET at 150°C [22].

- Higher Operating Temperatures:** On the thermal front, the SiC device benefits from the WBG properties for reducing the leakage current and has also superior thermal properties when compared to silicon. However, the later has a minimum impact since the thermal resistance of the device is largely dominated by the device area, packaging and cooling. Nevertheless, the low leakage currents at high temperatures allow SiC devices to operate at very high temperatures beyond 200°C. The limitations remain within the packaging technologies employed (encapsulation materials, joining techniques, etc.) and resulting reliability limitations which in principle are similar to those for silicon packages for high power applications. Hence, the majority of system improvements at the thermal level in terms of simplified cooling will be a consequence of the lower losses achieved with the SiC device. The simplified cooling in turn can contribute to volume and weight reduction and by that increase the overall system efficiency, especially in mobile applications (e.g. main and auxiliary systems in road vehicles, railway systems or avionics), where acceleration and

deceleration of any additional mass increase the energy consumption. The higher operating temperature capability is also considered in many cases to be useful in overload conditions and for system integration where the power electronics is positioned close to the high temperature components in the system.

- **Switch/Diode Integration:** An important trend towards utilizing the SiC MOSFET in diode mode operation in the third quadrant also appears to be gaining momentum due their optimum performance and the ease of gate drive implementation for the MOSFET conduction during free-wheeling mode. In diode mode, the SiC MOSFET offers two operational options (a) as a PiN diode with a negative gate bias and (b) as a MOS channel diode with a positive gate bias. The use of the MOSFET with the two modes of diode operation provides the same conduction and switching reduction benefits as described above. The diode mode also offers benefits in terms of increased power density in a power module, as more chips can fit inside the module or resulting in lower costs associated with extra SiC diodes. For power electronics applications, this approach presents a perfect opportunity to increase power densities and reliability.

Based on the above, it is very clear that the substantial lower losses from the first and second aspect can be easily beneficial to obtain

- Higher power densities and/or
- High efficiency for the different power electronics applications.
- Higher operational frequencies

The trade-off between the two will depend largely on the system requirements and effective cost associated with respect to both the setup and operational cost or energy savings.

On the other hand, the combined advantages from the lower conduction losses, lower switching losses, higher operating temperatures and chip integration will enable

- Compact designs with reduced footprint size and weight and
- More system integration options and
- The possibility to operate in harsher environments

3.4. Advances of GaN-based Semiconductor Devices

The major difference between SiC/Si vertical power devices and GaN High Electron Mobility Transistors (HEMTs) is that the latter is a lateral device. The commercial devices are implemented with a p-GaN e-mode (Panasonic [23]) or d-mode GaN device and a cascode Si MOSFET (Transphorm). The problem of current collapse has been addressed using a hybrid drain (HD-GIT), shown to operate up to 980 V [24] [25].

Recent work on vertical GaN power devices [26] has the potential to produce devices that can provide higher breakdown voltages and greater power density, compared to their lateral equivalents. Recent work is showing that higher breakdown voltages are possible, however further work is required, particularly on junction termination extension to achieve reliable devices [27].

3.5. Advantages of GaN-based Power Electronic Applications

The replacement of Silicon power devices with GaN devices is more complex than for SiC as in many regards GaN devices are not a like for like drop-in replacement. There are potentially further improvements to be made over Si and even SiC as the GaN unipolar limit is potentially further to right of both however both the fundamental device characteristics and implementation in circuit topology aspects are different for GaN.

The structure of GaN power devices is quite different from conventional Si and SiC devices, in that they are *Hetero-junction* devices – the current is carried in a *2-dimensional electron gas (2DEG)*, rather than an inversion layer. This is created by spontaneous polarization at AlGa_N/Ga_N interface and conduction is modulated by a gate electrode that overlays the 2DEG [28].

The main potential for GaN devices is in ultra-high switching speeds (these devices have originated from the RF world), with limited scope for high voltages (>650 V), however with great potential for consumer electronics, DC/DC converters and very compact converter design.

The key characteristics of the power devices in GaN can be summarized in the following list and how they compare to both Si and SiC devices [29]:

- **Gate Charge:** GaN devices generally have lower gate charge requirements than either Si or SiC.
- **Threshold Voltage:** GaN devices often have a threshold voltage of 1.2 V - 1.6V, compared to typical values of 3V for Si and SiC. However negative Gate to Source voltage might be required to ensure a reliable turn-off; nearly no enhanced mode GaN device today allows negative Gate to Source voltage, though.
- **Lower maximum Gate Source voltage:** GaN devices typically have a maximum V_{GS} of < 10 V, compared to 20V for Si and SiC devices, and are sensitive to overvoltage.
- **Off State Leakage Current:** This is a disadvantage of GaN, due to impurities; the off-state leakage drain current is often higher than with Si or SiC equivalent devices.
- **No Body Diode:** GaN devices do not have a body diode intrinsic to their structure, but they work in 3rd quadrant w/o reverse recovery charge.
- **Thermal performance:** GaN is broadly similar to Si, and both are worse than SiC.

Given these characteristics and parameters, GaN devices do have a particular mapping onto half bridge topologies as the intrinsic clamping of the bus voltage removes the problem of overvoltage.

The production of GaN-on-Si power devices is growing, as the market is clearly focussed on the ever growing consumer products market (particularly chargers and mobile devices) as well as PFC power supplies for telecom and servers, and the specific need for dedicated driver and logic circuitry also on GaN to enable monolithic integration and even smaller packaging. Commercial platforms for GaN-on-Si are becoming available from Infineon, ST, Navitas Semiconductor, Dialog Semiconductor, TI, and GaN Systems, with new players entering the field.

The key parameters that influence the behaviour of GaN HEMT (High Electron Mobility Transistors) is that the product of the gate charge (Q_G) and the Drain Source On Resistance ($R_{DS(on)}$) is substantially lower than that for Si or SiC MOSFETS. This behaviour is partly due to the fact that the die sizes of GaN HEMTs can be much smaller than equivalent MOSFETs of a similar rating. This combination of parameters can lead to much higher switching frequencies for GaN HEMT devices and resulting reduction in passive component sizes as a result [30]. While this is an obvious benefit from the perspective of circuit size, the increase in raw switching speed can lead to other issues such as higher EMC and this needs to be considered when designing filters and screens to ensure that unwanted radiation of switching noise is not made worse using GaN devices.

A comparison of the relative merits of the combination of Gate Charge and $R_{DS(on)}$ characteristics can be seen in Figure 16, where the difference can be seen between Si, SiC (vertical) devices and GaN HEMT (lateral) devices.

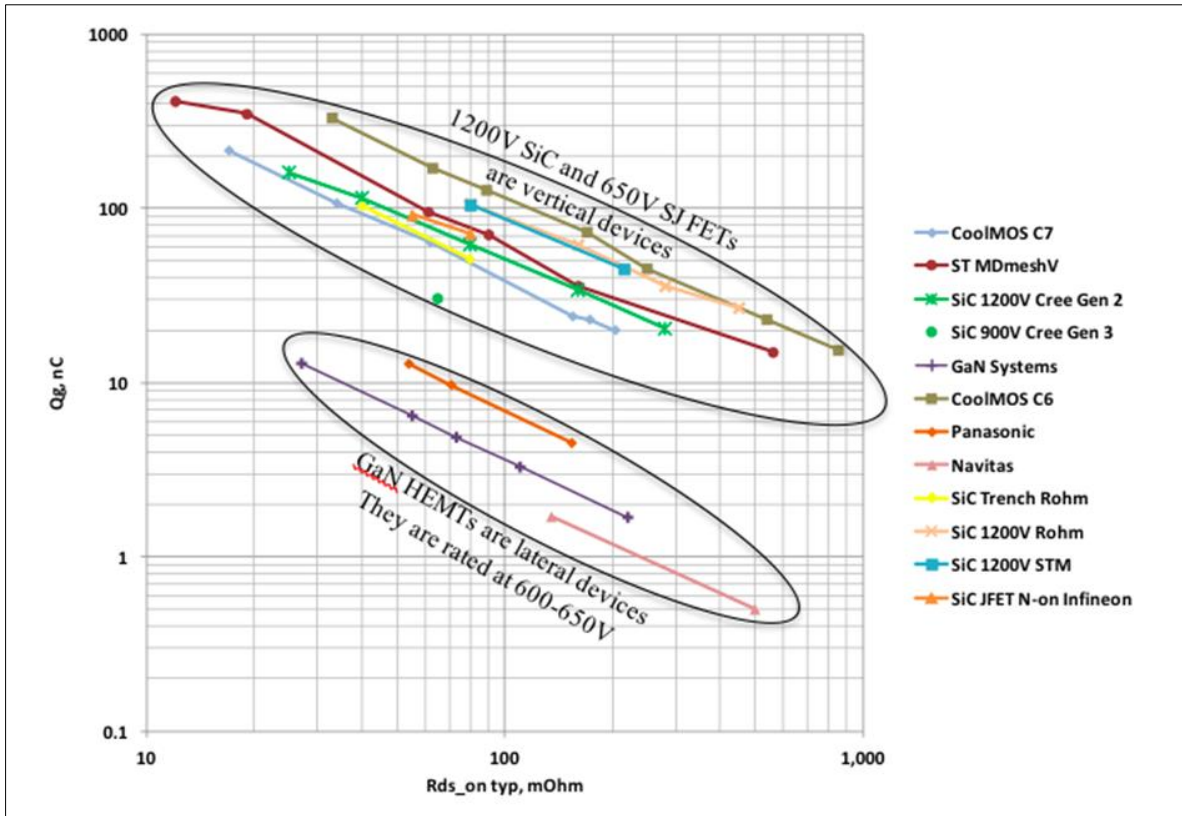


Figure 16: Comparison of Gate Charge and Rsd(on) for Si, SiC FETs and GaN HEMTs [29].

3.6. Summarizing Conclusions

To summarize, almost all power electronics applications could in principle benefit from the SiC unipolar devices low overall losses, higher operating temperature, switch/diode integration and higher switching speed albeit with certain adjustments to accommodate the new devices and their characteristics. Otherwise, new topologies and concepts operating at higher frequencies and temperatures need to be justified and developed to further benefit from the SiC properties. As an example, the production and long-term costs of wind inverters are reduced by replacing Si IGBTs with SiC MOSFETs. SiC devices brought a monetary improvement of the system efficiency up to $\mu_{\text{Euro}}=2.36\%$ in comparison with Si devices. If the trend of wind energy growth continues at the same rate, it is expected that the accumulated installed capacity will be about 860 GW by 2027. Replacing Si devices with SiC devices will lead to money saving up to 13 B\$ (by considering feed-in tariff of 0.12 \$/kWh and load factor of 38.9% for offshore wind turbines). More financial benefits can be gained by reducing the production cost of inductive components and heat-sink by employing SiC devices. If SiC devices are used in wind energy application, taking into consideration the benefit of increasing the overall system efficiency and power density rather than focusing only on individual device cost, SiC devices will definitely enable more efficient, reliable, high power density, low overall cost and thermally stable power converters.

However, SiC technology still shows limitations to its maximum exploitation, particularly in terms of power density, high temperature, parasitic inductance and common mode noise at higher switching frequencies due to lack of suitable packaging for SiC devices.

The role of GaN devices can be seen as complementary to that of Si and SiC, with most GaN devices not suitable for higher voltage applications such as grid connected power electronics due to their lower voltage rating, lower thermal performance and reduced mobility compared to SiC devices, however, the possibility of greatly reduced weight and volume means that they are potentially ideal

for consumer and mobile products, with a projected market of 1.8 B\$ by 2027, with significant growth across a range of sectors particularly power supplies and automotive applications as shown in Figure 17.

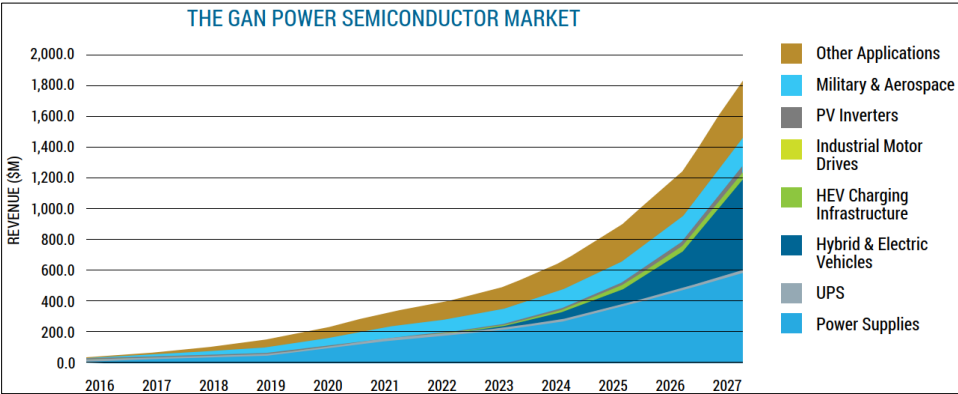


Figure 17: GaN Power market [31].

4. Existing Roadmaps

4.1. Overview

After extensive searching five different roadmaps for WBG power electronics were found, which have been active working for several years. These are produced by different organisations, either regionally or by different organisations concerned with power electronics (PE), including both industrial and institutional/academia members.

The different Roadmaps are briefly summarized below, and their conclusions are summarized in more detail in the following subsections. Common for all these roadmaps is that the full version is typically only available for each organisation members.

“WBG Roadmap Lead Applications for SiC and GaN” from ECPE European Center for Power Electronics³. ECPE was founded in 2003 on the initiative of leading power electronics industries as an industry-driven Research Network to promote education, innovation, science, research and technology transfer in the area of Power Electronics in Europe. The work with the roadmap started 2016 and was published in 2018 (it has been made available for PECTA internal). The roadmap 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.

PowerAmerica’s “Strategic Roadmap for Next Generation Wide Band Gap Power Electronics”⁴. PowerAmerica is an institute and a network of public and private partners committed to increasing U.S. manufacturing competitiveness. The work with the roadmap started 2016 and was internally published 2019. The roadmap outlines key markets and application areas for SiC and GaN PE, performance targets for competitive SiC and GaN technologies, technical barriers to achieving those targets, and the PowerAmerica activities needed to overcome those barriers.

ITRW “International Technology Roadmap on Wide Band Gap Semiconductors” developed by IEEE Power Electronic Society⁵. This roadmap has a technology focus describing WBG components and challenges. It describes the current state of the art and looks forward to the WBG power electronics future with commercial realisation in short term (< 5 years), medium term (5-15 years) and long term (> 15 years). This roadmap was internally published in September 2019 and has been made available as well for PECTA internal.

CASA China Advanced Semiconductor Industry Innovation Alliance was initiated by research institutes, universities and leading enterprises, which related to Wide Band Gap semiconductors with the support of the Ministry of Science and Technology, Ministry of Industry and Information Technology and the Beijing Municipal Government. The full roadmap is available at the CASA website⁶.

SiC Alliance was founded in 2010 to strengthen the network of researchers in SiC, within 3 national research projects on SiC R&D in Japan. The members of SiC Alliance were mainly the members of these 3 national projects. SiC Alliance comprises 32 companies, 19 universities, and 9 research centers. The main purpose of the roadmap is to guide the R&D plan of each member, and consists of 7 parts: Vision, Auto Mobil, Super Express Train, Industrial Inverter, Switching Device, Parts, and Wafer. The full information is restricted to SiC Alliance members, but an overview is published and available on the SiC Alliance web site⁷.

³ <https://www.ecpe.org/>

⁴ <https://poweramericainstitute.org/>

⁵ <https://www.ieee-pels.org/standards/about-itrw>

⁶ http://www.casa-china.cn/uploads/soft/190731/12_1010538821.pdf

⁷ http://www.sicalliance.jp/data/doc/1539751125_doc_2_0.pdf

4.2. ECPE Roadmap

The ECPE, European Center for Power Electronics, includes 93 industrial partners and 99 Competence Centers which are either Institutes or Universities. ECPE identifies very similar application areas as presented on the PECTA Task 1 report MS1.1. ECPE identifies automotive applications in the meaning of vehicles for personal use, as the largest and dominant application. Other application areas and main drivers considered in the report are Railway, PV Inverter, Wind, Industry Automation, Large Drives, Grid and ICT and Data Centers. The ECPE report concludes that the highest impact on energy saving by higher efficiency in reduction of static and dynamic losses are for ICT and Data Centers. The roadmap is presented as expected market share for 28 different applications today (2018), in the year 2025 and the year 2035.

Automotive applications and components are driven by weight and volume reduction, and higher conversion efficiency also translates to driving range extension without the need of additional battery capacity. WBG components which mainly concerns SiC MOSFET, 650 V or 1.2 kV, are already in products in the market and is expected to have a mayor or dominant market share by 2025 in the traction inverter (motor drive), DC/DC converter, on-board charger or inductive charging. The expected market share of GaN components, typically up to 650 V, is expected to be both lower and slower and limited to lower power DC/DC conversion or on-board charger.

For railway applications, both motor traction and auxiliary traction, SiC offers benefits in the system design of both motor and transformer. It requires reduced cooling systems, and gives reduced size and weight, SiC MOSFET are today already on the market, 1.7 kV - 3.3 kV, and are expected to have a significant or dominant market share by 2025. On a longer term by 2035 SiC MOSFET, 1.7 kV - 6.5 kV, are expected to the dominant solution.

For PV converter applications efficiency has highest priority, although size and volume could be important. Si-SiC hybrids (Si IGBT and SiC Diodes) are already on the market, and are expected to have a dominant market share in the coming years for both low power (650 V, < 600 W), medium power (1.2 kV, < 30 kW) and high power systems (1.2 kV - 1.7 kV, > 30 kW), while SiC MOSFET is expected to dominate on a longer timescale for both medium and high power applications. For low power and for power optimization GaN could be a future alternative in low voltage systems (100 V).

Converter systems for wind power, both on the generator- and grid-side, is heavily cost driven, and at present there are no SiC alternatives to the dominating 1.7 kV Si IGBT. However, on a longer timescale SiC MOSFET could be an alternative.

