

green
power
electronics



innovation via new materials



Green PE Transnational Technology and Product Roadmap


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1 Introduction

This output document formulates a roadmap for wide bandgap (WBG) electronics in the perspective of the increasing demand for electric energy and climate change. New WBG semiconductor materials facilitate revolutionary changes in the power electronics (PE) and enable a drastic increase of electric energy conversion efficiency and an increase in the power density of electric systems. The implementation of new efficient PE should speed up the electrification and efficient use of electric energy in many application areas with large energy savings as a result.

This roadmap provides general background information to the localised roadmaps of the development towards the implementation of green energy in the Baltic Sea Region presented in a separate document (Regional Mapping of the sectorial specialization for different countries/regions).

This roadmap aims to increase knowledge among industry (firms, component producers, system providers, consulting and financing, business incubators, business development agencies), research institutes (R&D institutions, technology parks, technology platforms), governmental organizations (policy maker, regulatory bodies, public procurement), and society about chances and barriers for the market uptake of Advanced Power Electronics.

The roadmap is meant to raise awareness among industry, especially small and medium sized enterprises (SME), research institutes, governmental bodies, and society in the Baltic Sea Region and beyond about the importance, market attractiveness and benefits of Advanced Power Electronics.

2 Energy perspective

The importance of power electronics and of the new WBG materials has to be seen in the perspective of the energy demand and climate change. One of the greatest challenges for mankind is the accelerating global demand for electric energy. Improved efficiency in production, distribution and consumption of electricity is a key factor on the road to a sustainable energy future. Efficient power electronics and WBG technologies play an important role.

2.1 Global challenges

The individual energy consumption in Europe has been growing almost exponentially in the history of mankind accelerating from the middle ages and throughout the industrial era and it continues to grow. A similar growth of energy consumption is now taking place in the developing part of the world. At present, 25 % of the world population is consuming 75 % of the energy. At the same time the world population is growing rapidly. The world population is predicted to reach 9 billion people in year 2050, which is a 5-fold increase since 1950. Most of this demographic explosion takes part in the developing countries. Consequently, a large increase in global energy demand is expected in the coming years.

There are two environmental challenges related to the production and consumption of energy. One is the limited supply of fossil energy resources (oil, gas and coal) and second is the climate warming due mainly to the CO₂ emissions.

Moreover, the demand for electricity is growing steadily. The consumption of electrical energy worldwide is estimated to grow by 160 % by year 2050. Access to this basic commodity is very unevenly distributed in the world and the biggest increase will take place in the developing world. The electricity is generally thought of as an environmentally friendly and clean energy source. However, about 70% of the electrical energy generation in 2025 is predicted to rely still on fossil energy sources, and only about 20 % on renewable energy sources and 10 % on nuclear power.

The focus on energy efficiency comes from two sources - one is the necessity to preserve natural resources by transforming them into electrical energy in the most efficient way, and second is saving electrical energy by using it in the most effective way mainly by reducing losses in the electrical power systems.

2.2 New paradigm

Power electronics is the key technology in controlling the flow of electrical energy from the source to load. The share of total electrical energy in industry, transportation, as well as home and office appliances, which is controlled by power electronics e.g. in variable speed drives (ac motors) was estimated to increase from 40 % to 80 % since 2000.

Energy saving, improved energy efficiency and environmental protection have become top priority political issues in Europe. The demand for electricity is expected to grow much faster compared to other energy sources until 2050. The consumption of electrical energy is predicted to grow from 40% to over 60% of all energy consumption. It becomes urgent to reduce consumption by increasing efficiency and to improve generation by increased use of renewable energy sources. Power electronics assume a key role in this perspective.

Efficiency of power electronic systems depends on losses in active and passive components. The efficiency can be greatly improved by replacing the silicon devices by silicon carbide (SiC) or gallium nitride (GaN) ones. The specific material properties of SiC translate into high value added for electronic power systems. Specifically, high electric field breakdown in combination with reasonably high electron mobility and high thermal conductivity translate into improved efficiency, dynamic performance and reliability of electronic and electric systems. It is relatively straight-forward to envisage savings on cooling requirements connected with increased working temperature of the devices well above the 125 to 150 °C typical of silicon power devices as well as reduced noise, size and weight of systems due to greatly increased switching frequency. To overcome both limitations has long been desirable especially in high voltage applications above 1 kV where bipolar silicon devices must be used. Such devices are necessarily slow and suffer from high switching losses due to substantial recovery charge which makes them the limiting component in the performance of many systems.

The appearance of wide bandgap (WBG) power devices on the market will bring about and accelerate new developments in the areas of packaging, passive components (capacitors), circuit and system design as well as improvements in construction and operation of electric motors. It will not be in general most effective just to substitute Si devices by WBG ones in existing circuits. It will be necessary to adopt new solutions in order to utilize the full potential of increased operational frequency, working temperature and reduced size of active devices. The advent of WBG power devices will reinforce thinking in terms of the total power system including electrical, mechanical and electromechanical components. It will provide an incentive towards an increased integration of electronics with electromagnetic and mechanical parts of the system. The electrical motors will have to be improved as well in order to facilitate the integration and utilisation of the benefits of high frequency operation.

The most dynamic R&D areas in the near future are advanced device concepts and high temperature WBG power semiconductor materials such as SiC, GaN, and diamond, compact high power density system design for Si and WBG semiconductors, new interconnection technologies for ultra-high power density systems and high temperature electronics, advanced materials for isolation, high thermal conductivity, high temperature compact passives and sensors, in lighting smart and simple dimming concepts, high efficiency light sources (LED/OLED) and their power electronic drivers, load management by power electronics in distributed energy generation networks, multi-domain/level modeling and simulation, stress analysis and built-in reliability, improved system reliability and fault-tolerant systems.

3 Efficient electric energy conversion

Power electronics is the enabling technology for efficient use, distribution and generation of electrical energy. Advanced power electronics could for example realize savings of more than 50 % in energy losses in converting from mains or battery voltages to that used in electronic equipment.

Power electronics is key technology for sustainable development. Sustainable development demands increasing use of electric energy. Increasing demand of electric energy demands electric energy saving and efficient use of electric energy. The generation, distribution and use of electric energy requires electric energy conversion which in turn requires power electronics. Those are the major drivers for power electronic systems and highly efficient electric energy conversion.

3.1 Applications of power electronics

Use of efficient power electronics is needed in many applications like a) electrification of transport (automobiles, busses, trains, airplanes, forklift trucks, ...), b) industrial electric motor drives (pumps, fans, compressors, conveyers, steel mills, ...), c) elevators and escalators, d) heat pumps and air conditioners, e) home appliances, f) high-frequency industrial applications (resonant converters), g) electric grid (HVDC, flexible AC transmission systems (FACTS)).

3.1.1 Saving potential by wide use of PE

The energy saving potential of widely used modern power electronics is related to highly efficient variable speed motor drives with energy recovery used in various applications, to smart power supplies enabling high efficiency over a wide load range and zero-power standby function as well as to energy efficient and low-emission mobility with hybrid and electric vehicles.

Power electronics is, furthermore, enabling a sustainable energy supply based on renewable energy sources such as wind and solar. Power electronics facilitates efficient transfer of the energy from these intermittent sources to the electricity grid. It also enables the connection of various energy storing solutions that will help managing the stability of the power grid.

The estimated energy savings potential of wide introduction of power electronics into systems is more than 25 % of the current electricity consumption by 25 EU member states.

Some examples of savings potential and key role of power electronics are:

- (a) Electric motor drives including industrial motor drives, elevators and escalators, heat pumps and air conditioning, home appliances and traction drives are estimated to account for 50% of total electricity consumption in Europe.

The energy savings potential by introducing Variable Speed Drives (VSDs) is estimated to be 30 – 40 % for most applications. The technical potential for energy savings is relevant for about 40 – 50 % of all motors depending on the application, and given that VSDs have already been applied to about 15 – 20 % of all motors the remaining potential is estimated to be about 30 %. There is an additional energy saving of 20 % through the recuperation of electrical machines during braking, which is frequently used in elevators and traction application of trains and heavy vehicles with power electronic converters. Combining all these figures, the total electrical energy-savings potential of VSDs is about 5 – 6 % of the current electrical energy consumption.

- (b) Mobility and transportation is responsible for 30 % of energy consumption and is the fastest growing sector of European economy.

Power electronics is an enabling technology for the development of drive trains and battery-charging for the hybrid and electrical vehicles. Hybrid and electric buses using electric vehicle propulsion technology are increasingly becoming part of transportation systems. They offer considerable fuel savings and reduce emissions. Power electronics is a necessary part of the drive train of these buses.

Furthermore, the increasing electrification of previously mechanical and hydraulic vehicle functions and introduction of such x-by-wire applications like electric power steering or electric braking, require the use of power electronics.

Aviation is responsible for ~12 % of the transport energy consumption and is the fastest-growing energy consumer in the EU, with an increase of 73 % between 1990 and 2006. Air transport demand is predicted to double in the next 10 - 15 years and triple in 20 years. Power electronics is also an enabling technology for the more electric aircraft, where various bleed air and hydraulic power functions are replaced with electrical equivalents. Which enables a significant improvement in efficiency, system flexibility, aircraft reliability and specific fuel consumption.

- (c) Smart grid and renewables are on the priority actions list by the European Commission in its Action Plan for Energy Efficiency. One of the priority actions is to make power generation and distribution more efficient. Transmission and distribution (T&D) losses of electrical energy are typically between 6 % and 8 %. A European Task Force T&D Working Group has identified a number of energy-efficient technologies for grids, including power electronics technologies such as HVDC, FACTS, power electronic transformers, distributed generation and micro grids. Power electronics is necessary to interface distributed generators such as wind turbines and solar cells to the grid.

Power electronics has been identified as a key technology in all four pillars of Smart Grids:

- (1) **Integration of renewables:** wind turbine converters, HVDC for offshore wind park connection, SVC/STATCOM for grid code compliance, energy storage for improving stability and decreasing power fluctuations, solar inverters,
- (2) **Integration of electric vehicles:** (fast) charging of electric vehicles, traction drive for hybrid electric vehicles, dynamic energy storage to absorb peaks due to simultaneous charging of electric vehicles,
- (3) **Reliability and efficiency:** efficient long distance transmission with HVDC, variable speed drives in industrial plants and pumped hydro stations, energy storage for emergency and peak power, power quality solutions for industry,
- (4) **Demand response:** converter interface to distributed generation with built-in load management capability drives in pumped hydro station with remote control from control center.

- (d) Data centers and base stations.

Electrical energy demanded by data centers and servers in Western Europe was 56 TWh in 2007 and is forecast to increase incrementally to 104 TWh in 2020. In a typical data center, less than half of this power is delivered to the compute load, which includes microprocessors, memory and disk drives. The rest of the power is lost in power conversion, distribution, and cooling. The use of advanced power electronics techniques, like new DC distribution networks, can lead to a 10 % reduction of the required energy. The integration of ICT technologies and power electronics and

improving energy management can save an additional 20 %. Further research on reliability, implementation and cost reduction can further improve these numbers.

Estimates indicate that the telecom industry consumes 1 % of the global electricity, and more than 90 % is consumed by network operators. Almost 30 % of electrical energy savings can be achieved in radio base stations (RBS) by employing efficient power electronics technologies such as efficient power amplifiers and techniques for low consumption in standby mode. In ICT applications power supplies require ultra-high power density along with high efficiency at the same time. With the new power devices and optimized passive components this target can be achieved.

The annual electricity consumption related to standby functionalities and off-mode losses in the EU was estimated to have been 47 TWh in 2005. It has been estimated that the total annual energy savings potential for standby consumption in the EU is 35TWh, and power semiconductor manufacturers claim that more than 90 % standby consumption reduction is feasible.

- (e) Lighting in commercial, industrial and residential building, and street lighting
The savings are related to new technologies based on solid-state lighting (light emitting diodes, LED) requiring electronic power conversion. By operating LEDs with pure digital controlled power converters, the lifetime is significantly longer along with an additional energy saving potential.
- (f) Intelligent buildings by control of lighting and energy consumption and occupancy sensing.

3.1.2 Efficient energy conversion with WBG electronics – boosted saving potential

WBG materials (primarily SiC and GaN) enable a revolutionary development in the field of electrical energy conversion. Electronic devices based on these materials enable dramatically lower losses, higher frequencies and compact highly efficient electrical power systems. The losses can be reduced by at least 50 % in most of the PE applications using WBG technologies.

The total savings potential by introduction of WBG based PE in all the applications is thus estimated to be for

- (a) Electric motor drives more than 20 % of the current electrical energy consumption assuming that WBG based VSDs are used in 50% of applications with additional energy savings of 50%. Other assumptions as in section 3.1.1 including the 20 % recovery of the energy at breaking.
- (b) E-mobility and transportation the total potential depends on the degree and pace of the electrification. Introduction of WBG electronics should accelerate electrification process enabling 4-6 % increase of efficiency of converters resulting in the increased range on the same battery charge and in the reduced fuel consumption and thus reduced CO₂ emissions from hybrid vehicles due to the compactness and thus reduced weight of the electric systems.
- (c) Smart grid and renewables more than 2-4 % of the total transmitted and distributed electrical energy. Environmental gains are dominant however 50 % savings from the level of the state of the art inverters is feasible.
- (d) Data centers and base stations about 50 % reduction of losses from the levels of the state of the art power electronics seems to be a good estimate.
- (e) Lighting and (f) Intelligent buildings saving potential should be significant also in these applications.

3.1.3 The concept of “Green Electronics”

Green Electronics is an interdisciplinary electronic technology for efficient use of electric energy based on PE, microelectronics, ICT (Information and Communication Technologies) and electronic materials. The concept fits the paradigm shift to the more electricity dependent and electric energy-oriented society.

Table 1 Paradigm shift. © Green Power Electronics 2017.

New Paradigm	Enabling technologies
• Energy efficiency • System perspective • System integration • System optimization • System cost • High power density • Heterogeneous integration	• Power electronics • ICT • WBG materials • Magnetic, dielectric & insulating materials • Interconnection materials • 3D & low inductive packaging • HT packaging & efficient cooling

3.2 Value proposition

Development of advanced power electronic products and systems for renewable energy sources, electrification of vehicles and transportation and smart grids means competitive advantages for national products on the global market and opportunity of industrial renewal and growth for the national economy.

3.3 Application opportunities versus maturity of the WBG technology

WBG electronics will make gradual intrusions into the PE market dominated today by Si devices. All different semiconductor materials and technologies will be utilized depending on the application, maturity and price.

The next five years are decisive and very promising for SiC and GaN devices. System manufacturers are developing new prototypes with these devices and in the next several years the results will reach the market. By 2020 WBG materials will be implemented in specific areas in each application segment.

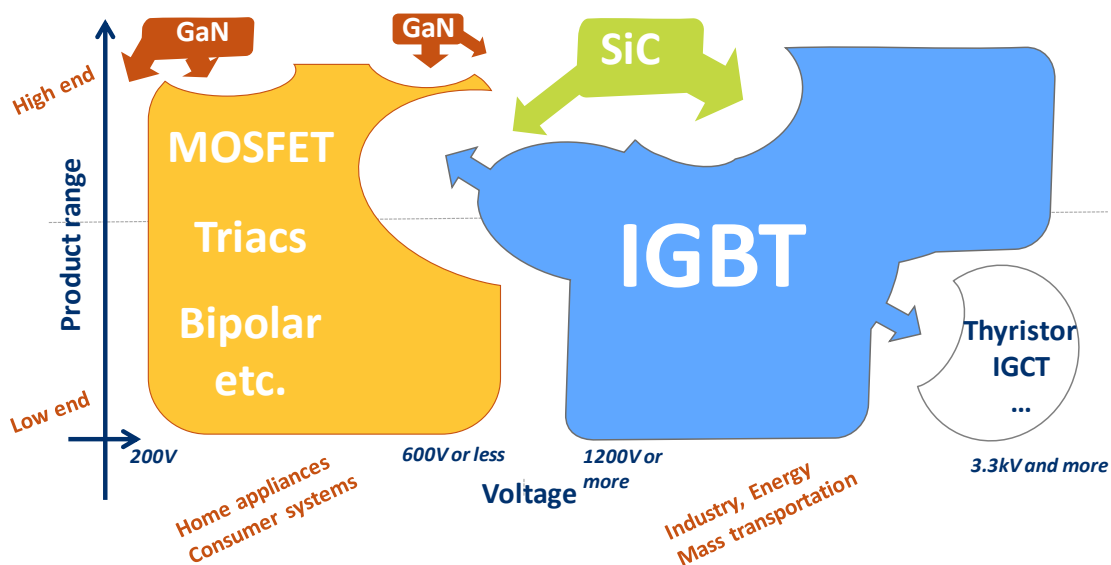


Figure 1 Power device positioning by voltage and low-to high-end applications. Based on information from [3].

3.4 PE market

The power electronics market is expected to remain steady after 2018.

According to [3], the power electronics market contracted in 2015, despite most indicators pointing towards continuing growth.

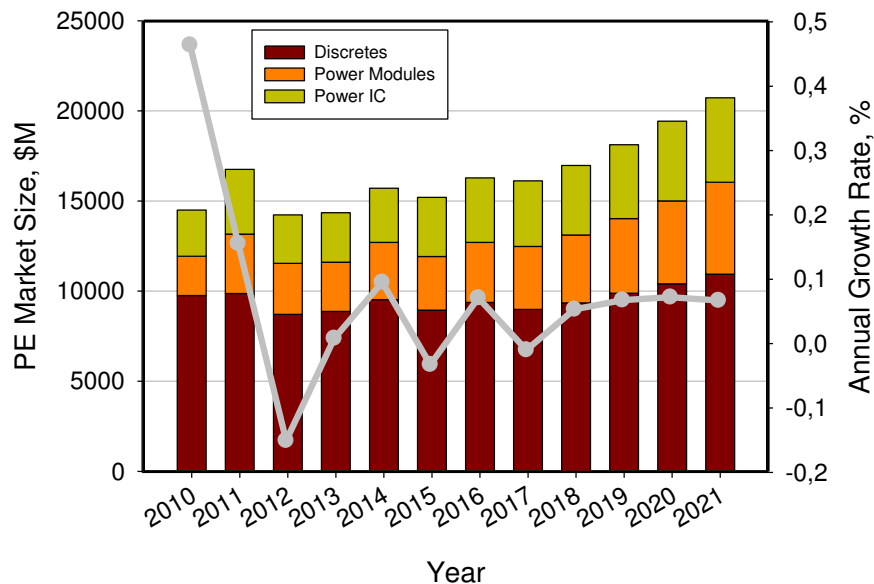


Figure 2 Power device market (2010-2021) for discrete devices, power modules, and power ICs. Based on information from [3].

Even though every device will see an increase with CAGR of +3.4 %, power modules & IPMs will have the biggest growth, reaching a CAGR of +9.4 %.

According to [3], modules will increase considerably, while discrete (IGBT & MOSFET) expansion will be slowed down.

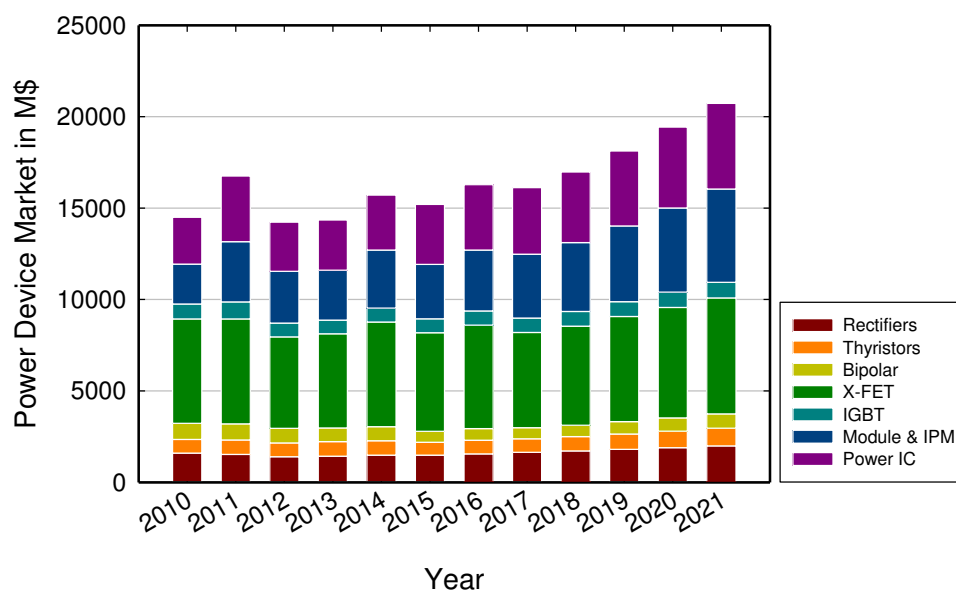


Figure 3 Market size for power devices from 2010 to 2021 in M\$ (Source: Yole Inverter Technology Trends and Market Expectations May 2016 data).

Transnational Roadmap

The global power electronics market is expected to steadily increase during 2015-2021. Particularly, the automotive industry is expanding with the evolution of electric vehicles (EVs) and hybrid electric vehicles (HEVs).

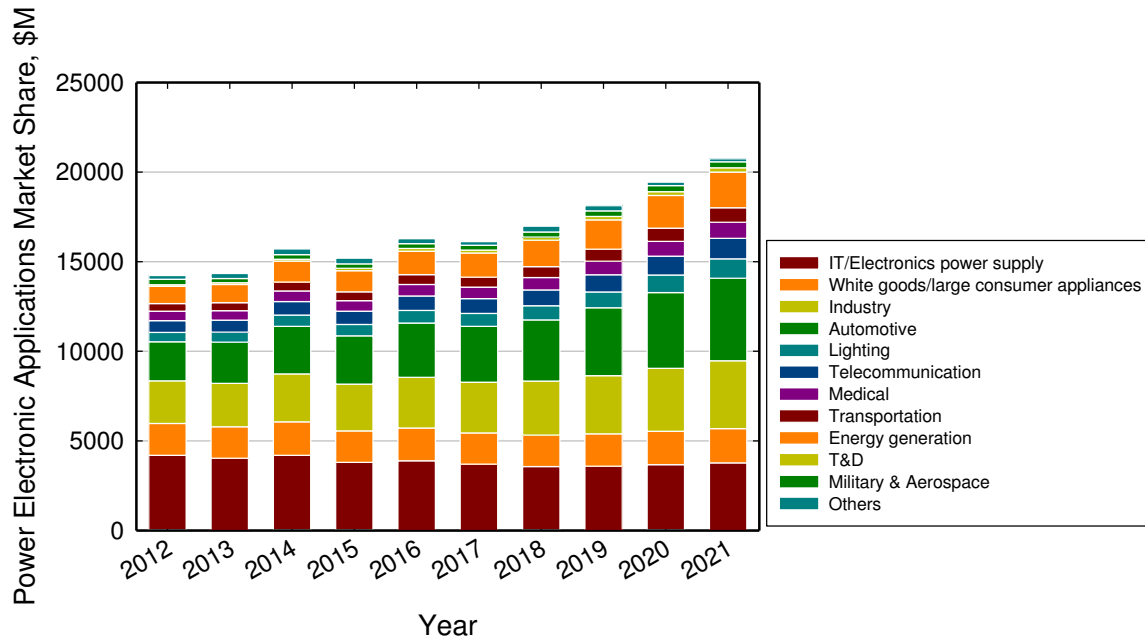


Figure 4 Market share distribution of power electronic applications (Source: Yole Inverter Technology Trends and Market Expectations May 2016 data).

