IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment

Power Electronic Conversion Technology Annex PECTA

PECTA, Power Electronic Conversion Technology Annex

Wide Bandgap Gap Technologies: Efficiency, Potential and Application Readiness Map

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PECTA, PECTA Publication

Power Electronic Conversion Technology Annex PECTA

Wide band Gap Technology:

Efficiency Potential and Application Readiness Map

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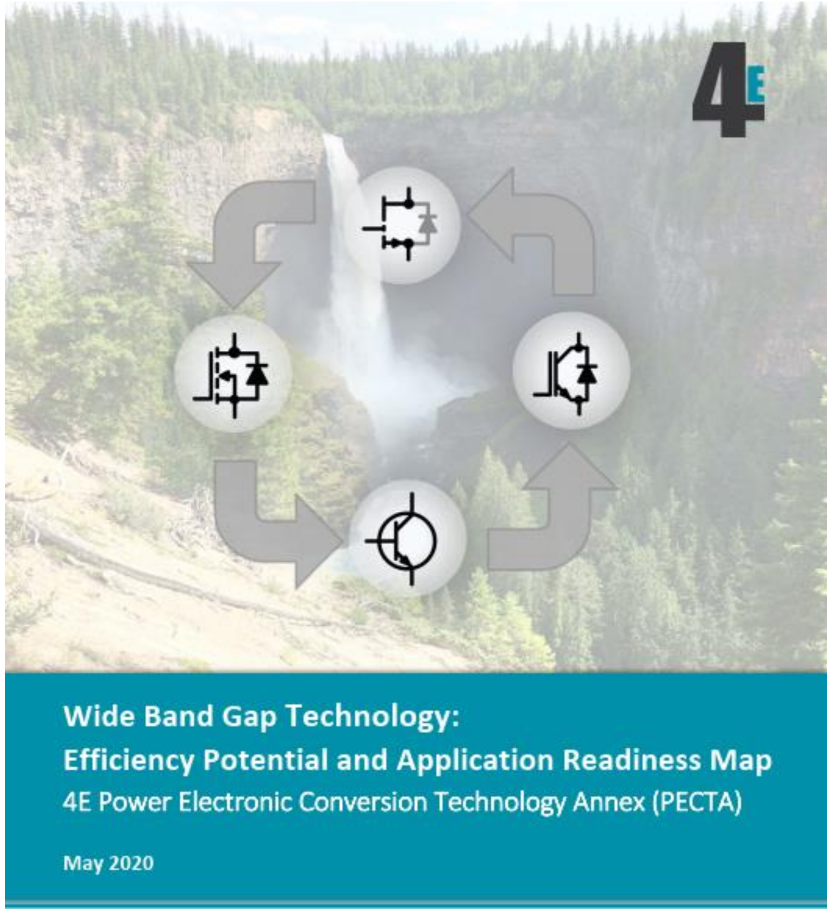


https://www.iea-4e.org/wp-content/uploads/publications/2020/05/PECTA_Report_Total-V10final-May-2020.pdf

Content

1. Applications
2. Advantages of WBG in applications
3. Potential Energy Savings
4. Existing WBG Roadmaps
5. Application Readiness Maps
6. WBG Challenges

WBG Applications

• Road Transport	Dominant Market
• Railway Transport	
• Lightning	
• Heating Cooling	
• Energy Storage	
• Wind Energy Generation	Energy efficiency
• PV Energy Generation	Energy efficiency
• Aviation	
• Ship Electric Drives	
• Energy Distribution	
• Power Supplies	
• Data centers	Energy efficiency

Advantages of WBG

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
Permitivity 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: $\varepsilon_r \cdot \mu_n \cdot E_{crit}^3$	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

- Strong atomic bonds, give high bandgap.
- High critical electrical field.
- High thermal conductivity
- High operating temperature
- High blocking voltage.

