Application Readiness Map for Wide Bandgap (WBG) Semiconductors

4E Power Electronic Conversion Technology Annex (PECTA)

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Abstract:
The Power Electronic Conversion Technology Annex (PECTA) Application Readiness Map for Wide Bandgap (WBG) Semiconductors describes their expected market position through 2035. It is based on interviews with many experts and various roadmaps and could be used as a basis for deciding which power semiconductor technology to choose. This report presents an updated version and the underlying assumptions.

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

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

Contents

List of Abbreviations

AlN	Aluminum Nitride
ARL	Adoption Readiness Level
ARM	Application Readiness Map
ECPE	European Center for Power Electronics
GaN	Gallium Nitride
GaO	Gallium Oxide
GPD	General Purpose Drive
HEMT	High Electron Mobility Transistor
HVAC	Heating, Ventilation, Air Conditioning
ISO	International Organization for Standardization
JFET	Junction Field Effect Transistor
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
MRL	Market Readiness Level
NPC	Neutral Point Clamped
PECTA	Power Electronic Conversion Technology Annex
SiC	Silicon Carbide
TRL	Technology Readiness Level
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus
WBG	Wide Band Gap

1. Introduction

One of the goals of PECTA is to analyze and aggregate information on wide bandgap (WBG) based power electronic devices and to develop a better understanding, also among governments and policy makers [1]. A sub-target is to derive roadmaps for the integration of WBG devices into current applications. In order to provide an overview of all markets, a first Application Readiness Map (ARM) was developed in 2020, based on the ECPE WBG Roadmap, considering silicon carbide (SiC) and gallium nitride (GaN) devices.

This report presents an update of the ARM. It describes the current status of the WBG market and of the WBG technology, explains changes in the roadmap topics, and adds additional market segments that are now also relevant for WBG power semiconductors. The focus lies still on SiC and GaN devices. In order to better assess the predictive validity of the presented ARM, the most influential factors are presented and discussed.

2. Target and Description of the ARM

Readiness levels can be defined in many different ways. For example, there is the Technology Readiness Level (TRL), the Market Readiness Level (MRL), and the Adoption Readiness Level (ARL), which focus on technology, market, and adoption risks, respectively,

The objective of the ARM, as seen by PECTA, is to visualize the readiness level of different WBG devices and corresponding WBG technologies for use in different applications. The ARM describes the introduction of WBG devices in existing markets in these steps: 1) demonstrator available, 2) first product available, 3) significant market share, and 4) dominant market share achieved.

In power electronics, the application readiness depends strongly on the specific application requirements. Here, the improved power efficiency and increased power density possible with WBG semiconductors are the main drivers for their use. In addition, higher levels of integration can be achieved in conjunction with advanced packaging and integration technologies such as sintering, chip embedding, and gate driver integration.

But application readiness requires more. Compatibility with existing control and protection systems, as well as existing production processes, is essential for bringing products to market. Requirements for operational safety (e.g., ISO26262 for automotive), robustness (including short-circuit capability in drive applications), and reliability influence technology selection and often require normally-off devices. In applications with long lifetimes and many operating hours (e.g., railway with 30 years life time), the introduction of products requires a high level of technology maturity, and the achievement of a significant market share is delayed compared to consumer applications.

Depending on the level of application maturity, other factors become important. Most importantly, a significant or dominant market share can only be achieved if cost savings can be realized compared to the silicon-based solution, e.g. through lower costs for passive components or reduced cooling effort, through lower power costs for server operation, and through smaller batteries in electric vehicles. Of course, this is highly application-dependent. Finally, to gain significant market share, the supply chain must be able to meet market demands, which often require a mandatory second source.

All of these factors must be met to varying degrees depending on the specific application, but also depending on the four steps in the ARM described above. This is summarized in Table 1, which reflects the authors´ perception.