In total power electronic market, the applications of automotive, industry, IT/electronics power supply have a big portion in a market share. The decreased market portion of IT/Electronics power supply is due to the increased market of automotive industry.

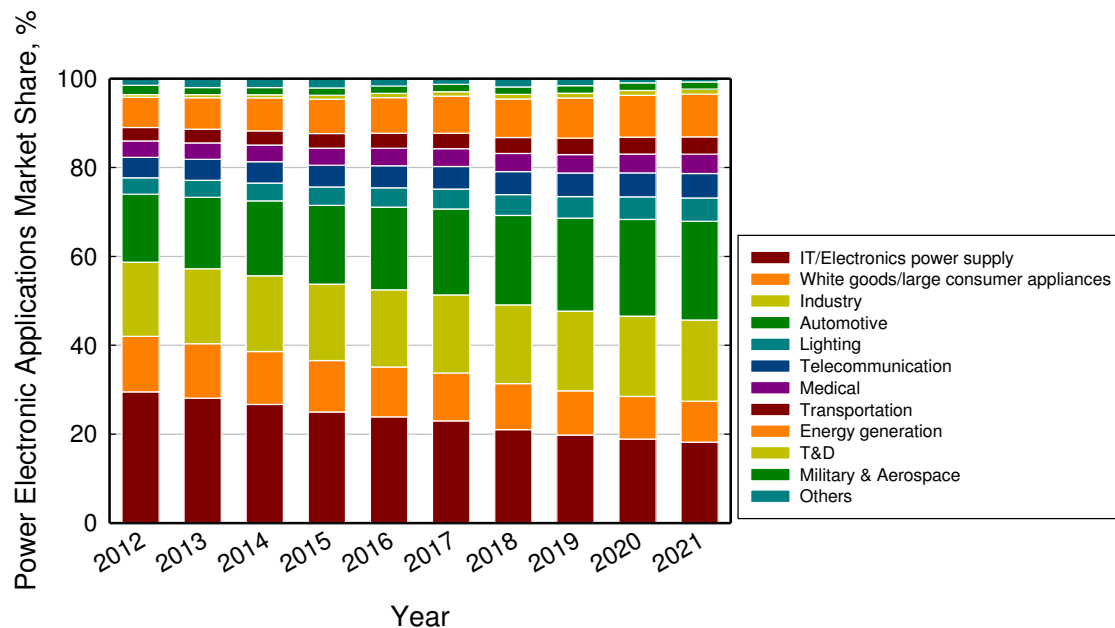


Figure 5 Market share portion of power electronic applications (Source: Yole Inverter Technology Trends and Market Expectations May 2016 data).

4 WBG electronics

4.1 SiC

The total SiC device market was estimated to be worth more than 200 M\$ in 2015 and a projection for 2021 is 600 M\$ with a mean growth rate (CAGR) of 20 %.

The growth is fueled by more players entering the market from material to device level, increased availability of SiC devices and increase in number of users of SiC devices.

The switch mode power supply (PFC) market is still leading SiC application with 100 M\$ worth in 2015.

The market of Photovoltaic (PV) applications is expected to reach more than 180 M\$ in 2021. The modification of micro-inverter topology caused the decrease in the use of SiC diodes, however the performance and price benefits of SiC on the system level for string PV inverters are now widely acknowledged motivating the use of both SiC diodes and SiC MOSFETs.

For EV and HEV applications the main market increase before 2021 is expected to be in on-board chargers. Regardless of the fact that many leading OEMs are testing SiC devices, no significant adoption of the SiC for power train inverter or DC/DC converter is expected before 2021 due to the high cost and relative lack of SiC MOSFET maturity. The pioneers like Toyota, Nissan and Honda will however continue to develop and test SiC based solutions.

The continued intense development and implementation of the SiC solutions is expected in the Traction applications during the coming 5 years in both auxiliary and propulsion systems at 1.7 kV and 3.3 kV. The mainly hybrid solutions (SiC diodes and Si IGBTs) by Hitachi, Mitsubishi Electric, Toshiba and Fuji will be followed by others. The present concerns about the reliability issues must be overcome before a widespread adaptation of SiC technologies can take place.

When it comes to SiC devices, the 85 % of the SiC device market worth 170 M\$ in 2016 is attributed to SiC diodes. The performance and the value added have been gradually improved and confirmed since the commercialization in 2001. Also, the price has been gradually reduced as more and more suppliers have entered the market since the 2009 reaching a number of 18 suppliers by May 2016. Considering the low integration effort, relative maturity of the diode technology and continued falling price the diode market is estimated to continue grow with a CAGR of 14 % and reach 400 M\$ in 2021.

The SiC MOSFET has become the switch concept that will dominate the market. Both DMOSFET and Trench MOSFET will be developed and available at the market during the coming years. The strong argument for the DMOSFET is a long-established process guaranteeing the reliability and for Trench MOSFET a better performance at the cost of more difficult process.

There are four main issues hindering the market growth of SiC MOSFETs. They are confirmation of long-term reliability, more independent sources of devices, device cost and integration issues (gate drivers). There are at present only four MOSFET suppliers, however more suppliers are expected to enter the market within nearest two years (Infineon, GE, Hestia-Power, Global Power Technologies, Panasonic, and Fairchild). The high device cost is mainly related to the high cost of SiC substrates and the lower yield compared to diodes.

Considering all the above the SiC switch market is estimated to be worth only 27 M\$ in 2015, representing less than 15 % of the total SiC device market. However, as more suppliers enter the market after 2018, the market is expected to reach about 200 M\$ by 2021, representing more than 30 % of the total SiC device market.

4.2 GaN

The GaN power business was only 6.8 M\$ in 2015.

A couple of developments during 2015 and 2016 constitute a positive change in market development. Since 2016 not only low voltage GaN (<200V) devices from Efficient Power Conversion (EPC), but also high voltage (600V/650V) components from several players including Transphorm, GaN Systems and Panasonic became available.

2016 has also seen introduction of the GaN power ICs by Navitas Semiconductor and Dialog Semiconductor. Other companies entering the GaN IC market are EPC, GaN Systems and OnSemiconductors.

Power supply applications for datacenters, telecom and AC fast chargers are expected to be the leading applications during the 2016 – 2021 period. The power supply market is expected to grow from 2 M\$ in 2015 to more than 170M\$ in 2021, representing more than 60% of the total market.

The market looks promising also for low voltage GaN. Demand for high efficiency amplifiers in base stations together or without Envelope Tracking (ET) technique becomes more critical with introduction of 5G. GaN multimode devices are also convenient for system manufacturers considering development of different wireless charging standards as Qi and AirFuel. Finally, with development of different robotic and automotive applications, specifically those requiring lidar, GaN devices will play an integral role in offering high switching frequency and high efficiency.

Considering the above, the total GaN power device market is expected to reach 280 M\$ in 2021, with a 2015-2021 CAGR of 86 %.

EPC is the leading manufacturer in the total device market, followed by IR (now part of Infineon), Transphorm, and GaNSystems.

5 WBG substrates

5.1 SiC substrates

The increase in substrate size has been dramatic over the last 15 years, motivated by the prospect for SiC technology to enter production phase. Today 100 mm wafers can be purchased, and 150 mm and 200 mm wafers have been demonstrated. The introduction of 150 mm (6 inch) substrates can be the turning point for SiC device production since much of the equipment used for processing Si can also be used for SiC.

Market introduction of the SiC technology requires in addition to the reasonable wafer size an adequate quality of the semiconductor material. All the SiC power devices require at least one epitaxial layer with controlled doping and thickness to be grown on top of the highly doped substrates. The major limiting factor for the quality of SiC epitaxial films is the substrate material itself. Even if the development of SiC substrates has been successful during the last fifteen years the quality is still much poorer compared to the Si substrates.

Best SiC epitaxial layers still contain a high density of detrimental defects like Threading Edge Dislocations (TEDs) ($2000 - 5000 \text{ cm}^{-2}$), Threading Screw Dislocations (TSDs) ($300 - 1000 \text{ cm}^{-2}$), Basal Plane Dislocations (BPDs) ($0.1 - 10 \text{ cm}^{-2}$), Stacking Faults (SFs) ($0.1 - 1 \text{ cm}^{-2}$) and micropipes ($0 - 0.02 \text{ cm}^{-2}$), the majority of which propagate from the bulk of the substrate into the epi-layers [Kimoto]. In addition, other defects that are generated during epitaxial growth include different growth pits ($10^2 - 10^4 \text{ cm}^{-2}$) most likely caused by substrate surface damage introduced during cutting and polishing. The maximum chip size is still about 50% of that for Si IGBTs. Production of large area power devices requires further significant improvement of substrate quality.

5.1.1 Status and trends

Table 2 Quality of SiC wafers and epilayers © Green Power Electronics 2017.

Extended defects	Density in substrates (cm^{-2})	Density in epilayers (cm^{-2})
Micropipe	< 1	0 – 0.02
BPD	300 - 500	0.1 - 10
TED	2000 - 5000	2000 - 5000
TSD	300 - 1000	300 - 1000
SF	< 1	0.1 - 1

BPD - Basal plane dislocations

TSD – Threading screw dislocations

TED – Threading edge dislocations

SF – Stacking faults

The state-of-the art of SiC substrates and epilayers is best described by the summary of the most common defects still present in the device material. The different types of defects are listed in Table 2 in the order from most detrimental to the device performance to the ones with minor influence on device performance and device yield and cost. Micropipes are so called “killer defects” ruining voltage blocking capability of devices, BPDs cause instability of the on-state voltage in the bipolar devices inclusive body diode of MOSFETs, remaining defects are a cause of softer performance degradation typically increased leakage currents. The concentrations of defects are still orders of magnitude larger compared to silicon.

Transnational Roadmap

5.1.2 Suppliers and market

According to [1], the U.S., Europe, and Asia have their own SiC wafer suppliers.



Figure 6 Regional SiC substrate suppliers. © Green Power Electronics 2017.

According to [1], all companies supply 4H n-type substrates for power electronics applications.

SiC Wafer Supplier Status

Supplier		Material polytypes, doping, and orientation				
		4H n-type	4H semi-insulating	6H n-type	6H semi-insulating	Epiwafers
CREE		√ (6"), demo(8")	√ (4")			√
Denso		√ (4")				
Dow Corning		√ (6")				√
Hebei Tongguang		√ (4")				
SiCrystal (affiliated to ROHM)		√ (6")		√ (3")		√ (ROHM)
II-VI		√ (6"), demo(8")		√ (6"), on or off-axis	√ (6"), on or off-axis	
Nippon Steel		√ (4")				√
Norstel		√ (4")	√ (4")			√
POSCO		demo (5")				
Nitride Crystals		√ (3")				
SKC (former Crysband)		√ (4")				
SICC		√ (4")	√ (4")			√
TankeBlue		√ (4"), demo(6")	√ (4")	√ (4")	√ (3")	

√ : Maximum wafer diameter fully commercially available, off-the-shelf, as of today

Figure 7 SiC wafer supplier status considering material polytypes, doping, and orientation.
© Green Power Electronics 2017.

According to [1], Cree still leads the SiC market with approximately 40 % market share in 2014 and 2015.

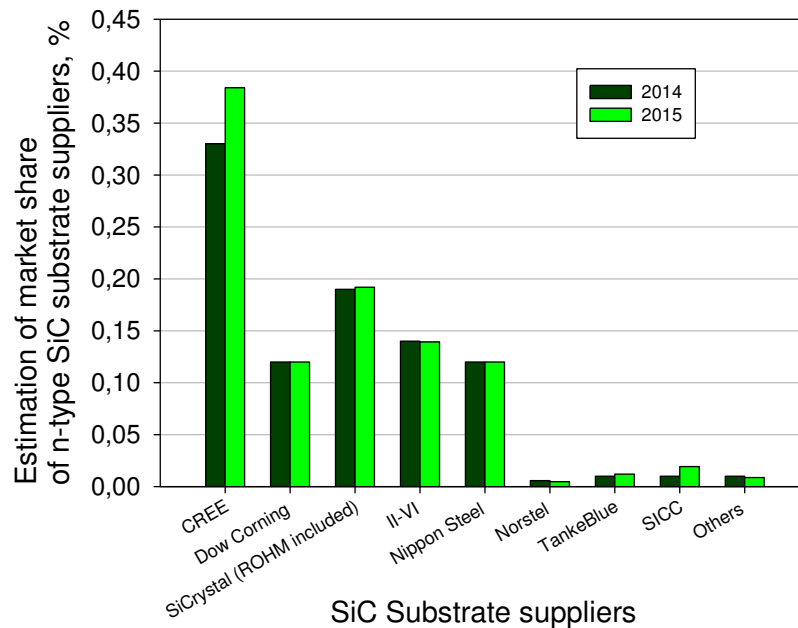


Figure 8 Market share estimate for n-type SiC substrate players. Based on information from [1].

According to [1], the volume increase was partially offset by a reduction in selling prices, but the market continues to grow.

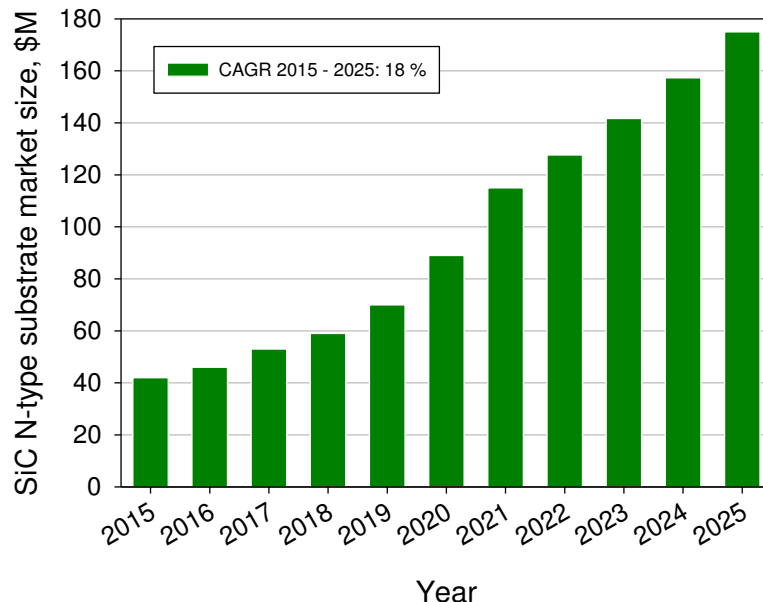


Figure 9 Market size projection for SiC n-type substrates 2015-2025, reaching a CAGR of 18 % Based on information from [1].

According to [1], the price of both 4" and 6" substrates continues to decrease. 4" to 6" transition has begun (about 20 % of wafers in the SiC power business is estimated to be 6"). The wafer is the major cost contributor and the cost pressure of a SiC power device is

transferred to the material suppliers. Some players with a strong position ask suppliers to align with their targets. In addition, some suppliers are willing to provide wafers at pricing 20-40 % lower in large quantities.

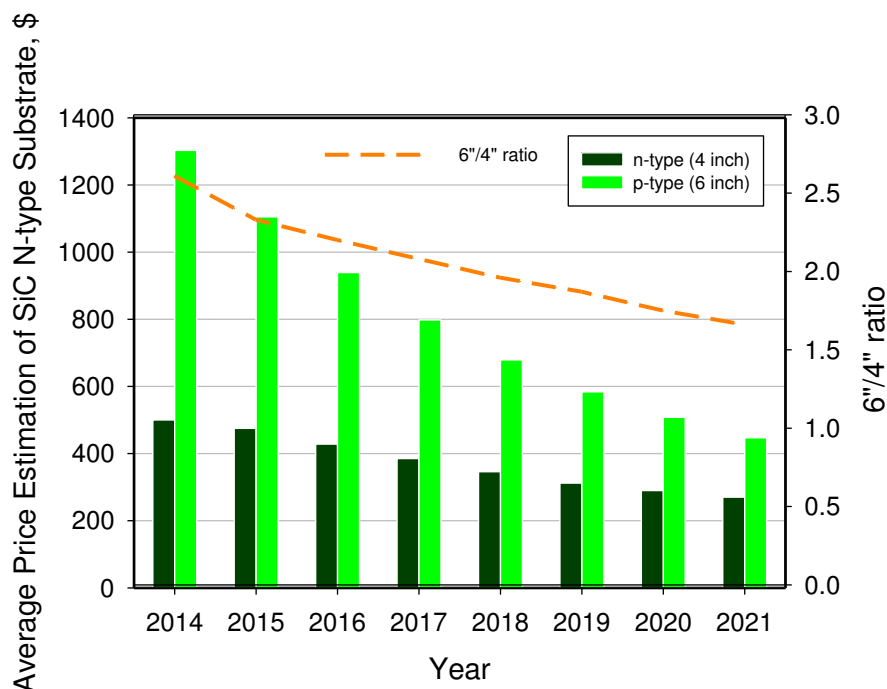


Figure 10 Average price estimation for SiC n-type substrate. Based on information from [1].

5.2 GaN substrates

GaN substrates for device manufacturing can be obtained by homoepitaxy on bulk GaN substrates or by heteroepitaxy mainly on SiC or Si bulk substrates. The cost and size of the bulk substrates determines the cost of the GaN substrates for device manufacturing. This is the main driving force behind GaN-on Si epitaxy development.

5.2.1 Status and trends

GaN substrates facilitating homoepitaxy and development and production of GaN-on-GaN devices are still small in size and contain orders of magnitude higher dislocation densities compared to the SiC substrates. Small size of the GaN substrates is a major factor when it comes to the manufacturing cost.

Alternative way of obtaining GaN substrates for device development and manufacturing is by GaN-on-Si epitaxy. Problems of the lattice and thermal expansion coefficient mismatch leading to the wafer bow and cracking has been solved to a large extent. Remaining issues are yield, large dislocation densities and process reproducibility and stability. Reliability issues are as yet not in focus. However large dislocation densities cause serious device problems influencing blocking capability and reliability and giving rise to excessive leakage currents and dynamic on-resistance instabilities related to the charge trapping at the defect sites and impurities.

5.2.2 Suppliers and market

According to [2], more and more players are entering the GaN-on-Si field. GaN-on-Si is the dominant solution, however an increasing interest in GaN-on-GaN technology at the R&D level amongst GaN HEMT players and wafer/epi suppliers is observed.



Figure 11 Regional players map for GaN-on-Si epitaxy. © Green Power Electronics 2017.

According to [2], the epi market is expected to reach around 39 K units, 6-inch equivalent in 2020. Several company types are likely to buy epi: a) Established silicon power players with a weak IP portfolio or lacking IP/know-how, b) Old CMOS foundries that could enter the GaN power business, c) Second-sourcing to help device makers with production peak, and d) R&D activities.

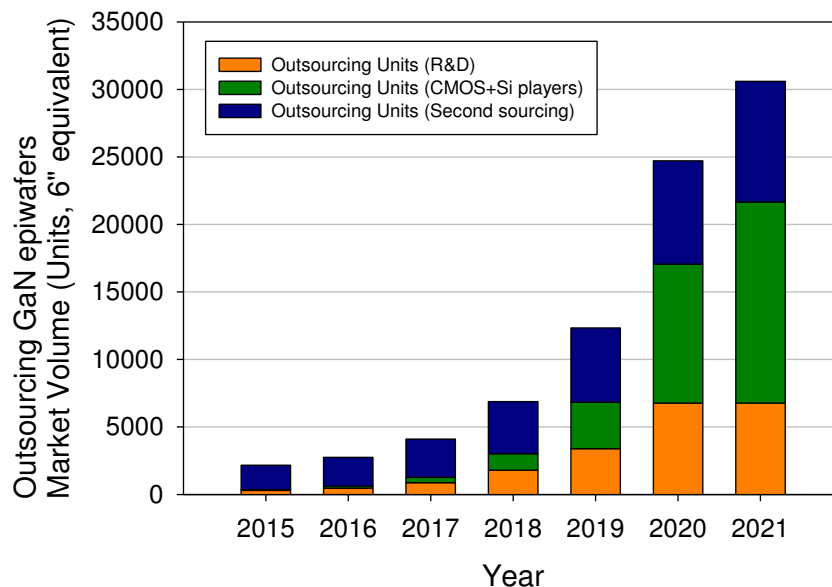


Figure 12 Outsourcing GaN epiwafers market volume (Unit, 6" equivalent) during 2016-2021. Based on information from [2].

According to [2], the outsourced epi-wafers market is expected to reach \$6.7M in 2021.

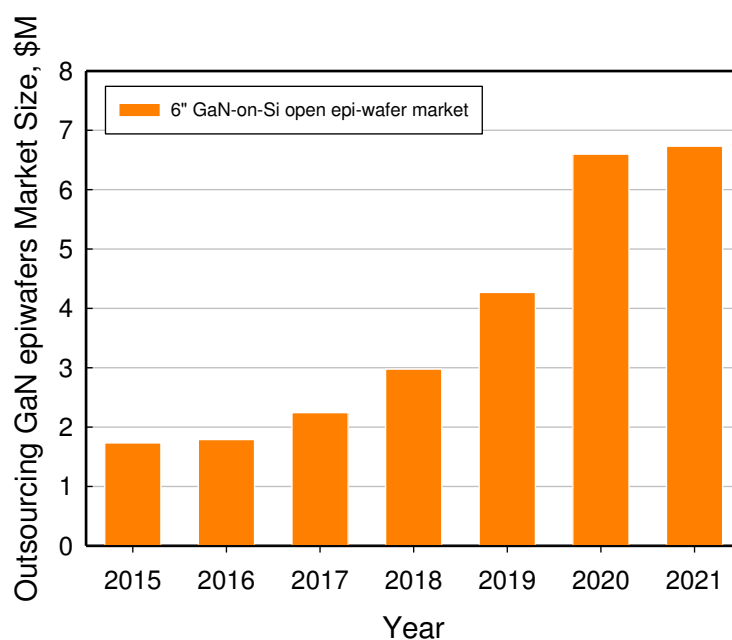


Figure 13 Market size of outsourcing GaN epi-wafers. Based on information from [2].

6 WBG devices

6.1 SiC discretes and power modules

6.1.1 Overall Status and trends

19 suppliers provide commercially-available diodes as of November 2016.

10 suppliers provide commercially-available MOSFET devices, including planar and trench types, as of November 2016. Higher voltage than 1700 V has been released by several companies, i.e. ROHM, Microsemi, and Wolfspeed.

For other transistors, only 3 suppliers provide commercially-available transistors.