Advantages of WBG in different applications

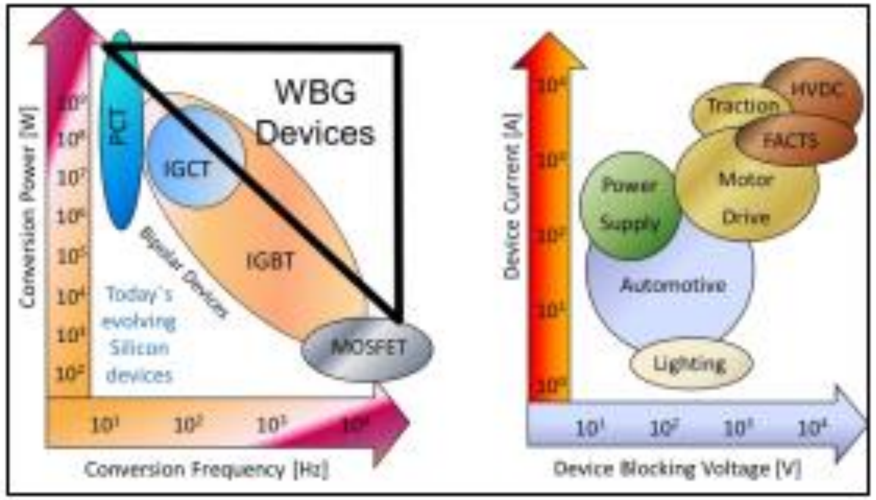


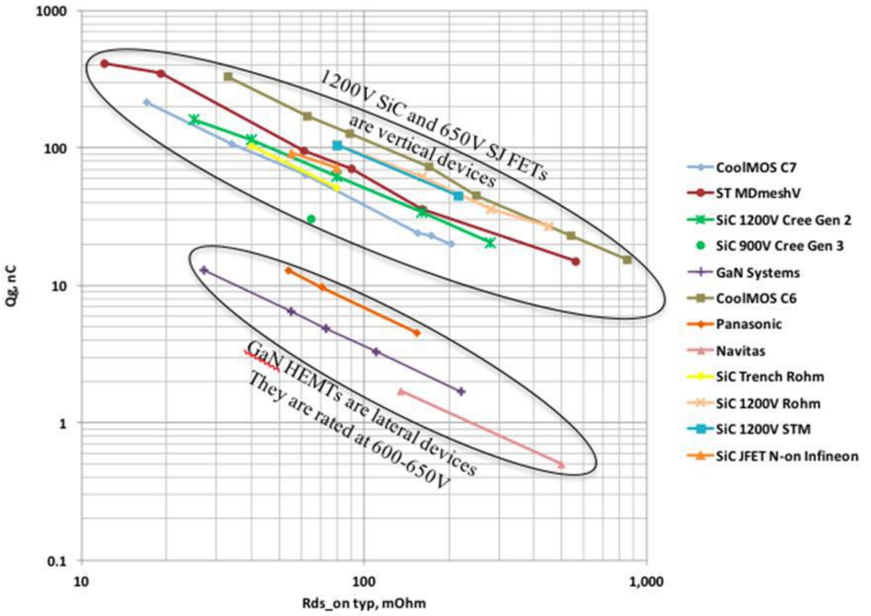
Figure 11: Power Devices and Applications: Conversion power and device classification (based on [18]).

Advantages of SiC MOSFET.

- Low conducting losses.
- Low switching losses.
- High operating temperature.
- Switch/Diode Integration.

- Higher power densities.
- High efficiency.
- Higher operating frequency.
- Compact design. Size and weight.
- More system integration.
- Harsh operating environments.

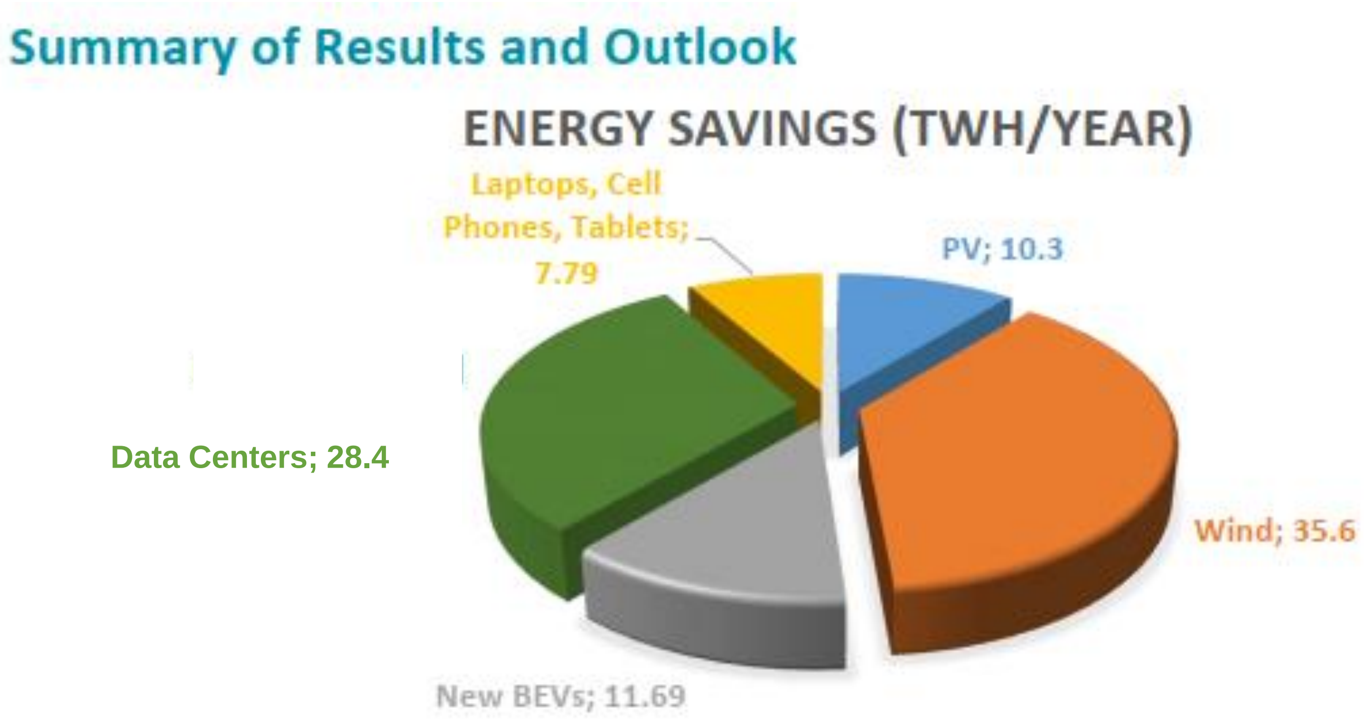
PECTA, Advantages of WBG in different applications



GaN HEMT characteristics.

- Low gate charge.
- Low threshold voltage.
- Low $R_{DS(on)}$.
- Switch/Diode Integration.
- High switching speed.
- Reduction of passives.
- Smaller die size..
- Integration with Si.