Table 1: Requirements for power electronics to achieve readiness level (own adaptation)

Requirement	Demonstration	Product	Significant market share	Predominant market share
Power density	x	x	x	x
Efficiency	x	x	x	x
Integration and packaging	x	x	x	x
Compatibility		x	x	x
Operational safety		x	x	x
Reliability		x	x	x
Robustness		x	x	x
Cost effectiveness			x	x
Delivery capability			x	x

3. Status of the WBG market

Tables 2 and 3 show the market share of WBG power device suppliers in 2020 and 2021. The market size for gallium nitride (GaN) power devices is growing faster compared to silicon carbide (SiC), but even in 2027, the market size for SiC power devices is expected to be three times larger compared to GaN.

For SiC, all major power semiconductor manufacturers produce in their own front-end wafer fabs and package in their back-end production lines. Investments in new 200mm wafer fabs have been announced, samples are available, and by 2027 all major SiC power device manufacturers will have 200mm SiC production facilities [2], [3]. Further cost reductions for SiC substrates are expected, e.g. [4].

For power GaN, the supply chain is different. As shown in Figure 1, most power vendors with a large market share design the transistors but do not manufacture the chips and packages. Changes in the supply chain have occurred with the acquisition of GaN Systems by Infineon [5] (still shown separately in Figure 1 and Table 2 due to different gate device concepts), and more are expected.

Table 2: Market shares of SiC power device suppliers per estimated revenue [2]

Global power SiC sales $1090M (2021)

Company	2020	2021
ST Micro	42%	42%
Infineon	16%	23%
Wolfspeed	16%	15%
Rohm	15%	10%
Onsemi	8%	7%
Mitsubishi Electric	4%	3%

Table 3: Market shares of GaN power device suppliers per million chips shipped [6]

Global power GaN sales $126M (2021)

Company	2020	2021
Navitas	26%	29%
Power Integrations	27%	24%
Innoscience	6%	20%
EPC	21%	14%
Transphorm	8%	6%
Infineon	5%	3%
GaN Systems	6%	3%
Other	1%	1%

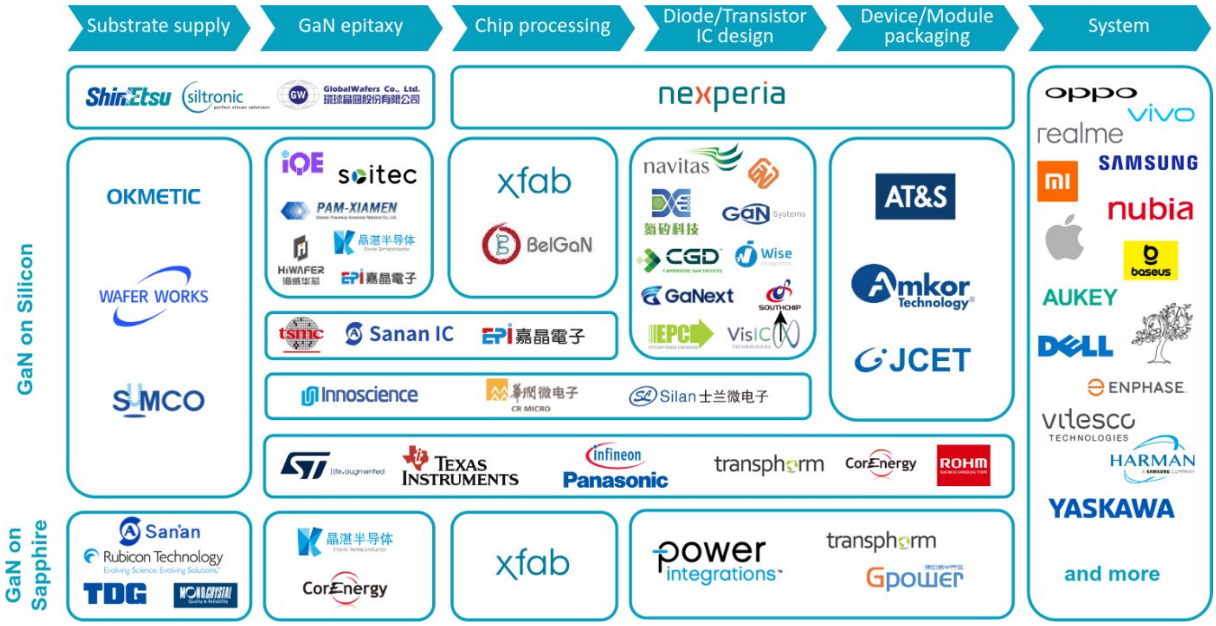


Figure 1: Global power GaN supply chain, based on [7]