6.1.2 Suppliers and market

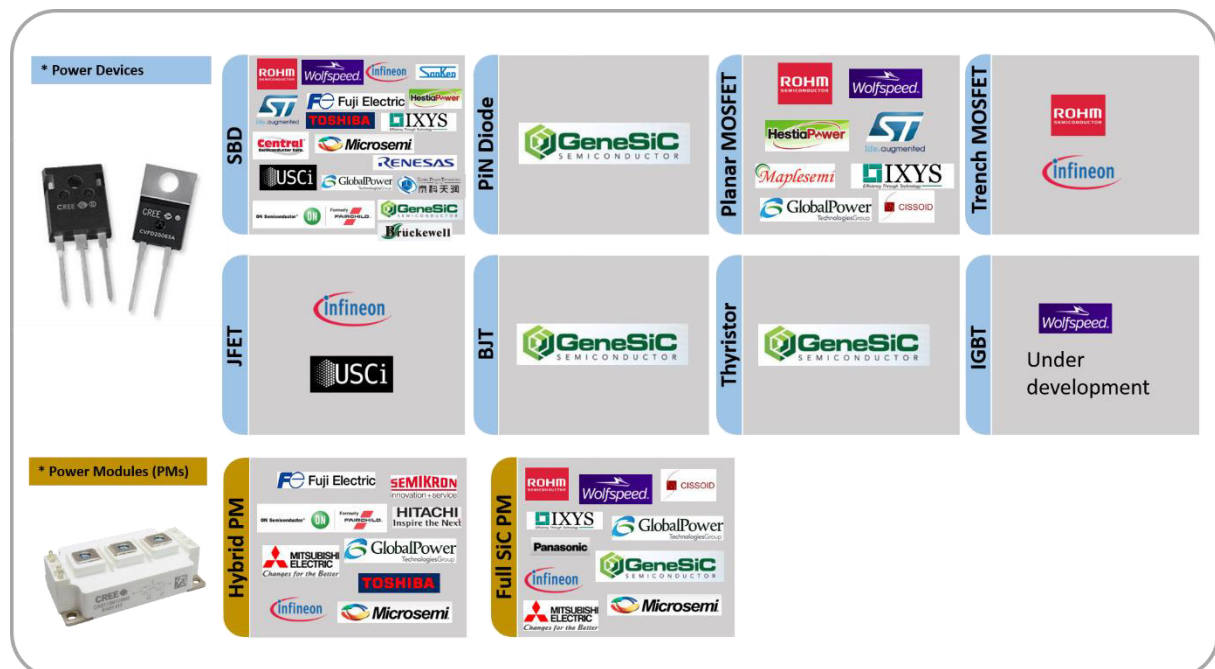


Figure 14 SiC power devices and modules makers according to different types of power devices
© Green Power Electronics 2017.

According to [1], we are in a growing market with more and more players. Even with revenue increasing, the leading players' market share is reducing.

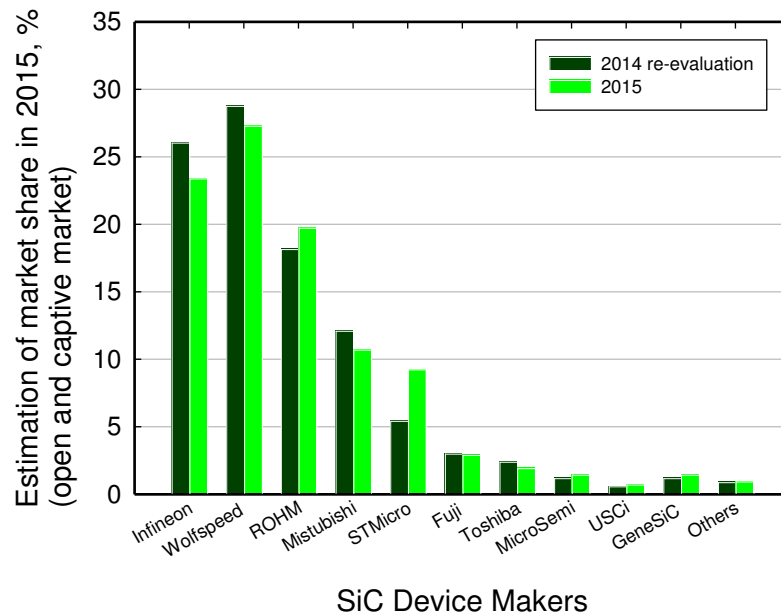


Figure 15 Market share comparison of SiC device makers. Based on information from [1].

The overall market for silicon carbide (SiC) devices was more than 200M\$ in 2015 and the expectation for 2025 reaches almost 1000M\$ at an estimated CAGR of 20 % from 2015 to 2025. The market is segmented into eight different applications.

According to [1], the total SiC-based power device market is expected to grow steadily to 1124M\$.

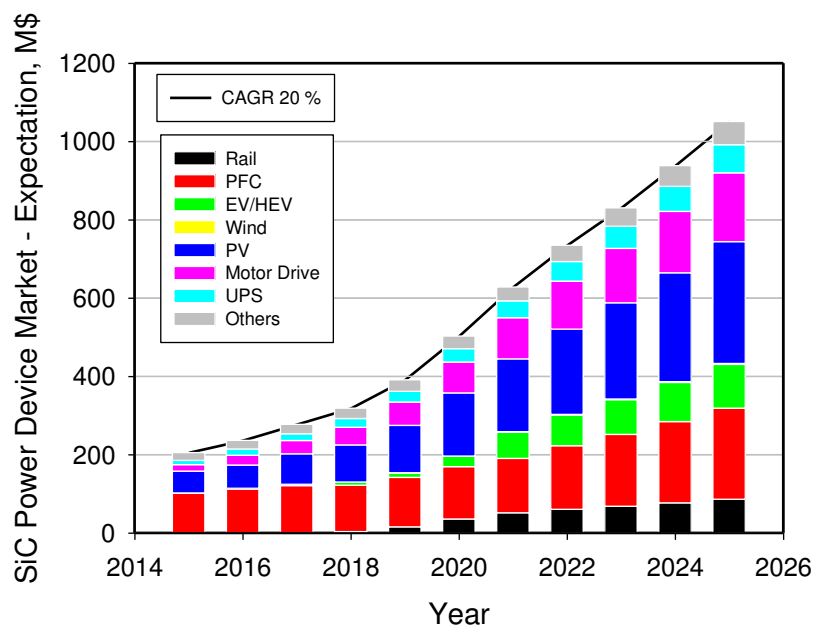


Figure 16 Expectation of SiC power device market split by applications, reaching a CAGR of 20% (Source: Yole Power SiC Materials Devices Modules Applications June 2016 data).

Transistor market share is expected to grow faster in the 2016-2025 period.

In 2015, the SiC market was dominated by 600 V and 1.2 kV diodes due to PFC/Power supply market.

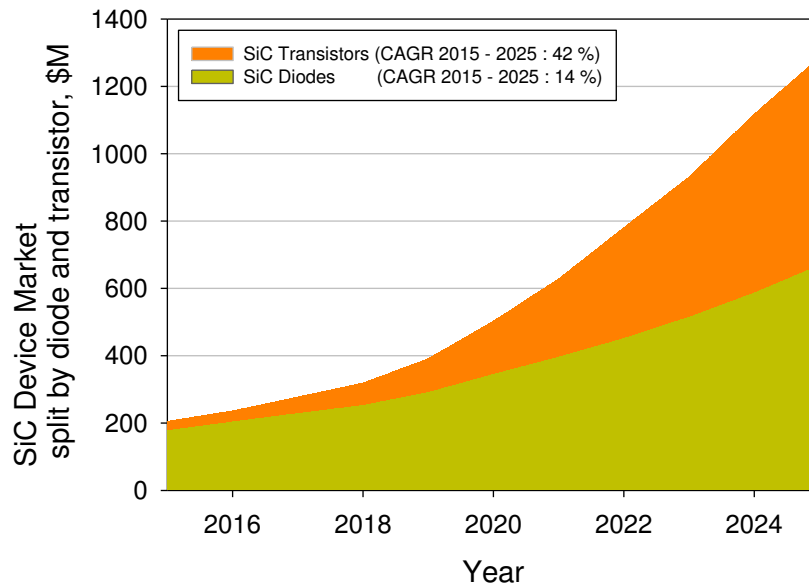


Figure 17 SiC device market split by diode and transistor during 2015-2025. Based on information from [1].

6.1.3 Suppliers and market

6.1.3.1 Discrete devices – Diodes

19 suppliers provide commercially-available diodes as of November 2016. Concerning main players, ROHM diode features an epitaxially-formed planar diode structure while Wolfspeed diode has an implanted planar diode structure.

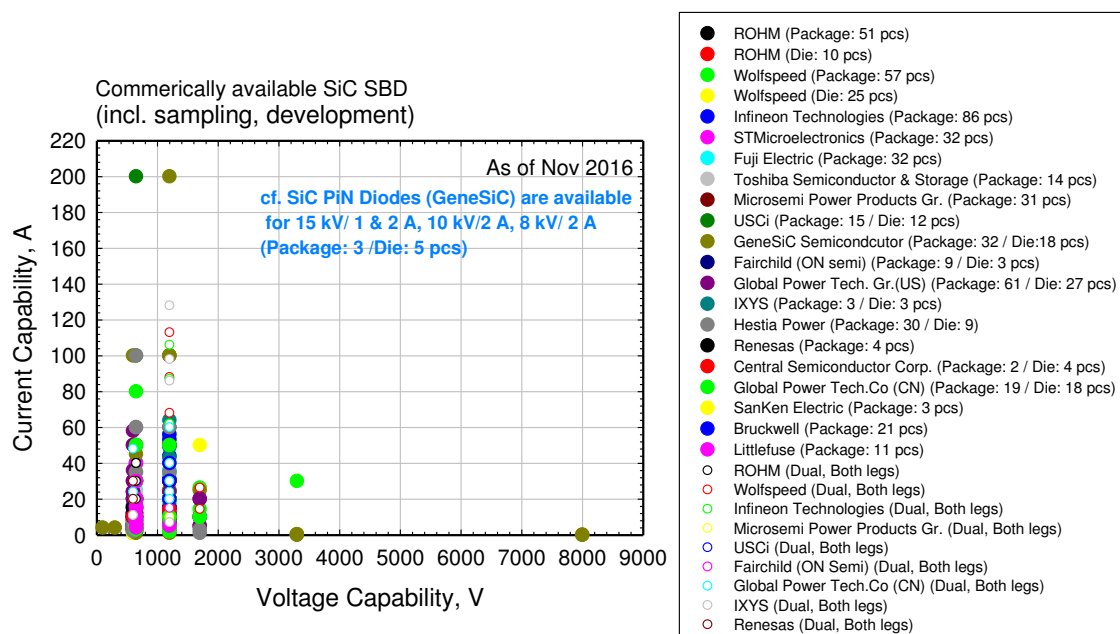


Figure 18 Commercially-available SiC diode suppliers. © Green Power Electronics 2017.

6.1.3.2 Discrete devices – MOSFETs

10 suppliers provide commercially-available MOSFET devices, including planar and trench types, as of November 2016. Higher voltage than 1700 V has been released by several companies, i.e. ROHM, Microsemi, and Wolfspeed.

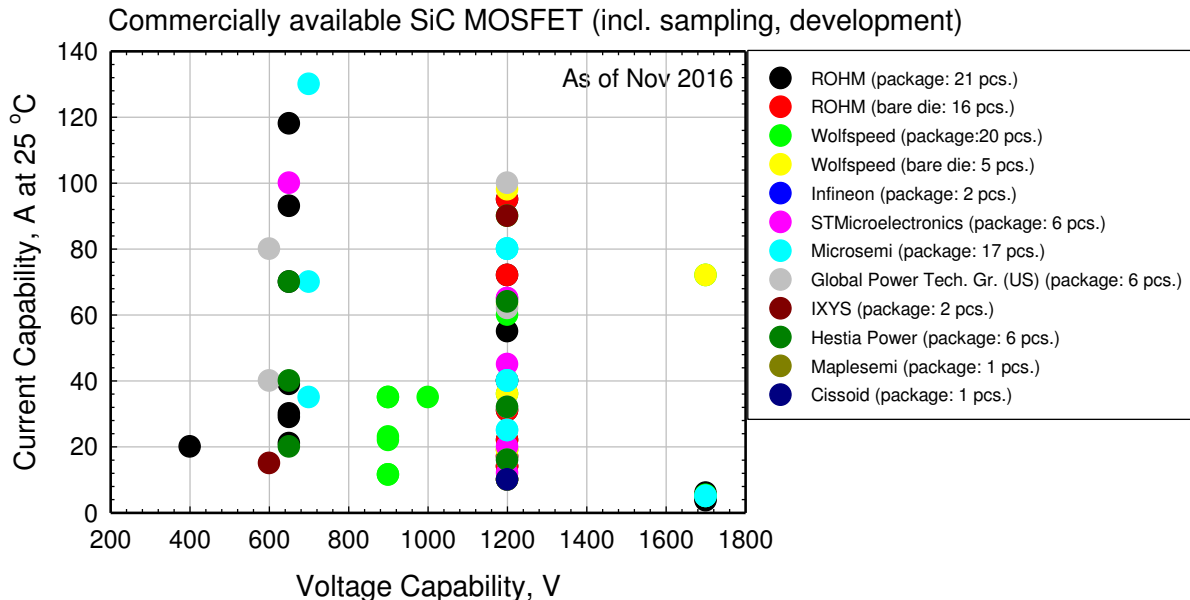


Figure 19 Commercially-available SiC MOSFET suppliers. © Green Power Electronics 2017.

6.1.3.3 Discrete devices – Transistors

Only 3 suppliers provide commercially-available transistors of other type than mainstream MOSFETs.

According to [1], Wolfspeed is pre-releasing up to 15 kV MOSFET as well as SiC IGBT and p-GTOs. Mitsubishi is in trial production for 6.5 kV MOSFET.

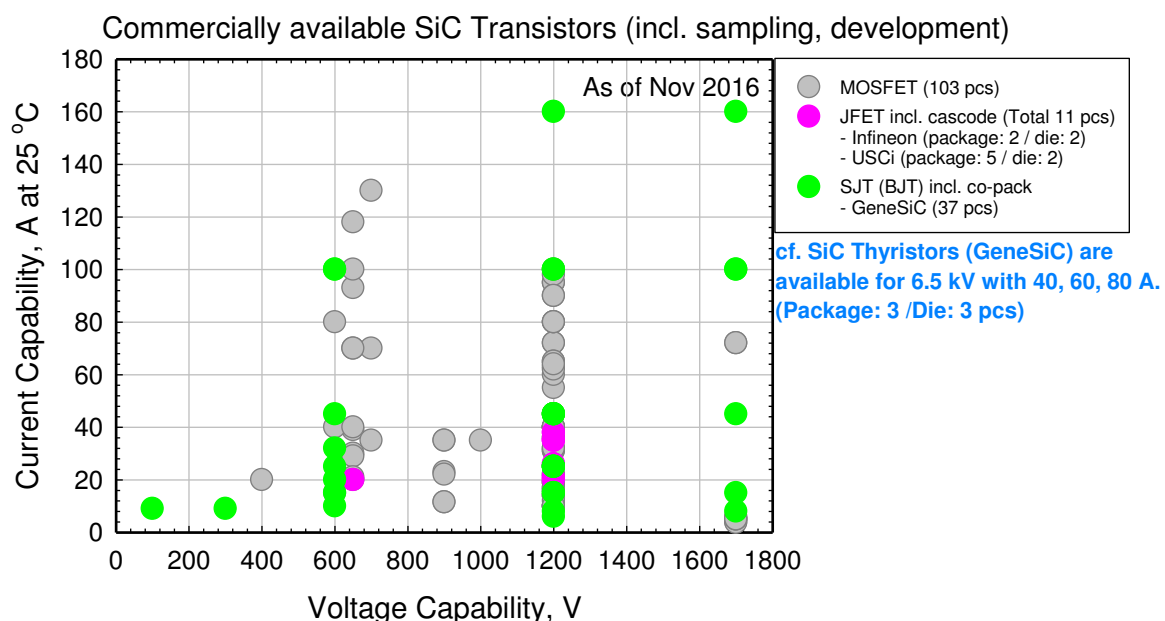


Figure 20 Commercially-available SiC transistor suppliers (other types compared to MOSFET). © Green Power Electronics 2017.

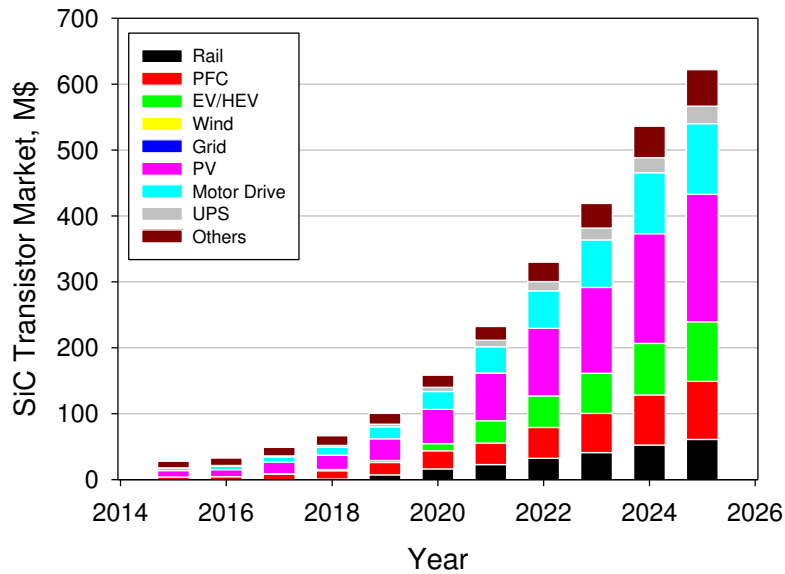


Figure 21 Estimation of SiC transistor market split by applications. Based on information from [1].

6.1.3.4 Power modules

YOLE [1] is expecting more and more full SiC solutions without SiC diode in the future.

In the meantime, the choice of full or hybrid solution will strongly depend on application and the commercial availability of SiC MOSFETs at a certain voltage and power range.

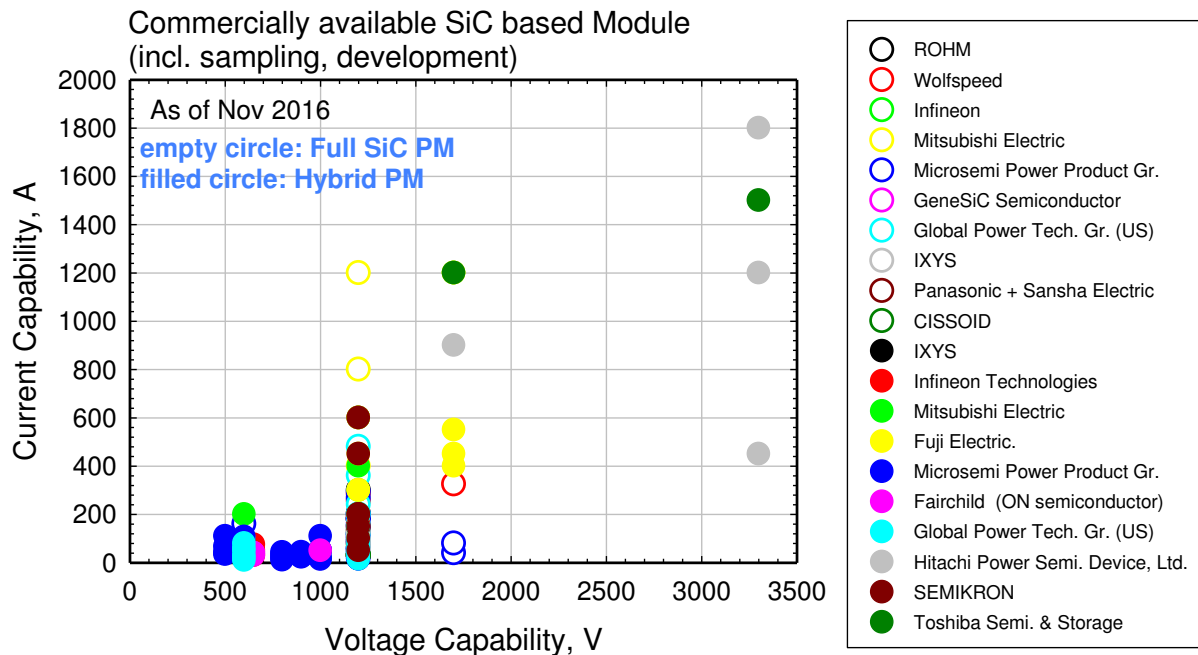


Figure 22 Commercially available SiC-based power module suppliers.
© Green Power Electronics 2017.

According to [1], diode share used as discrete will decrease, while module share will increase.

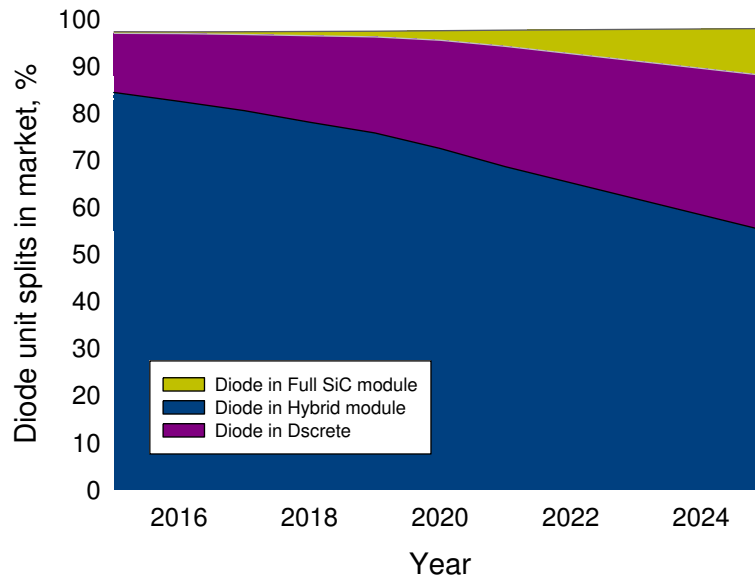


Figure 23 Diode market portion split by discrete, hybrid module, and full SiC module. Based on information from [1].

6.2 GaN discretes and power modules

6.2.1 Status and trends

According to [2], the GaN device market is mainly dominated by <200 V devices in the whole forecast period. However, 600 V devices are expected to take off and keep growing.