Energy Savings WBG



Estimation of energy saving with a complete replacement of Si power electronics to WBG powerelectronics

Energy Savings WBG - Automotive

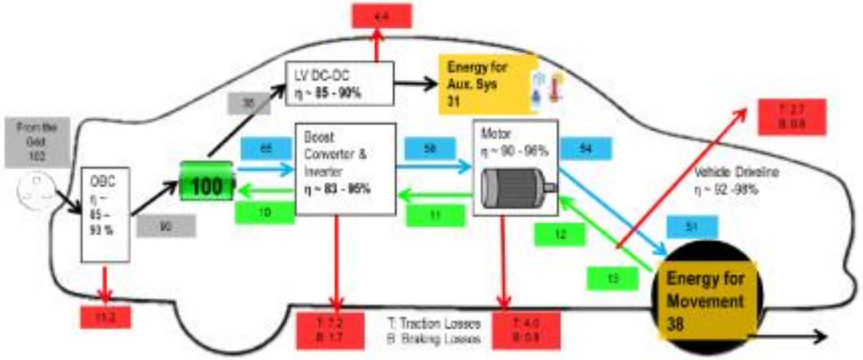


Fig. 3: Energy flow diagram of a Si-based BEV as illustrated and published in [2].

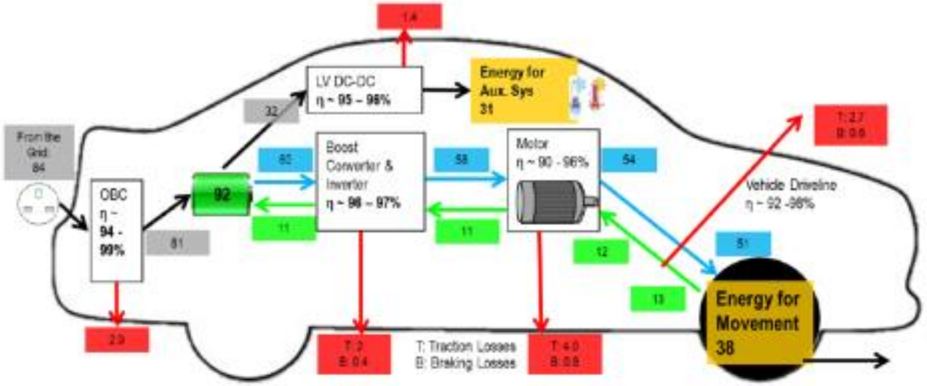


Fig. 4: Energy flow diagram of a WBG-based BEV as illustrated and published in [2].

Energy flow diagram comparing Si based and WBG based Batteri Electrical Vehicule.

Total Efficiency improvements: 17.7 %

Existing WBG Roadmaps

- **ECPE** European Center for Power Electronics,
  "WBG Roadmap Lead Applications for SiC and GaN"

- **PowerAmericas**
  "Strategic Roadmap for Next Generation Wide Bandgap Power Electronics"

- **ITRW** developed by IEEE Power Electronic Society.
  "International Technology Roadmap on Wide Bandgap Semiconductors"
  developed by IEEE Power Electronic Society.

- **CASA** China Advanced Semiconductor Industry Innovation Alliance
  "Technology Roadmap for Wide Band Gap Power Electronics 2018"

- **Yole Roadmap**
  "Technology Roadmap for Wide Band Gap Power Electronics 2018"

Roadmaps - ECPE

ECPE, European Center for Power Electronics, includes 93 industrial partners and 99 competence centers.

The roadmap is presented as expected market share for 28 different applications for

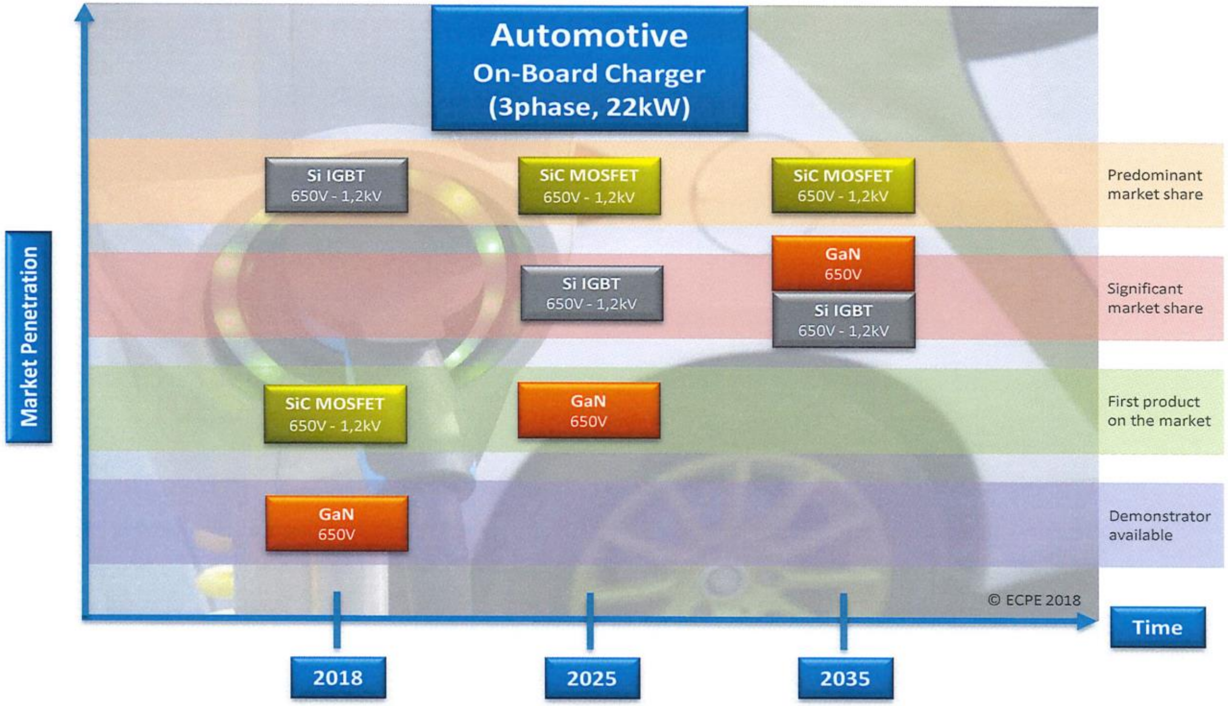
- Today (2019)
- Year 2025
- Year 2035

They identify dominant application as:

- Automotive

Followed by

- Railway
- PV Inverter
- Industry automation
- Large drives
- Grid
- ICT and Data centers



Roadmaps - Power America

This 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 for GaN.
Automotive is defined as the main driver followed by PV and ICT and Data centers.