Power electronics for Industry, Automation and Robotics includes drive inverter and servo drives, which are under a high cost pressure to compete with the dominating Si IGBT (650 V - 1.2 kV) devices, and on short time scale only the SiC-Si hybrid will obtain any significant market share. On the longer time scale up to 2035 1.2 kV - 1.7 kV SiC MOSFET is expected to gain a major market share. As for many applications GaN devices will have a slower and weaker influence and limited to lower voltage range (< 650 V).

For large drives, both at low and high voltages (1.2 kV - 6.5 kV) the Si IGBT is expected to be the dominant component on all timescales. SiC MOSFET has been demonstrated at viable different voltages but hybrid solutions are the most likely device (and device combinations) to obtain market shares.

4.3. Power America Roadmap

Power America (PA) is an institute based at North Carolina State University (NCSSU) and has a strong funding from US government. It Started 2016 and includes companies, institutes and academia. They support both internal work and funding of projects at companies and research institutes. The roadmap outlines key markets and application areas for SiC and GaN PE, performance targets for competitive SiC and GaN technologies, technical barriers to achieving those targets, and the activities needed to overcome the barriers.

The PowerAmerica roadmap is very technical, comparing device performance and cost/ampere, and focus for strategies for a 5-year roadmap to:

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

Their market forecast sees a tremendous growth opportunity for WBG materials, particularly SiC but also to some extent GaN. Automotive is defined as the main driver, followed by PV and ITC and Data centers. In the roadmap SiC is considered for higher voltage application (> 600 V), while nitrides are a candidate for lower voltages and consumer/enterprise applications which is a high-volume application. The roadmap highlights critical factors such as cost factor, especially for high current applications, and reliability and validating, especially for nitride applications.

Their roadmap also focusses on standardisation, workforce training and education and development of peripheral and related technologies such as packaging, motor insulation and insulations.

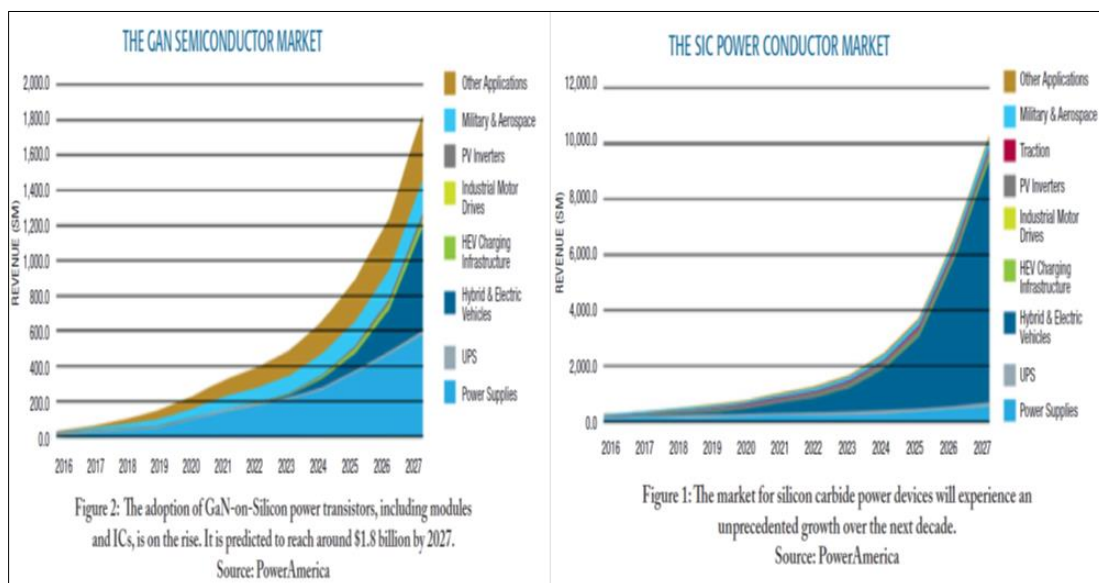


Figure 18: SiC and GaN Market development as published by ITRW (and used by Power America).

4.4. ITRW Roadmap

ITRW stands for “International Technology Roadmap on Wide Band Gap Semiconductors” and is a part of the IEEE power electronic society. The ITRW started 2015, and has the most extensive, detailed and recent roadmap published in September 2019.

A Key role for the roadmap is 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.

The roadmap is looking at short term (0 - 5 years), medium term (5-10 years) and long term (10 - 20+ years) perspective. The roadmap anticipates a large expansion of special SiC based PE on the short-term time scale. The main application is expected to be in automotive, including both traction drive and fast charging for electrical vehicles, but also inverters for photovoltaic based power production and traction drives and auxiliary power supplies for high speed and commuter trains.

The main device components for SiC are Schottky barrier diodes and MOSFET transistors in the voltage range from 650 V to 2.7 kV, but also other devices such as bipolar junction transistors (BJT), JFET and super junction (SJ) devices are investigated for different applications.

The ITRW has a more optimistic view on GaN technology than the other roadmaps, even if the technology is less mature than SiC and is expected to be relevant on a medium-term timeframe. Main areas for nitride power electronics are for the lower voltage, but higher volume applications such as data centers, consumer power electronics and chargers, on-board chargers for electrical vehicles and photovoltaic inverters.

The ITRW roadmap presents the same figures for SiC and GaN market development as used by Power America, see Figure 18.

4.5. Yole Roadmap

Yole is a commercial company doing market analysis and roadmaps for different technology fields, as well as device comparison and reverse engineering of devices.

Yole has been active to forecast the SiC market as well as the GaN power electronic markets for several years. They have always been over ambitious but have in the recent years well predicted the growth for SiC power electronics.

The predictions below are their spring 2019 expected roadmaps for SiC and GaN power electronics.

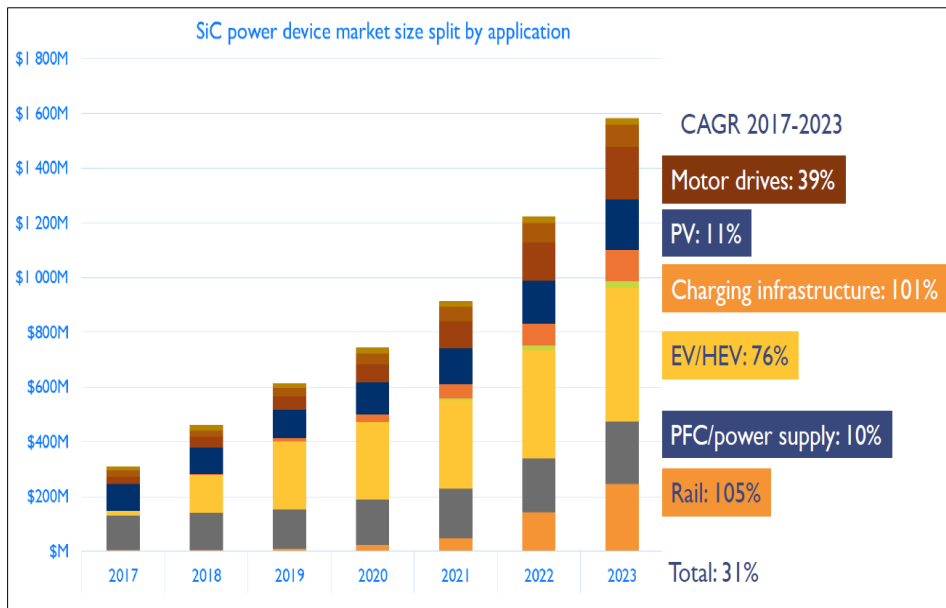


Figure 19: Estimated SiC power device market by application (Yole).

For the GaN market Yole presents two different scenarios, one more conservative labelled as “Base case scenario #2”. The second is more aggressive labelled as “Bull case scenario” and assumes a killer application in the form of wireless charger for household equipment such as mobile phones. This is based on Apples possible interest for GaN in their phone chargers.

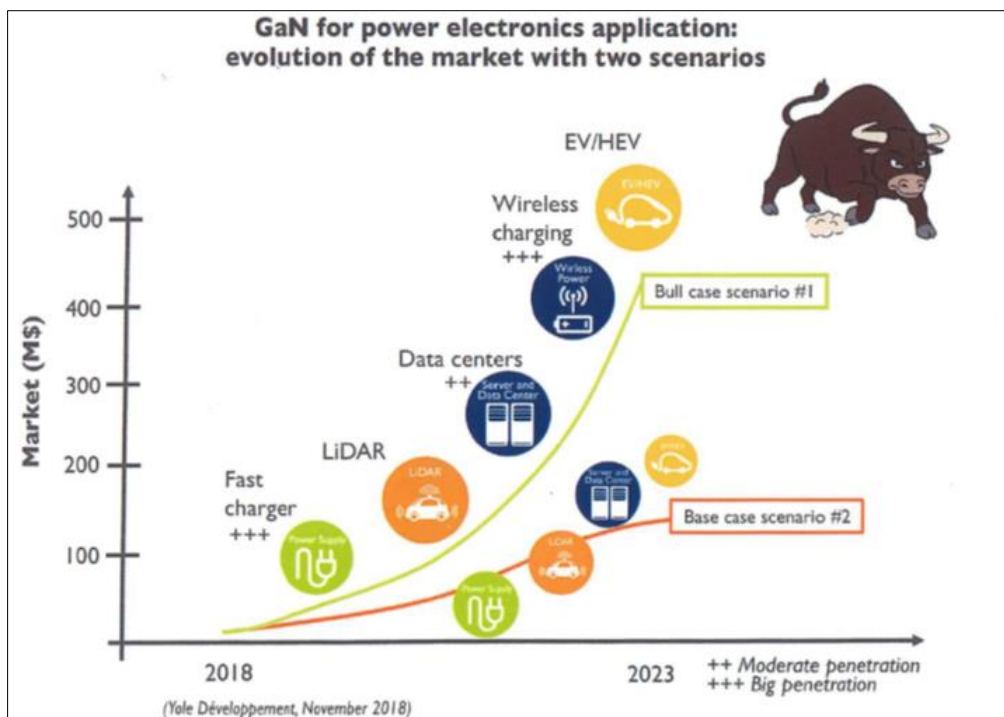


Figure 20: Estimated GaN power device market in two different scenarios according to Yole.

4.6. SiC Alliance

The published part of the Japanese SiC Alliance roadmap is not a roadmap as the other, but a presentation and motivation of recent year’s national SiC projects. They focus on mainly SiC but also mentions GaN at a later stage.

The main applications are automotive, industrial inverters and trains for both subways and high-speed trains.

4.7. Major outcomes and conclusions of existing Roadmaps

All available roadmaps expect a drastic increase for the use of WBG power electronics in the coming years. This includes both SiC and GaN while other material solutions have a longer technological development time.

The main driver, both regarding volume and price, is the automotive application with EV for personal use. This driver will increase volume and reduce price which will be beneficial also for other applications where WBG PE will increase efficiency and reduce energy consumption, although the cost barrier to present Si-based technologies, especially IGBT, will limit the use of WBG for high current and high-power application.

5. Application Readiness Map

5.1. Introduction / Overview

As explored in the previous chapter SiC and GaN-based technologies has been recently the subject of roadmap initiatives of different industrial organisations and/or associations. Therefore, it was decided by PECTA to elaborate - based on these technology maps - a so called Application Readiness Map (ARM). With these ARMs it was possible to visualize the development of WBG-based-Applications in the coming years. The elaborated ARMs are based on the actual ECPE Roadmap primarily as this Roadmap is very sophisticated and extensive. Additionally, ECPE agreed to the development of the PECTA ARMs based on its roadmap.

In the Appendix several ARMs have been developed and visualized. On one hand, the focus was on the applications and on the other hand, the focus was on the material. The information content is always the same, but the visualization and focus is different. So, the following ARMs have been developed (see Appendix):

- **Application Readiness Map (ARM)**
- **GaN-based Application Readiness Map (GaN-ARM)**
- **SiC-based Application Readiness Map (SiC-ARM)**

In the following chapters the major outcomes of the ARMs are - based on timeline and materials – analysed and discussed.

5.2. Analysis and Conclusions of Today's Situation (SiC-based)

There are today many applications using especially SiC diodes and SiC MOSFET switches in the voltage range from 650 V to 1.7 kV. One of the relevant applications (besides PV and Battery storage) is in automotive with electrical vehicles (EV) and hybrid electrical personal vehicles (EHV). SiC MOSFET are today used both for the traction inverter, internal DC/DC converter as well as battery charging, both on-board, infrastructure and inductive charging. One milestone was the decision of Tesla to use SiC MOSFET in the traction inverter of their Tesla Model 3 and is now produced at just below 100'000 cars per quarter. The main advantage and motivation for using SiC PE was the reduced electrical losses, both conductive and switching, and the reduced volume and size which could more easily be integrated in the to the traction drive. The main consumer benefit was a substantial increase in driving distance on given battery capacity. This was especially important for the US customer, with a mostly longer commuting pattern than Europe and Asia.

The traction inverter for an EV includes a large number SiC switches and diodes (2x24 for Tesla Model 3) which give an important volume increase for the devices. The interest and decision from Tesla, who is considered as a technology leader, has initiated plans from most major automotive companies, including most Chinese manufacturers, to utilize SiC for charging traction drives.

Another application for SiC is in railway, both for traction and auxiliary inverters. SiC has since several years been used in subways and commuter trains in Japan, but a breakthrough was announced last year when New Japan Railways (NJR) announced that next generation of bullet trains servicing the Osaka-Tokyo line will use 3.3 kV SiC MOSFET switches. The first trains (12 units N700S) are expected to be delivered in fiscal year 2020. The increased efficiency, and the reduced size and volume, have managed a complete redesign of the trains set. Instead of previously having two dedicated motor wagons in the set of several cars, most of the cars will now have traction drives below the floor. This enables flexibility and easy redesign of different configurations of trains from the original 16-car train (for example 8-car train or 12-car train), which can be called "Standard Shinkansen train." This increases the passenger capacity and allows more extensive diagnostic for maintenance and service.

For photovoltaic applications (one of the largest area) SiC is used in medium (> 600 W) and high power (> 30 kW) systems, as well as in industrial applications such as large drives and servo inverters. SiC is also used in ICT and data centers for HV DC, power supplies and UPS systems.

In general, the SiC technology has evolved for almost 25 years and has today reached a maturity. The material quality has successively increased proving better yield and reliability. The wafer growth has in recent years transferred from 4" to 6" which now is the industry standard. The device design has also improved and stabilized, and large efforts for screening and testing have been developed which increase the yield and reliability of devices in applications. There are several suppliers of material, devices and modules which facilitates the introduction into systems and applications.

The expected increase in the demand for WBG power electronics, especially from the automotive applications, has initiated large investments in future increased capacity for material and devices, from leading companies such as Wolfspeed, ST Microelectronics, Infineon and Rohm. CREE for example has announced \$450 M investment in a new mega factory and \$450 M investment in new 200 mm capable crystal growth facility. Rohm has announced a \$560 M investment in both crystal growth, in Nuremburg Germany, and processing fab, in Miyazaki Japan, increasing their capacity by 16 times by 2025. ST Microelectronics has also announced investments, signed large long-term deals for SiC wafer supply deals with both Wolfspeed and SiCrystal, and also acquired the Swedish wafer producer Norstel to secure wafer access. They have also announced an investment in a second fab for SiC MOSFET production in Catania, Italy.

Only SBD and MOSFET have today any substantial use in applications. Although devices such as PN-diodes, BJT, JFET and IGBT have been demonstrated, they have not been able to replace their corresponding Si components. One obstacle is still the high cost for SiC which makes the competition with Si difficult, especially for higher current, higher voltage and high-power application.

5.3. Analysis and Conclusions of “Five-Years Perspective”

For the coming 5 years all available roadmaps as well as industry investments expects a drastic increase in the demand for WGP power electronics. This is both due to the maturity and now demonstrated reliability of the technology. This combined with the increasingly aggressive plans for electrification from the automotive industry will create a large demand and volume for especially SiC based solutions. It is most likely that the automotive application for personal EV will dominate and lead the further expansion and determine the cost structure and device concepts. This means production and development of SiC MOSFET switches in the voltage range from 650 V up to 1.7 kV.

The automotive electrification will further expand into heavy vehicles, such as trucks, buses and high-power specialized vehicles. With the increased volume and decreased cost SiC PE will further expand to the automotive market regarding traction inverter, DC/DC conversions, and different charging concepts. The same is expected to occur in rail applications, both for traction and auxiliary inverters, in industrial application and large motor drives. A further electrification in other fields of the transport sector such as aircraft and shipping is also expected.

The increased demand for SiC will require extensive increase in material and processing capabilities. It is likely that the SiC wafer production will partly move from 150 mm to 200 mm, during this period. This is already started for example within the EU funded REACTION project with the ambition to develop a European 200 mm 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 tools.

This application is a large volume with many units, and an application where GaN PE could significantly reduce the energy cost and reduce losses. This application also has a large influence of energy

saving, since it is less dependent on size and weight reduction which otherwise is used as a compromise to energy reductions and savings.

For other high voltage and high-power applications, the introduction of WBG solutions will be limited, such as HVDC power transmission. Even if SiC technology has benefits and possibility for energy reduction. It will require development of new components such as PiN-diodes, HV MOSFETs or SiC IGBTs which is very expensive for a limited volume market.

5.4. Analysis and Conclusions of “Ten-Years Perspective”

An estimation of WBG power electronics in different applications is difficult and dependent of several different factors. For example, how fast is the electrification of the automotive and transport sector, and further political initiatives and legislations to reduce CO₂ emissions. The “Green Deal Initiative”⁸ by the European Commission was announced December 2019, and details will be presented during beginning of 2020. This includes large investment to reduce stop climate change and could on a 10-year horizon influence also the development of power electronics in different applications.

A prediction below is based on mainly the ECPE roadmap from 2019. Both SiC MOSFET and GaN HEMT are suggested to replace existing Si technology for most applications.

For the automotive applications SiC MOSFET (650 V – 1.2 kV) and GaN HEMT (650 V) are expected to be the dominant devices for all power conversion applications, this includes inverter drives, charging technology and DC/DC conversion. The same is also the case for ITC and large data centers 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.