4. Expected Developments of WBG Technologies

SiC power semiconductors today are mostly MOSFETs and Schottky diodes, JFETs are the exception, in all cases a vertical device structure is used. Continuous improvement is expected, with MOSFET channel resistance decreasing. Superjunction MOSFETs are also likely to enter the market in the medium term, but in contrast to the introduction of silicon superjunction devices, they will not open up a completely new market segment, but rather contribute to further cost reductions.

The situation for GaN devices is likely to be more dynamic. Nowadays, almost all GaN power devices are lateral high electron mobility transistors (HEMTs). The drive for higher blocking voltages and higher power densities will be addressed by vertical power devices, made possible by lower GaN substrate costs and the introduction of new backside wafer handling techniques. The first vertical GaN devices have been announced in 2023 [8]. In addition, we expect bidirectional GaN devices (HEMTs with two gates) to become available in the near future. Such devices are very attractive for T-type neutral point clamped (NPC) architectures.

Other WBG materials are under investigation. Diamond has long been considered the perfect power semiconductor material, but technological challenges such as doping remain difficult, and the cost position is questionable. The authors of this paper do not expect these devices to be commercially viable before 2035, probably excluding some niche applications. Gallium oxide (GaO) is also under discussion. This could have a much better cost position, but significant technical difficulties remain, and given the number of publications, there is still a long way to go. Therefore, we will not consider either diamond or GaO in the ARM, and Aluminum Nitride (AlN) will also be ignored for the time being.

5. Development of WBG Market and Update of ARM

5.1. SiC and GaN Device Positioning

As shown in Table 4, in 2027, the share of SiC power devices in automotive and transportation is expected to be about 80%, while the majority of GaN devices (about 50%) will be used in consumer applications. Please note that this includes applications where WBG power semiconductors are attractive to use and therefore commercially available, and excludes power electronic systems operating at low voltages such as 12V/24V with moderate switching frequencies, where silicon devices are the better option.

Table 4: WBG power device market in 2027 [2], [9]. The total SiC/GaN power device market is expected to amount to \$6.3B or \$2B, respectively, in 2027.

Application	SiC	GaN
Automotive & Transportation	82%	15%
Industrial	9%	4%
Energy	7%	1%
Telecom	1%	31%
Consumer	<1%	48%

Figure 2 shows different applications that are suitable for WBG devices. An overlap in the voltage range of 600 to 900 V affects the photovoltaic inverter and automotive markets. In order to reduce the charging time of large batteries to less than 20 minutes (from 10% to 80% state of charge), the battery voltages of a large proportion of electric vehicles will increase from 400V to 800-850V, some even higher.