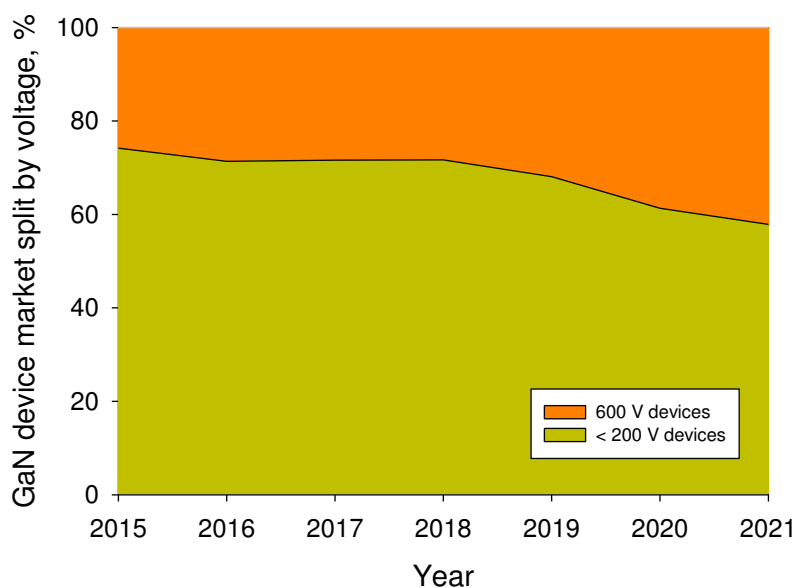


Figure 24 GaN device market split by voltages (200 and 600 V) during 2015-2021. Based on information from [2].

6.2.2 Suppliers and market

According to [2], the total GaN-based power device market is expected to reach 280M\$ in 2021.

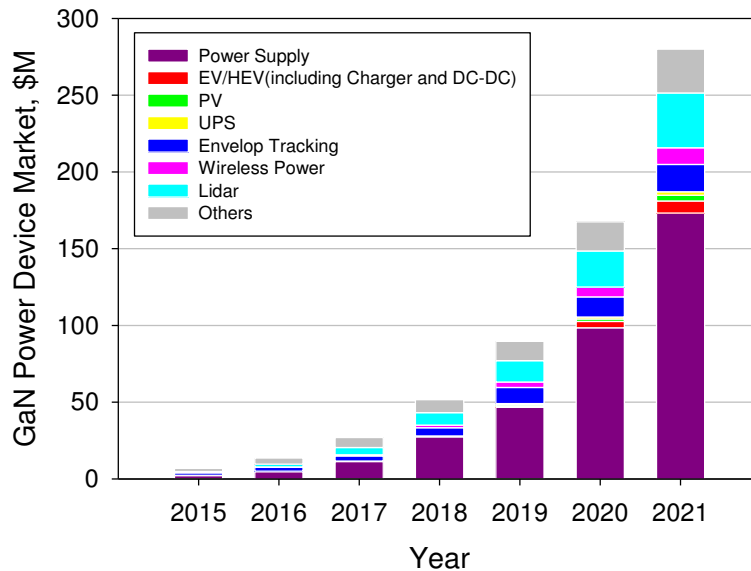


Figure 25 GaN power device market split by application 2015-2021, reaching a CAGR of 86 %. Based on information from [2].

EPC is highly focused on low-voltage GaN devices while most players are working in the 600-650 V range.

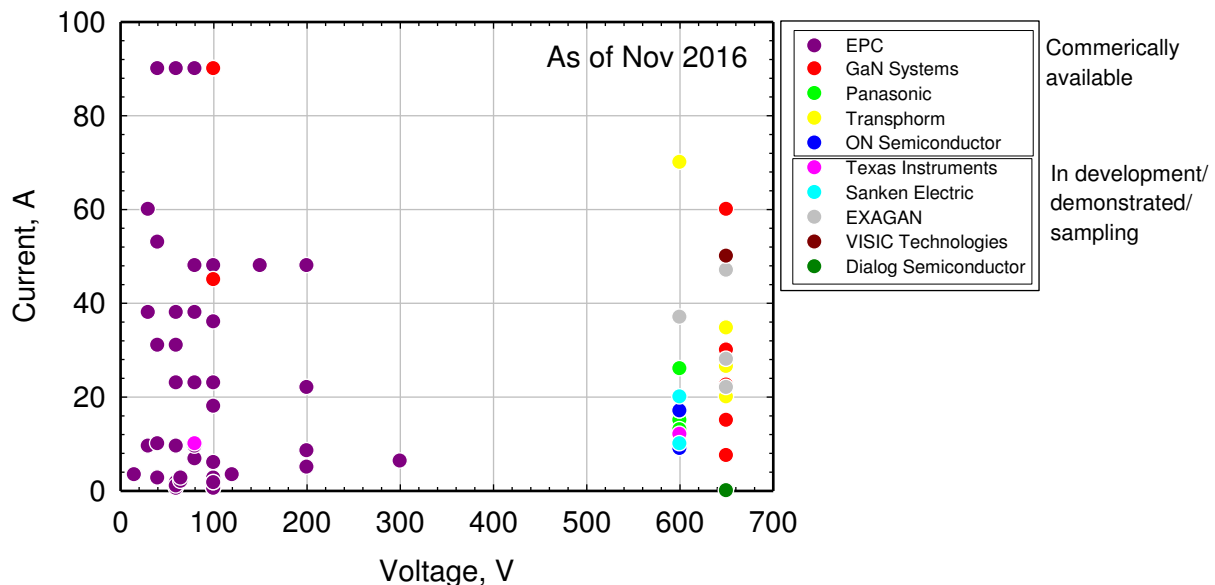


Figure 26 Existing GaN power device suppliers (including devices commercially available, under development, demonstrated, and in sampling). © Green Power Electronics 2017.

7 Renewable energy sources

The renewable energy sources consist of solar, wind, hydroelectric, wave, tidal, and geothermal power sources. However, the hydroelectric and geothermal power are not considered in the report because they are not so interesting from power electronics point of view. For the same reason, the biomass and biofuels, which are two types of solar energy sources, are not discussed in this document.

The photovoltaic (PV), wind, wave, and tidal power generation are intermittent electricity sources. The electric power grid has a theoretical limit of renewable energy penetration, beyond which the stability of the grid cannot be guaranteed. This limit can be increased by adding sufficient energy storage capacity in the grid. Most energy storage technologies require power electronics and attract the attention of power electronic players. Therefore, we have added a section on energy storage in this chapter.

7.1 PV and wind

There are urgent needs to decrease the CO₂ emissions and air pollution, especially those generated by electricity generation and by transportation. The energy transition is already underway, with renewable energy sources dominating the new electricity generation capacities.

Very high, still untapped potential for electricity generation is offered by photovoltaics, wind and marine energies. The systems associated with these renewable energies require power electronic components such as power converters and inverters. The drivers for deployment of renewable energy sources are sustainable, and so are the business opportunities for power electronics players.

Photovoltaics and wind are relatively mature technologies that already have a large market, both in terms of annual new capacities as well as in cumulative installed capacities. The exploitation of marine energies is still in the development stage, with no significant market expected before 2020. Cost and technology challenges are very high for marine energy systems.

Photovoltaics and wind have reached high percentage of electricity generation in several countries of the world. In these more mature markets the needs for demand/response solutions to stabilize the electricity grid are sought. Energy storage, especially battery electricity storage, offer numerous benefits to the grids in high percentage of intermittent PV and/or wind electricity as well as to the new markets with poor grid quality.

The deployment of new PV and wind installations will likely be strongly interlinked with building new battery electricity storage solutions.

The opportunities for power electronics are not limited only to power converters and inverters. The power electronics companies can find opportunities also in providing additional components needed for PV and wind systems (protection devices, electrical connections...) and components and systems used in associated markets (transmission and distribution, energy storage...). The power electronic players can also benefit from the synergies between different applications.

7.1.1 Photovoltaic (PV)

During the last few years the PV system costs have been falling very significantly. The *levelised cost of electricity* (LCOE) by source is a measure used to compare the cost of electricity from different power sources. According to [10], the current LCOE of European PV is between 100

and 240 €/MWh. It differs depending on the irradiation at any particular site, operational costs, etc. The projection for 2020 is that it will be between 80 and 190 €/MWh.

In regions with high sunlight potential the LCOE can be much lower. For example, the electricity from a 200 MW PV plant in Dubai, which will be operational in 2017, is projected to be sold for 58.5 \$/MWh. Therefore, the electricity from PV panels is already competitive with conventional sources of electricity.

The key power electronic component in a PV system is the PV inverter and the key semiconductor devices in any PV inverter are the diodes and transistors. Thanks to much better performance in comparison to Si diodes, the SiC Schottky diodes are already widely used in PV inverters as discrete devices as well as in power modules for PV inverters. SiC power transistors are also gaining acceptance in the industry and steadily increasing their market share.

7.1.1.1 Power devices & modules

According to Wolfspeed, SiC-based inverters can reduce the typical installation costs for a PV inverter by 40 % due to a lower overall weight and a higher power density.

SiC MOSFETs are used today for the string inverter's boost stage (10 kW to 70-80 kW range). Full SiC solutions for central PV inverters are in development.

In low power range (<300 W), the use of SiC diodes is declining due to new topology called as microinverter which does not need high-voltage diodes.

According to [1], PV inverters adopting both SiC diodes and transistors are expected to grow steadily to 2021.

PV will continue to be an important market for SiC devices in the coming years. The SiC device market for PV is forecast to exceed 180M\$ in 2021.

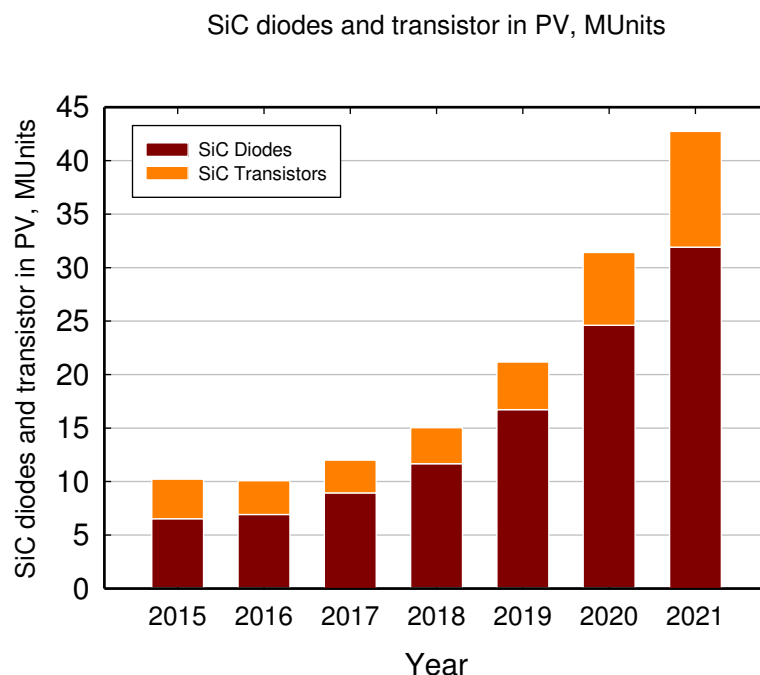


Figure 27 Market forecast in units for SiC diodes and transistors in PV during 2015-2021.
Based on information from [1].

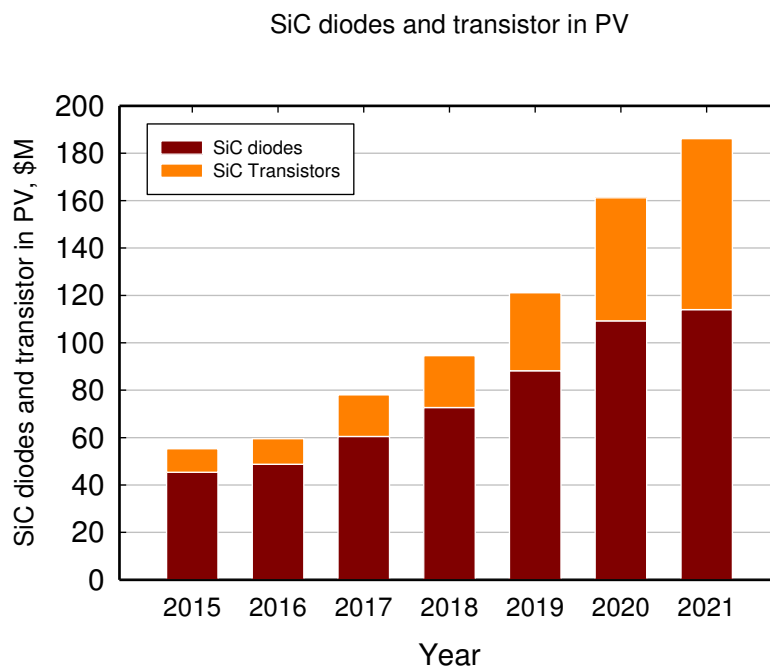


Figure 28 Market share for SiC diodes and transistors in PV during 2015-2021. Reproduced from [1].

According to [2], GaN could bring distinct advantages in micro-PV applications.

Smaller inverter size, lower weight and low noise level are especially important for small residential PV inverters.

GaN revenue is expected from EV/HEV in 2018. Since 2019, this market is expected to accelerate.

The GaN device market for PV is estimated to be small until 2021 in comparison with the SiC device market.

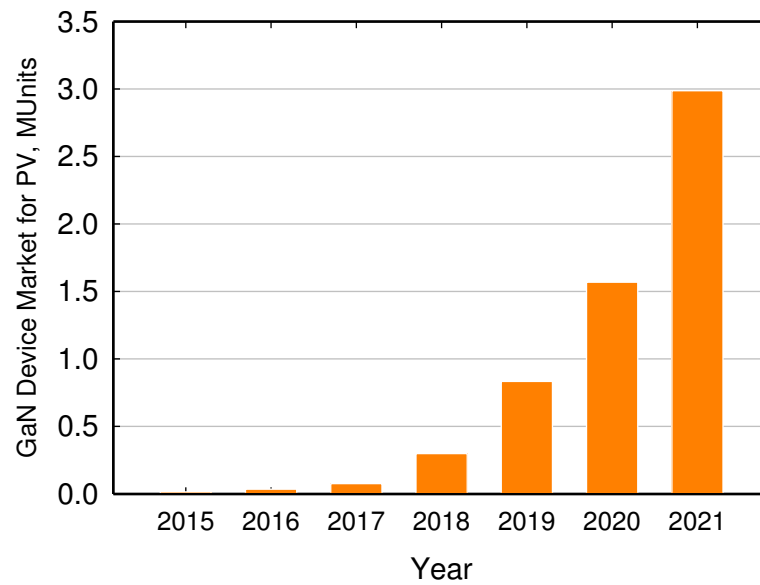


Figure 29 Market forecast for GaN devices in PV during 2015-2021 in units. Reproduced from [2].

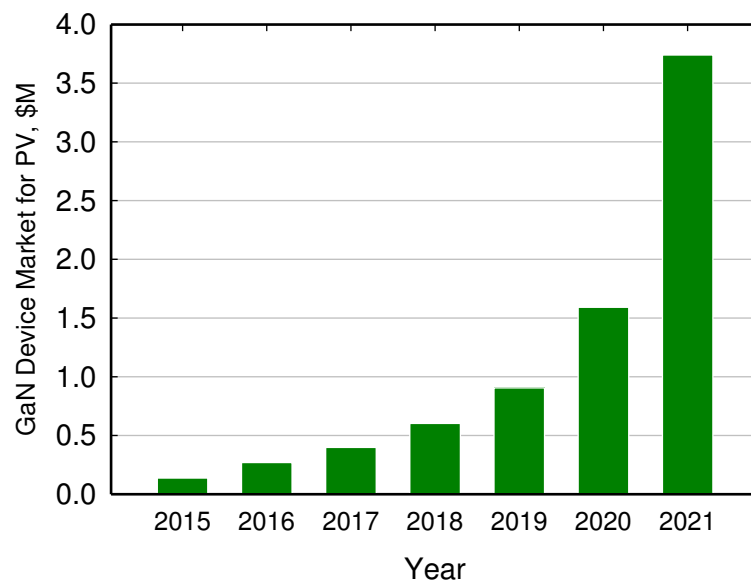


Figure 30 Market for GaN devices in PV during 2015-2021. Based on information from [2].

7.1.1.2 Manufacturers

SMA is the leading PV inverter manufacturer in North and South America.

Enphase Energy is the leader in North America for micro-inverters.

ABB has been among the TOP 3 PV inverter manufacturers since the acquisition of Power One in 2013.

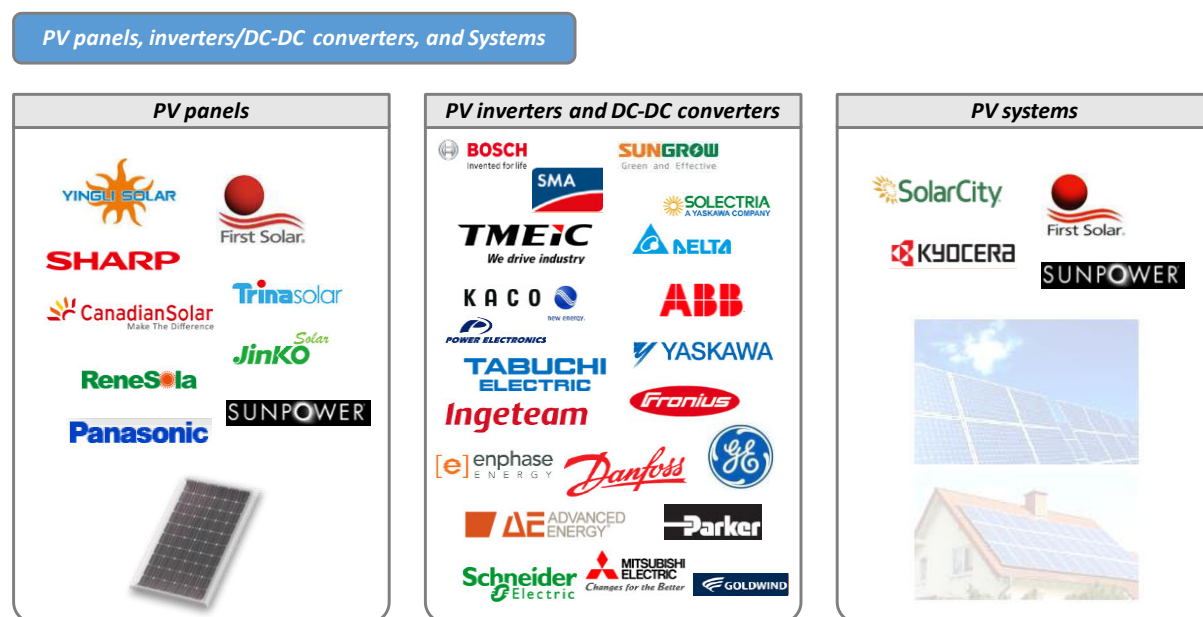


Figure 31 Manufacturers in different parts of the supply chain for PV market.
© Green Power Electronics 2017.

7.1.1.3 Markets

According to [3 and 4], the PV inverter demand will continue to grow and reach 93.3 GW by 2021.

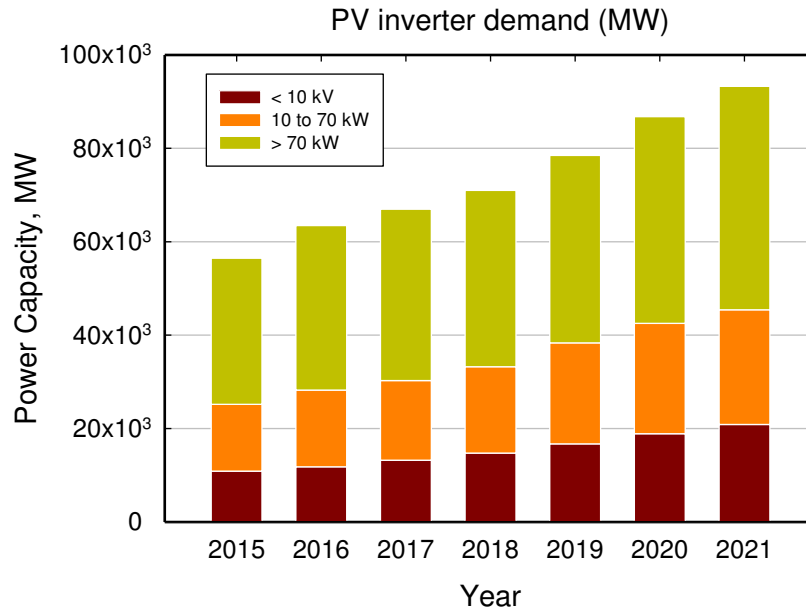


Figure 32 Market forecast segmented by inverter size during 2015-2021. Based on information from [3 and 4].

According to [3 and 4], approximately 90 GW of solar power capacity will be installed per year. Newly installed PV capacity will continue increasing over the next couple of years.

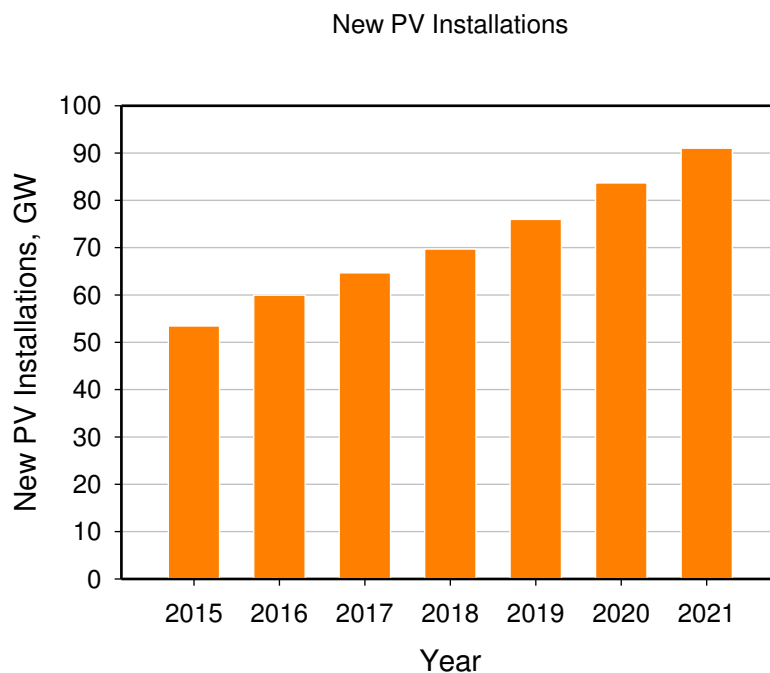


Figure 33 Installed PV capacity forecast during 2015-2021. Based on information from [3 and 4].

Transnational Roadmap

According [3 and 4], the PV inverter market will grow steadily and will reach approximately 8 billion\$ by 2025.

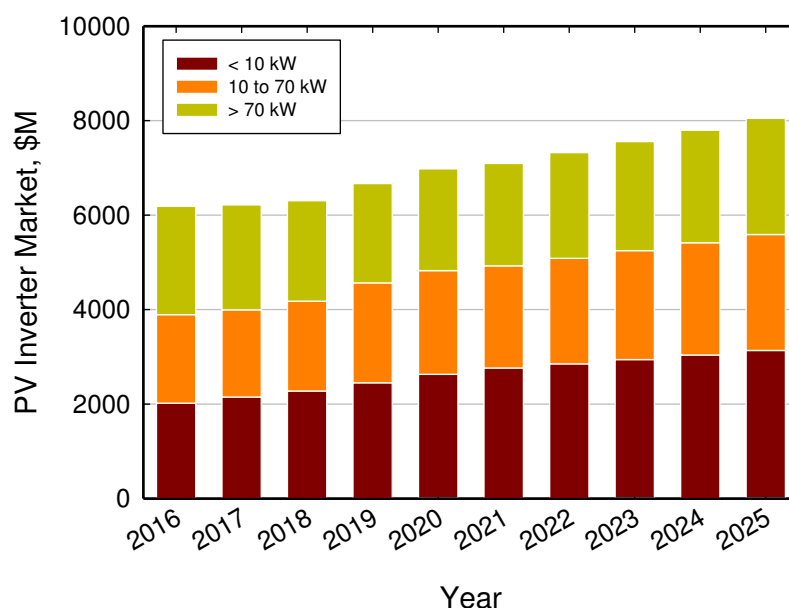


Figure 34 Market forecast for PV inverter during 2016-2025, showing a CAGR of 3.2 %. Based on information from [3 and 4].