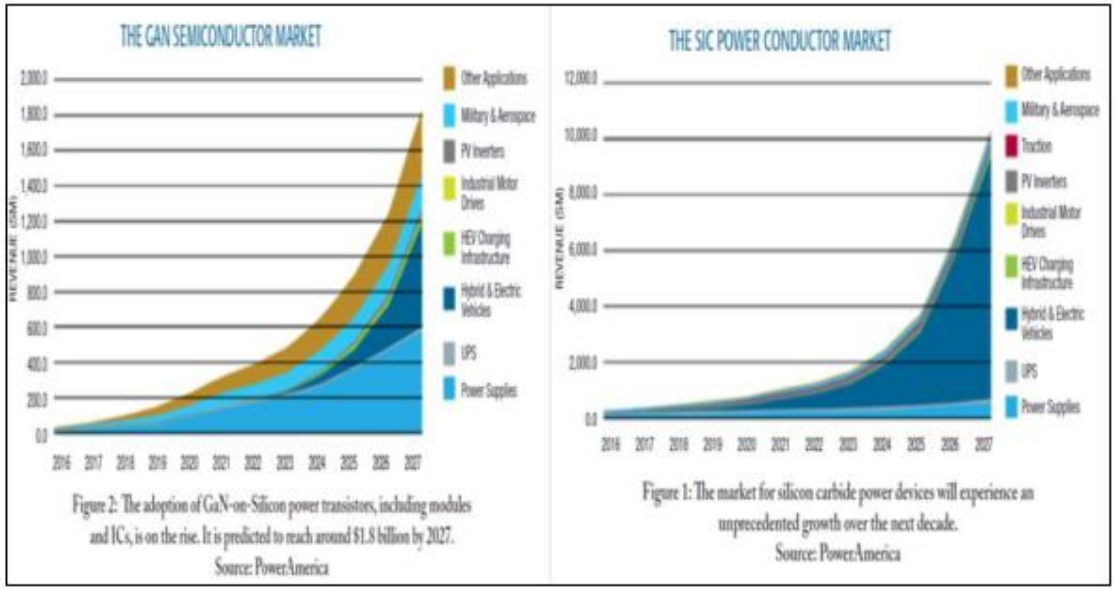


Figure 18: SiC and GaN Market development as published by ITRW (and used by Power America).

Roadmaps - ITRW

ITRW stands for "International Technology Roadmap on Wide Band Gap Technology" and is a part of the IEEE power electronic society.
The ITRW started 2015 and has an extensive and detailed roadmap published in 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 years).

Main application is expected to be automotive including both traction drives and charging for electrical vehicles.
Other applications are PV inverters, traction drives and power supplies.
ITRW are more optimistic of GaN power electronics for lower voltage power electronics and chargers.

Roadmaps - Yole

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 as the GaN power electronic markets for several years. They have always been overambitious but have in recent years well predicted the growth of SiC power applications.

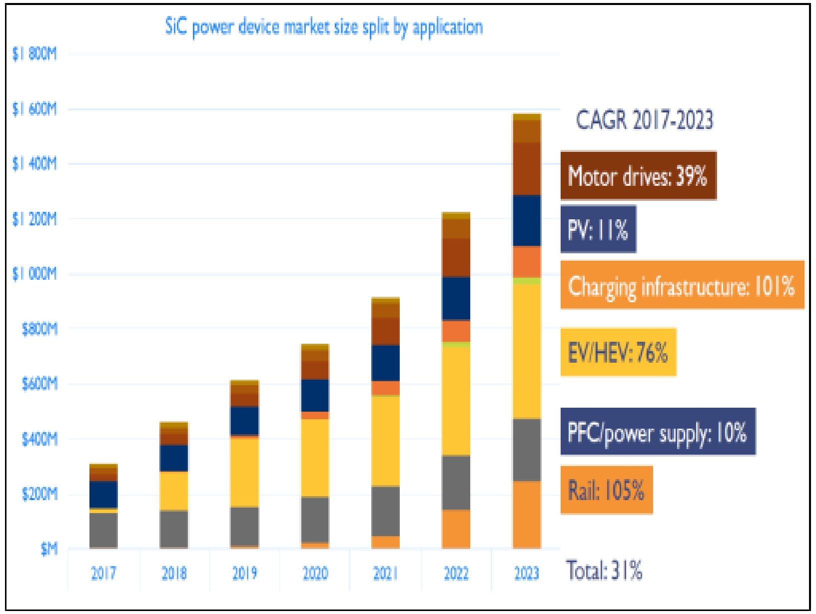


Figure 19: Estimated SiC power device market by application (Yole).