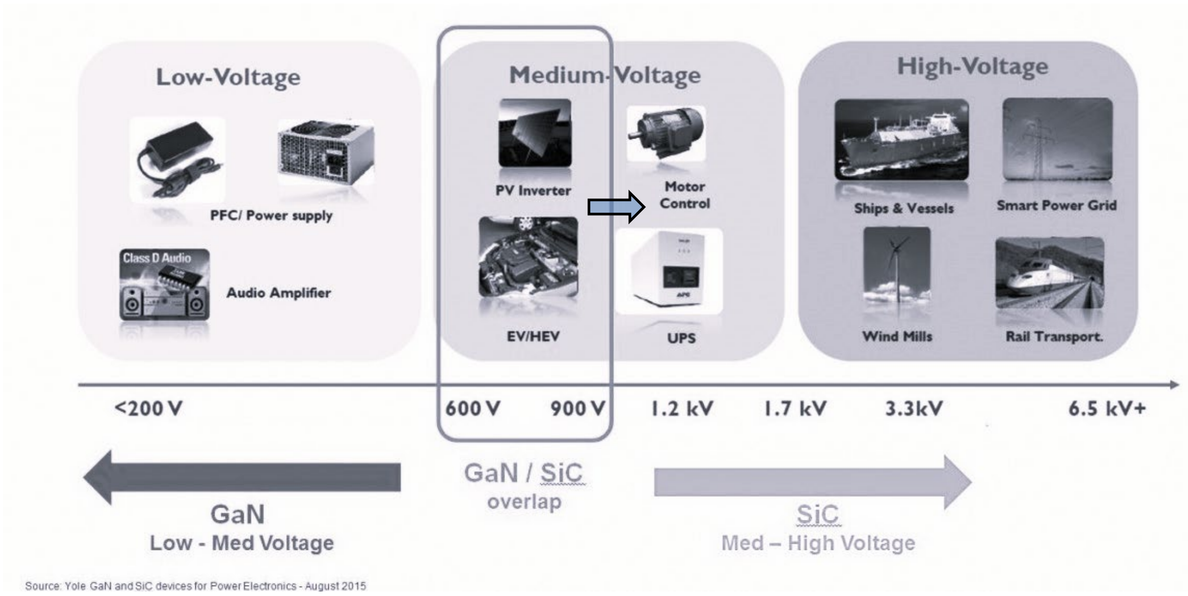


Figure 2: Automotive: shift to higher battery voltage, figure from [10], graph originally from Yole "GaN and SiC Devices for Power Electronics", August 2015

Applying this to WBG devices, we see that 1200V SiC MOSFETs are highly advantageous and have consequently been introduced into products even earlier than predicted in the previous ARM from 2020. GaN for on-board chargers and DC/DC converters is expected to gain significant market share as 1200V devices become available from major suppliers but the technological basis for this (lateral or vertical) and the corresponding timeline are difficult to assess.

The majority of SiC devices are used in drive inverters for electric vehicles. As shown in Figure 3, the predominant operation is at partial load, where SiC MOSFET inverters are clearly superior.

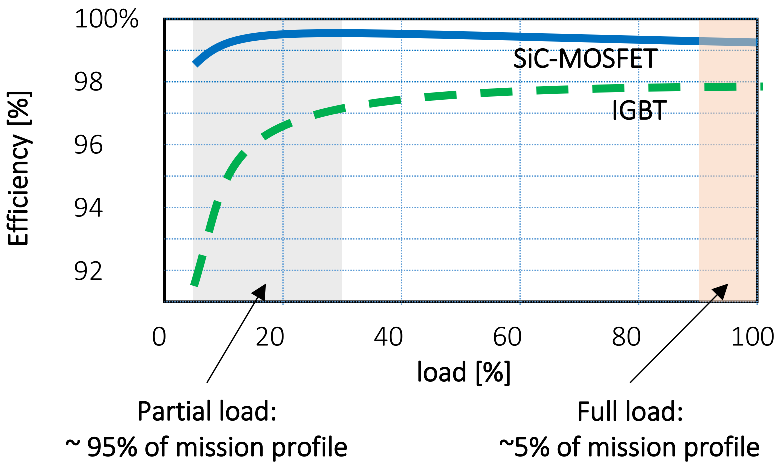


Figure 3: Efficiency for SiC- and Si-based automotive drive inverters plotted over the load condition [11], [12]. Note that the inverter mostly operates in partial load condition.

Because of this advantage, some scenarios show that the automotive SiC device market is expected to grow at a CAGR of more than 26% from 2022 to 2028, even considering recent announcements to reduce the number of SiC components in automotive powertrains [3].