According to [3 and 4], both Sungrow and Huawei have installed more PV inverters with MV capacity than the leader SMA.

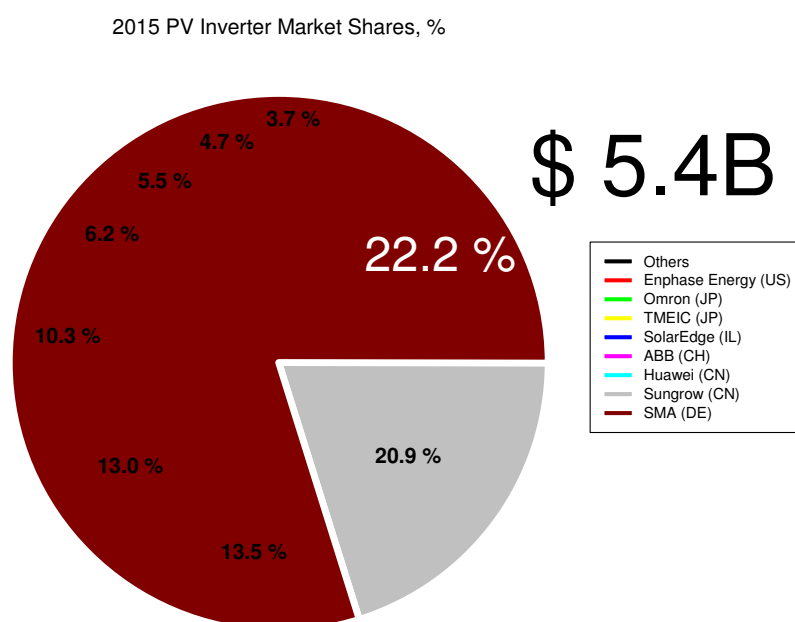


Figure 35 PV market split in 2015. Produced by [3].

7.1.2 Wind turbines

The wind turbine manufacturers are hindered by the availability and cost of high current SiC devices.

Today's wind converter requires a transformer working at 50 Hz which does not motivate the use of SiC transistors.

Implementation of medium/high frequency (10 kHz) converters could motivate the use of SiC transistors and bring value added by reducing the transformer size and maintaining an overall high efficiency.

The change of the transformer from a 50 Hz to 10 kHz range would impact the way the connection is made to the grid. So, the decision to adopt new architectures may take a long time.

7.1.2.1 Power devices & modules

There are some efforts at research level to understand the benefits of SiC for this market. However, due to relative cost of SiC devices YOLE, [1] does not expect a significant market penetration of SiC devices in this application until 2021.

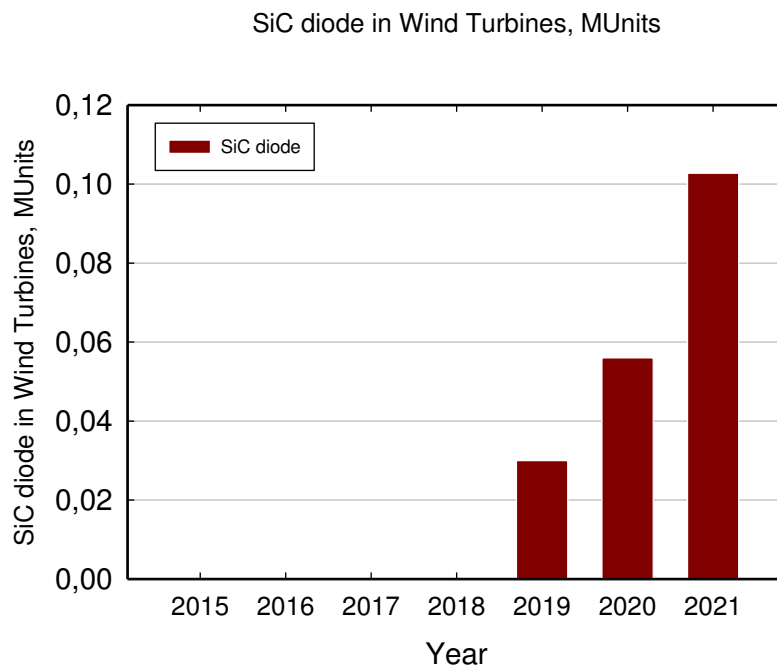


Figure 36 Market forecast for SiC diodes in Wind Turbines in units. Based on information from [1].

SiC diode in Wind Turbines

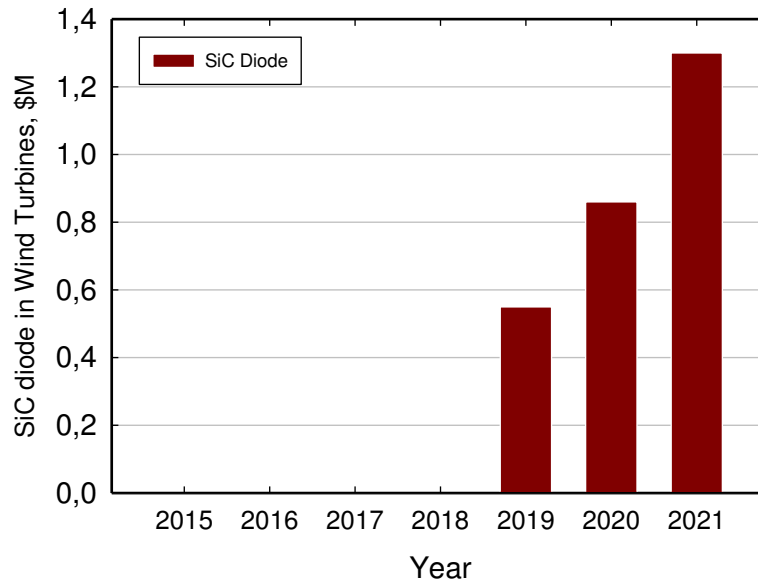


Figure 37 SiC diode market in Wind Turbines. Based on information from [1].

7.1.2.2 Manufacturers

According to [4], Chinese players are rapidly growing and looking for foreign markets. Manufacturers are looking for new market opportunities in a) large turbines with 6MW+ sizes for off shore applications and b) promising new markets, especially in South America.

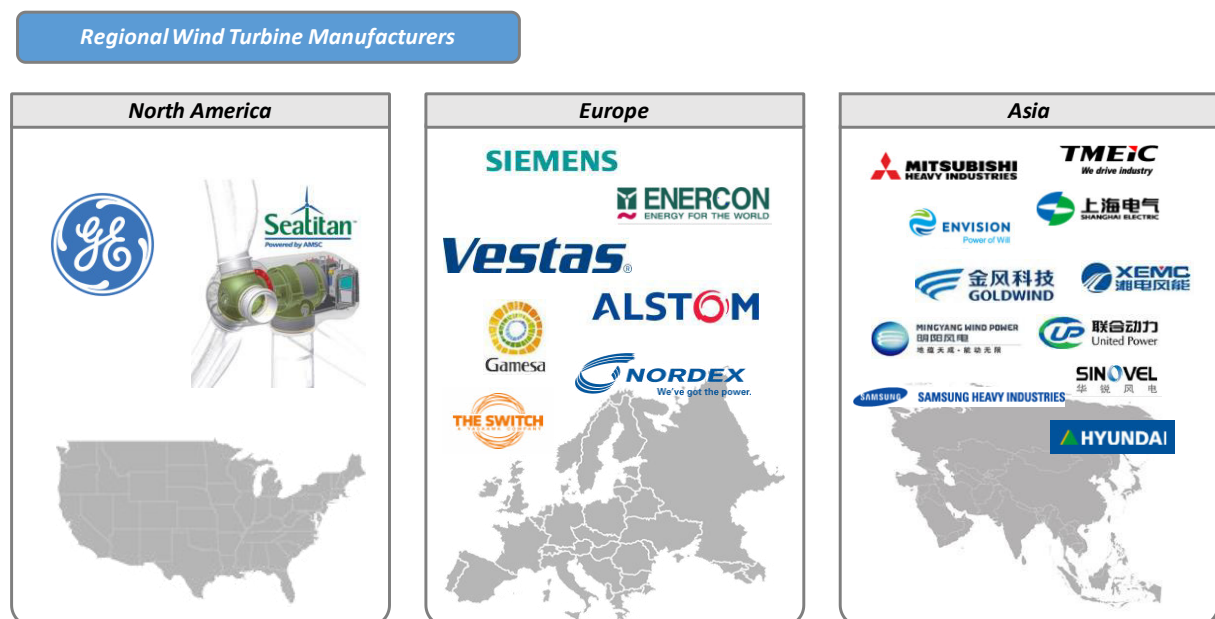


Figure 38 Regional wind turbines manufacturers © Green Power Electronics 2017.

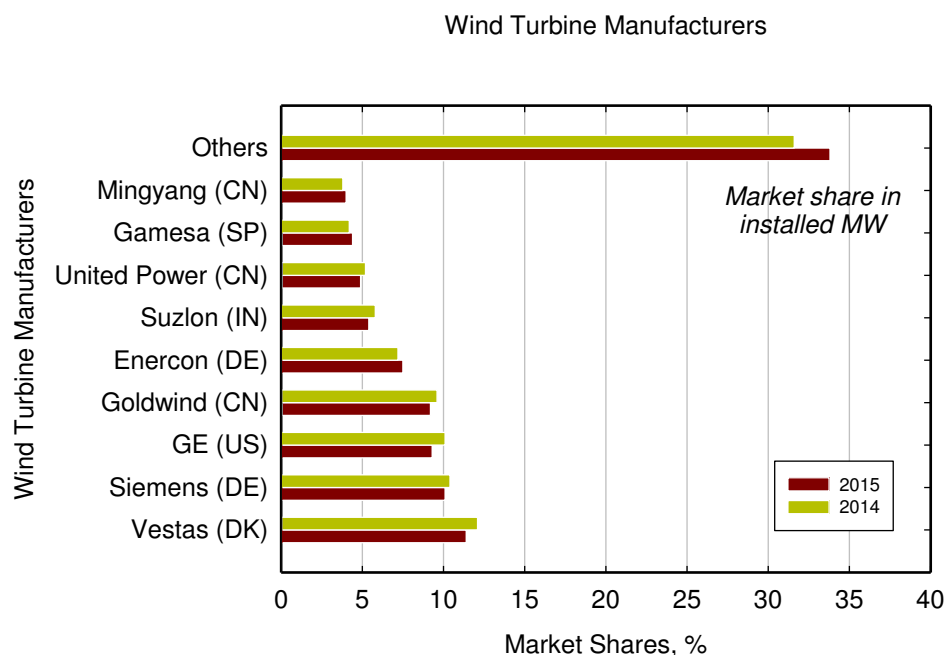


Figure 39 Comparison of market shares between 2014 and 2015. Based on information from [3].

7.1.2.3 Markets

According to [4], positive market development will take place in Brazil.

In Europe, some onshore markets have reached their saturation. Development opportunities exist predominantly in the offshore wind market.

In Asia, China will start exploiting the offshore wind resources. Low speed turbines in the south are continually installed at present.

Japan is expected to be a new market.

Also India is expected to expand the market.

7.2 Marine energy

There is a large variety of marine energy technologies to generate electricity.

- Tidal turbines
- Wave energy converters
- Salinity gradient technologies
- etc.

These technologies have different principles, very different characteristics and designs, and system sizes.

Tidal turbines convert the kinetic energy of tidal stream to electricity.

Their principle is similar to wind turbines, but they use tidal stream instead of wind. Because of the higher density of water relative to air, an individual tidal turbine can provide greater power at low tidal flow velocities compared to a wind generator with similar wind speed and rotor diameter.

The advantages of tidal stream energy is a good predictability of electricity generated.

Among the main challenges are the conflict with maritime transport and fishing, high cost of installation and operation and maintenance (O&M), reliability and lifetime issues in harsh marine environment.

The deployment of tidal turbines is still in the nascent stage. Only a few projects of notable size, which were heavily subsidized, have been realized so far. The total market size for new installations is expected to not surpass 100MW by 2020. Considering the new installed capacity, the tidal turbines energy market will be thus about 1000x smaller compared to wind turbines market.

The development of tidal turbines technologies is very strongly represented by the European players (similarly to offshore wind turbines).

7.2.1 Power devices & modules

A typical size of a tidal turbine is about 1-2 MW. Power converters used with tidal turbines adapt electricity generated to the grid. The semiconductor devices used are of the same type and ratings as for the wind turbines. Market of power devices is difficult to estimate because of the limited commercial activities. Power devices used today are entirely Si semiconductor devices.

7.2.2 Manufacturers

Main tidal turbine manufacturers are Atlantis Resources Limited (ARL), Andritz Hydro Hammerfest (AHH) and GE. The converter manufacturers are GE and ABB.

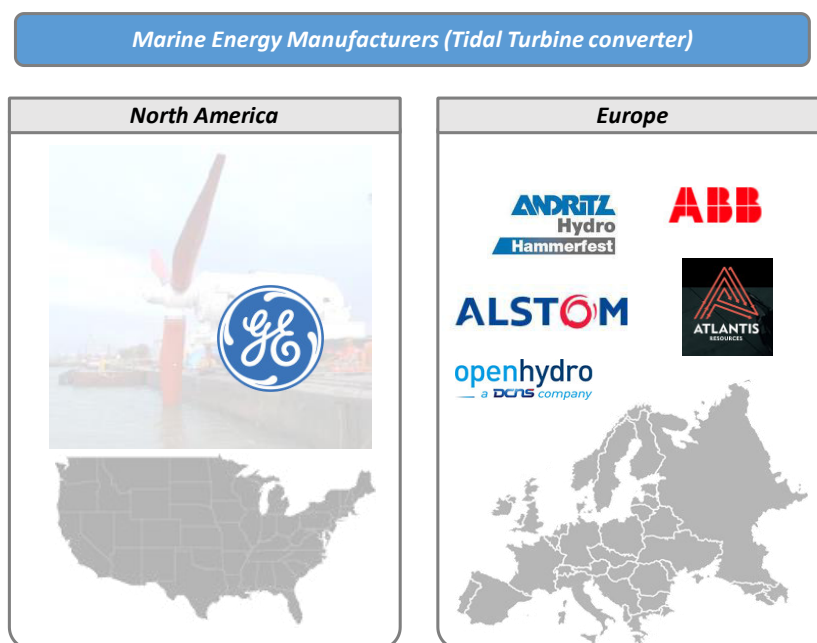


Figure 40 Regional manufacturers for tidal turbine converter © Green Power Electronics 2017.

7.2.3 Markets

The tidal turbines technology is still at the nascent stage. According to [4], the cumulative installed capacity is expected to remain at relatively low levels until 2020. By comparison, this market is smaller than the cumulative PV or wind installations.

7.3 Energy storage

As the share of renewable, intermittent energy sources increases, the only way to match the electricity demand and generation is to turn on or off conventional power plants. Every grid, depending on its robustness, has a theoretical limit for renewable energy penetration. Adding energy storage in the grid increases this limit.

Battery storage systems are well suited to be used with PV or wind generators, but can also be connected at critical points in the grid to increase its robustness. The most obvious benefit of a battery storage is the so-called “load shifting” – the renewable energy is stored in the battery and fed to the grid during the peak hours when the electricity price or demand are higher. This reduces the grid saturation at peak hours. Another benefit is the “renewable firming” – the highly intermittent renewable power is used to charge the batteries, and the grid connected inverter feeds the electricity to the grid at a steady rate, which also contributes to the stability of the grid.

7.3.1 Power devices & modules

The power semiconductor devices and modules used for energy storage power electronics are the same that are used in the equivalent PV and wind power systems.

7.3.2 Manufacturers

The energy storage manufacturers may differ depending on the size and energy storage technology, but the power electronic converters used in the energy storage systems are from well-established power converter manufacturers, such as ABB, GE, Danfoss, SMA, and others.

7.3.3 Markets

The most promising markets for energy storage systems are countries with high penetration of renewables. These are also the countries that are most likely to give incentives for installing energy storage systems. One such example is Germany that started promoting battery storage since May 2013. The second stage of their incentive program (KfW 275) started in March 2016 and will continue until end of 2018.

However, the energy storage technology is seen as important also in countries with low penetration of renewables. Sweden, for example, started offering 60% rebate for the cost of energy storage, connected to a renewable source for all installations that have started no earlier than 2016 and will be completed by the end of 2019.

The German energy storage market is projected to reach \$1B by 2021 [11].

8 Switch mode power supplies

In most electronics, power supply is an indispensable unit consisting of an AC-DC unit for converting the electricity, and an isolated DC-DC unit for lowering the voltage for use in device applications.

In most cases, a MOSFET is needed in PFC and DC/DC converters. In order to prevent device breakdown from current turbulence, as well as other potential risks, a 600V MOSFET is often used for 110V/220V AC power.

Power supply requirements differ by application. However, the common trends present in almost all power supply market segments are: increased efficiency, higher power density, and cost reduction. Power supply applications can be grouped into following categories: Consumer electronics, Portable and wireless, Industrial, Medical, Lighting, Computer and office, Telecom and net, Data Servers.

Power supply efficiency is a key selection criterion. This is supported by legislation in more and more regions around the world.

8.1 Power devices & modules

PFC was the first application targeted by SiC devices, which it has addressed since 2001. This application is perfectly matched with SiC diodes because they provide virtually zero reverse recovery current resulting in: a) reduced losses, b) improved power conversion efficiency, c) smaller modules and d) less EMI noise.

A large volume of SiC diodes is being consumed since in this market.

According to [1], the SiC device market for PFC is estimated to be approximately 100M\$ in 2015, especially in the high-end telecom and server and industrial power supply segments. This market is expected to steadily grow to 140M\$ in 2021.

SiC transistors (MOSFETs) could be adopted instead of SiC-based diodes.

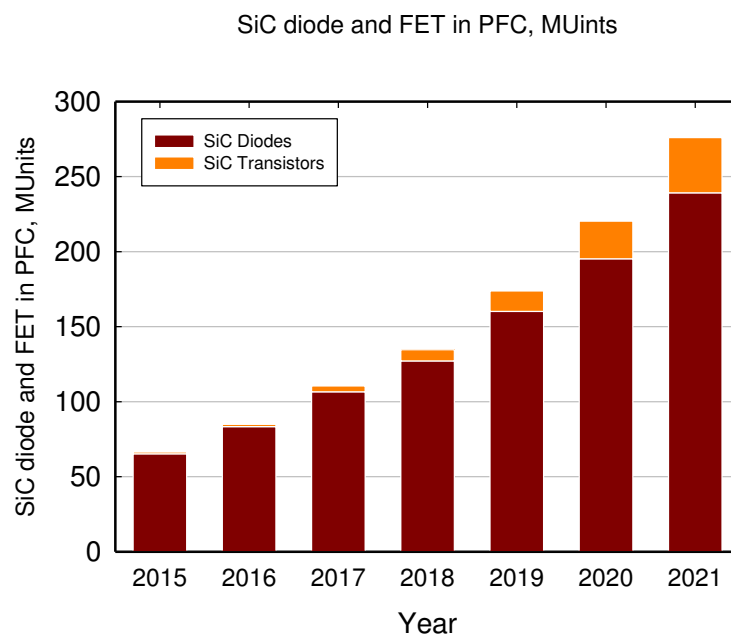


Figure 41 SiC device market for PFC in units. Based on information from [1].

SiC diode and FET in PFC

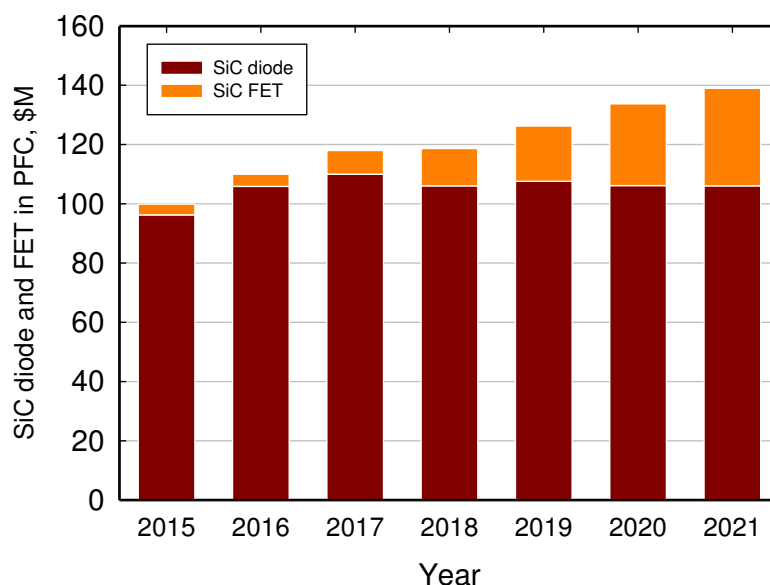


Figure 42 SiC device market for PFC. Based on information from [1].

The power supply market for GaN devices is expected to consume a large quantity of devices and reach around 173M\$ in 2021.

GaN devices can be used in different power supply parts in a) AC-DC inverter, b) isolated DC-DC converter, and non-isolated POL.

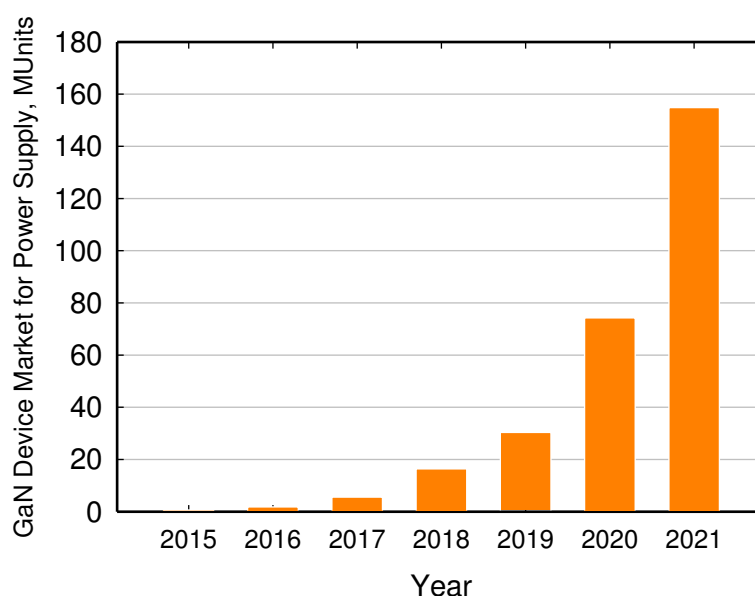


Figure 43 GaN device market for PFC in units. Based on information from [2].