Also, for photovoltaic applications and industrial applications GaN HEMT is expected to be the dominant device in low power systems < 600 W and for power optimization, while SiC MOSFET (1.2 kV-1.7 kV) will dominate for higher power in residential or commercial systems.

For railway traction and auxiliary systems SiC MOSFET (1.2 kV – 6.5 kV) will be the dominant device solution.

For wind power, both generator and connection to the grid, SiC MOSFET together with the Si IGBT will be used, while for medium voltage large drives such as naval Si IGBT (1.2 kV-6.5 kV) will still be dominating but together with SiC MOSFET at the same voltage range.

5.5. Analysis and Conclusions of GaN-based Technology

GaN power electronics have today been demonstrated in different applications, usually at lower voltages and power. The present available and used power device is the 650 V GaN HEMT but at a smaller volume than SiC. Present GaN application is in automotive for DC/DC converters and on-board chargers, in photovoltaic applications as power optimizer and in small (< 600 W) and medium (< 30 kW) inverters. GaN HEMTs switches are also used in industrial inverter drives and servo drives and in ICT and data centers as power supplies, DC/DC converters and in UPS systems.

When the quality and maturity of the GaN technology improves it will also expand further into the present applications and the applications where SiC now is used. But it will be at smaller scale than the SiC applications.

⁸ https://ec.europa.eu/commission/presscorner/detail/e%20n/ip_19_6691

One exception could be the ITC and data center applications for lower voltages up to 650 V, which is now dominated by Si solutions. This includes, power supplies, low voltage DC/DC conversions and UPS, where the possibility for higher switching frequency and lower losses, will give higher efficiency than corresponding Si super junction and MOSFET components. This could also include household power supplies and chargers.

6. WBG-Technology Challenges

There are several different types of challenges to enable the expected increase of WBG in power electronics. In the foreground are the following topics:

- **Temperature increase:** Even though, especially SiC devices might be operated at elevated temperatures, when compared to silicon devices, the conduction losses will increase, and gaining conversion efficiency might not be possible. Still, the advantage of reduced volume requirements for cooling might justify the higher temperature design. However, the interface and insulation materials allowing for reasonable temperature rise are not available yet.
- **Gate voltage limits:** In spite of high switching speeds of GaN devices, the gate to source voltage demands for proper driving are rather close to the limits, specified for reliable operation.
- **Reliability:** Together with the packaging, some of the failure mechanisms are still to be investigated, long time experience for transistors need to be acquired.
- **High switching speed:** SiC and especially GaN devices can be operated with very high switching speed justifying the potential, mentioned above. With the high frequency content of the resultant voltage signals, even very low capacitances show low impedance and for the high frequency current components small inductance turn to high impedance. Thus, not only the passive components, used for filtering and intermediate energy storage, need to be carefully selected and designed for very low parasitics as well as low losses, but the layout – the interconnection of the individual components – needs to be also carefully designed. Reduction of inductance by shortening the connection length may be limited by requirements on insulation distances and/or loss density. The steep voltage slopes increase the challenge of insulation design in electric drive applications, as well as bearing currents and EMI mitigation; capacitive residual currents will also be increased.
- **New Packages and topology solutions:** High current density, the higher operating temperature and the higher switching frequency requires general better handling. This includes new package solutions, improved passive components such as capacitors and inductors, improved magnetic and dielectric materials as well as new materials solutions with low-CTE (coefficient of thermal expansion) to increase yield and reliability during thermal stress. Furthermore, completely new topologies could be needed to better make use of the WBG devices and modules.
- **Cost:** Silicon device production processes have undergone decades of development and will still be further improved regarding various aspects, such as material purity, process stability, production quality and energy consumption. The same or similar developments and achievements are still ahead of WBG material and device production.
- **Shortage of materials:** Despite the great progress made in WBG-specific manufacturing, processing and characterization, supply and demand of especially the SiC base material should be closely monitored. Shortages may occur when demand explodes, and may result in a slowed-down adaptation of SiC devices just due to the lack of high-quality base material.
- **Wafer diameter:** The expected diameter expansion is also a critical step. A few years ago, there was also a shortage of material and devices due to the expansion from 4" to 150 mm, both regarding tools availability and maintain the required quality. In the case of moving towards 200 mm the equipment problem is expected to be lower, due to the high availability of 200 mm tools presently used in the Si industry. A general increased wafer quality, reducing and identifying critical defects at an early stage is critical to improve yield and reduce cost.

- **Standardization:** Increased standardization in the entire production chain for WBG power electronics is needed. This includes wafer and material, device, modules and packaging. It could also include standardization of electrical parameters, efficiency measurements, power measurements and developing on accelerated reliability tests and expected module lifetime. Active work with standardization in existing organisations such as SEMI, IEEE, JEDEC, IEC, ISO etc. should be done to include WBG power device, to be introduced in other applications.

7. Potential Energy Savings for Selected Applications

Table 3 lists estimates on the potential global energy savings, based on the assumption that in all existing applications of the respective type, the silicon based power electronics were replaced by wide Band Gap material based power electronics, taking advantage of all the properties and effects, as described in the previous sections. The numbers, given below, are the result of more elaborated considerations and deductions, which are outlined in the Appendix.

Table 3: Annual energy savings resp. increased energy production for selected applications.

Application	Savings [TWh/year]	Remarks
Road Transport Electrification	11.7	7.1
Wind Energy Generation	35.6	7.2
PV Energy Generation	10.3	7.3
Power Supply (AC-DC)	7.8	7.4
Data Centers	28.4	7.5

7.1. Road Transport Electrification

The amount of energy saving is calculated under the assumption that all new cars that are produced will be Battery Electric Vehicles on a global scale (70 M/year), for average driving behaviour and distance.

7.2. Wind Energy Generation

The listed number denotes an increase in energy production, achieved by the reduction of conversion losses in the power electronic circuits.

7.3. PV Energy Generation

The listed number denotes an increase in energy production, achieved by the reduction of conversion losses in the power electronic circuits.

7.4. Power Supply (AC-DC)

The saving estimate covers laptops, tablets and cell phones.

7.5. Data Centers

The estimate represents the scenario including both, replacing silicon-based power electronics by WBG based power electronics and also a second scenario of utilising optimisation potentials (e.g. DC based internal energy distribution).

8. Exploring Policies for WBG technology

8.1. Position of the Technologies (PoT)

SiC and GaN-based products are already available today. GaN-based power devices are being used primarily for low to medium voltage applications, and SiC for medium to high voltage applications, as shown in Figure 21 (voltage class definition as referenced in Figure 21). While the performance benefits are undeniable, the open question is whether WBG devices can overcome the present cost and manufacturing challenges and achieve high volumes. Several companies, consortia and university research centers are focused on solving WBG power device challenges. The costs must come down significantly before the benefits of WBG - including power savings, simplified circuitry and reduction in module size - can provide a meaningful return on investment compared with silicon substrates⁹.

As recently reported by several market analysts, GaN is better suited for the low-medium voltage range (200 V – 600 V), which includes a large portion of the consumer electronic market (e.g., computer power supplies, audio amplifiers, etc.). In this voltage range, the material is indicated as the best candidate to replace the existing Si devices. Clearly, the 600 V – 900 V voltage range is strategic, as it covers the converters for electric (EV) and hybrid electric vehicles (HEV), as well as inverters for renewable energy (e.g., PV). In this voltage range, GaN devices are expected to be in competition or to coexist with SiC ones. Finally, for the high voltage applications (> 1.2 kV), e.g., industrial applications, trains/ships transportation, electric energy distribution grids, etc.), SiC remains at the moment the preferable choice, owing to a better material quality and device reliability. The future applications of GaN for high-voltage devices will strongly depend on the improvement of the material quality and the development of vertical devices based on bulk GaN. In this wide scenario, SiC and GaN are expected to grow in share in the future of power electronics, as each material will enter in different applications, penetrating the market with a different speed [32].

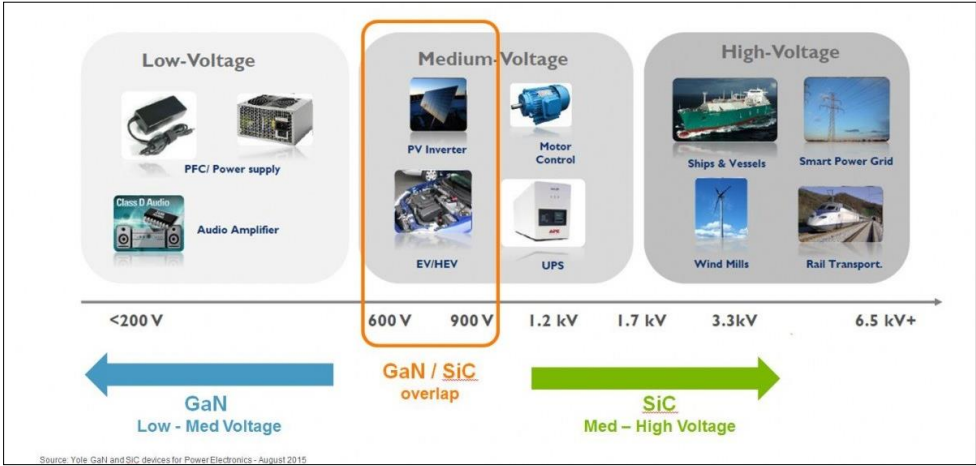


Figure 21: SiC vs GaN Device Positioning ¹⁰.

The Applications Readiness Maps (ARM, in Appendices) show that the number of market ready devices with WBG technology will grow in the future, and it is estimated that most of the existing “demonstrators” will reach market readiness within the next 10 to 15 years. Still, the penetration of GaN in selected applications is a path away from SiC, e.g., for automotive chargers; driver inverters for industrial applications and PV inverters.

⁹ <https://semiengineering.com/will-iii-v-power-devices-happen/>
¹⁰ <https://semiengineering.com/will-iii-v-power-devices-happen/>
 (Graph originally from Yole “GaN and SiC Devices for Power Electronics”, August 2015).

8.2. State of Standardization

PECTA's recent analysis on industry roadmaps for WBG power electronics suggests that there might be increased standardization in the entire production chain for WBG power electronics. This includes wafer and material, device, modules and packaging. It could also include standardization of electrical parameters, efficiency measurements, power measurements and developing on accelerated reliability tests and expected module lifetime.

The JEDEC Solid-state Technology Association, a collaborative organization for developing standards for the microelectronic industry, recently launched the committee JC-70 "Wide Band Gap Power Electronic Conversion Semiconductors"^{11, 12}. This committee is responsible for the development and establishment of industry standards concerned with reliability verification and qualification procedures, test methods and measurement techniques, data sheet elements and device specifications, unique packaging considerations, and other related engineering issues. Activities also include cataloging and consideration of mission profiles, and formulation of terms, definitions, and symbols for the products defined above [33]. This new JC-70 committee has two sub-committees:

- **JC-70.1 Sub-committee for GaN Power Electronic Conversion Semiconductor Standards:** The sub-committee is responsible for the development and establishment of industry standards for GaN Power Electronic Conversion devices. Activities include coordination of the task groups. The task groups are responsible for the development of draft documents (guidelines, standards, etc.) to be proposed to JC-70.1 which will place the documents into vote by the JC-70.1 membership; and similarly,
- **JC-70.2 Sub-committee for SiC Power Electronic Conversion Semiconductor Standards:** The sub-committee is responsible for the development and establishment of industry standards for SiC Power Electronic Conversion devices. Activities include coordination of the task groups. The task groups are responsible for the development of draft documents (guidelines, standards, etc.) to be proposed to JC-70.2 which will place the documents into vote by the JC-70.2 membership [33].

The products within their scope include discrete devices and integrated circuits that employ Wide Band Gap and ultra Wide Band Gap semiconductors and are intended for use in power conversion circuits regardless of device type, polarity, mode of operation, packaging, electrical ratings, and end applications. This also includes bare die devices and modules that incorporate at least one such bare die device. In addition, the scope includes packaging unique to the products [33]. Two documents from this committee have been published, as follows:

- *Guidelines for switching reliability evaluation procedures for Gallium Nitride Power Conversion Devices*, February 2020 [34], and
- *Dynamic ON-Resistance Test Method Guidelines for GaN HEMT Based Power Conversion Devices*, Version 1.0, January 2019 [35].

Apart from JC-70, the JEDEC committee JC-14 Quality and Reliability of Solid-state Devices and Associated Microelectronic Products is responsible for standardizing quality, reliability, and qualification methodologies for solid-state devices and associated microelectronics products and the constituent components of each used in commercial applications such as computers, automobiles, telecommuni-

¹¹ JEDEC Solid State Technology Association is an independent semiconductor engineering trade organization and standardization body. JEDEC is the abbreviation of the original name when founded: *Joint Electron Device Engineering Council*.

¹² As of 2017 the JC-70 was led by interim chairs from Infineon, Texas Instruments, and Wolfspeed, a Cree company (<https://www.electronicdesign.com/technologies/analog/article/21805916/as-wide-bandgap-technology-rises-a-new-jedec-committee-kicks-off>).

cations equipment, consumer electronics, etc. The committee develops reliability test methods and standards for quality management systems for commercial and other applications of solid-state devices and associated microelectronics products and the constituent components of each. The committee also develops standards for board-level reliability of solid-state devices and associated microelectronics products used in commercial equipment.

In this committee, the sub-committee JC-14.3 Silicon Devices Reliability Qualification and Monitoring is responsible for establishing standards and procedures for evaluating and reporting the reliability of solid-state devices and sub-assemblies used in commercial applications. This includes qualification, monitoring, and field reliability [33]. This sub-committee has released the *Standard No. 47K, Stress-Test-Driven Qualification of Integrated Circuits*¹³. This standard, published in 2018, describes a baseline set of acceptance tests for use in qualifying electronic components as new products, a product family, or as products in a process which is being changed.

Apart from the JEDEC standards mentioned before, no specific standard for energy efficiency WBG power electronic devices was found.

8.3. Energy efficiency policies

The technological industry is shaped by policies and other types of control measures that ensure a regulated and prospective market. Depending on the perspective, policies do aim at different goals; for example, from an economical point of view, policies shall create a positive business environment, e. g., by eliminating tariffs or provide tax benefits [36]. Economic leadership of a state or a company, for example, can be considered “the result of a focused long-term government policy and investment” [37].

In times of growing energy demand, especially considering the limited availability of resources, environmental requirements and requirements related to energy efficiency, are subject to introduced policies. Statistics show that policies do have a positive impact on reducing energy consumption: “in the absence of energy policies, consumption in EU29 countries would have been approximately 11% higher in 2013” [38]. The objective is therefore to explore the possible policy measures that promote the adoption of semiconductors with WBG as an emerging technology widely applicable in power electronics, and especially in the context of realizing the associated energy savings discussed in numerous studies. The categorization suggested by [39] illustrates the different levels of (mandatory) commitment to which policies or other kinds of regulative measures can be allocated to:

- High-level target: such as the EU 2020 climate and energy package
- Energy efficiency (EE) strategies and white papers: presenting general orientation for government actions, such as The Green Deal¹⁴ and the Circular Action Plan¹⁵ and
- EE laws: translating strategies into concrete *policies actions or instruments*, such as the European Directives of Eco-design and Energy Labelling¹⁶.

The International Energy Agency (IEA) policy classification presented in Table 4 shows the types and sub-types of instruments. These IEA categories are useful in understanding the perspectives of a governing body and in helping organize a portfolio of policies [40].

¹³ See: <https://www.jedec.org/standards-documents/docs/jesd-47g>

¹⁴ See: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

¹⁵ See: https://ec.europa.eu/environment/circular-economy/index_en.htm

¹⁶ See: https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/ecodesign_en

Table 4: IEA Policy Classification System [40].

Main Type		Sub Type 1		Sub type 2			
Economic Instrument	E	Direct investment	D	Funds to sub-national governments	F		
				Infrastructure investments	I		
				Procurement rules	P		
				RD&D Funding	R		
		Fiscal/Financial incentives	F			Feed-in tariffs/premiums	F
						Grants and subsidies	G
						Loans	L
						Tax relief	Tr
						Taxes	T
						User charges	C
		Market-based instruments	M			GHG emissions allowances	A
						Green certificates	G
White certificates	W						
Information & education	I			Implementation advice/Aid	A		
				Information provision	I		
				Performance label	L	Comparison label	C
						Endorsement label	E
Professional training & qualification	T						
				Institution creation	I		
Auditing	A						
				Regulatory instruments	R		
Product standards	P						
Sectoral standards	S						
Vehicle fuel economy & emissions standards	V						
Monitoring	M						
Obligation schemes	Ob						
Other mandatory requirements	O						
Research, development & deployment (RD&D)	RD			Demonstration project	D		
				Research program	R	Technology deployment and diffusion	Dp
						Technology development	Dv
Voluntary approaches	V			Negotiated agreements (Public-private sector)	N		
				Public voluntary schemes	V		
				Unilateral commitments (Private sector)	C		

With the perspective of mandatory or voluntary nature of policies, these are organized left to right and top to bottom in Table 5, with more voluntary, informational policies towards the upper left; and mandatory, coercive policies to the lower right. The abbreviations (letters) cited in Table 5 refer to the types and sub-types of instruments from the IEA policy classification shown above.

Table 5: Categorization of policy types and nature, including examples [41].

		Nature of policy measure		
		<i>Supportive</i>	<i>Voluntary</i>	<i>Mandatory</i>
Type of policy measure	<i>Information</i>	Policy: making available information (I-I, I-T) Example: disseminating information on smart lighting systems	Policy: voluntary energy label (I-L-E) Example: ENERGYSTAR	Policy: mandatory energy label (I-L-C) Example: Korean Rational Energy Utilization Act
	<i>Financial</i>	Policy: direct investment in infrastructure and RD&D (E-D-I, -R) Examples: OpenADR, National Laboratories	Policy: grants, loans, tax incentives for energy efficiency (E-F-G, -Tr) Example: grants and tax relief in Korea	Policy: taxes and fees on devices and networks (E-F-T, -C) Example: absence of taxes or fees on Internet
	<i>Conformity</i>	Policy: technology development and deployment (RD-R-Dp) Example: Green Button	Policy: voluntary agreement by manufacturers (V-N) Example: Set-Top Box voluntary agreement	Policy: minimum efficiency performance standards (R-C-B, R-C-P) Examples: building codes and product standards

As illustrated with the examples in Table 5, energy savings can be promoted through policy measures targeting the **device level** (e.g., the EU voluntary agreements for set-top boxes, imaging equipment and game consoles; energy labelling and eco-design (minimum energy and functional performance) requirements; and the various *system levels* (e.g., smart lighting systems or building codes for whole buildings).