In the consumer market, GaN devices (nowadays almost always lateral HEMTs) already achieve a dominant market share for USB power supplies. Here, the priority of application requirements is first cost, then power density, and finally efficiency. A typical efficiency of only 91% is accepted for USB power adapters, 93% is common, higher values are often achieved in more powerful USB chargers. The demand for smaller adapters requires high switching frequencies of 150 kHz or more, which can be achieved with GaN devices, even though most chargers still use frequencies below that.

In comparison, server power supplies have a different priority in the application requirements due to the 24/7 service. Now it is efficiency first, then cost, then power density. Therefore, this application uses 40 to 70 kHz switching frequency to achieve efficiencies above 96% (with over 99% for the power factor correction), where also SiC devices are a good choice [13], [14].

5.2. Additional energy-relevant segments

Photovoltaic microinverter products with 650V GaN HEMTs are already available [15]. Products for bi-directional charging integrated in the vehicle as on-board chargers and also wall-mountable are being introduced with SiC MOSFETs [16]. GaN HEMTs are used in automotive backup DC/DC converters. For high power DC/DC converters, SiC MOSFET solutions are used now and GaN is expected to be used later when reliable 1200V devices are available.

In railway applications, auxiliary converter products are equipped with 3.3 kV SiC MOSFETs, e.g. in the battery-powered hybrid train demo for DC/DC converters [17], [18].

Inductive charging is expected to remain a niche market for automotive applications in the next years, but SiC will also be used in industrial applications, e.g. wireless charging of electric forklifts or warehouse robots. GaN HEMTs are being used for 48 V servo drives by various system suppliers, but GaN devices are also suitable for higher voltage applications, e.g. for flying capacitor multilevel topologies in line infeed modules [19].

Several other applications with partial load conditions will benefit from WBG devices. In HVAC (Heating, Ventilation, Air Conditioning) applications, efficiency regulations consider seasonal energy efficiency in heating and cooling, and therefore partial load conditions. It is expected that SiC MOSFETs will be introduced in HVAC applications [20], but due to the uncertainty of the product introduction, it is marked with a dotted line in the ARM, see Appendix, Figure 5.

5.3. Application Readiness Maps

The updated and expanded Application Readiness Maps are presented on the following pages. They visualize the status of the ARM for various application areas, reflecting the authors' expectations based on discussions with experts, information gathered at international conferences and national workshops, in-depth literature studies, and their own judgment. Compared to [10], additional WBG-relevant market segments have been added. Figure 4 focuses on automotive and railway, Figure 5 on photovoltaic inverters, wind, grid, and consumer applications, and Figure 6 on industry, automation & robotics, large drives, information/communication technology and data centers.

Please note that Figures 4-6 may indicate a much higher market penetration for some applications than Table 4 suggests. For example, high-end industrial drive inverters will see significant WBG penetration much sooner than the majority of the general-purpose AC drive (GPD) inverters. However, these GPD inverters dominate the industrial market [21] and thus the expectation shown in Table 4.

6. Conclusion and Outlook

Power devices based on wide bandgap semiconductors, in particular SiC and GaN devices, are already successfully used in a wide range of applications due to their unique advantages such as improved efficiency, higher power density and weight reduction. In addition, the ruggedness and reliability of WBG power devices are increasing. Device availability is also improving and costs are trending downward. Regulations requiring higher efficiency and subsidies that support R&D and the introduction of mature, innovative WBG semiconductors could further boost the adoption of WBG devices in all applications [22]. Because of these factors, the authors believe that WBG devices will enter more applications in the future, as shown in the application readiness maps for a variety of different applications.

However, the underlying assumptions need to be verified. Therefore, the PECTA ARM will be continuously monitored and updated. In the next phase, a closer look will be taken at drive applications, as a more dynamic development is expected in this area. Since there is no doubt that power electronics and power semiconductors play a crucial role in successfully achieving carbon neutrality [22], other power electronics for energy conversion technologies, such as large-scale green hydrogen production or fuel cells, will also be monitored.