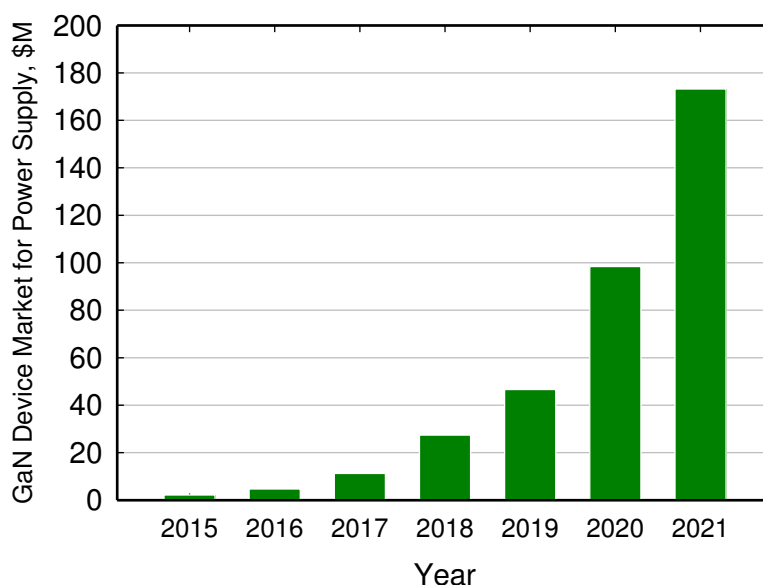


Figure 44 GaN device market for PFC. Based on information from [2].

8.2 Manufacturers

Power supplies SiC. Many manufacturers of power supplies use more and more SiC diodes and MOSFETs from commercial suppliers like Wolfspeed, Infineon, ST and Rohm in their products.

Power supplies GaN. Panasonic, transphorm, Navitas have demonstrated totem-pole topologies with GaN and 99% efficiency. GaN is also predicted to be technology of choice for Point-of load (POL) applications in data servers and telecom.

Today's data servers generally use 12V power supplies (400V/12V) with efficiency levels of around 84%. Using 48V-based solutions for data centers leads to increased efficiency. EPC and TI (Texas Instruments) have teamed up to propose a GaN-based solution for 48V architecture yielding revolutionary improvement of efficiency.

Fujitsu demonstrated an GaN-HEMT based fast AC charger followed by Navitas and dialog.

8.3 Markets

Active PFC uses active switching devices in combination with passive components to change the wave form of applications current drawn by a load to improve the power factor.

Market opportunities for SiC devices; primary SiC diodes in high-end telecom and data server and industrial power supply segments and secondary SiC MOSFETs (Wolfspeed since 2013 with Delta Elektronika and 2015 with Avogy).

The PFC applications suitable for GaN are air conditioners, data servers and industrial equipment (power range 1-10 kW), computer and TV (power range 100W-1kW) and AC adaptors, monitors and LED drivers (power range 50W–100W).

The applications for SiC devices are generally

from rated voltage 600 V and higher and for GaN devices up to rated voltage of 600 V.

9 Electric and hybrid vehicles

9.1 Power devices & modules

According to [1], the first market segment to enter by SiC diodes is on-board chargers, followed by SiC-based DC/DC converters. This trend is expected to develop gradually.

SiC is not expected to be used in a power before 2020. The initial introduction will likely be in small series of car models. Massive adoption is more likely to happen between 2020-2025 when SiC cost reduces.

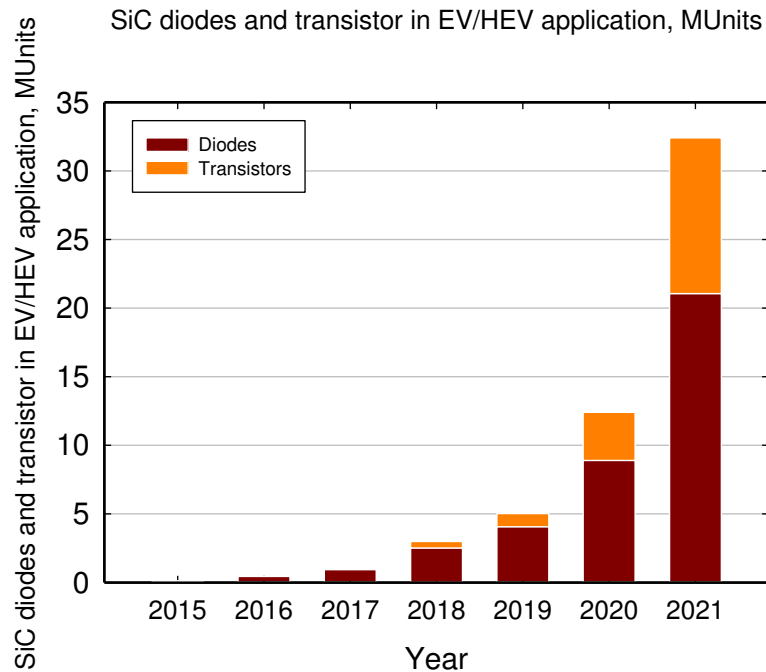


Figure 45 SiC device market for EV/HEV application in units. Based on information from [1].

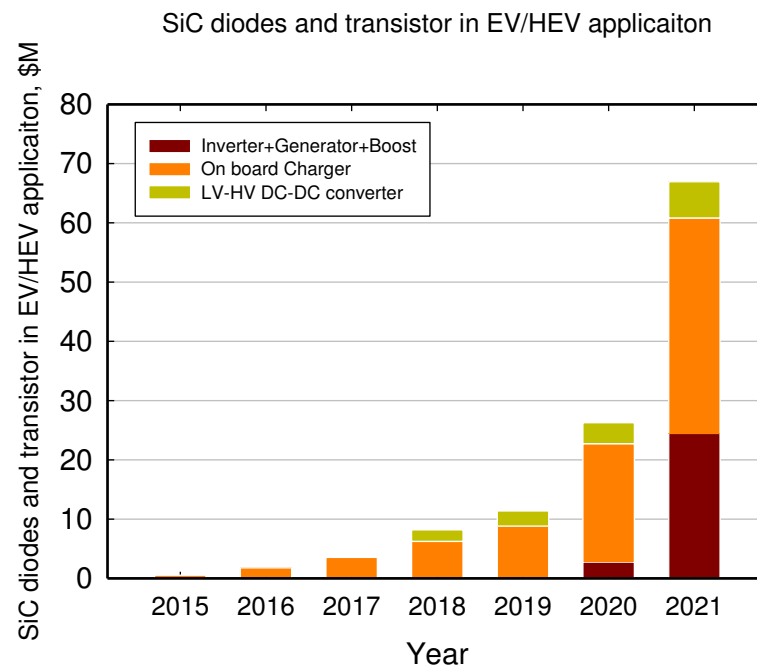


Figure 46 SiC device market for EV/HEV application. Based on information from [1].

Large GaN device volume must be provided to satisfy this market, leading to price reduction and many existing industries, i.e. aeronautics and space, tend to follow the automotive industry's path.

According to [2], market penetration by GaN is expected to start in 2019 for EV/HEV applications.

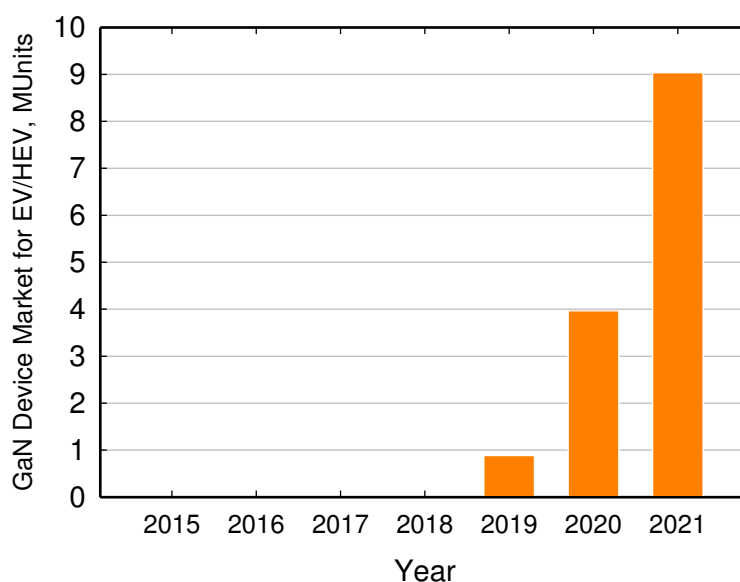


Figure 47 GaN device market for EV/HEV application in units. Based on information from [2].

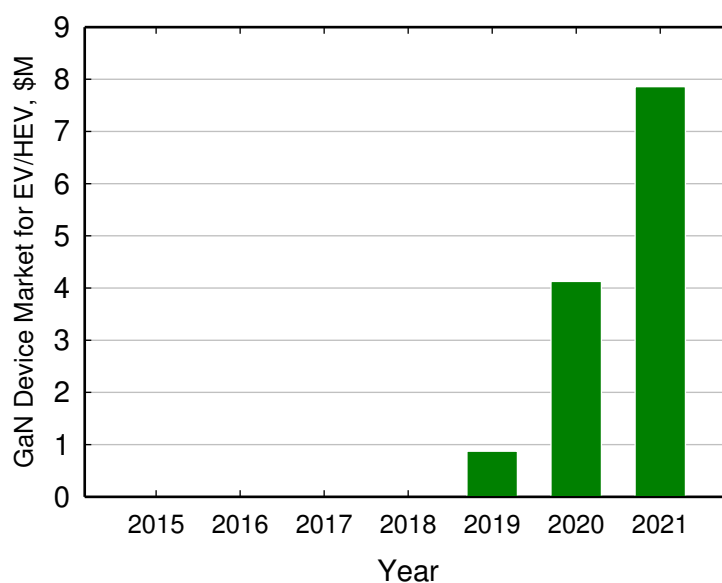


Figure 48 GaN device market for EV/HEV application. Based on information from [2].

9.2 Manufacturers

Toyota has been the dominant player in the HEV market and in power module value chain for the application.

With the market growth and involvement of many players in different parts (car makers, tier one suppliers, and semiconductor companies) of this market, changes in the supply chain are expected. In the strive to master electric motor know-how car manufacturers are capturing competencies from tier-one suppliers. Their goal is to manufacture the whole power train. Some car makers are also working on batteries to complete another value chain integration.

Different car makers are in the development stages, testing both SiC and GaN devices. Toyota is the pioneer in this field, but it will still be some time before it enters manufacturing phase.

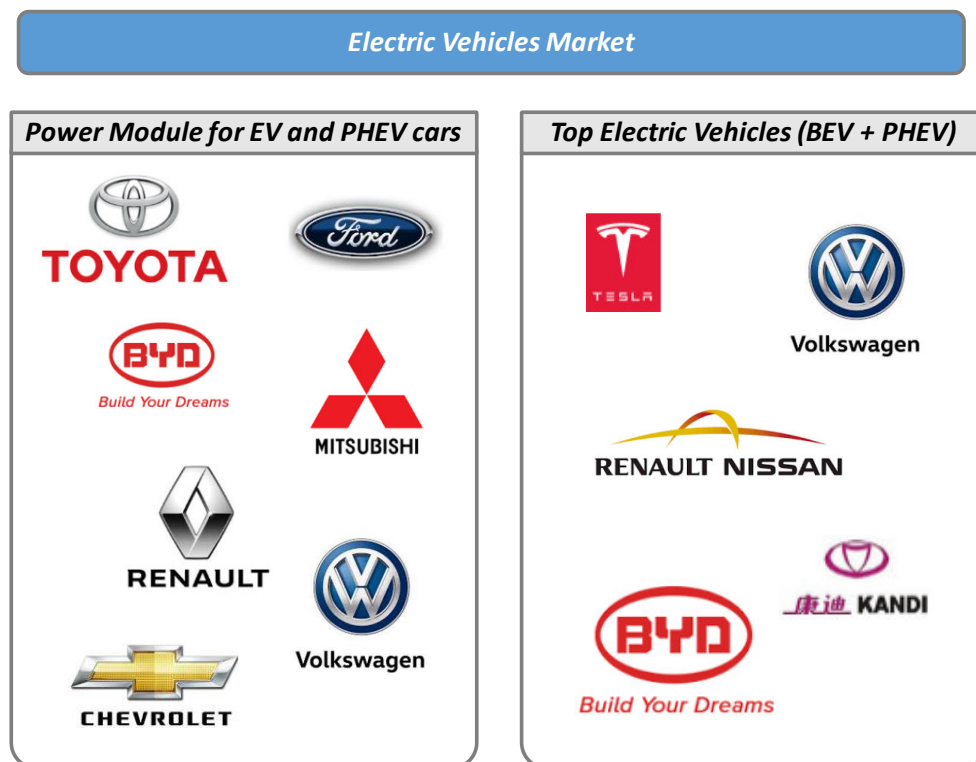


Figure 49 Electric vehicle manufacturers © Green Power Electronics 2017.

9.3 Markets

The EV/HEV market has a huge potential and is expected to grow with a CAGR of +19.5 % during 2015-2021 and to reach 10.5 billion\$ by 2023.

The HEV segment could drive the inverter market in this market.

According to [3], EV would remain a small segment of the overall EV/HEV market without a breakthrough in battery or deployment of charging infrastructure.

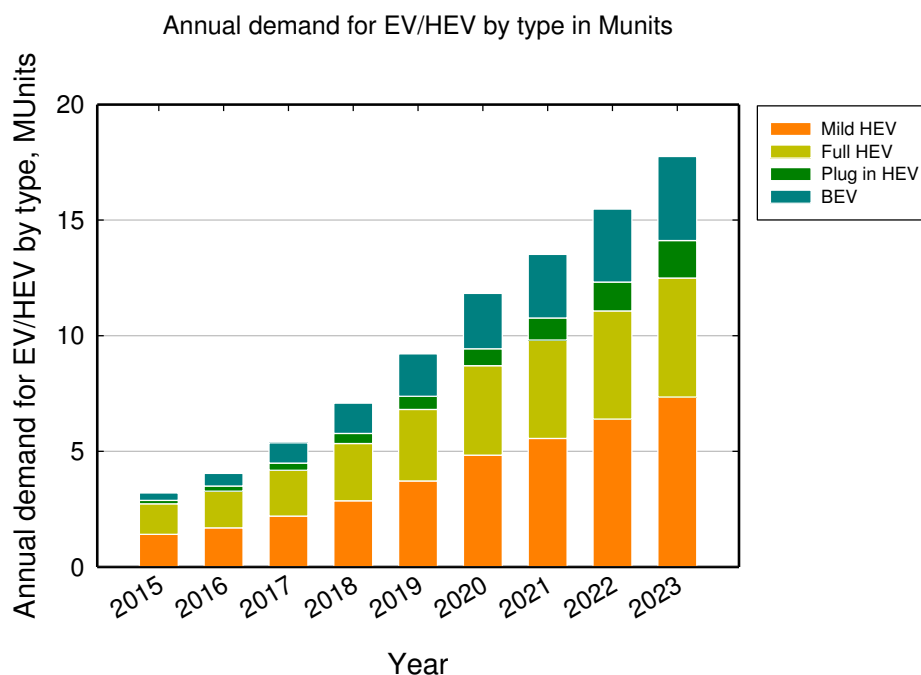


Figure 50 Annual demand for EV/HEV by vehicle type in units. Based on information from [3].

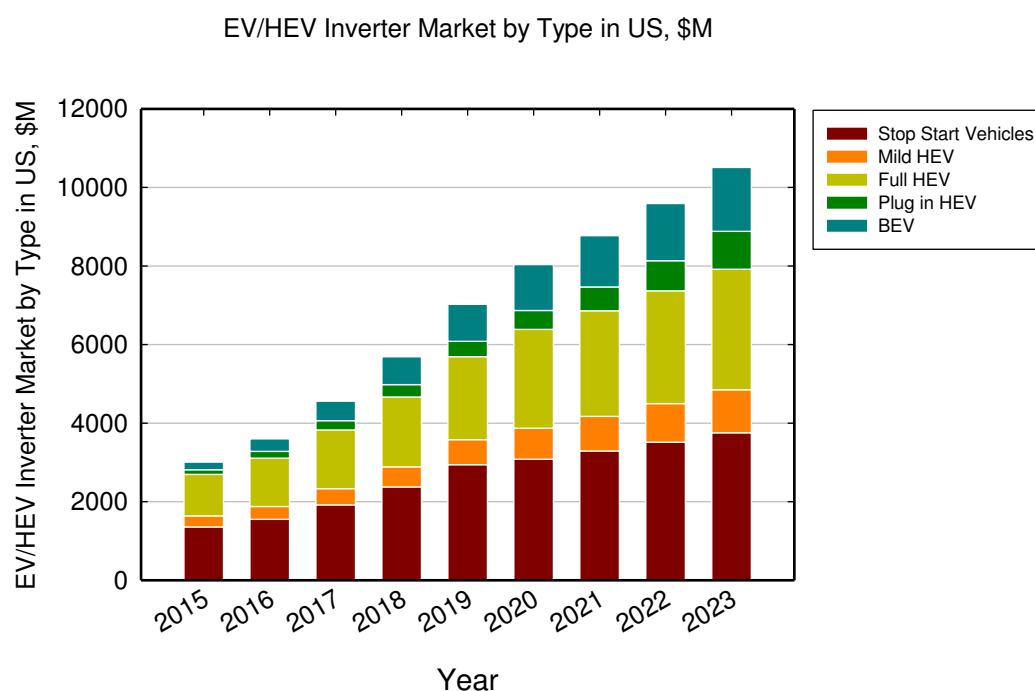


Figure 51 Market forecast for EV/HEV inverter by vehicle type. Based on information from [3].

10 Industrial motor drives

10.1 Power devices & modules

SiC diodes have been used in AC drives for more than 10 years which contributes to growth of this market. YOLE [1] expects full SiC solutions to be used, especially in air conditioning, elevators, and portable tool applications. Under these assumptions, the market is forecasted to grow steadily to more than 100 M\$ by 2021.

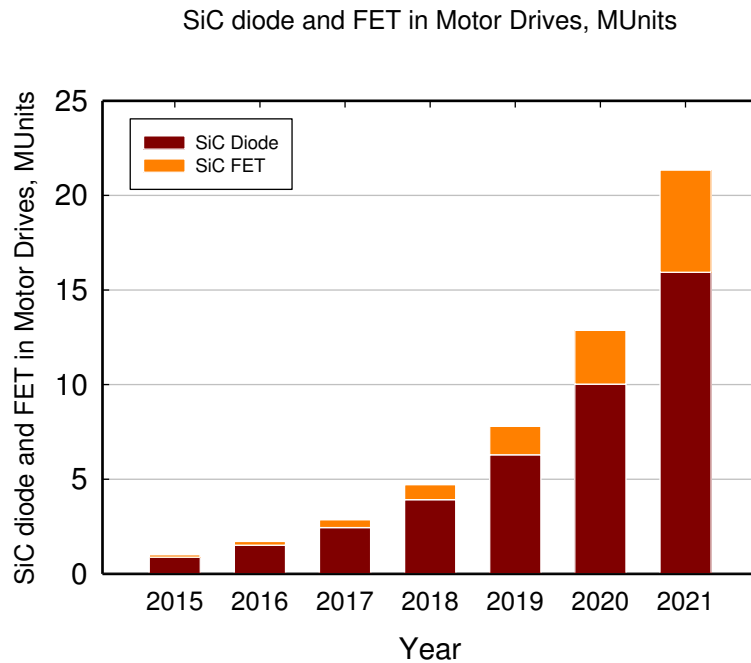


Figure 52 SiC device market for motor drives in units. Based on information from [1].

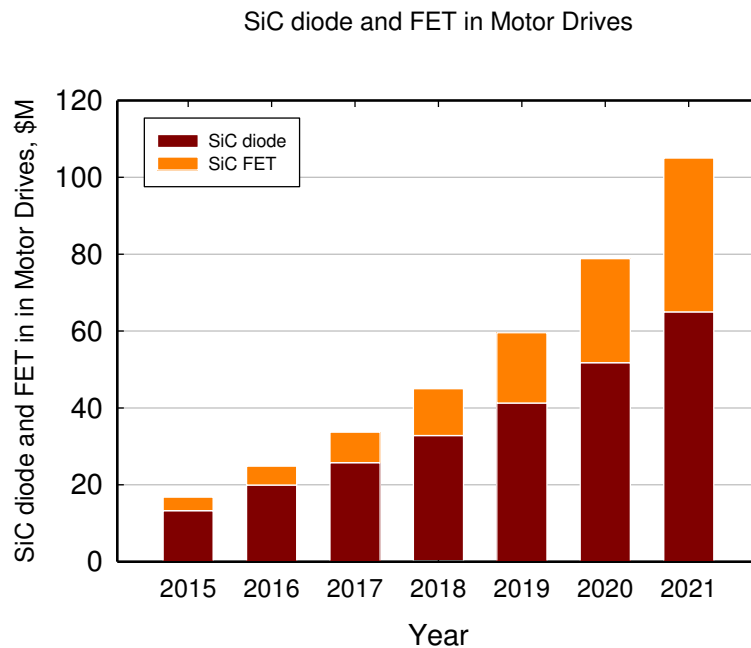


Figure 53 SiC device market for motor drives. Based on information from [1].

10.2 Manufacturers

ABB, Siemens, and Danfoss are the main players which occupy over 40 % of the AC drive market.

The total market for AC motor drive is the largest power converter market reaching around \$20.3 billion in 2015.

Small local players are being acquired by bigger global players.

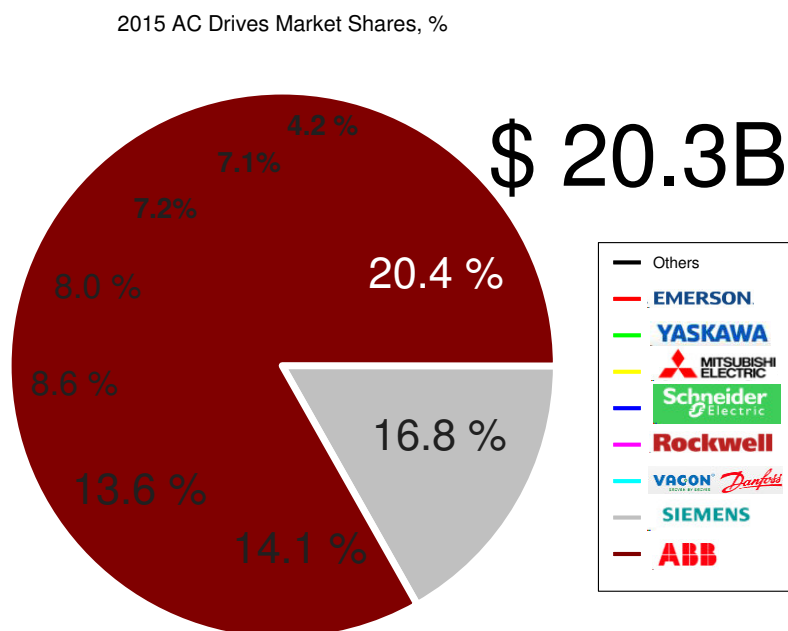


Figure 54 AC motor drive market split in 2015. Based on information from [3].