Correspondingly, device level energy savings are typically realized through superior product design resulting in a more efficient technology, for example: LEDs replacing incandescent bulbs. System-level savings are achievable through designing and selecting the components of a system with the goals of the system in mind [40].

As policies are settled at various levels, they can have an integrative approach by involving, technology, market, and policy players. In addition, the process of policy adoption might as well be spread over different agencies and organizations [37].

8.4. Energy efficiency in the power electronic industry

A 2017 study of the US Oak Ridge National Laboratory [42] discusses the market drivers for WBG, according to certain applications, as shown in Table 6.

Table 6: Market drivers for major potential WBG applications [42].

	Power Supply	UPS	PV Solar	Wind	Motor Drives	Rail	H/EV	Key
Efficiency	●	◐	●	●	●	◐	●	High ●
Weight/Size	◐	○	○	◐	◐	●	●	Medium ◐
Operating Temperature	○	◐	○	○	●	◐	●	Low ○
Switching Frequency	○	○	○	○	◐	◐	●	
Cost	◐	●	●	◐	◐	○	●	

The report [42] indicates that “one of the major market drivers for the increase in WBG utilization is the growing demand for energy accountability including efficiency and generation sources. As energy demand and environmental awareness grows, there has been an increase in regulations relating to energy efficiency and growing incentives for increasing renewable energy generation, alternative transportation energy, and further increasing energy efficiency. Other application-specific drivers include the reduction in power converter size and the growing evidence of decreased system cost.”

In general, semiconductor research and development (R&D) and its commercialization rely on a global wide, intertwined supply chain; it is estimated that one single semiconductor company in the US has over 16.000 suppliers [36]. In Figure 22, the supply chain of semiconductor modules and devices is depicted (in relation to PECTA) in a condensed way, showing that various and different stakeholders could be potentially *targeted* by policies (i.e., for energy efficiency), but could also *contribute* to the development of policies in the future. As indicated before, as policies are settled at various levels, they can have an integrative approach by involving, **technology, market, and policy** players.

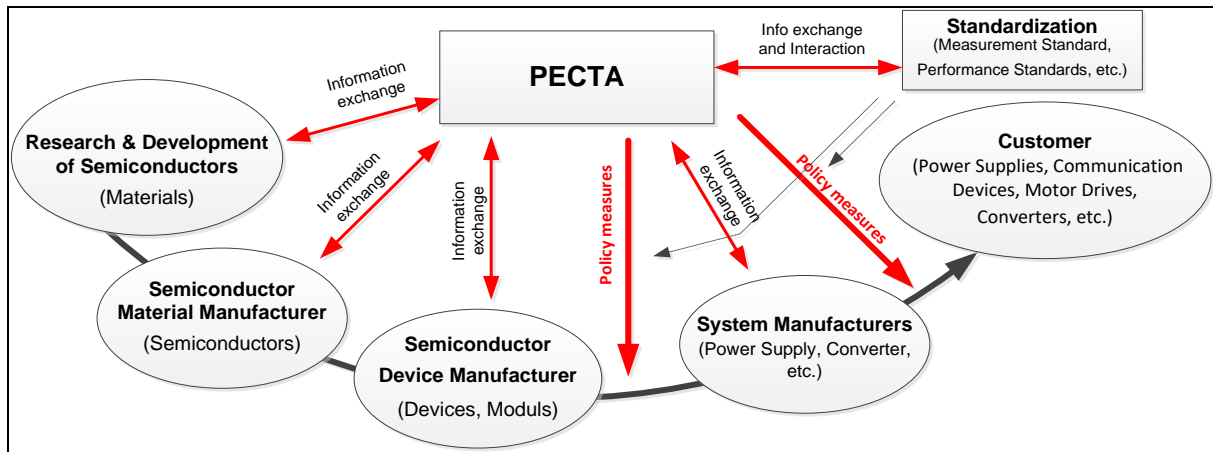


Figure 22: PECTA's role and interaction within the industrial value chain.

No specific energy efficiency policies targeting WBG semiconductors as such were found within the research activity conducted when preparing this report, but some observations might give an idea on forthcoming developments.

To this point, one could say that since WBG involves solutions widely applicable for a large range of applications areas and industry sectors, the WBG sector is strongly focusing on R&D activities in first place, in order to move WBG towards a broader market readiness. The majority of researched position papers and roadmaps concerning the future of WBG therefore stress out the need for developing of policies to favor R&D, which means that the priority is rather the creation of positive scientific conditions, than on setting technical or environmental guidelines [43], [37].

For certain fields of applications, the WBG technologies still need to achieve a desired and/or expected technical performance. For example, in [44] it is discussed that *“the GaN technology journey is in its early years. There are profound improvements that can be made in basic device performance as measured by figures of merit as for example $R_{DS,on}$ times chip area (or cost) over breakdown voltage¹⁷. Today's GaN transistor performance is still more than two orders of magnitude away from the theoretical limits and it is therefore quite reasonable to expect the pace to continue with factors of two or more reductions in the key figures of merit every two to four years.”*

The members of the power electronic industry also recognize that *“regulations and standards are important tools to encourage efficiency improvements in power electronics, defining product types and establishing minimum levels of quality and reliability. Standards help companies to invest more strategically in R&D rather than designing everything from scratch. Once common formats are established, companies can offer products based on standards, and focus R&D efforts on developing innovations to differentiate their products”¹⁸.*

For example, the technology company Infineon, one of the leading semiconductor manufacturers in Europe, has published datasheets for its products, including WBG technologies such as SiC MOSFETs¹⁹. The datasheets show technological characteristics and also include (own) labeling “symbols” to indicate the compliance with particular standards and regulations, as shown in the example of Figure 23, which is an extract of the datasheet of the CoolSiC™ 1200V SiC Trench MOSFET [45]:

¹⁷ <https://epc-co.com/epc/EventsandNews/Events/ImprovingSystemPerformanceDCDCApplications.aspx>

¹⁸ <https://www.electronicdesign.com/technologies/analog/article/21805916/as-wide-bandgap-technology-rises-a-new-jedec-committee-kicks-off>

¹⁹ MOSFET: Metal-oxide-semiconductor Field-effect transistor

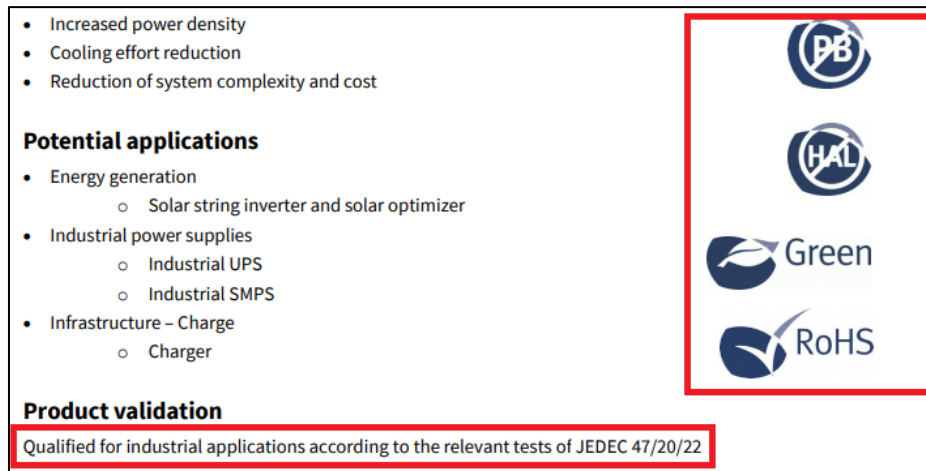


Figure 23: Extract of the datasheet of the CoolSiC™ (SiC) MOSFET from Infineon technologies [45].

Points worth mentioning are:

- Looking at the information under product validation (in Figure 23) the product is declared as complying with JEDEC 47/20/22. Although no standard was found with this numbering reference, this likely refers to the JEDEC Standard No. 47K, “Stress-Test-Driven Qualification of Integrated Circuits”, already discussed before in Section 1.
- The four symbols to the right in Figure 23 PB (free from lead); HAL (free from halogen), “green”, and RoHS (RoHS conformity) illustrate the environmental attributes considered on a device level (in this case, self-declared by Infineon), meaning that the product complies with environmental requirements that are set in European policies for electronic products/devices, in this case the EU RoHS²⁰ legislation restricting the use of hazardous substances in electrical and electronic equipment (EEE).
- The broad term “green” in this information sheet though is not referring to a specific “regulated” aspect (and it is free for interpretations), and it is not indicating a particular assessment, standard or existing regulation.

In the recent selection catalogue of the same company [46], it is stated that:

“...The key to the next essential step towards an energy-efficient world is to use new materials, such as Wide Band Gap semiconductors that allow for greater power efficiency, smaller size, lighter weight, lower overall cost – or all of these together.”

This catalogue includes energy efficiency information for many products, including selected WBG for many applications e.g., server, telecom, hyperscale data centers, wireless charging, adapter/charger, and audio, as shown in Figure 24 for the CoolGaN™ 600 V e-mode GaN HEMTs [46]:

²⁰ EU Directive on restricting the use of hazardous substances in electrical and electronic equipment - RoHS: https://ec.europa.eu/environment/waste/rohs_eee/index_en.htm

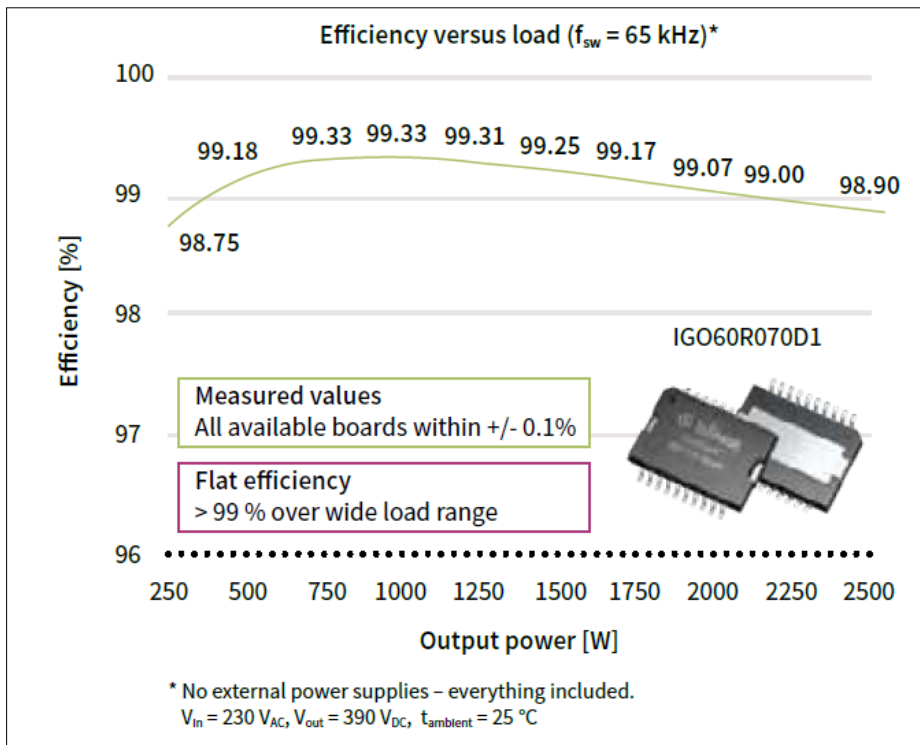


Figure 24: Efficiency information for the CoolGaN™ 600 V e-mode GaN HEMTs [46].

For selected SiC products in the same selection catalogue, there is information on efficiency provided in comparative graphs for SiC products as shown in Figure 25 and Figure 26.

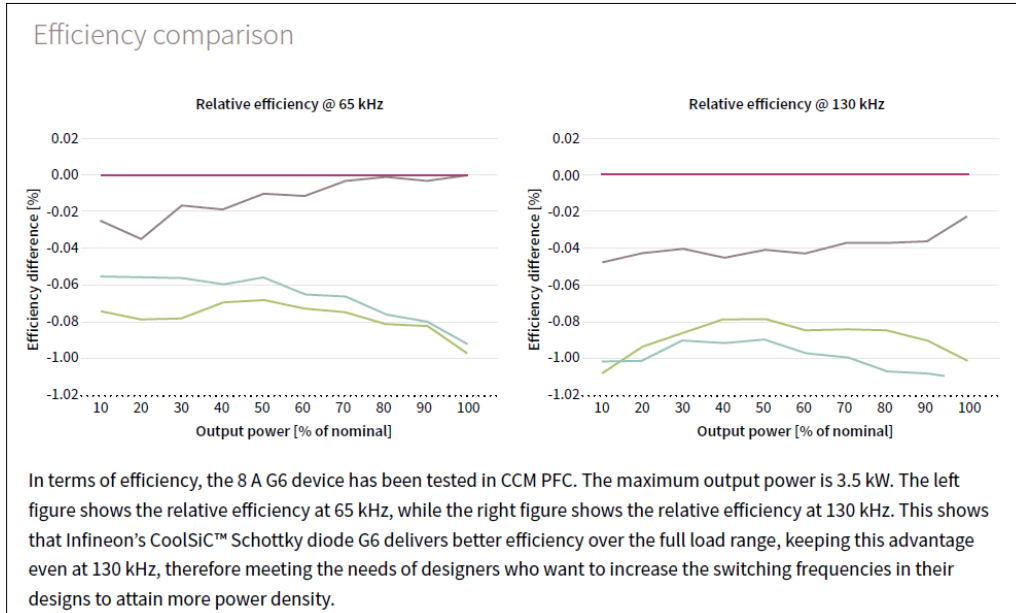


Figure 25: Extract from the selection catalogue with information on Infineon's CoolSiC™ Schottky diodes [46].

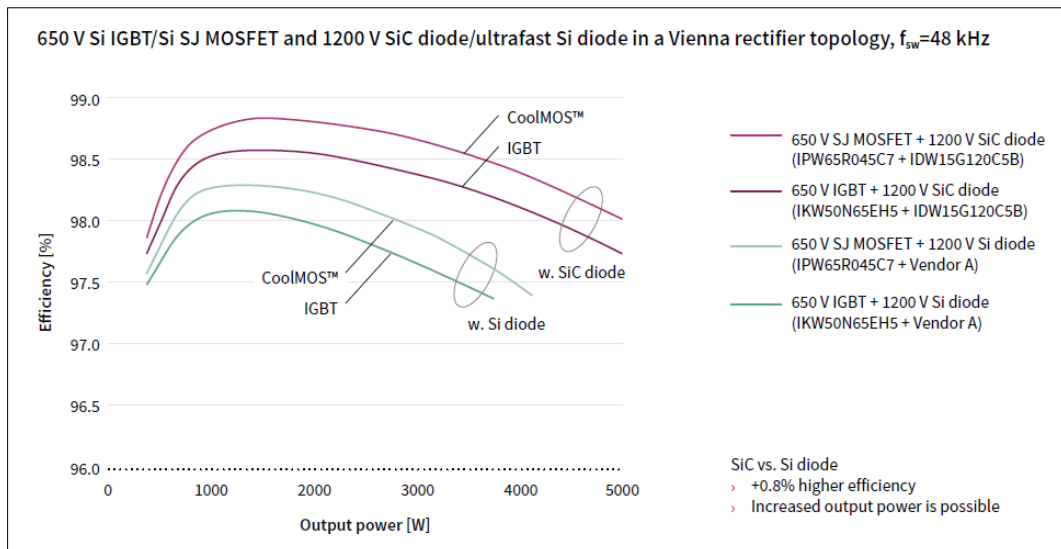


Figure 26: Comparison of devices in a Vienna rectifier²¹. (Extract from selection catalogue, [46]).

A comparison of system efficiency for another product of a different company (Power Integrations) is shown in Figure 27, showing a 50W adapter design [47].

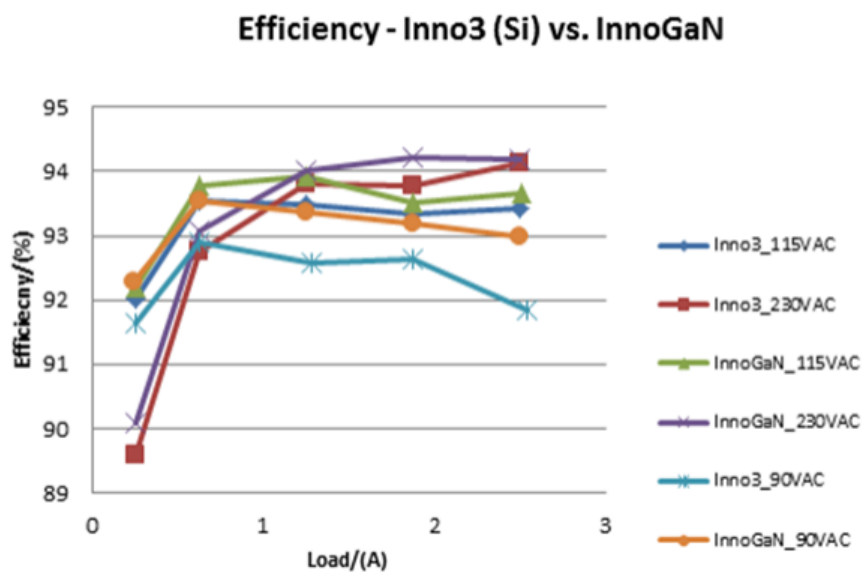


Figure 27: Comparison of GaN and Si for a 50W adapter design [47].