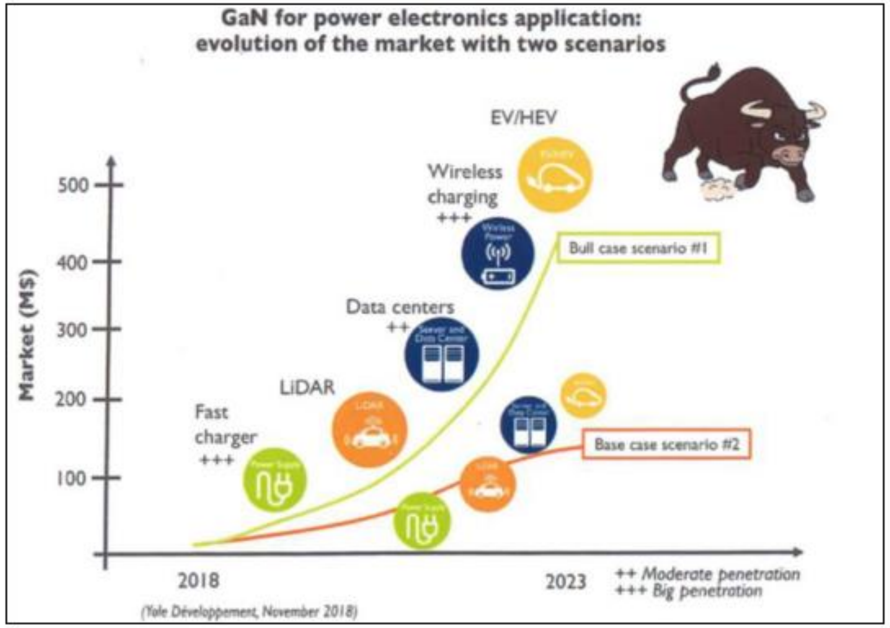


Figure 20: Estimated GaN power device market in two different scenarios according to Yole.

Roadmaps - Summary

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

The main driver, both regarding volume and price, is the automotive application for EV for personal use. The automotive application will increase volume and decrease price which will be beneficial for other applications.

For WBG technology and device the market forecast is (simplified).

- Low voltage applications (<650 V). GaN in cost competition with Si MOSFET.
- Medium voltage (650 V – 3.3 kV). SiC MOSFET in competition with Si-SiC hybrids (SiC diode and SI IGBT).
- High voltage (>1.7 kV) and high power, SiC MOSFET in competition with Si IGBT.
- High voltage (6.5 kV), Si IGBT will dominate but SiC IGBT on a longer timescale.

Application Readiness Maps ARM

Based on the different roadmaps PECTA has together with ECPE summarized the technology status in a so called Application Readiness Maps.

Todays Situation

- Main use of WBG power electronics is SiC MOSFET from 650 kV – 1.7 kV.
- Dominant application is electrical vehicles (EV) and hybrid EV (HEV).
- SiC used in both traction inverter, DC-DC converter and battery charging.
- Milestone was the use of SiC in Tesla Model 3, giving lower losses and longer driving range.

- For railway traction 3.3 kV SiC MOSFET are used in NJR Shinkasen N700S.
- Main advantage is reduced size and volume, and redesign of motor drives and cars.

- For PV applications SiC is used in medium (>600 W) and high (>30 kW) systems.

- Due to the increased demand, there are today a shortage of SiC devices and material.
- This has initiated large investment plans from many suppliers (Wolfspeed, STMicroelectronics, Infinion and Rohm).

Application Readiness Maps ARM

5-years Perspective

- For the coming 5 years all available roadmaps as well as industry investments expects a drastic increase in the demand for WBG power electronics.
- 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.
- The increased volume, processing capabilities and wafer diameter will reduce cost for specially SiC power-electronics.
- The reduced cost will make SiC power-electronic more cost effective in further application.
- The automotive electrification will further expand into heavy vehicles, such as trucks, buses and high-power specialized vehicles.
- The main device will be the SiC MOSFET from 650 V to 3.3 kV, while for higher power Si will still dominate.

Application Readiness Maps ARM

10 Years

- An estimation of WBG power electronics in different applications is difficult and dependent of several different factors.
- The speed of the electrification of the automotive and transport sector.
- Future political initiatives and legislations to reduce CO_2 emissions. The “Green Deal Initiative” by the European Commission.
- SiC power-electronics is however expected to be the dominant technology for all power conversions related to automotive applications.
- The same is the case for ICT and large Data Centers where SiC will dominate higher voltage applications.
- For Railway traction and auxiliary system SiC MOSFET will be the dominant device up to 6.5 kV.
- For wind power, larger drives and naval applications Si IGBT together with SiC MOSFET will dominate.