10.3 Markets

According to [3], low-power AC drives (≤ 40 kW) represent just 20 % of the whole market by revenue but occupy more than 80 % by volume.

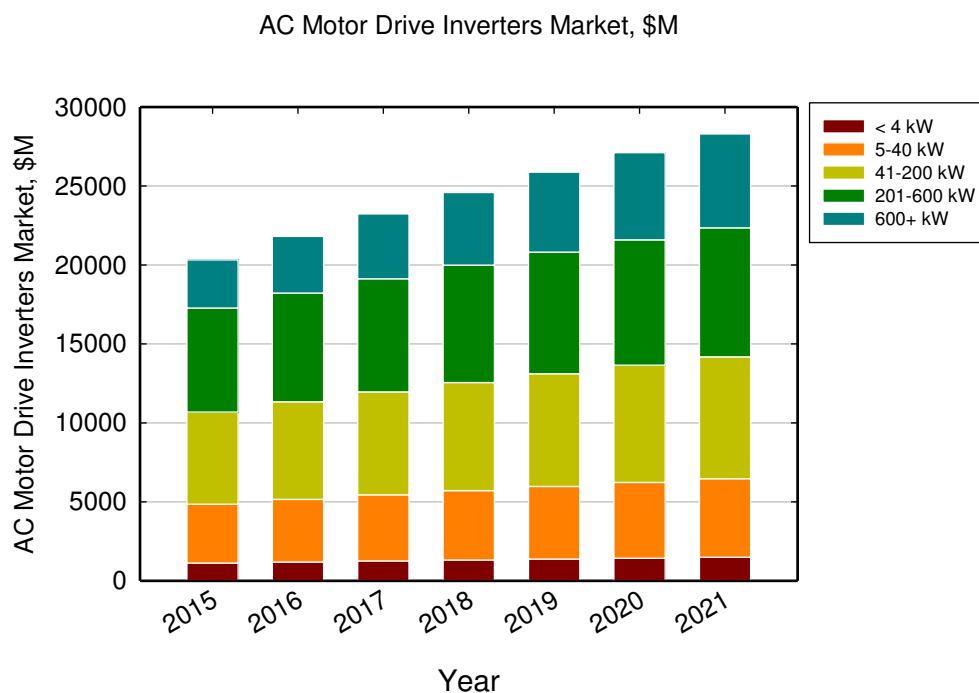


Figure 55 AC motor drive inverters market. Based on information from [3].

11 Railways

11.1 Power devices & modules

YOLE, [1] expects SiC market in this application to accelerate around 2019.

The voltage range for this application is 1.7 kV, 3.3k V, 4.5 kV and 6.5 kV, all of which are suitable for SiC device. However, the utilization of SiC devices must overcome some technological barriers such as reliability, availability of high-voltage and high current-ratings for this application.

YOLE, [1] expects SiC power module introduction in trains within the coming 3-4 years. In the beginning of the adoption, 1.7 kV and 3.3 kV devices and power modules will be implemented in auxiliary and then propulsion systems.

SiC diode and FET in Trains, MUnits

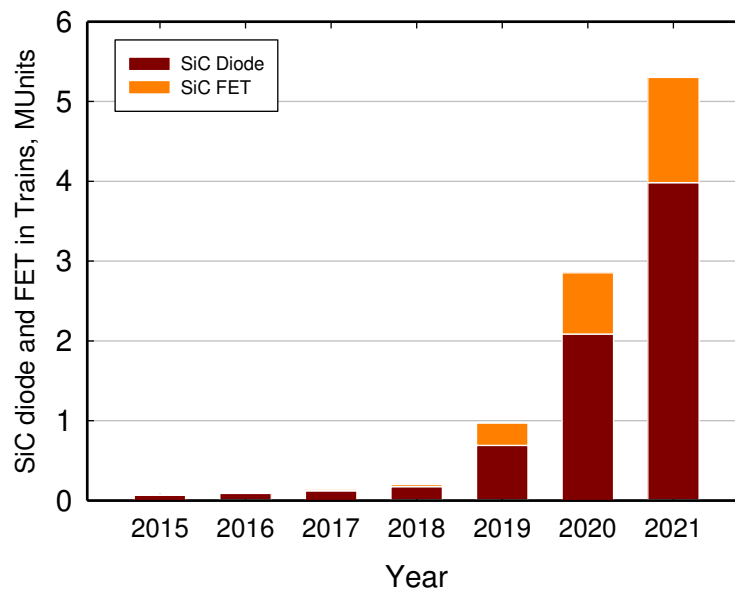


Figure 56 SiC device market for trains in units. Based on information from [1].

SiC diode and FET in Trains

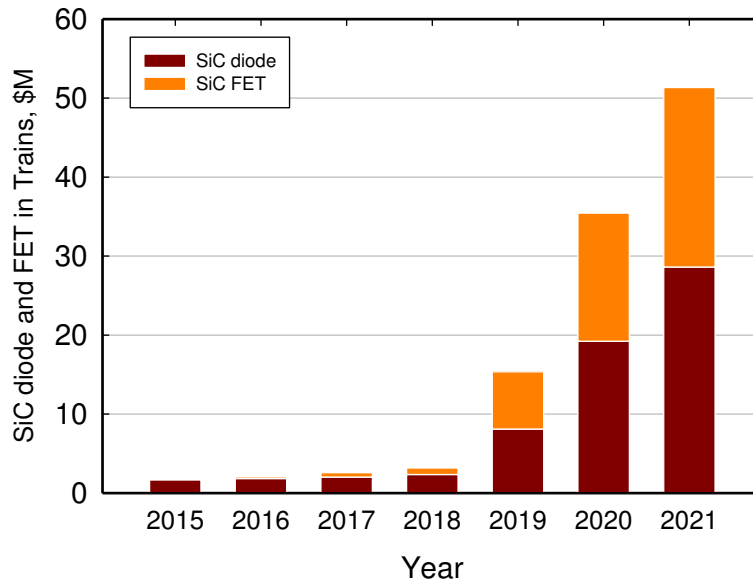


Figure 57 SiC device market for trains. Based on information from [1].

11.2 Manufacturers

According to [3], the merger between the two giant Chinese companies CSR & CNR has made them (CRRC) the leader of the rail traction market which occupies over 40 % of the whole market.

Bombardier, Alstom, and Siemens are in the following positions.

Alstom decided to focus on the rail business and sold its two energy divisions to GE.

2015 Main Train Manufacturer Market Shares, %
(Rolling stock market shares)

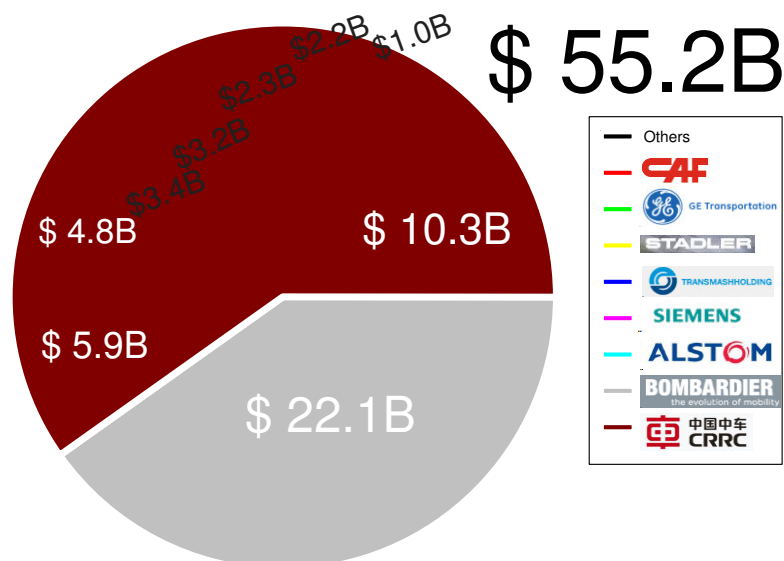


Figure 58 Train manufacturers market split in 2015. Based on information from [3].

11.3 Markets

In this application, inverter market revenues come mostly from Electrical Multiple Units (EMUs) with over \$2 billion market share which accounts for approximately 40 % of the whole market.

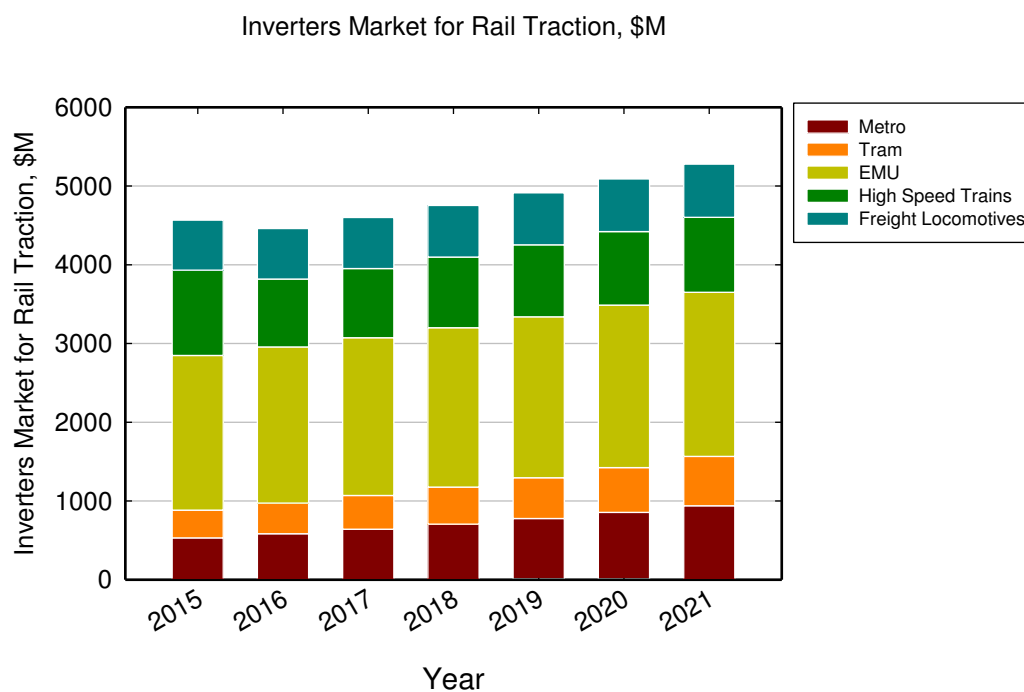


Figure 59 Inverter market for different train types. Based on information from [3].

12 UPS, data centers, base stations for telecom

12.1 Power devices & modules

According to [1], UPS market is slow to adopt new materials and technologies. UPS makers will wait for prices to drop before adopting SiC. Nevertheless, SiC module makers are very motivated to enter the UPS market.

SiC diode and FET in UPS, MUnits

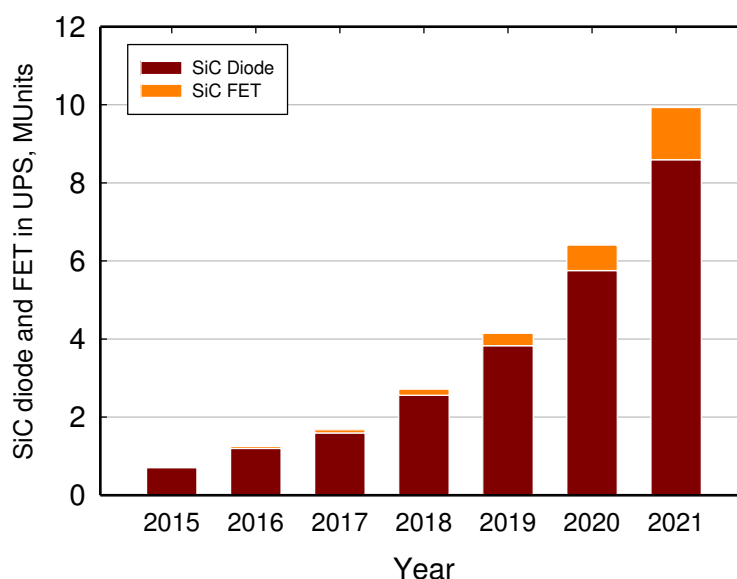


Figure 60 Market forecast for SiC diodes and transistors for UPS during 2015-2021 in units. Based on information from [1].

The SiC device market for UPS is expected to be more than \$40M by 2021.

SiC diode and FET in UPS

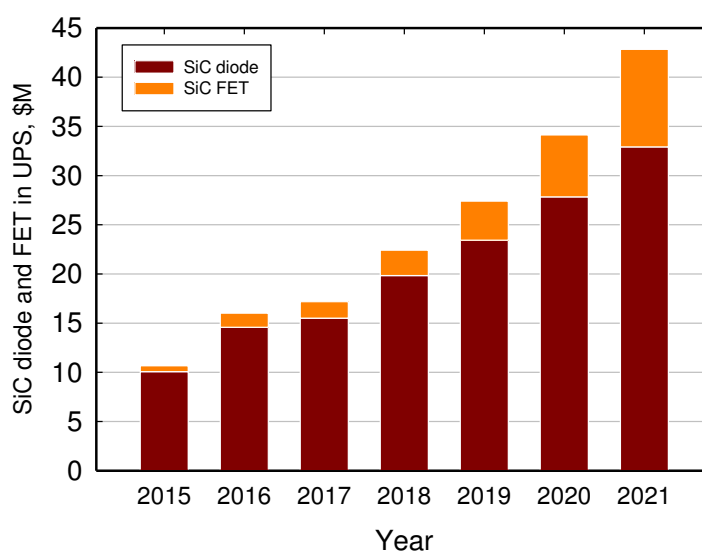


Figure 61 Market of SiC diodes and transistors for UPS during 2015-2021. Based on information from [1].

According to [2], this market for GaN devices is expected to begin from 2019 with modular UPS application and to reach \$2.5M by 2021.

However, GaN devices are not yet mature enough to support high voltage and current ratings for this application. Therefore, a limited penetration of GaN devices to UPS market segments over the next five years is predicted.

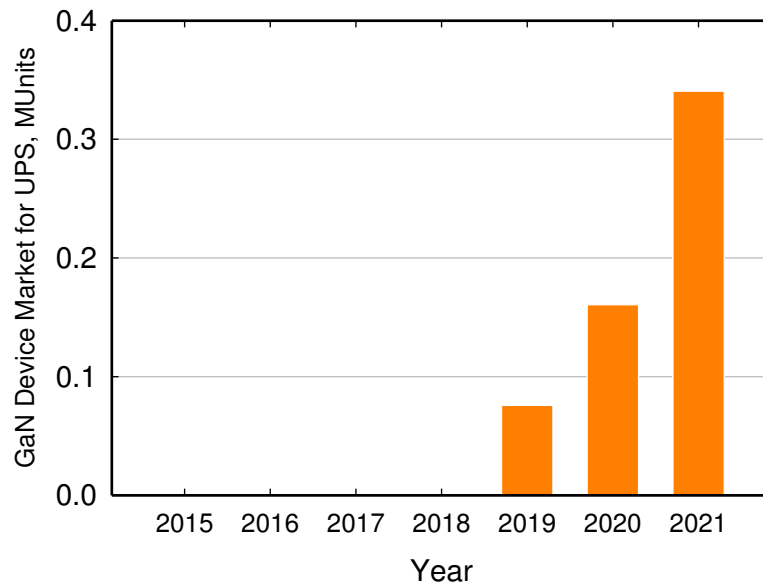


Figure 62 GaN device market for UPS in units. Based on information from [2].

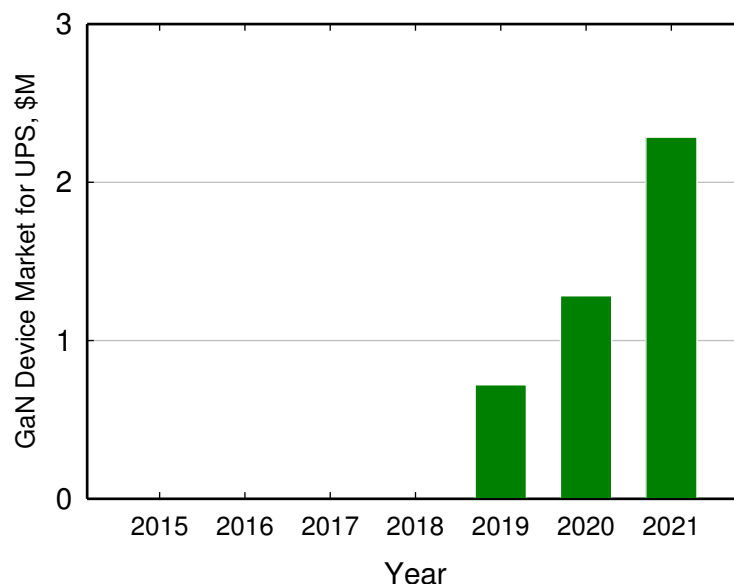


Figure 63 GaN device market for UPS. Based on information from [2].

12.2 Manufacturers

Emerson Electric and Schneider Electric own together half of the UPS market for data centres.

Total market was around \$8.4 billion in 2015.

2015 Large UPS Market Shares for Data Centers, %

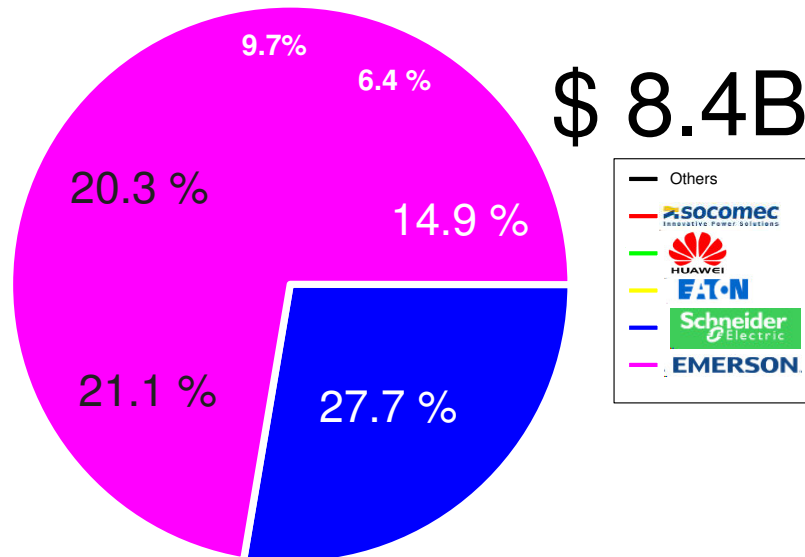


Figure 64 Large UPS manufacturer market split in 2015. Based on information from [3].

12.3 Markets

According to [3], the large UPS market will have the strongest growth driven by the expansion of data centres. Low-power UPS represent over 90 % of the whole market by volume but less than 50 % of revenues.

UPS is one of the biggest segments for power electronics by annual production volume and market.

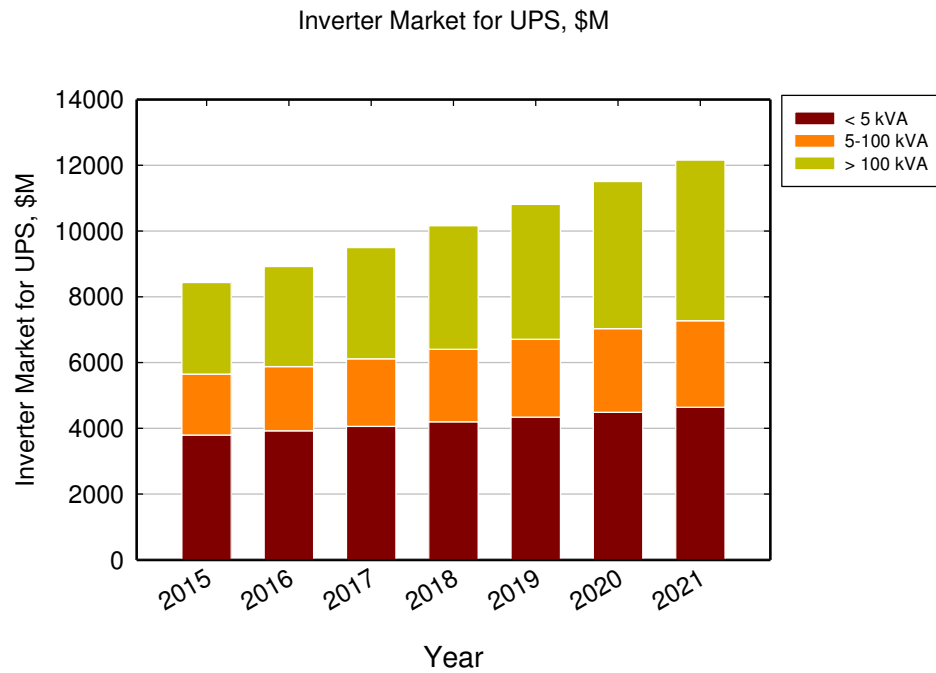


Figure 65 Inverter market size for UPS split by power range. Based on information from [3].

13 Emerging applications

13.1 Power devices & modules

a) Wireless Power application

The primary target is expected in resonant coupling circuit for wireless communication technology. In particular, GaN-based devices has the benefit of higher frequency than existing MOSFETs and allow a higher efficiency, which are crucial factors for wireless charging application. By using GaN transistors, we can have multi-mode systems that are compatible with different wireless charging standards.

This market is not activated yet. But, YOLE expects the market to grow from 2016, reaching more than 10M\$ by 2021.

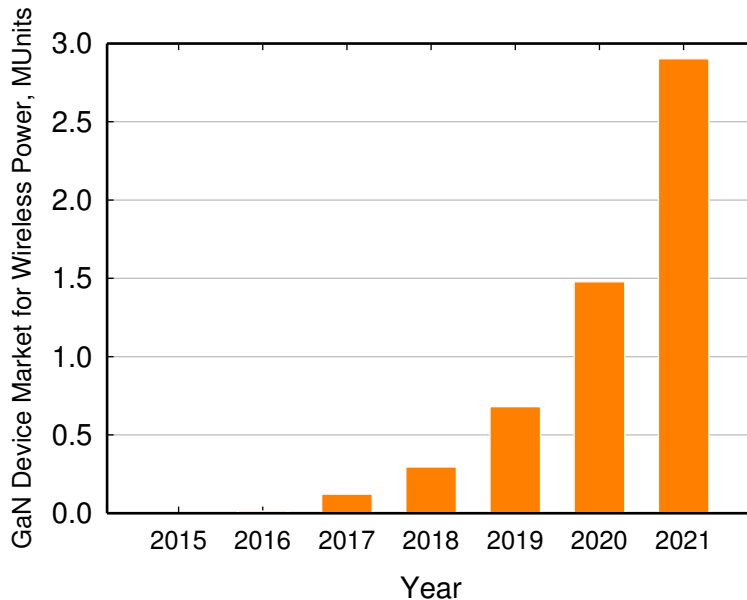


Figure 66 GaN device market for wireless power in units. Based on information from [2].