The fact that the energy efficiency information for some SiC and GaN devices (or systems using these) exists suggest that:

1. There are already procedures to measure efficiency in use by large and internationally oriented companies working with WBG semiconductor devices, which could be included in a standard.
2. Some companies are ready to disclose this information to (B2B) clients and even to the general public (e.g., the selection catalogue with efficiency information is easily accessible online).

²¹ Vienna rectifier is a three-phase three-level boost converter used for active power factor correction (APFC) applications. It utilizes an AC switching element in combination with diodes and capacitor to realize it. Current and voltage rating of components in a topology can be calculated. Power dissipated by each component is calculated and efficiency of the topologies is compared at a specific switching frequency. ([https://www.researchgate.net/publication/299404796 Comparative study of VIENNA rectifier topologies](https://www.researchgate.net/publication/299404796_Comparative_study_of_VIENNA_rectifier_topologies))

3. Having and showing efficiency data is advantageous, as this efficiency is an important part of the value proposition of the products in new portfolios. E.g., for Infineon products the slogan for the GaN product portfolio is “CoolGaN™ – ultimate efficiency and reliability”, and for SiC portfolio is “Improve efficiency and solution costs”, or “New level of system efficiency and reliability”. Showing data makes these statements stronger and credible.
4. Finally, this suggests that efficiency requirements on the device level, can be developed in a regulation.

8.5. Possible Policies in considering the product cycle

Without entering in a greater level of detail about specific types of policy from Table 4, this section explores some concrete aspects of possible policies for WBG technology for power electronics, especially focusing on their timing with respect to the maturity of the technology.

Figure 28 shows the types of technology policies and their market penetration over time. As seen from the previous discussion WBG as innovative, emerging technology is currently under intense development, and not yet broadly present on the market. PECTA’s Application Readiness Maps (see Appendices) describe the areas in which demonstrators, first products and numerous products will be available in the market, covering the span from 2018 to 2035.

The types of possible policies are based on 3 stages before commercialization, after build-up, during initial commercialization, and after initial commercialization, which broadly correspond to the 3 phases in Figure 28.

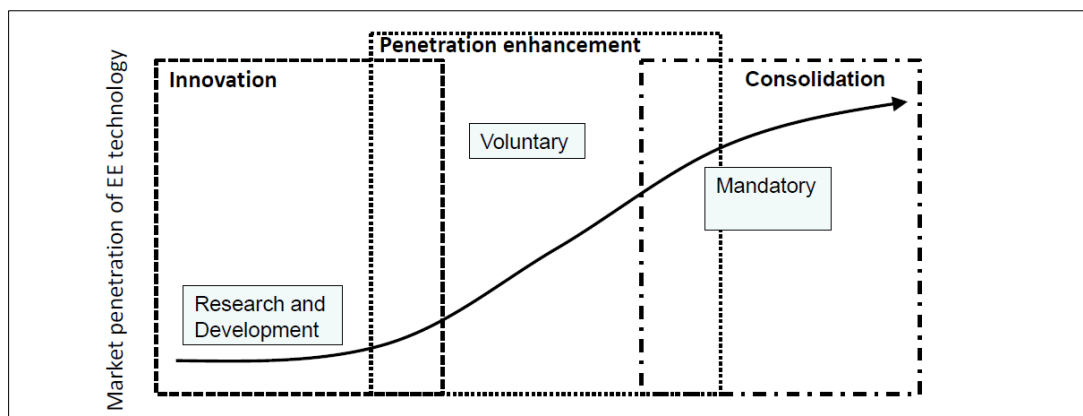


Figure 28: Types of technology policies and their market penetration over time [39] .

Stage 1: Before commercialization

Examples of policies before commercialization could include RD&D “build-up”, namely public research, development and deployment (RD&D) support before take-off and later commercialization. Figure 29 shows an example of the commercialization of the technology for solar heated swimming pools (for two competing technologies for capturing solar energy: collector and absorber systems). From 1988 there was no more public support, and the collector technology increased in comparison with competing absorber technology [48].

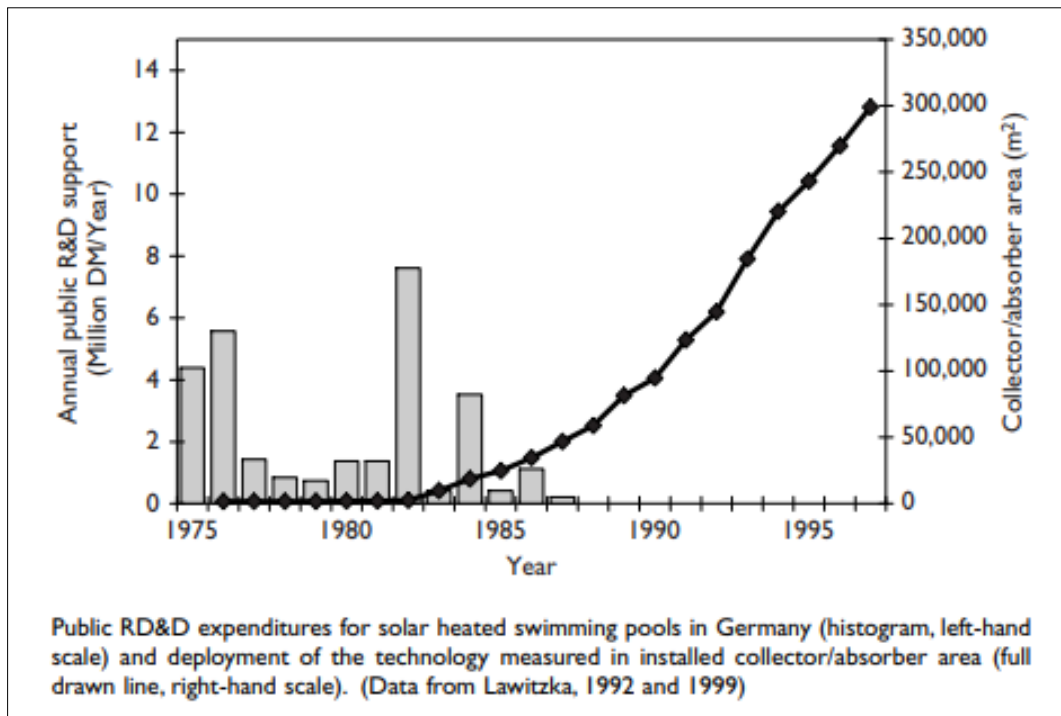


Figure 29: Public RD&D expenditures for solar heated swimming pools in Germany (1975-1997) and deployment of the technology [48].

A comparison between federal RD&D spending and learning investments illustrates how public spending seeds the development process. Table 7 shows expenditures during three different phases of the ride down the experience curve: from 1975 until RD&D support peaked out in 1982. (“RD&D build up”), from 1983 until the docking point in 1987 (“take-off”) and from 1988 until break-even around 1990 (“commercialization”). Public RD&D spending dominated the build-up phase. Public funds provided most of the learning investments for the deployment of the technology, but the major part of the funds supported activities necessary to initiate and feed the development process. Examples of such activities are build-up of competence and search for new knowledge within research organizations, and measurement and evaluation programs around the pilot installations [48].

Table 7: Learning investments and Federal RD&D support for solar heated swimming pools [48].

Period	Federal RD&D Support (million DM)	Deployment	
		Learning Investments (million DM)	Total Investments (million DM)
<i>RD&D build up: 1975-1982</i>	23	4	5
<i>Take-off: 1983-1987</i>	6	8	15
<i>Commercialisation: 1988-1990</i>	0	1	6
<i>After break-even: 1991-1997</i>	-	-	(25)*
Total: 1975-1997	29	13	(51)

* Estimated assuming 82% progress ratio after break even.

Relevance for PECTA: WBG-semiconductor technology might be different from this case (of solar heating technologies) because the current technology is already (widely) applied. A RD&D support policy is relevant in a build-up stage. PECTA could assess the maturity of WBG semiconductor technology, to determine if initiating “build-up” for GaN or “Mid-stage” build-up support policies for SiC would be appropriate.

Stage 2: After build-up, during initial commercialization

Example of the Danish Building Regulation: In 2008 the Danish Building Regulation facilitated a voluntary improvement on Energy Efficiency (EE), by forecasting minimum EE requirements the coming 10 years (until 2018), and this motivated actors to be proactive and develop solutions.

Relevance for PECTA: Voluntary approaches such as Negotiated agreements (public-private sector), Public voluntary schemes or Unilateral commitments (Private sector) (IEA terms) could be effective in combination with announcement of long-term incremental EE goals.

Stage 3: After initial commercialization

Minimum requirements for standby energy consumption through the horizontal European Ecodesign Standby Regulation²² moved the industry to implement an already existing lower standby chip technology, which was affordable.

Relevance for PECTA: After a proof of concept of the WBG technology, minimum requirements can help scale up the production and phase out the old semiconductor technologies (initially in prioritized sectors).

²² https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/energy-efficient-products/mode-standby-and-networked-standby_en

9. Key Findings and Outlook

The following relevant findings were identified from the phase 1 of PECTA. These preliminary observations are presented taking into consideration the goals of IEA 4E. For each observation, possible further actions are proposed.

- *Observation point 1:* Even though IEA 4E focuses on residential and commercial end-use equipment, the applications in this first phase of PECTA were not constrained to end-use equipment only. Although transport and wind applications are considered to be “out of scope” of IEA 4E, the found energy savings for transport were significant, mainly in the electro-mobility (vehicles and railway) sector. The energy savings estimates for wind generation are significant as well. Therefore, although these applications are “out of scope” of IEA 4E, the PECTA results for these should be further investigated.

Possible actions:

- ➔ *Action 1 a):* Distinguish between the devices and equipment in the scope of IEA 4E and those out of scope.
 - ➔ *Action 1 b):* Explore options for exchange and transfer of the PECTA results for the “out of scope” applications, e.g., to other IEA Technology Collaboration Programmes (TCP) and/or organizations which might take these up.
 - ➔ *Action 1 c):* Continue within PECTA with work for the identified equipment “in the scope of IEA 4E”.
- *Observation point 2:* The following applications are, at first glance, within the scope of IEA 4E, and should be included in further analysis:
 - Power supply (AC-DC) for any end-use equipment: e.g., Mobile phones, laptops, desktops, data centers, and in particular devices like UPS or low power DC/DC converters.
 - PV energy generators for residential use.
 - Drive inverters for small and medium motors as well as for servo drives.
 - Battery storage for residential use.
 - E-vehicle chargers.
 - HVACR-Appliances with variable speed drives

Possible actions:

- ➔ *Action 2 a):* Verify and expand the list of relevant equipment “in the scope of IEA 4E”, where WBG technologies will play an important role.
- ➔ *Action 2 b):* Analyse further which relevant applications “in the scope of IEA 4E” are more for the residential (private) sector and – if this is still in line with other elaborated results – concentrate possible regulations on first-hand on residential use applications.
- ➔ *Action 2 c):* It might be very helpful to make evidence of the saving potential based on a concrete use case in the residential area. The concept is therefore to find existing examples of the (higher) efficiency of the WBG technology in comparison of a conventional, Si-based technology on the basis of common, available products on the market. The concrete idea would be the analysis of a WBG-based power supply for mobile and portable devices and compare it with conventional Si-based products.

- *Observation point 3:* The estimations completed on the efficiency potential do not include the energy consumption for the production of the WBG devices or the disposal of the semiconductor devices, or their materials (Si, SiC, GaN) as well as the passive, and cooling materials. Furthermore, also hybrid semiconductor device and material configurations (e.g. Si-IGBT with parallel SiC diode, multilevel power stage with Si-IGBTs and GaN devices or SiC-MOSFETs and GaN transistors etc.) within a specific converter stage are not considered so far. Especially hybrid configurations could be beneficial in terms of optimizing efficiency and meeting cost targets of a power electronics converter or system.

Possible actions:

➔ *Action 3 a):* Other impacts of GaN and SiC to the environment have not yet been fully investigated in comparison to the use of classic Si based technology for the same applications. For example, other effects would need to be considered, for example that by using WBG devices the whole system design could have reduced size and therefore generates less impact even if semiconductor production might need more energy. These trade-offs need to be evaluated and this is an area of interest for PECTA. The idea is not to conduct LCAs that would demand extensive resources from PECTA, but to follow an approach similar to the one in the Solid-State Lighting Annex Task LCA. In this work the focus is on compiling the available literature associated with already completed LCAs to answer key questions on the new lighting technologies based on light emitting diodes (LED).

- *Observation point 4:* It can be observed that in particular applications, where there are multiple benefits with WBG technology, the market is very active and tries to expedite the entrance of WBG-based devices/products. For example, the higher efficiency of an inverter (with WBG technology) in an electrical vehicle leads to a higher driving range per charging of the vehicle battery. This is very critical, and it is a competitive aspect for an automotive manufacturer to gain visible market advantage with improved efficiency. As such this development will be pushed intensively further, e.g. the company Tesla is equipping the Tesla 3 models only with SiC-based traction inverters. Recent discussions with a large component supplier for truck and bus manufacturers indicate that the power electronic converters for large electric vehicles (trucks, and buses) will be developed exclusively on the base of WBG technology. The reasoning is the same as in the case of Tesla, extension of the driving range with a certain battery package, and even less battery weight for a certain driving range.

Possible actions:

➔ *Action 4 a):* Analyse the multiple benefits of WBG technology for relevant applications “in the scope of IEA 4E” and consider the results in relation to possible policy measures.

- *Observation point 5:* The challenges for adopting efficient products with more expensive WBG based components needs to be better understood. Then the introduction and wide adoption of power electronics with WBG technologies might be hindered for those applications where there is high cost pressure for manufacturing.

Possible actions:

➔ *Action 5 a):* Experiences in the past in other regulation areas could be collected. Based on these results, it should be analysed which policy measures could be supportive in the area of WBG devices and applications. A differentiation between residential applications (like mobile

phone chargers) and industrial products (like motor drives with power electronic converter) might be helpful.

- ➔ *Action 5 b):* It should be additionally investigated how policy measures could help reducing the costs of WBG based devices, for example initiating a large procurement program (for efficient technologies/devices), which would take advantage of economies of scale.
- ➔ *Action 5 c):* Converters for motors are widely spread and the estimated energy saving is extremely large. Standards have been already in place with an IEC Level available (IEC 61800-9-2:2017, test method for converters and IEC 60034-2-3:2020 for motors driven by converters). These products are already covered in the scope of the 4E Electric Motor Systems Annex (EMSA). At the moment a specific EMSA Task “Round Robin tests for converter losses (RR’C)” enables international verification of the usability and repeatability of testing for the IEC standards. The extensive knowhow of EMSA in this field could be used as well for analysis other equipment in the scope of PECTA. A strong interaction between 4E EMSA and 4E PECTA shall therefore be established.
- *Observation point 6:* Energy savings of applications can be achieved with the reduction of the standby losses and/or with high efficiency in the on-mode. For example, different ICT equipment is regulated in relation to their standby losses, while motors are regulated concerning their on-mode under defined conditions. From an energy perspective the use of WBG technology for power conversion means reduction of losses in the on-mode. Therefore, policy measures considering for example Minimum Energy Performance Standards (MEPS) or Energy Efficiency Performance Index (EEI) would focus on the on-mode of an application. This is rather easy in the case of electric motors having a continuous operation. But when it comes for example to the charging of a mobile phone, the charging circle, the status of the battery at the beginning and at the end of charging (e.g., charging from 20% to 100%) and as well as the charging time would need to be defined. So, when it comes to MEPS based regulation of WBG-based applications the focus should be on a defined “charging cycle” or a somehow defined “on mode”.

Possible actions:

- ➔ *Action 6 a):* Further analyse, based on the estimated energy savings potential, for which equipment it is possible to define repeatable and reliable testing conditions for on-mode cycles or other parameters, to lay down the ground for MEPS or EEI based policy measures.
- *Observation point 7:* Policy measures are manifold, and the policy exploration conducted in PECTA’s phase 1 showed that the stage of maturity of the (WBG) technologies is relevant. The intention for developing the PECTA Application Readiness Map was to better understand the penetration of specific devices in the market over time (due to their maturity and availability), to then further analyse possible policy actions.

Possible actions:

- ➔ *Action 7 a):* Further analyse, based on the estimated energy savings potential, for which application and in which stage appropriate policy measures to support their market adoption could be developed.

- *Observation point 8-1:* Many regulations are based on the availability of clear and reproducible (testing) standards. But in the case of WBG technologies based on SiC and GaN, the standardisation work is still at its beginning, focusing mainly on quality and reliability aspects of these technologies. It might be worth further investigating for WBG technologies in which areas and what standards are needed, e.g., at the application level (technology neutral), or considering the devices that are used in any power conversion circuits, regardless of the device type, polarity, mode of operation, packaging, electrical ratings. From the perspective of a policy maker, the target might be rather on an application level. Nevertheless, standards at the component/device level might be required to expedite policy measures at the level of applications. This needs to be further explored in PECTA.

Observation point 8-2: Manufacturers are, in specific cases, willingly declaring the energy efficiency of products in datasheets and other sources. Generic terminology is often found, such as the term “green” and/or “sustainable”, although these might not be referring to a particularly regulated aspect, and then remains open for interpretations. This is also not backed by specific assessments, e.g., testing standard or existing regulation. Moreover, the declared energy efficiency might not be fully aligned to internationally recognized, harmonized, and repeatable measurement methods.

Possible actions:

- ➔ *Action 8 a):* Further analyse which topics in the large standardisation field could be relevant and most appropriate for engaging in the scope of PECTA, especially when exploring further work on policy actions e.g., for developing recommendations for regulations and or measurement standards. As first step it should be analysed at which level (i.e., application, device, module, etc.) ongoing standardization activities could be relevant for PECTA. The initial work in PECTA showed that no further standardization work outside of the one undertaken by JEDEC is visible and ongoing. Experience shows that standardization heavily depends on the active engagement and contribution from industry. In this case, it might be useful to analyse at the beginning the kind of possibilities available and/or how PECTA could initiate work on standardization.
- ➔ *Action 8 b):* It might be appropriate to have clear standards for declaring the efficiency at the device level (e.g., in product datasheets). This standard should be elaborated with the active contribution of industry.