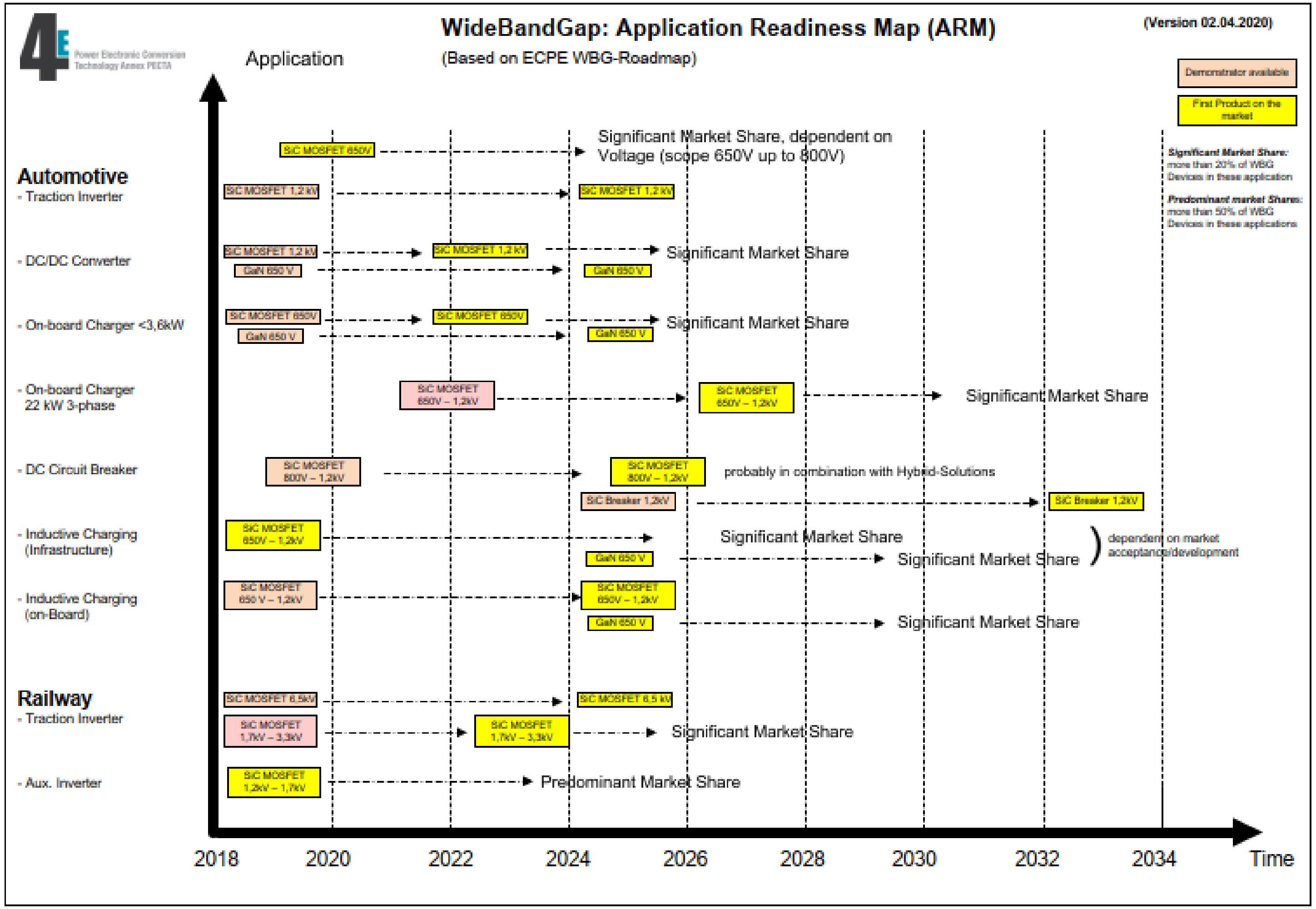
Application Readiness Maps ARM

GaN Power Electronics

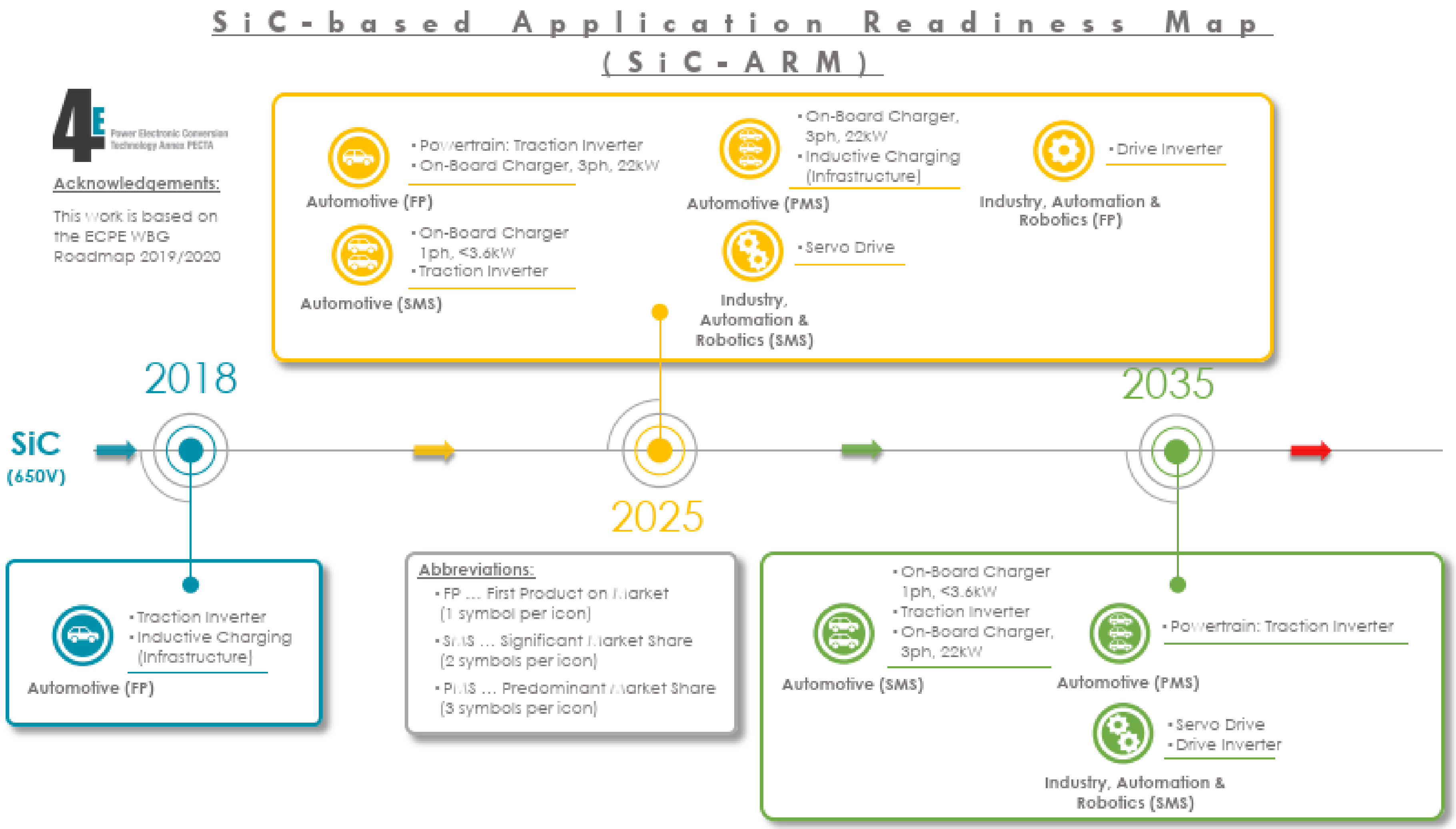
- GaN power electronics have today been demonstrated in different applications, usually at lower voltages up to 650 V and power, but at a smaller volume than SiC.
- Present GaN application is in automotive for DC/DC converters and onboard chargers, in photovoltaic applications as power optimizer.
- GaN 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.
- One exception could be the ITC and data center applications for lower voltages up to 650 V, and household suppliers and chargers, which is now dominated by Si solutions.
- GaN power-electronics have the possibility for higher switching frequency and lower losses, will give higher efficiency. This application is a large volume with many units.