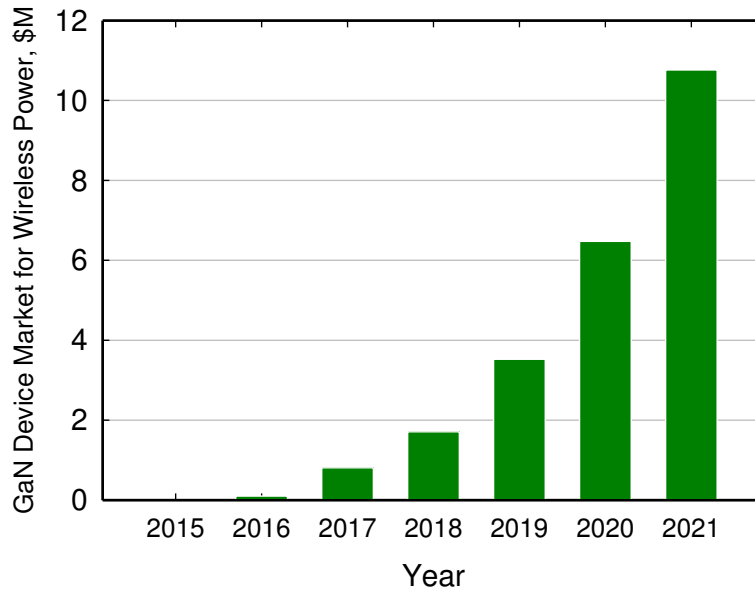


Figure 67 GaN device market for wireless power. Reproduced by [2].

b) Envelope tracking (ET)

In this application, power amplifier efficiency with increasing power and limited battery capacity has been a challenge for industries. GaN devices could be used in adaptive switching power supply in order to save energy and reduce heat dissipation.

Market expectation is still small in 2015. However, market is anticipated to grow to around 18M\$ by 2021 due to the increasing number of base stations requiring ET.

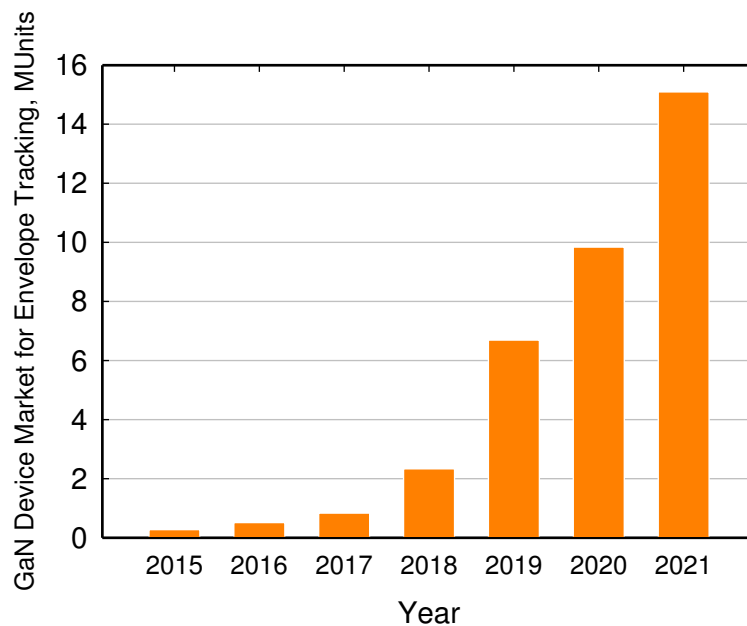


Figure 68 GaN device market for envelop tracking in units. Based on information from [2].

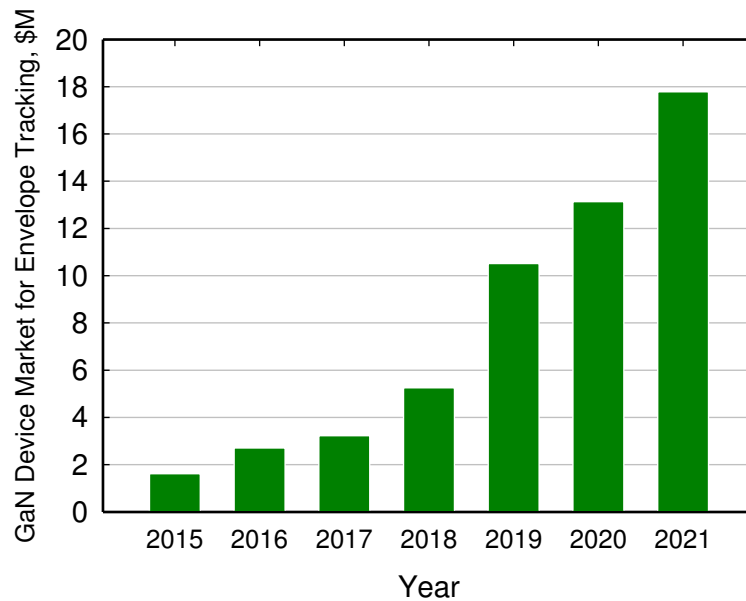


Figure 69 GaN device market for envelope tracking. Reproduced by [2].

c) Lidar applications

Higher switching speed is required in the application because LiDAR uses pulsed lasers to rapidly create a three-dimensional image of a surrounding area. From this point of view, GaN devices could give LiDAR systems superior resolution with faster response time and greater accuracy.

This market for GaN devices is still quite small since it is in the initial stage of introduction into the application but is anticipated to reach around 36M\$ by 2021.

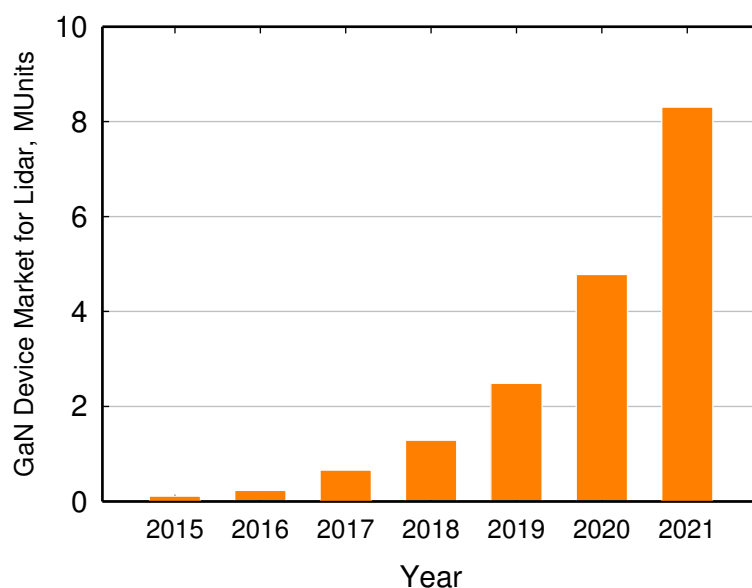


Figure 70 GaN device market for Lidar in units. Based on information from [2].

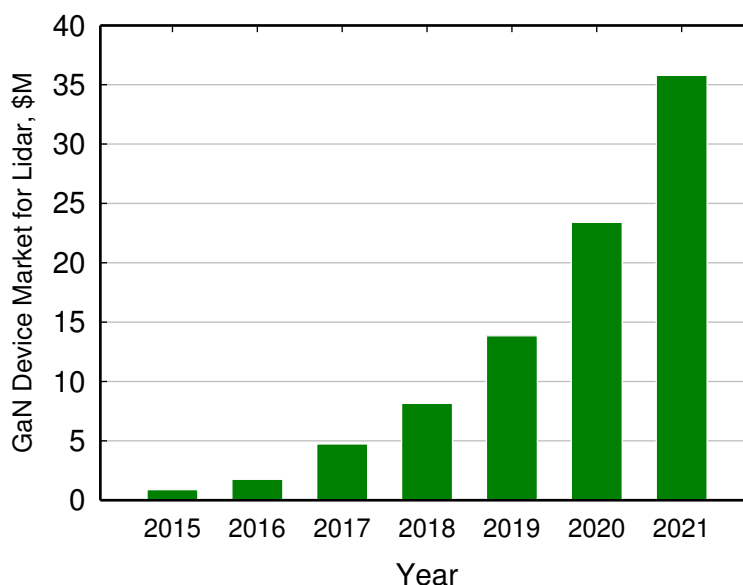


Figure 71 GaN market for Lidar. Based on information from [2].

13.2 Manufacturers

There are many companies working with wireless charging many belonging to the two international associations for adoption of wireless charging standards AirFuel Alliance and the Wireless Power Consortium. The leading players on the Wireless Charging market for GaN are EPC, Murata and Navitas Semiconductor.

The main players on the Envelope Tracking and Lidar markets for GaN are EPC, Velodyne and Quaenergy.

13.3 Markets

Wireless charging. So far, wireless power is mainly for mobile electronics, i.e. smart phones and tablets. Wireless power is expected to extend into numerous domains including toys, home appliances, medical devices, and military devices. Despite several advances, Yole believes that wireless charging for electric vehicle powering is still in an early stage and not likely to become widespread in the near future. Several issues, i.e. cost, safety, charging station-car positioning, efficiency, and worldwide standards compliance still require resolution.

Envelope Tracking (ET). The implementation of ET in base stations began several years ago. Since then, it has gained in popularity because it permits a significant reduction in power dissipation and operational temperature, as well as higher total efficiency.

- Telecom operators are now demanding radio equipment that offers high flexibility, small size, and above all, high energy efficiency. The availability of broadband PAs with efficiency approaching 50% is critical to meeting these needs, and ET is a key enabling technology. In 5G technology, the efficiency need is even greater. Replacing the switching device with a GaN HEMT, improves in overall ET efficiency and increases system bandwidth.

LiDAR stands for Light Distancing and Ranging, a remote sensing technology that uses a laser to measure the distance to a target. Main LiDAR platforms include aerial, satellite, and

automotive applications. For a long time, LiDAR has been used for military and government applications dedicated to remote measurement and mapping.

Due to various technological advancements and cost-effective solutions, LiDAR is penetrating into commercial sectors like ADAS (advanced driver assistance systems), corridor mapping, mining, wind measurement, augmented reality, and robotics. Since LiDAR permits 3D mapping by sending a laser beam that moves a full 360 degrees, it is also considered the breakthrough technology in autonomous cars.

Since LiDAR uses pulsed lasers to rapidly create a three-dimensional image of a surrounding area, a higher switching speed is demanded in the circuit design. GaN's high-frequency switching gives LiDAR systems superior resolution, faster response time, and greater accuracy.

As of 2016, LiDAR's automotive presence is minimal. However, by 2021 the LiDAR automotive market is expected to be as high as that of industrial applications. Recent investments in Velodyne and Quaenergy are very positive signs for the market.

14 WBG market potential

14.1 Power devices & modules

The large power inverter markets (EV/HEV, wind turbines, PV inverters, rail traction, UPS and industrial motor drives), are all promising business opportunities for power electronics.

14.2 Inverter market

The automotive industry is by large the main inverter market in units.

According to [3],

- PV market segment will continue growing and reach approximately 7 billion\$ in 2021.
- EV/HEV market segment has largest potential, with the strongest CAGR of 19.5 % during 2015-2021.
- Wind turbine market segment suffered a painful decrease around 20% in 2013, but had a historical revenue over 4.7 billion\$ for 60GW in 2015. Negative market expectation is estimated with a CAGR of -1.7 % during 2015-2021.
- Rail market segment will increase slowly with a CAGR of +2.4 % during 2015-2021. New markets can be introduced from Iran or China which will boost this market.
- UPS market segment is expected to grow and reach 12 billion\$ in 2021, especially in new data centre installations.
- Industrial AC motor drivers will continue to lead inverter demand with more than 40% of the whole market.

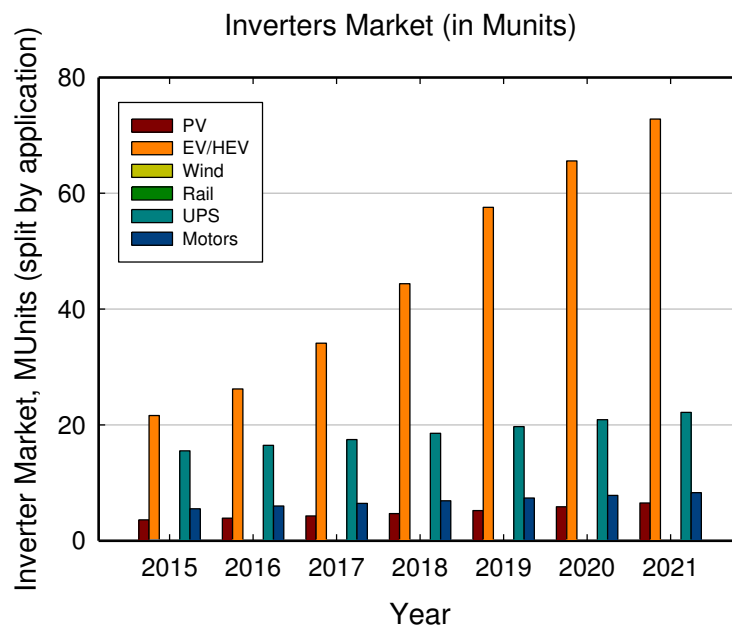


Figure 72 Whole inverter market in units split by application. Based on information from [3].

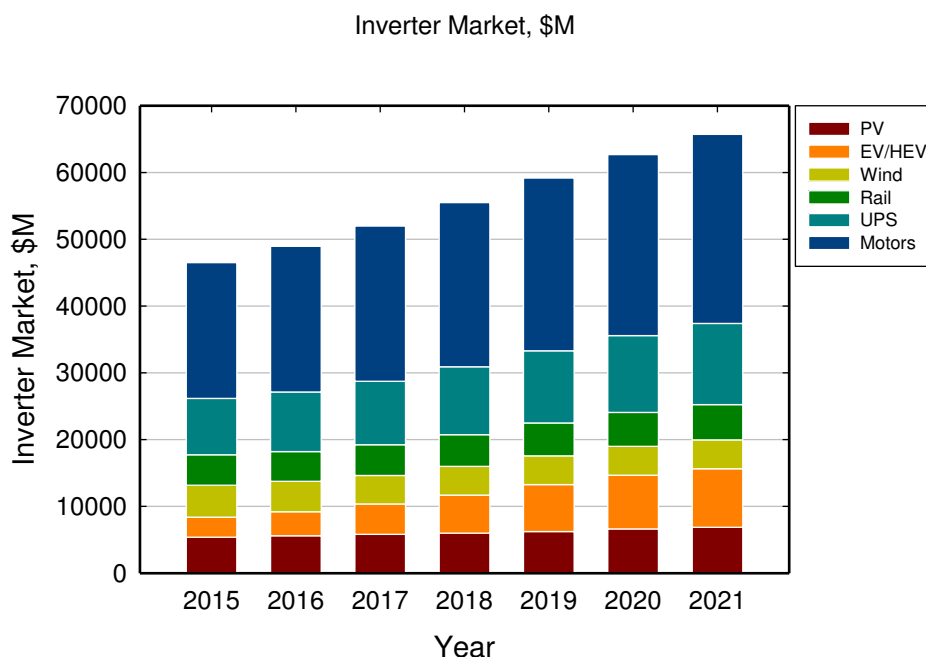


Figure 73 Inverter market forecast split by application. Based on information from [3].

14.3 Technical challenges

On the technological level, the power electronics industry will evolve more in the next 5 years than during the last 10–15 years.

The inverter market shows a CAGR 2015-2021 of almost 6%, which is considerably higher than most other industrial markets.

EV/HEV shows the highest annual growth rate with +19.5%!!!

UPS, industrial drives and PV will also have a CAGR around 5%–6%.

However, wind turbine converter market will decrease a bit, due to its flat market and decreasing power converter prices.

Rail traction market will also have one of the smallest annual growth rates of about 2.4%.

The market is getting very competitive, due to new entrants in some of the attractive markets and also due to the stronger position of Chinese players.

Chinese players are leading wind turbine and rail traction markets, with Gold wind and CRRC. But also threatening historical leaders such as SMA in the PV inverter market (by Sungrow and Huawei).

The integration of SiC and GaN devices will transform the way inverters are designed. Engineers and companies will have to adapt to these new technologies, with new solutions required in terms of power packaging, thermal management and passive components.

Several technical challenges are to be overcome in the next 5 -10 years.

OEMs are seeking two main technical targets: higher efficiency and power density (compactness). With the objective to increase efficiency and power densities, many new technical challenges need to be addressed.

Main efforts on power density are being done in the automotive industry, and followed by interest in the aerospace industry.

Transnational Roadmap

At the inverter level new trends with shared cooling systems or air-cooled systems will be increasingly used. The objective being to reduce the volume and the cost of the whole system.

At power module level, main innovations are coming from double-sided cooled modules, which improves their thermal management and the performance of the devices. New power packaging technologies, such as silver sintering will also become widespread as well as low inductive designs of power modules and systems.

Silicon carbide devices will enable higher power densities at the device and system level with enhanced performances.

Efficiency improvements are a must in most of applications.

Converter topologies, architecture and their control strategies are also key to efficient power conversion inverters.

For the next 5–10 years most innovations and improvements will come in the field of SiC and GaN device integration in converters.

The possible integration of SiC and GaN devices in the automotive industry will have a major impact on the whole power electronics market.

According to [1], many efforts are still needed by power business players with following issues, in order to take full advantage of SiC power devices.

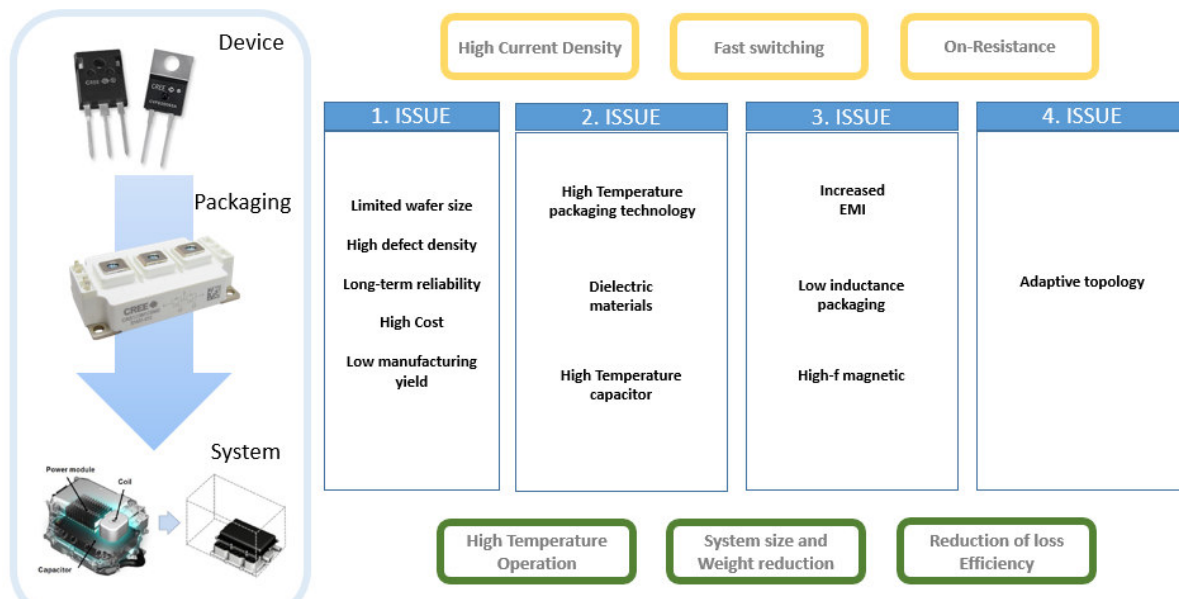


Figure 74 Expected benefits from device to system with SiC-based power devices vs issues.
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14.4 Price development

An example of the device cost breakdown is given in Figure 14.4.

SiC-Based MOSFET DEVICE COST BREAKDOWN

Based on System Plus' reverse cost analysis

Manufacturer	Device Type	Breakdown voltage	Current @ 25 °C	Wafer Size	Die area	Pitch	Current Density
CREE	Planar	1200 V	36 A	100 mm	10.4 mm ²	9 μm	3.46 A/mm ²
ROHM	Planar	1200 V	40 A	100 mm	12.7 mm ²	12 μm	3.16 A/mm ²
ROHM	Trench	1200 V	36 A	100 mm	12.9 mm ²	6 μm	2.77 A/mm ²

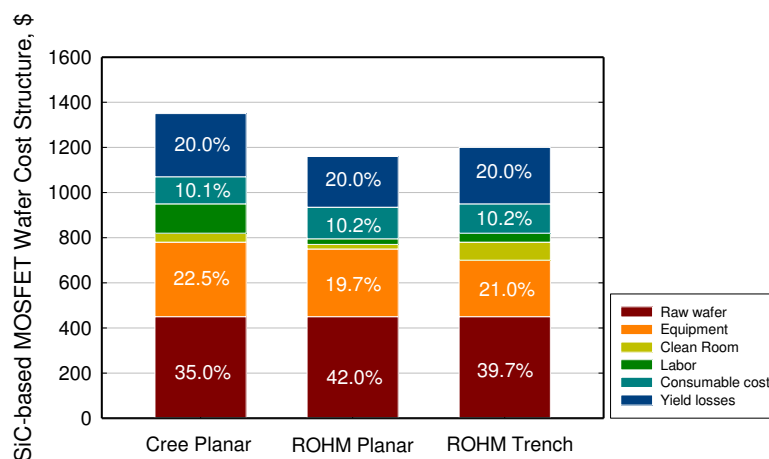


Figure 75 SiC MOSFET cost breakdown. The cost of the SiC MOSFET is calculated to be 3.05, 3.12 and 3.4 \$/device, respectively, counting from left to right. Based on information from [1].

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Project Facts

- 17 project partners: research institutions, companies and technology transfer organisations
- Duration from 2016 to 2019
- Budget: EUR 3.1 million
- European Regional Development Fund
- Interreg Baltic Sea Region Programme
- Led by University of Southern Denmark

Project Partners

- University of Southern Denmark (Denmark)
- Applied Research Institute for Prospective Technologies (Lithuania)
- Christian Albrechts Universität Kiel (Germany)
- CLEAN (Denmark)
- Converdan A/S (Denmark)
- Kaunas Science and Technology Park (Lithuania)
- Kaunas University of Technology (Lithuania)
- Latvian Technological Center (Latvia)
- NATEK Power Systems AB (Sweden)
- Polish Chamber of Commerce for Electronics and Telecommunications (Poland)
- Renewable Energy Hamburg (Germany)
- RISE Research Institutes of Sweden AB (Sweden)
- Sustainable Smart Houses in Småland (Sweden)
- Ubik Solutions OÜ (Estonia)
- University of Latvia (Latvia)
- University of Tartu (Estonia)
- Warsaw University of Technology (Poland)