Figure 4: Applications Readiness Map for Automotive and Railway

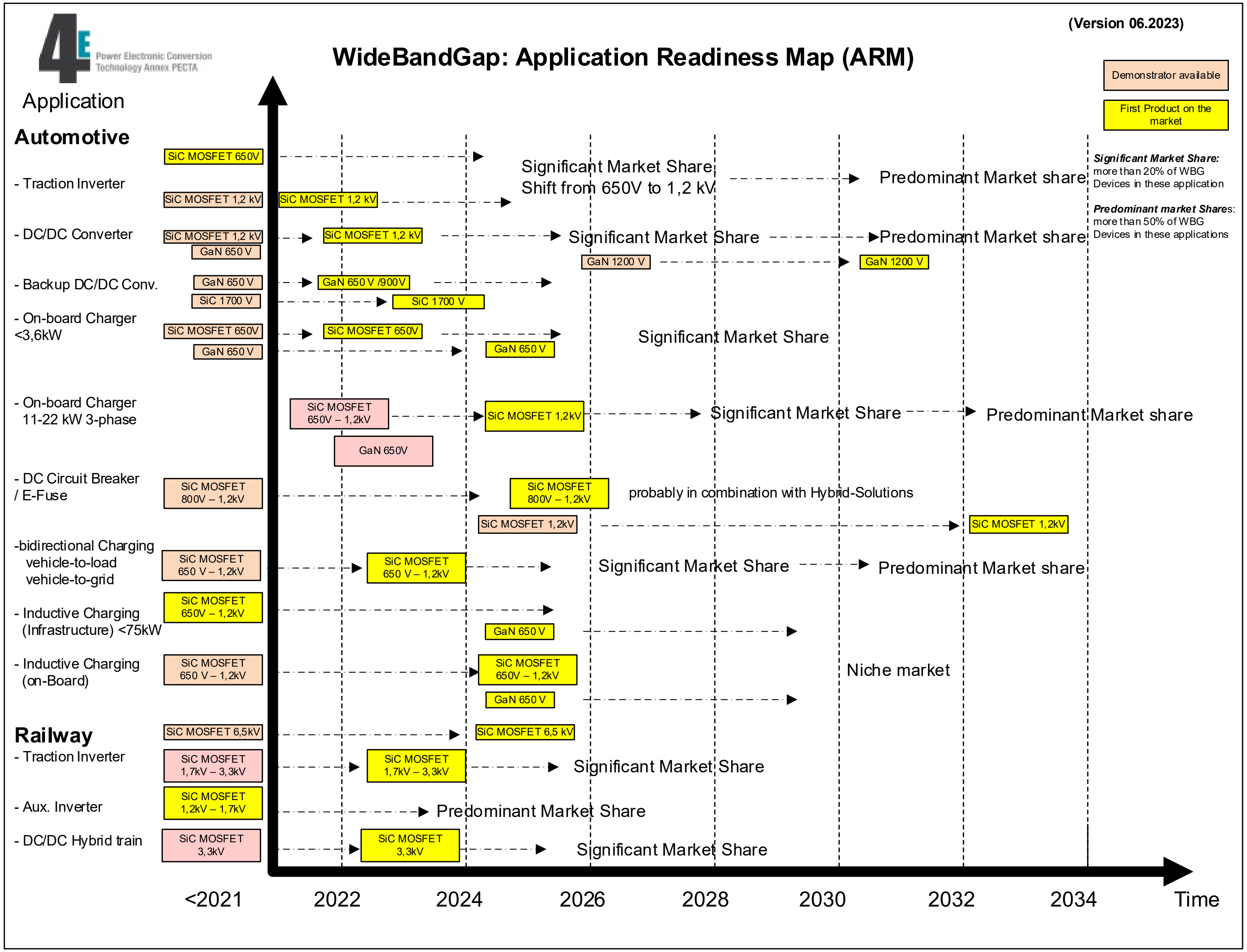


Figure 5: Applications Readiness Map for photovoltaic inverters, wind, grid, and consumer