Observation point 9-1: WBG Technology is at present primarily based on the two materials SiC and GaN. The costs for manufacturing of devices based on these two materials are at the moment very high (GaN even higher than SiC) and it is therefore very hard for industry to compete – particular in prize sensitive markets - against well-established Si-based devices. This hurdle for the market entrance applies to both materials.

Observation point 9-2: The elaborated ARMs show that on the one hand GaN seems to be promising primarily in applications where high switching frequencies are applied and rather low blocking voltages (< 650 V) are required. SiC on the other hand is used in those applications where high-current and higher blocking voltage levels (> 650 V) are of interest. In both areas Si-based applications are still predominant in the market and innovative Si-based topologies and circuitries gain as well still relevant energy savings. Additionally, Si-based devices are very mature and (quantifiable) reliable, whereas the reliability and its verification is for WBG still a ra-

ther open issue for the moment. So called hybrid devices and systems (e.g. Si-based device with a SiC diode) are as well interesting alternatives, at least in a transition phase to full WBG-based devices.

- ➔ *Action 9a*): PECTA should as well consider both, Si-based hybrid solutions as well as (only) Si-based solutions for particular application areas, which could be highly efficient due to special structures, topologies, and circuitries.
- ➔ *Action 9b*): PECTA should focus on applications with high saving potential, where the major hurdle for adoption still remains their manufacturing costs (as other aspects such as reliability, resilience, safety and other non-efficiency related issues are not decisively playing a major role).

Final remark and Outlook:

A variety of tasks are foreseen in the coming 3 years of IEA 4E PECTA's "Establishing phase". PECTA will explore and continue advancing its knowledge base with the engagement and exchange between government delegates, academic, research, and industry experts. The tasks will mainly build upon the outcomes, observations and suggested actions presented in this report. It is clear though that due to limited funding and resources capability, not all tasks and actions proposed will be started immediately.

With this action path 4E PECTA enables a unique opportunity to develop an ambitious, international based and targeted work plan, which is leveraging the efforts and commitments of its founding member governments (AT, SE, DK and CH). PECTA extends an invitation to more governments and countries interested in energy efficient power conversion technologies to join these endeavours, and to support 4E PECTA in expediting and extending the foreseen tasks.

Appendices

Appendix 1:
Energy Savings WBG.

Appendix 2:
Application Readiness Map (ARM)
Industry, Automation & Robotics, Large Drives, ICT and Data centers.

Appendix 3:
Application Readiness Map (ARM)
PV-Inverter, Wind, Grid.

Appendix 4:
Application Readiness Map (ARM)
Automotive, Railways.

Appendix 5:
GaN-based Application Readiness Map (GaN-ARM).

Appendix 6:
SiC-based Application Readiness Map (SiC-ARM).

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Appendix 1

Energy Savings WBG

Appendix: Energy Savings WBG

Data Centers (2018)

According to [1], 71% of all servers are installed enterprise class. A comparison of efficiency rates of large data centers for AC distribution based on silicon and based on WBG are depicted in **Fig. 1**. Energy savings of up to 17% can be achieved over to total conversion chain when replacing silicon devices by WBG semiconductors.

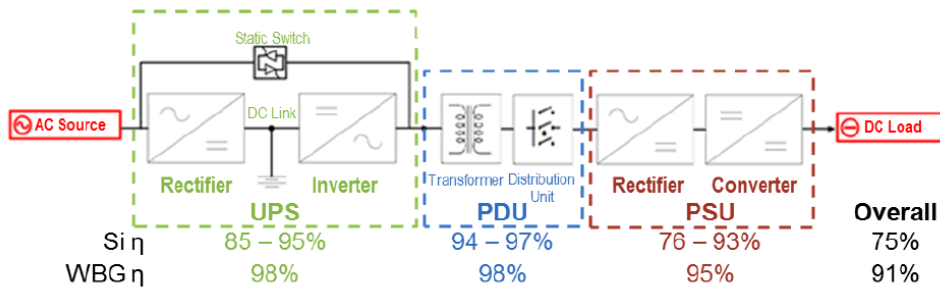


Fig. 1: Efficiency rates of large data centers for AC distribution as illustrated in [2].

It is furthermore stated in [2], that the efficiency can be further improved (also feasible for silicon), when DC instead of AC distribution is considered (illustrated in **Fig. 1**).

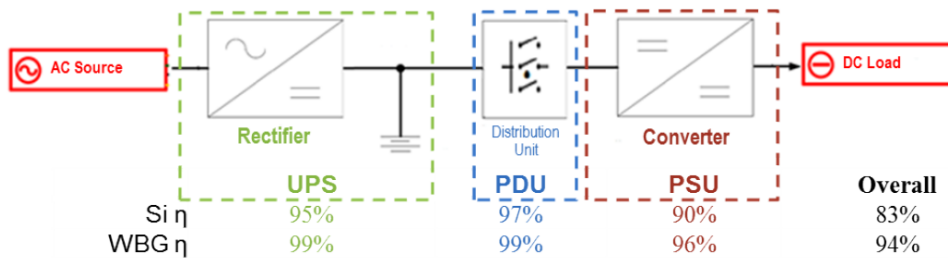


Fig. 2: Efficiency rates of large data centers for DC distribution as illustrated in [2].

The global data center electricity demand in **2018 was 198TWh** (1% of global final demand for electricity). This number includes Infrastructure (non-IT equipment such as cooling, lighting etc.), Network, Storage, Servers.¹

¹ Source: <https://www.iea.org/tcep/buildings/datacentres/>

According to the given data, the following global energy savings for WBG-based data centers are derived in **Table 1**.

According to **Table 1**, supporting WBG in the area of data centers can facilitate:

- Energy savings **up to 28.7 TWh/year**,

Table 1: Derived energy savings of Si and WBG-based data centers (both AC and DC distribution).

Data Centers				
	AC Si	AC WBG	DC Si	DC WBG
Efficiency (according to [2])	75%	91%	83%	94%
Consumption (TWh/year):	140.6	116	127	112
Energy Savings (TWh/year):	0	24.7	13.5	28.4
Energy Savings (%):	0.00	17.58	9.64	20.21

PV Inverters (2018)

According to [2] and [3] the energy efficiency rates of PV inverters from the kW range up to the MW range can vary from 90% up to 98.5%. Different SiC and GaN prototype showed that efficiency rates in the 99.1% area are viable (cf., [2]). The global amount of PV energy production in **2018 was approximately 500 TWh²**. Based on this data a realistic scenario in terms of energy savings and thus increased energy production is presented in **Table 2**.

Table 2: Derived energy savings of Silicon and WBG-based inverters for PV applications.

PV		
	Si Inv.	WBG Inv.
Average Efficiency (according to [2])	96.8%	98.8%
Production (TWh/year):	500	510.3
Increased Energy Production (TWh/year):	0	10.3
Energy Savings (%):	0.00	2.02

According to **Table 2**, supporting penetration of WBG in the field of PV inverters could lead to:

- an increased energy production of **10.3 TWh/year**,

² Source: <https://www.iea.org/topics/renewables/solar/>

Wind (2018)

The global amount of wind energy produced in **2018** was **approximately 4.06 EJ³**.

According to [3] the average energy efficiency of Si-based inverters for wind generators are approximately 95% and for an equivalent SiC-based inverter would result in 98% (summarized in **Table 3**).

Table 3: Derived energy savings of Silicon and WBG-based inverters for wind generators.

Wind		
	Si Inv. Eff	SiC Inv. Eff
Average Efficiency	95.0%	98.0%
Production (TWh/year):	1127.8	1163
Energy Savings (TWh/year):	0	35.6
Energy Savings (%):	0.00	3.06

³ Source: <https://eto.dnvgl.com/2018/#132548>

BEV (2015)

In general, it can be distinguished between different types of electric vehicles. Some of them are listed below:

- Battery Electric Vehicle (BEV)
- Plug-in electric vehicle (PEV)
- Hybrid electric vehicle (HEV)

In order to simplify the calculation of energy savings only BEVs are considered in this subsection. In [3], both types of BEVs (Si- and WBG-based) are illustrated (see Fig. 3 and Fig. 4, respectively).

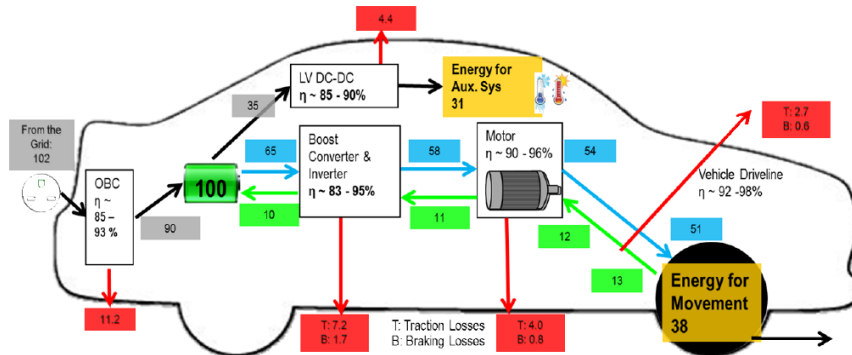


Fig. 3: Energy flow diagram of a Si-based BEV as illustrated and published in [2].

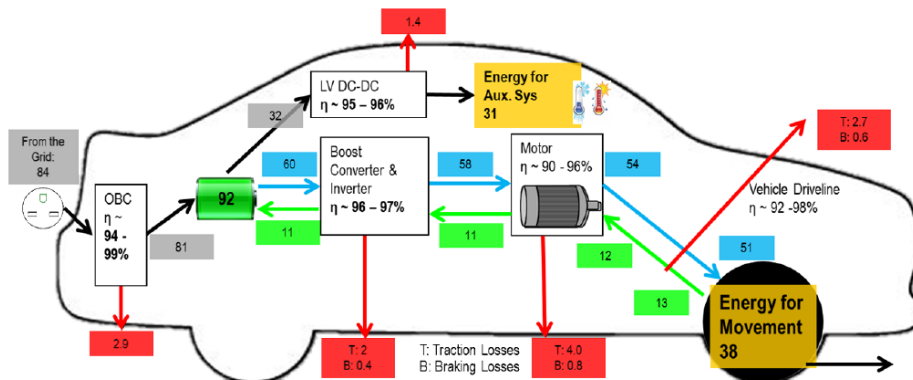


Fig. 4: Energy flow diagram of a WBG-based BEV as illustrated and published in [2].

Based on the literature study from [2] the following data has been recorded:

- BEV vehicle stock U.S. 2015: 300 000
- Expected annual primary use (Si): 14.7 PJ/year = 4.08TWh/year
- Expected annual primary use (WBG): 12.1 PJ/year = 3.36TWh/year
- Savings total: 2.6PJ/year
- **On-site electricity savings: 0.23 TWh/year**

Dedicated efficiency and energy are listed in Table 4.

Table 4: Derived energy savings WBG-based BEVs per car.

Battery Electric Vehicle	
	WBG
On-Site Electricity Efficiency improvement of BEV:	5.6 %
Total Efficiency Improvement (%)	17.7 %
On-Site Electricity savings:	767 kWh/year per car

Globals stock of passenger cars and new vehicles produced each year:

The global stock of passenger cars currently available can be found on and is approximately **1 000 000 000**.

Furthermore, there are approximately **70 000 000 new vehicles produced each year**.⁴

Energy Savings for different distance traveling (Germany/Europe):⁵

- <5000km: 17%
- 5000-10000km: 32%
- 10000-20000km: 33%
- 20000-30000km: 12%
- 30000-40000: 3%
- >40000: 2%

Table 5: Electric vehicles – characteristic numbers:⁶

	Energy (kWh)	Range (km)	Energy kWh/100km
Lightyear One	60	580	10.34
Hyundai IONIQ Electric	38.3	265	14.45
Tesla Model 3 Standard Range Plus	55	340	16.18
Tesla Model 3 Standard Range	55	310	17.74
Mini Cooper SE	32.6	185	17.62
Tesla Model 3 Long Range Dual Motor	75	475	15.79
Sono Sion	35	225	15.56
Smart EQ fortwo coupe	17.6	105	16.76
Skoda Vision IV	83	450	18.44
Porsche Taycan Turbo	93.4	390	23.95
Nissan e-NV200 Evalia	40	190	21.05

Energy Savings for different distance travelers:

- Short distance traveler: 5000km/year
- Commuter (short distance): 15000km/year
- Commuter (long distance): 40000km/year

⁴ <https://www.worldometers.info/cars/>

⁵ <https://www.tz.de/auto/auto-so-viel-fahren-deutschen-kilometer-im-jahr-zr-7134604.html>

⁶ <https://ev-database.org/compare/efficiency-electric-vehicle-most-efficient>

Table 6: Energy Savings for different types of vehicles and traveling behaviour

	Energy Savings Short Distance Traveler (kWh/Jahr)	Energy Savings Commuter (short distance) (kWh/Jahr)	Energy Savings Commuter (long distance) (kWh/Jahr)
Lightyear One	29	87	233
Hyundai IONIQ Electric	41	122	326
Tesla Model 3 Standard Range Plus	46	137	364
Tesla Model 3 Standard Range	50	150	400
Mini Cooper SE	50	149	397
Tesla Model 3 Long Range Dual Motor	44	133	356
Sono Sion	44	131	350
Smart EQ fortwo coupe	47	142	378
Skoda Vision IV	52	156	416
Porsche Taycan Turbo	67	202	540
Nissan e-NV200 Evalia	59	178	474

Estimated Energy Savings EV (Europe):

It has to be noted that the result for BEVs is under the assumption that all new cars that are produced will be BEVs on a global scale, thus 70 M/year. Assumed parameters are:

- Energy (TESLA): 18kWh/100km
- Average range per year Europe: 16650 km
- Savings: 5.6%

On-Site Electricity savings per BEV: 167.8kWh/year

Laptops, Tablets and Cell Phones (2015)

A very detailed list of energy savings for wide band gap compared to Si-based laptops, tablets and cell phones is listed in **Table 7**.

Table 7: Energy consumption of laptops, tablets and cell phones as recorded in [4]

Laptops, Tablets and Cell Phones						
	Si			WBG		
	Laptop	Tablet	Cell Phone	Laptop	Tablet	Cell Phone
Nameplate Power Rating (W)	60	12	5	60	12	5
Average active mode efficiency (%)	87	80	63	90	85	72
Annual loss per unit (kWh)	11	1.9	4.2	8.5	1.5	3.2
Global stock (million units in service) - 2014	750	750	5610	750	750	5610
Total annual electricity loss by global stock (TWh)	8.250	1.425	23.562	6.375	1.125	17.952
Total energy consumption (TWh/year)	33.237			25.452		
Total Energy Savings (TWh/year)	0			7.785		

This results in:

- Energy savings of **7.785 TWh/year**

Summary of Results and Outlook

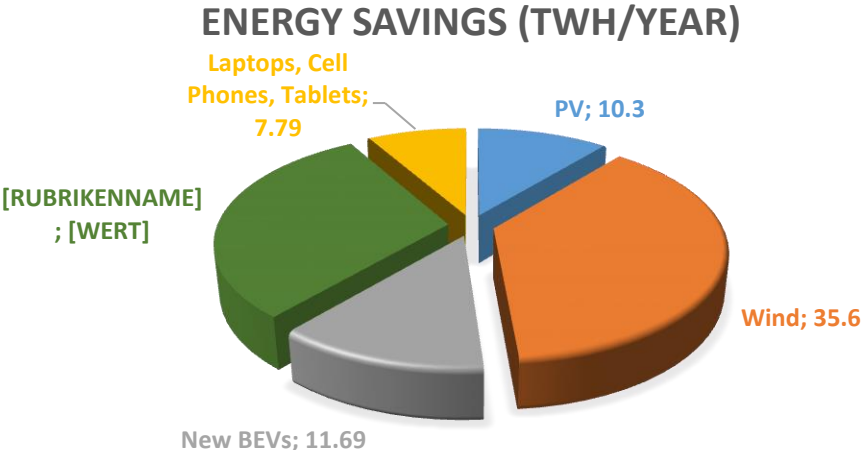


Fig. 5: Summary of energy savings for different applications such as PV, Wind, BEVs, laptops, cell phones and tablets.

- EV: It has to be noted that the result for BEVs is under the assumption that **all new cars that are produced will be BEVs** on a global scale, thus **70 M/year** and are coming with energy savings of approximately **167kWh/year per car** (dependent on driving behavior and distance).
- PV & Wind: Furthermore, it has to be noted that the share of PV and wind power will strongly increase in the next 30 years. Compared to 2018 the energy generation due to **wind power** generators is predicted to be **17 times higher** in 2050 (see Fig. 6).

Forecast of Energy production resources:

Moreover, it is forecasted the share of energy generation according to **PV** power plants will increase from 1.99 EJ in 2018 up to 96 EJ, which is **48 times** higher than in 2018.⁷

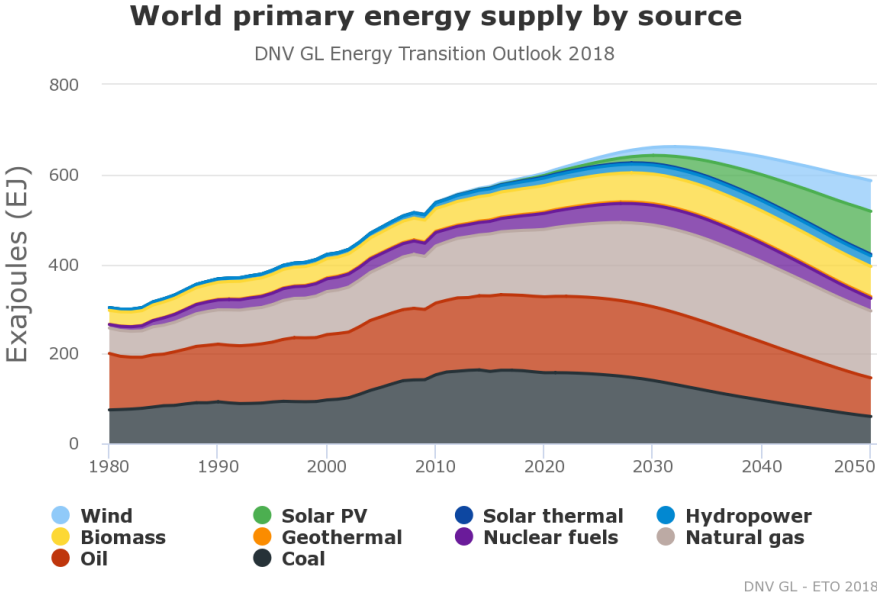


Fig. 6: World primary energy supply by source as illustrated in <https://eto.dnvgl.com>.