Application Readiness Maps ARM

Based on the different roadmaps PECTA has together with ECPE summarized the technology status in a so called Application Readiness Maps.



ARM – SiC 650V



SiC-based Application Readiness Map
(SiC-ARM)
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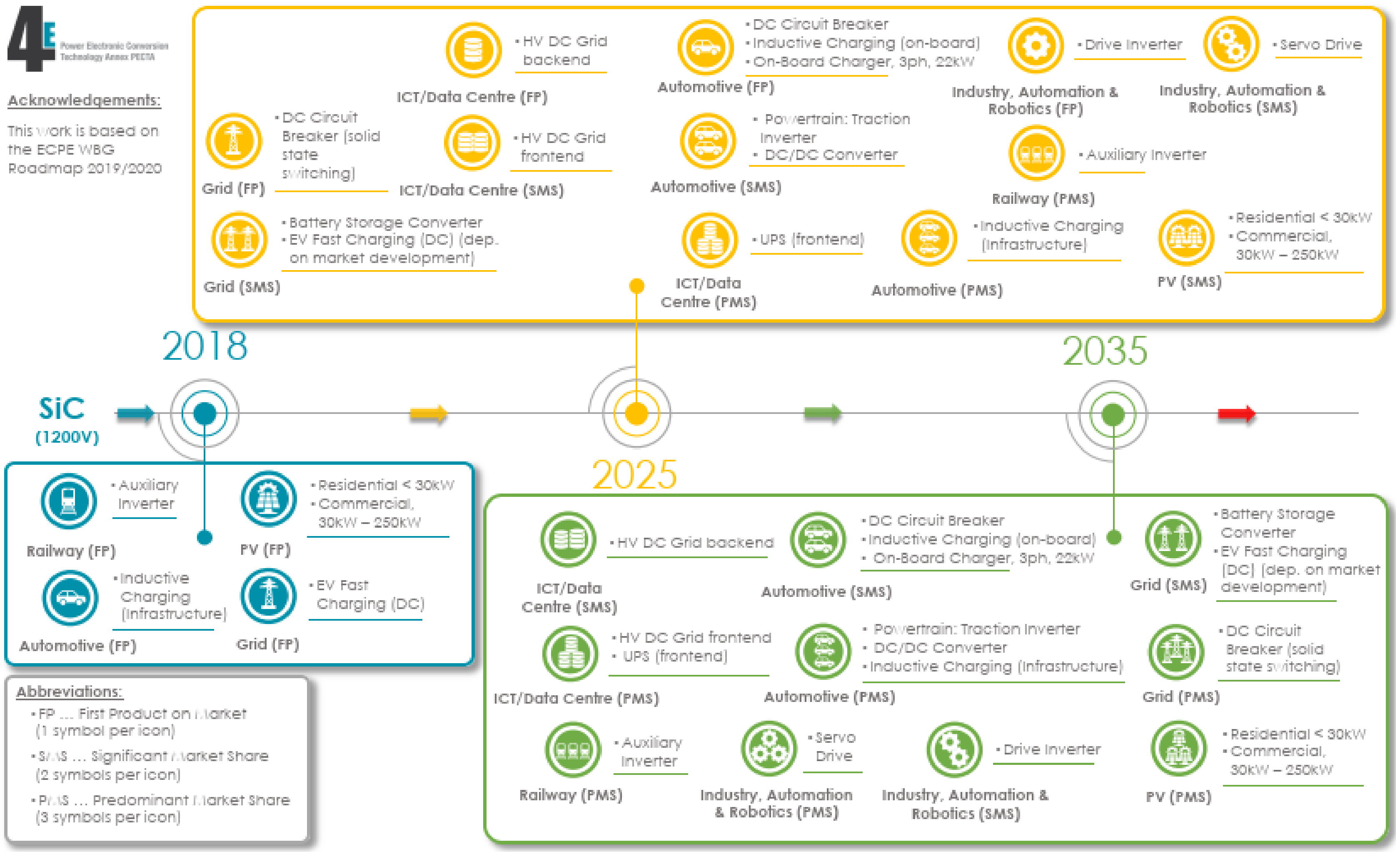
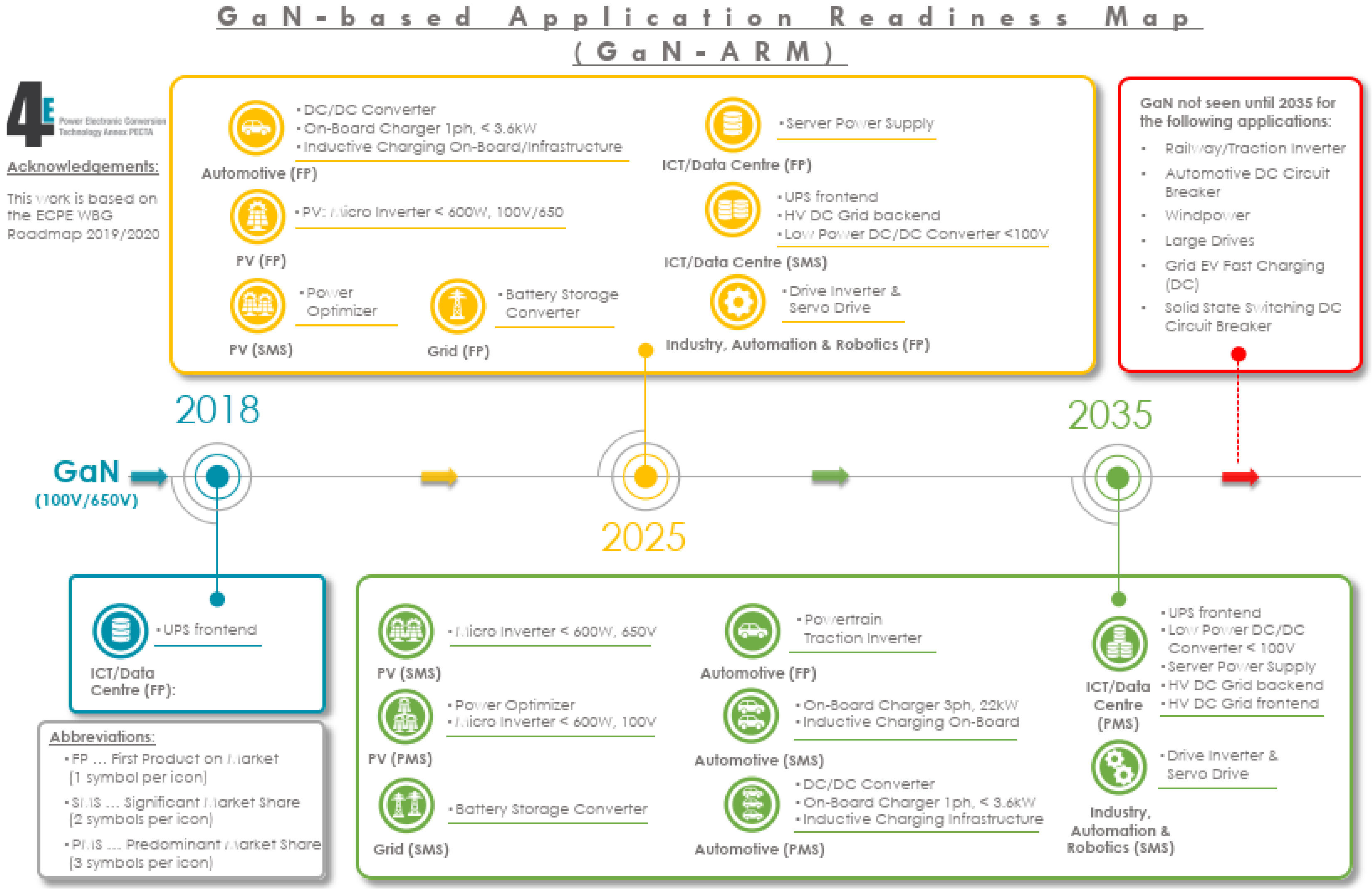
Acknowledgements:
This work is based on the ECPE WBG Roadmap 2019/2020
SiC
(650V)
2018
2025
2035
▪ Powertrain: Traction Inverter
▪ On-Board Charger, 3ph, 22kW
Automotive (FP)
▪ On-Board Charger 1ph, <3.6kW
▪ Traction Inverter
Automotive (SMS)
▪ On-Board Charger, 3ph, 22kW
▪ Inductive Charging (Infrastructure)
Automotive (PMS)
▪ Servo Drive
Industry, Automation & Robotics (SMS)
▪ Drive Inverter
Industry, Automation & Robotics (FP)
▪ Traction Inverter
▪ Inductive Charging (Infrastructure)
Automotive (FP)
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)
▪ On-Board Charger 1ph, <3.6kW
▪ Traction Inverter
▪ On-Board Charger, 3ph, 22kW
Automotive (SMS)
▪ Powertrain: Traction Inverter
Automotive (PMS)
▪ Servo Drive
▪ Drive Inverter
Industry, Automation & Robotics (SMS)

ARM – SiC 1200 V

SiC-based Application Readiness Map (SiC-ARM)



ARM – GaN 100/650 V



WBG - Technology Challenges

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• **Temperature increase.**	Increased conduction losses Problem with interface and insulation
• **Reliability**	Long time failure machanisms
• **High Switching Speed**	High impedance EMI challanges
• **New package solutions**	Higher current, temperature and frequency Improved passives, magnetic and dielectric components Low CTE
• **Cost**	Compared to Si
• **Shortage of materials**	Substrates, manufacturing, processing and testing
• **Standardization**	wafer and material Devices, modules and packaging Power and efficiency measurements LCA

Thanks for your Attention