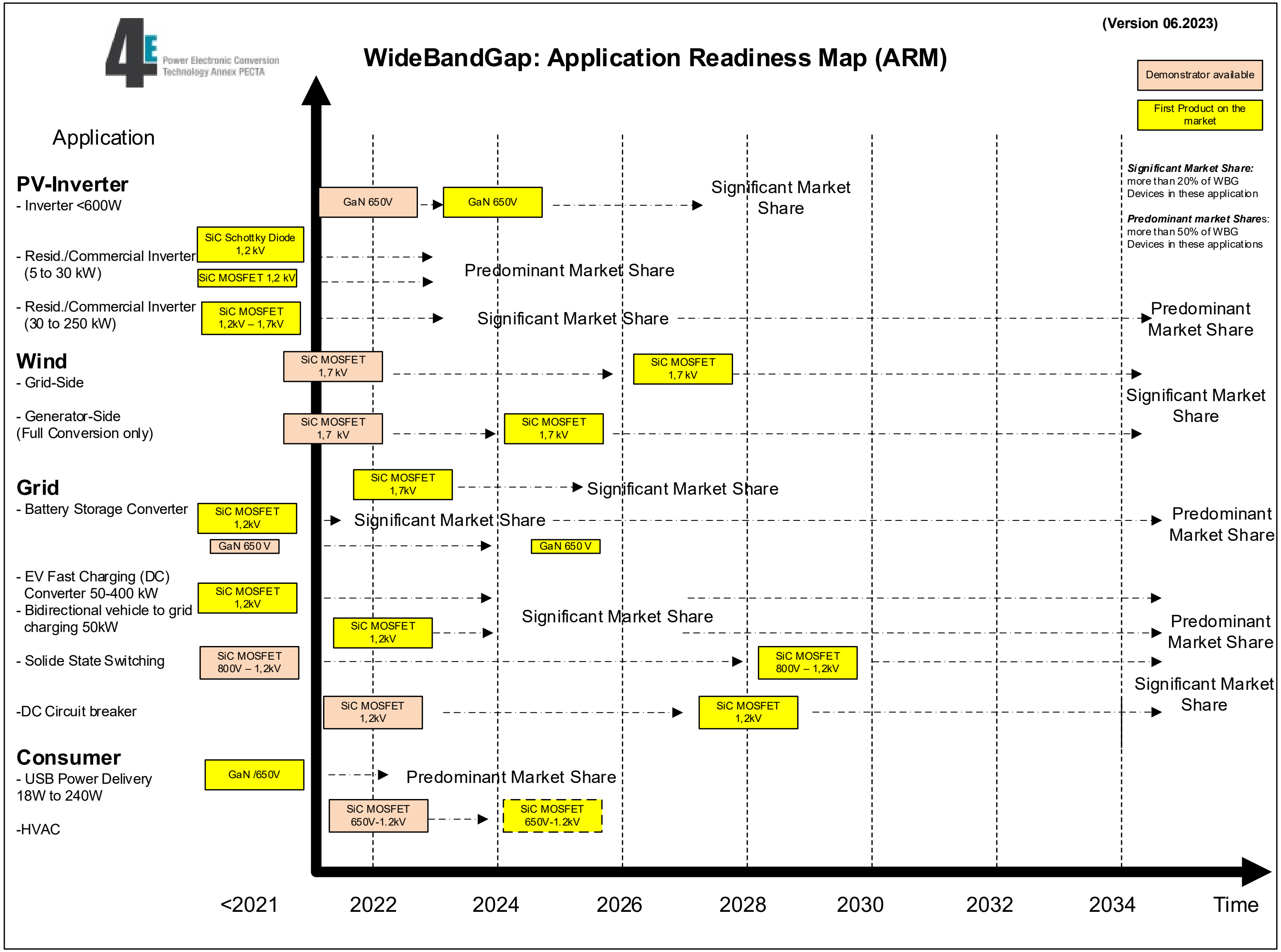
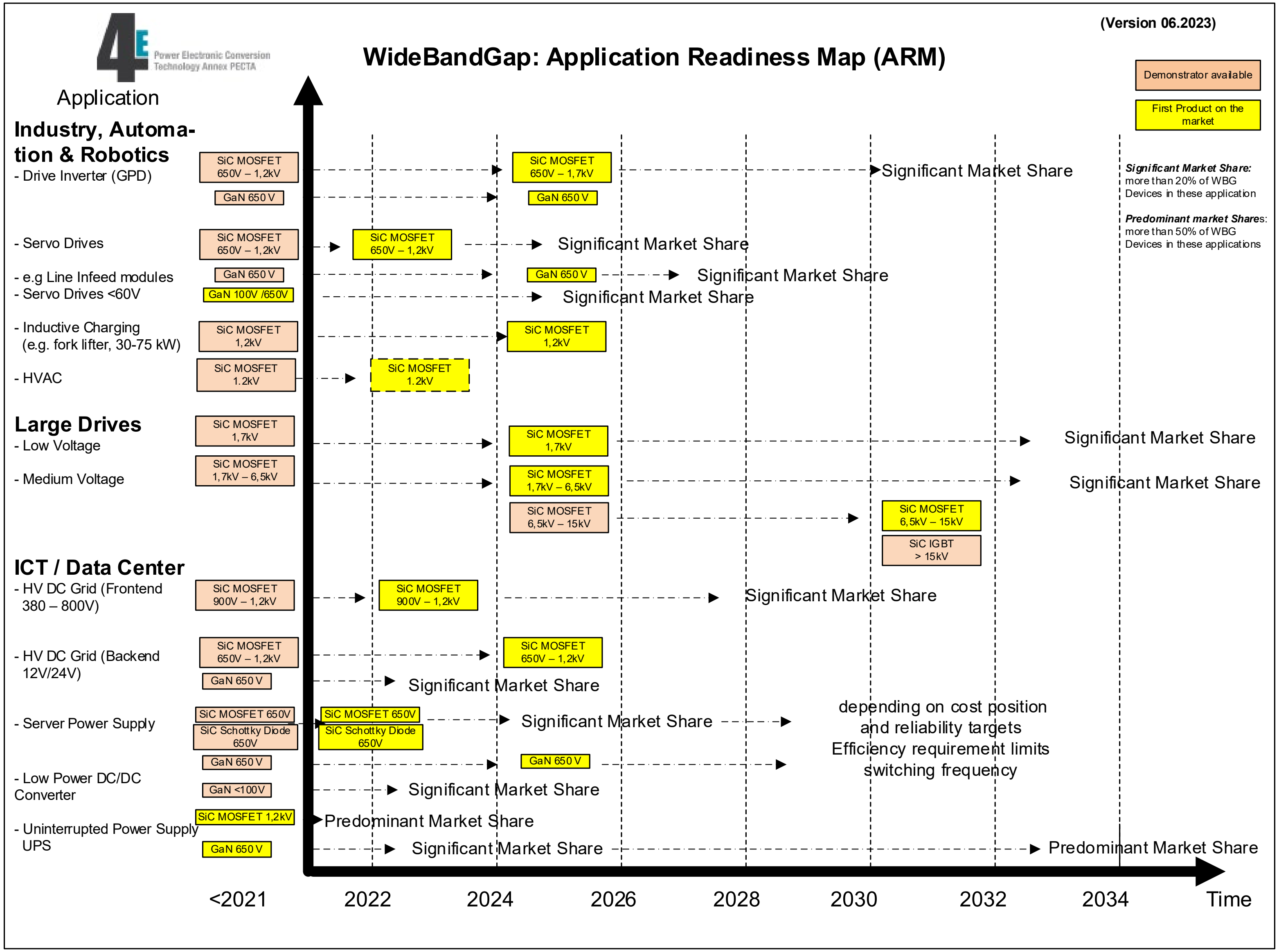


Figure 6: Applications Readiness Map (ARM) for industry, automation & robotics, large drives, and ICT/data center



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