Therefore, the energy saving potential of Wide Band Gap will become even more efficacious during the next years.

⁷ <https://eto.dnvgl.com>

Appendix 2

Application Readiness Map (ARM)

Industry, Automation & Robotics, Large Drives, ICT and Data centers

WideBandGap: Application Readiness Map (ARM)

(Version 02.04.2020)

(Based on ECPE WBG-Roadmap)

Industry, Automation & Robotics

- Drive Inverter (GPD)

SiC MOSFET
650V – 1,2kV
GaN 650 V

SiC MOSFET
650V – 1,7kV
GaN 650 V

Significant Market Share

- Servo Drives

SiC MOSFET
650V – 1,2kV
GaN 650 V

SiC MOSFET
650V – 1,2kV

GaN 650 V

Significant Market Share

Large Drives

- Low Voltage

SiC MOSFET
1,7kV

SiC MOSFET
1,7kV

- Medium Voltage

SiC MOSFET
1,7kV – 6,5kV

SiC MOSFET
1,7kV – 6,5kV
SiC MOSFET
6,5kV – 15kV

SiC IGBT
> 15kV
SiC MOSFET
6,5kV – 15kV

ICT / Data Center

- HV DC Grid (Frontend
380 – 800V)

SiC MOSFET
900V – 1,2kV

SiC MOSFET
900V – 1,2kV

Significant Market Share

- HV DC Grid (Backend
12V/24V)

SiC MOSFET
650V – 1,2kV
GaN 650 V

SiC MOSFET
650V – 1,2kV

Significant Market Share

- Server Power Supply

SiC MOSFET 650V
GaN 650 V

Dependent on GaN Development

GaN 650 V

- Low Power DC/DC Converter

GaN <100V

Significant Market Share

- Uninterrupted Power Supply
UPS

SiC MOSFET 1,2kV
GaN 650 V

Predominant Market Share

Significant Market Share

2018

2020

2022

2024

2026

2028

2030

2032

2034

Time

Demonstrator available

First Product on the market

Significant Market Share:
more than 20% of WBG
Devices in these application

Predominant market Shares:
more than 50% of WBG
Devices in these applications

Appendix 3

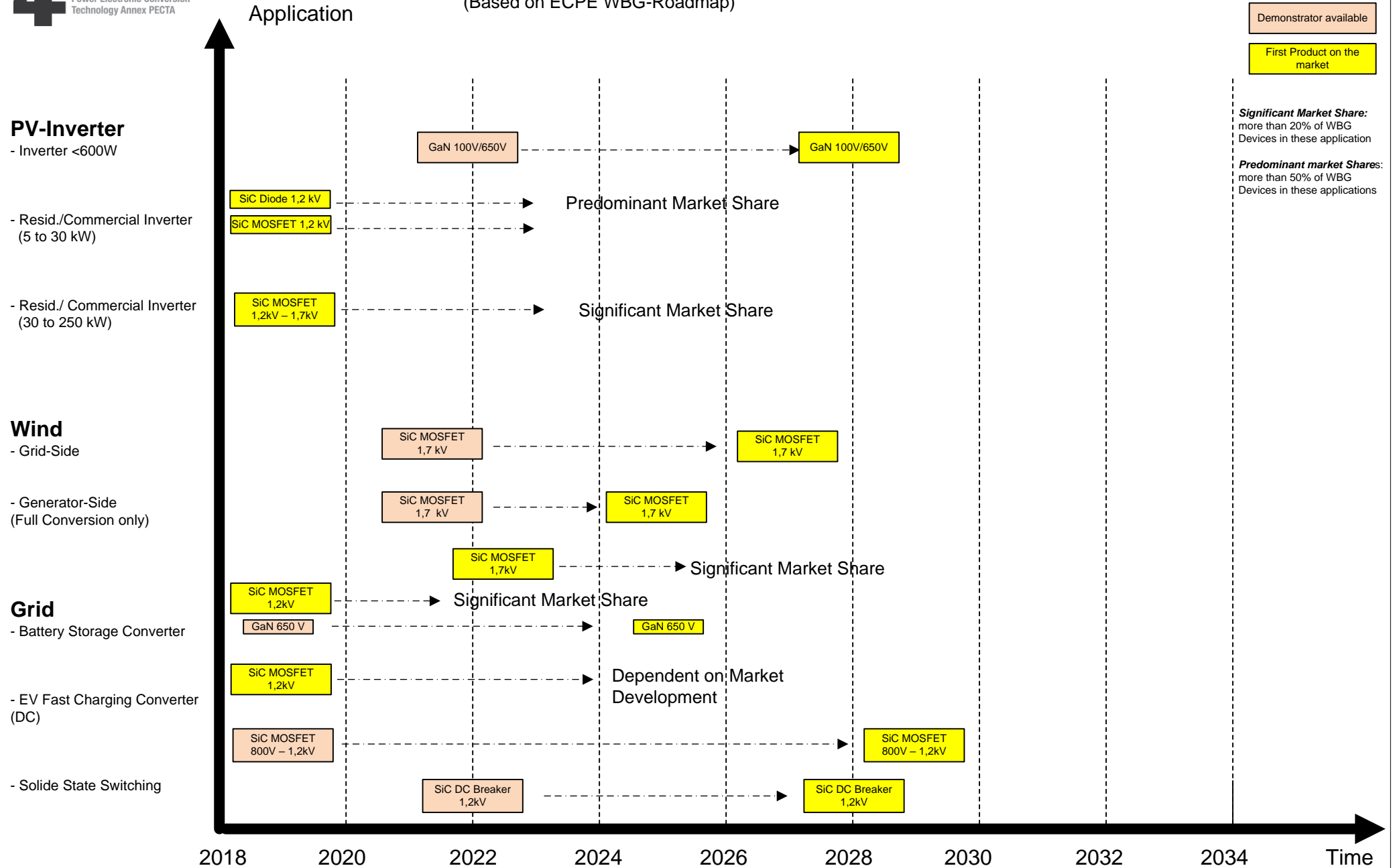
Application Readiness Map (ARM)

PV-Inverter, Wind, Grid

WideBandGap: Application Readiness Map (ARM)

(Version 02.04.2020)

(Based on ECPE WBG-Roadmap)



Appendix 4

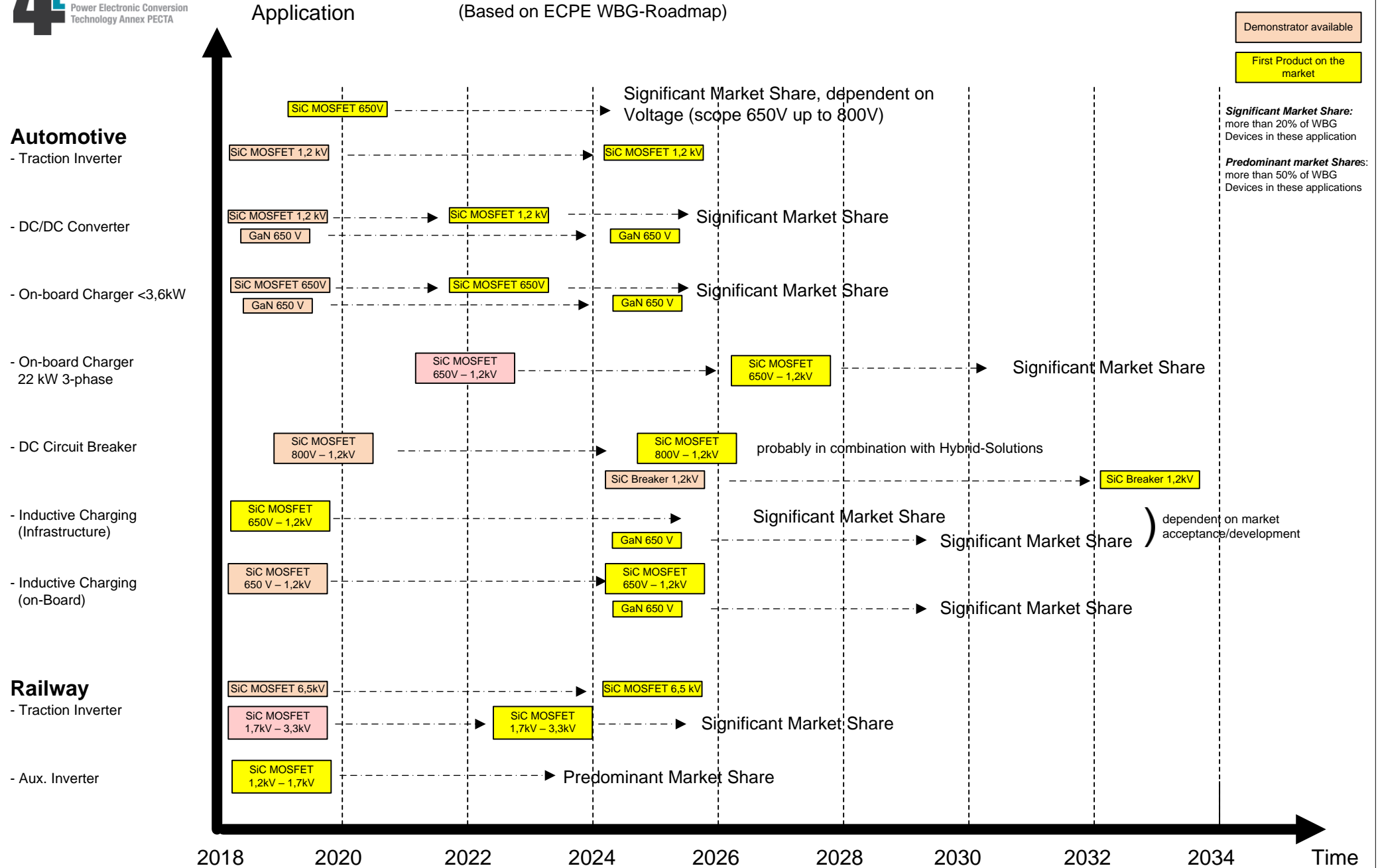
Application Readiness Map (ARM)

Automotive, Railways

WideBandGap: Application Readiness Map (ARM)

(Version 02.04.2020)

(Based on ECPE WBG-Roadmap)



Appendix 5

GaN-based Application Readiness Map (GaN-ARM)

GaN - based Application Readiness Map (GaN - A R M)



Acknowledgements:
This work is based on the ECPE WBG Roadmap 2019/2020

Automotive (FP)

- DC/DC Converter
- On-Board Charger 1ph, < 3.6kW
- Inductive Charging On-Board/Infrastructure

ICT/Data Centre (FP)

- Server Power Supply

PV (FP)

- PV: Micro Inverter < 600W, 100V/650

ICT/Data Centre (SMS)

- UPS frontend
- HV DC Grid backend
- Low Power DC/DC Converter <100V

PV (SMS)

- Power Optimizer

Grid (FP)

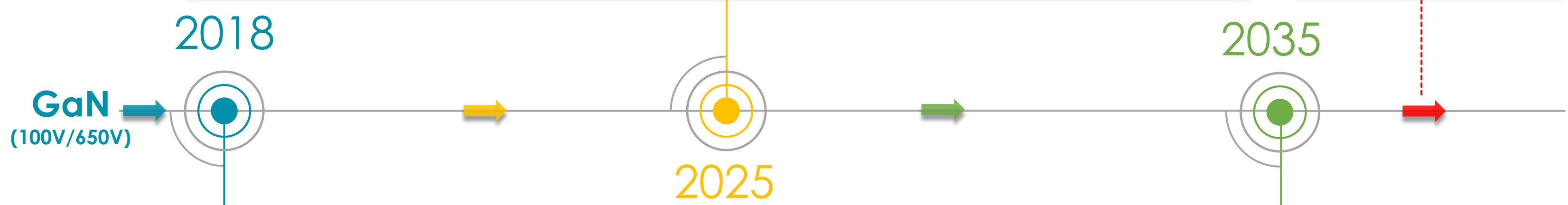
- Battery Storage Converter

Industry, Automation & Robotics (FP)

- Drive Inverter & Servo Drive

GaN not seen until 2035 for the following applications:

- Railway/Traction Inverter
- Automotive DC Circuit Breaker
- Windpower
- Large Drives
- Grid EV Fast Charging (DC)
- Solid State Switching DC Circuit Breaker



ICT/Data Centre (FP):

- UPS frontend

PV (SMS)

- Micro Inverter < 600W, 650V

Automotive (FP)

- Powertrain Traction Inverter

ICT/Data Centre (PMS)

- UPS frontend
- Low Power DC/DC Converter < 100V
- Server Power Supply
- HV DC Grid backend
- HV DC Grid frontend

PV (PMS)

- Power Optimizer
- Micro Inverter < 600W, 100V

Automotive (SMS)

- On-Board Charger 3ph, 22kW
- Inductive Charging On-Board

Industry, Automation & Robotics (SMS)

- Drive Inverter & Servo Drive

Grid (SMS)

- Battery Storage Converter

Automotive (PMS)

- DC/DC Converter
- On-Board Charger 1ph, < 3.6kW
- Inductive Charging Infrastructure

Abbreviations:

- FP ... First Product on Market (1 symbol per icon)
- SMS ... Significant Market Share (2 symbols per icon)
- PMS ... Predominant Market Share (3 symbols per icon)

Appendix 6

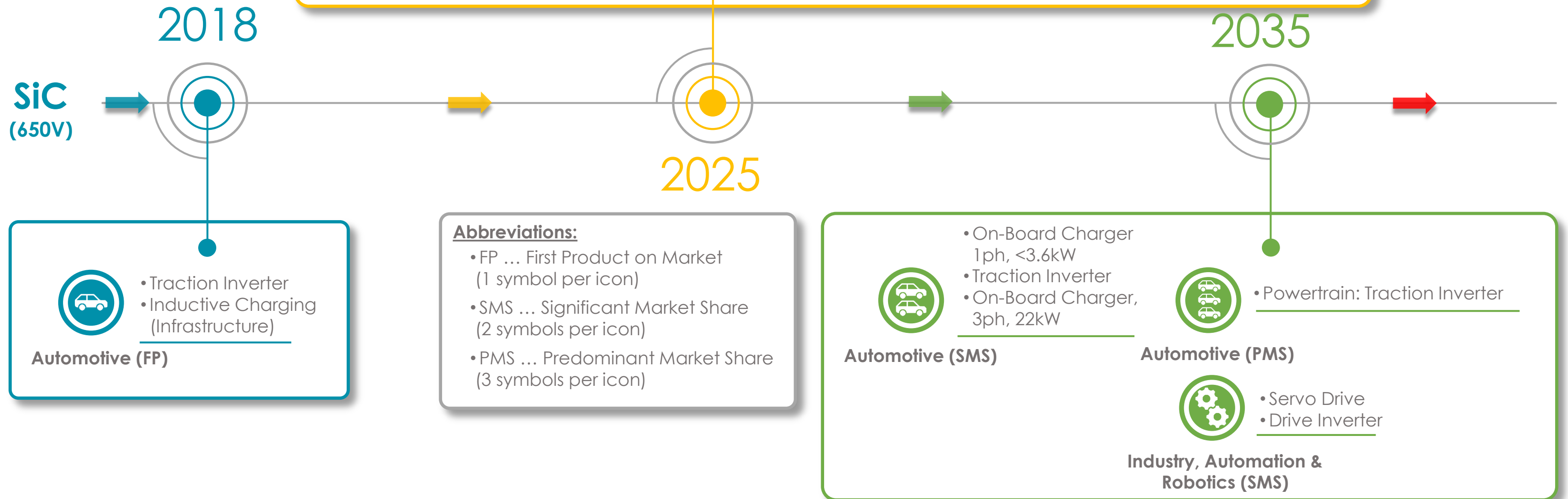
SiC-based Application Readiness Map (SiC-ARM)

S i C - b a s e d A p p l i c a t i o n R e a d i n e s s M a p (S i C - A R M)



Acknowledgements:

This work is based on the ECPE WBG Roadmap 2019/2020

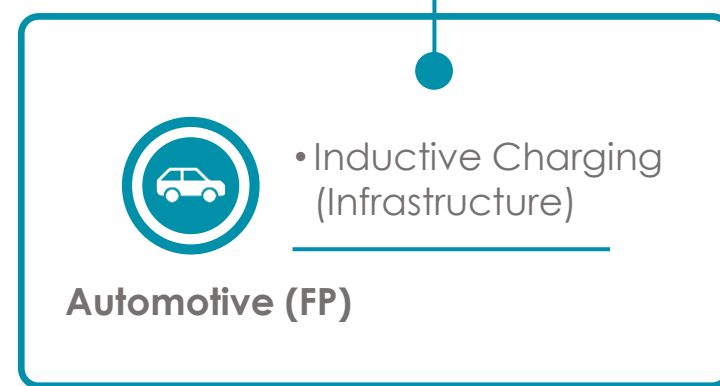
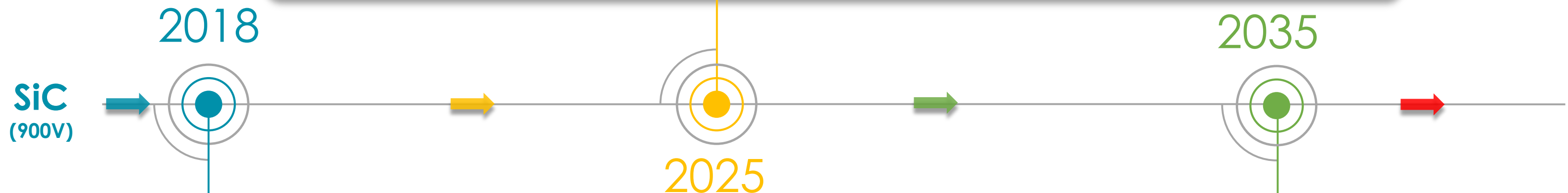
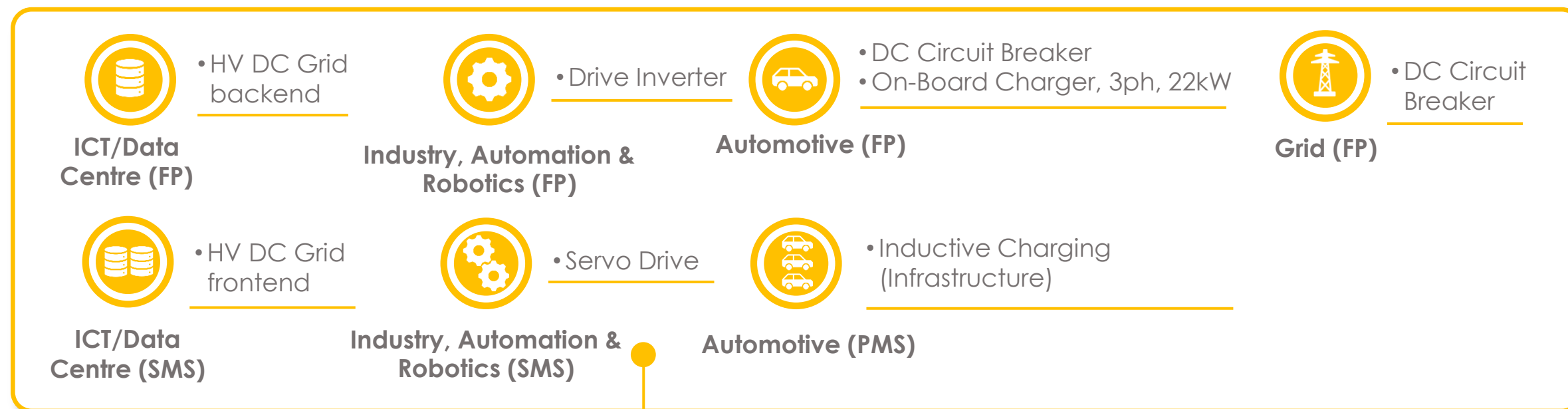


SiC-based Application Readiness Map (SiC-ARM)



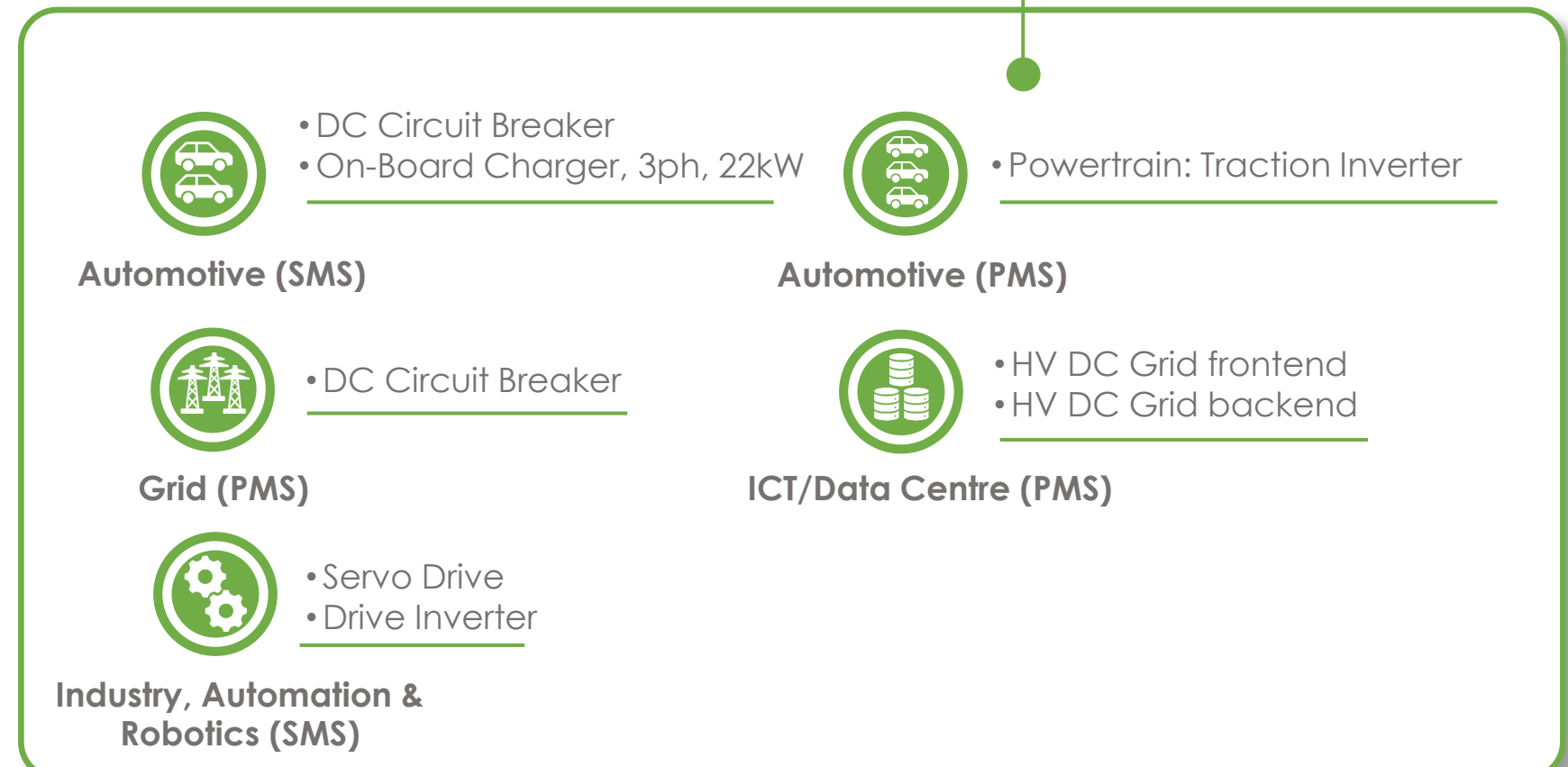
Acknowledgements:

This work is based on the ECPE WBG Roadmap 2019/2020



Abbreviations:

- FP ... First Product on Market (1 symbol per icon)
- SMS ... Significant Market Share (2 symbols per icon)
- PMS ... Predominant Market Share (3 symbols per icon)

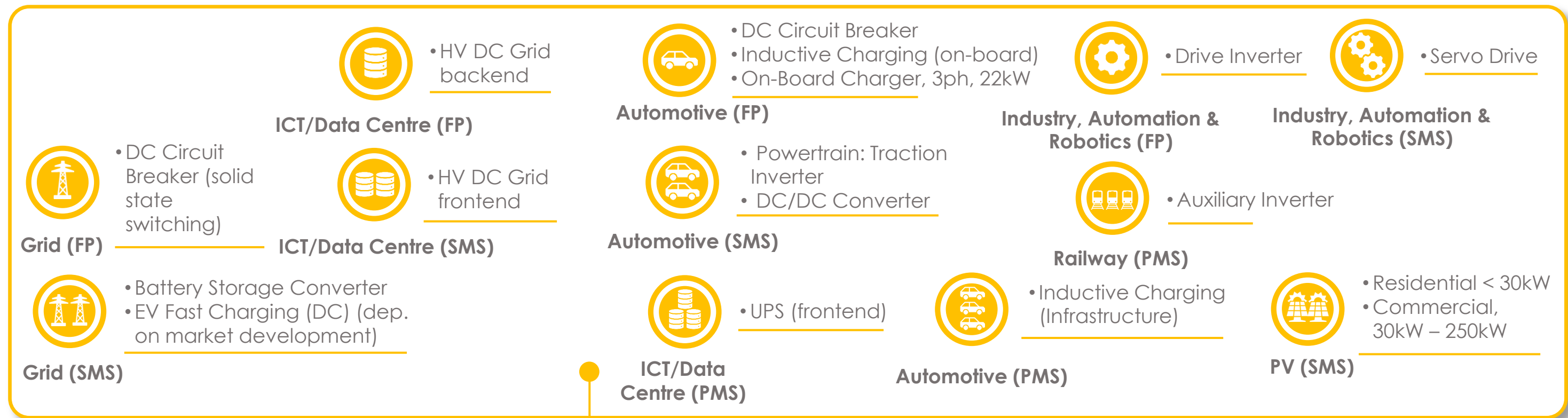


SiC-based Application Readiness Map (SiC-ARM)



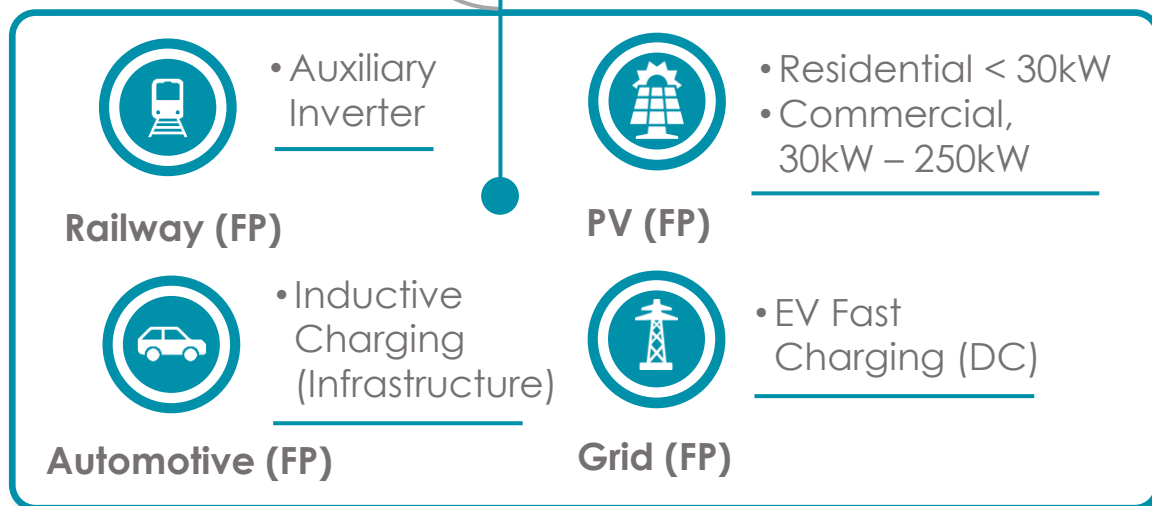
Acknowledgements:

This work is based on the ECPE WBG Roadmap 2019/2020

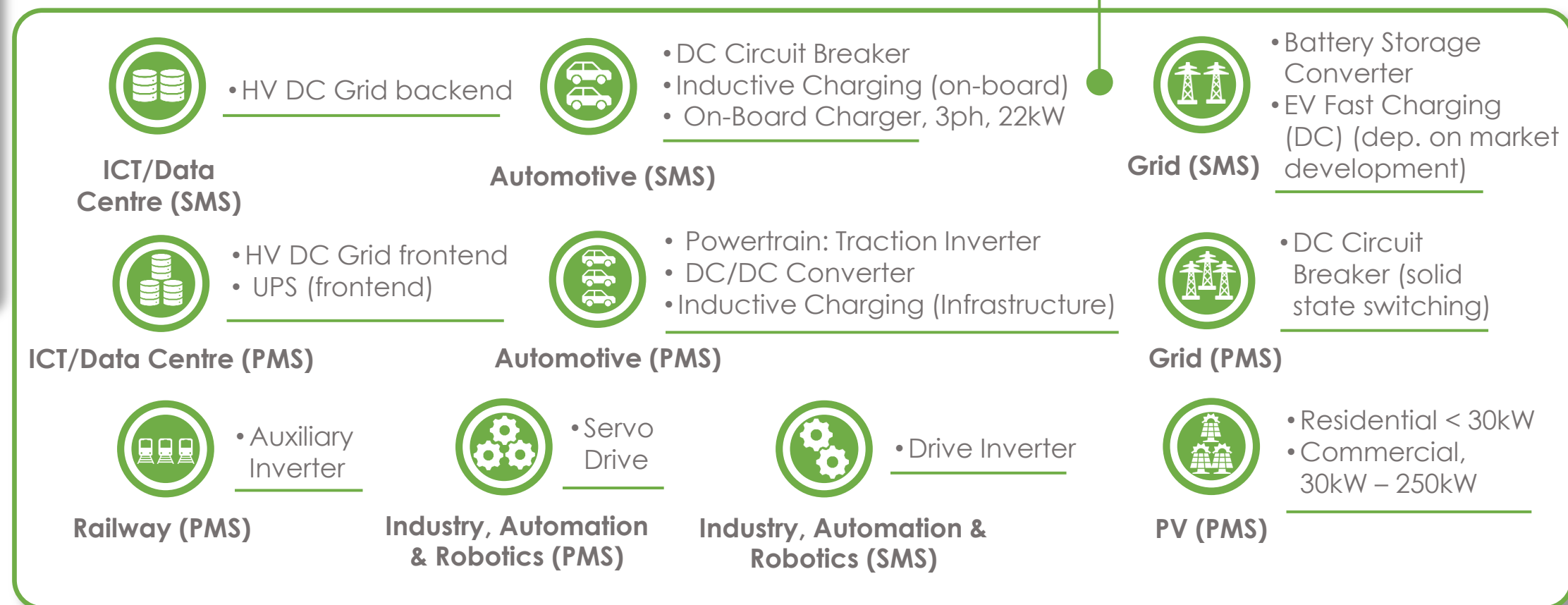


2018

SiC (1200V)



2025



2035

Abbreviations:

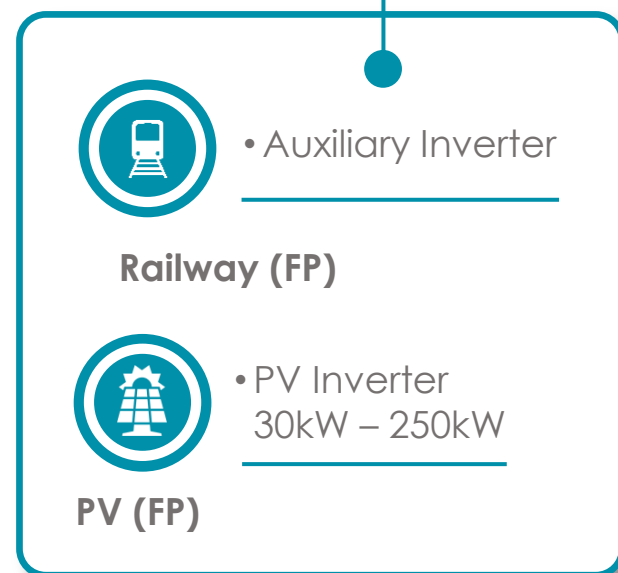
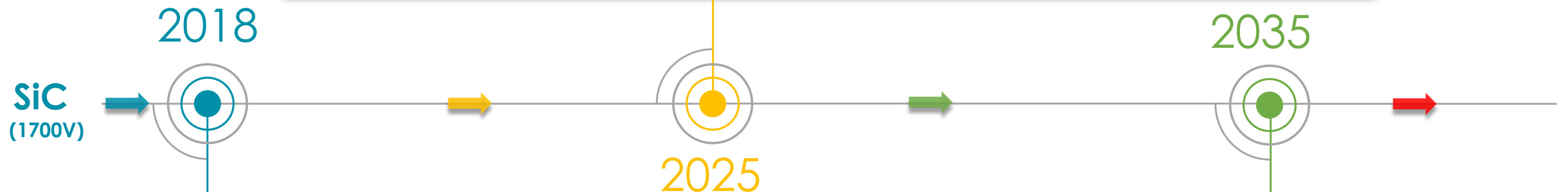
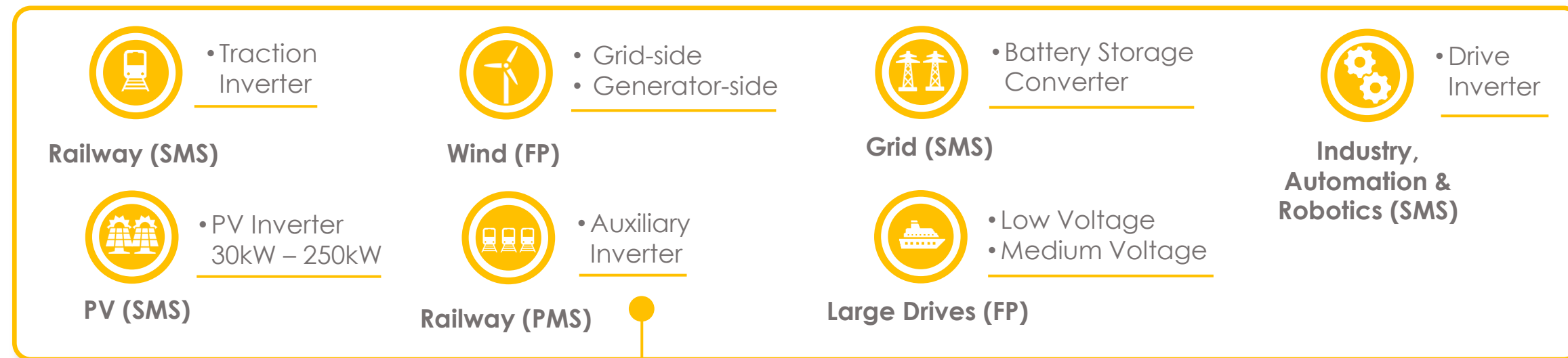
- FP ... First Product on Market (1 symbol per icon)
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SiC-based Application Readiness Map (SiC-ARM)



Acknowledgements:

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Abbreviations:

- FP ... First Product on Market (1 symbol per icon)
- SMS ... Significant Market Share (2 symbols per icon)
- PMS ... Predominant Market Share (3 symbols per icon)

