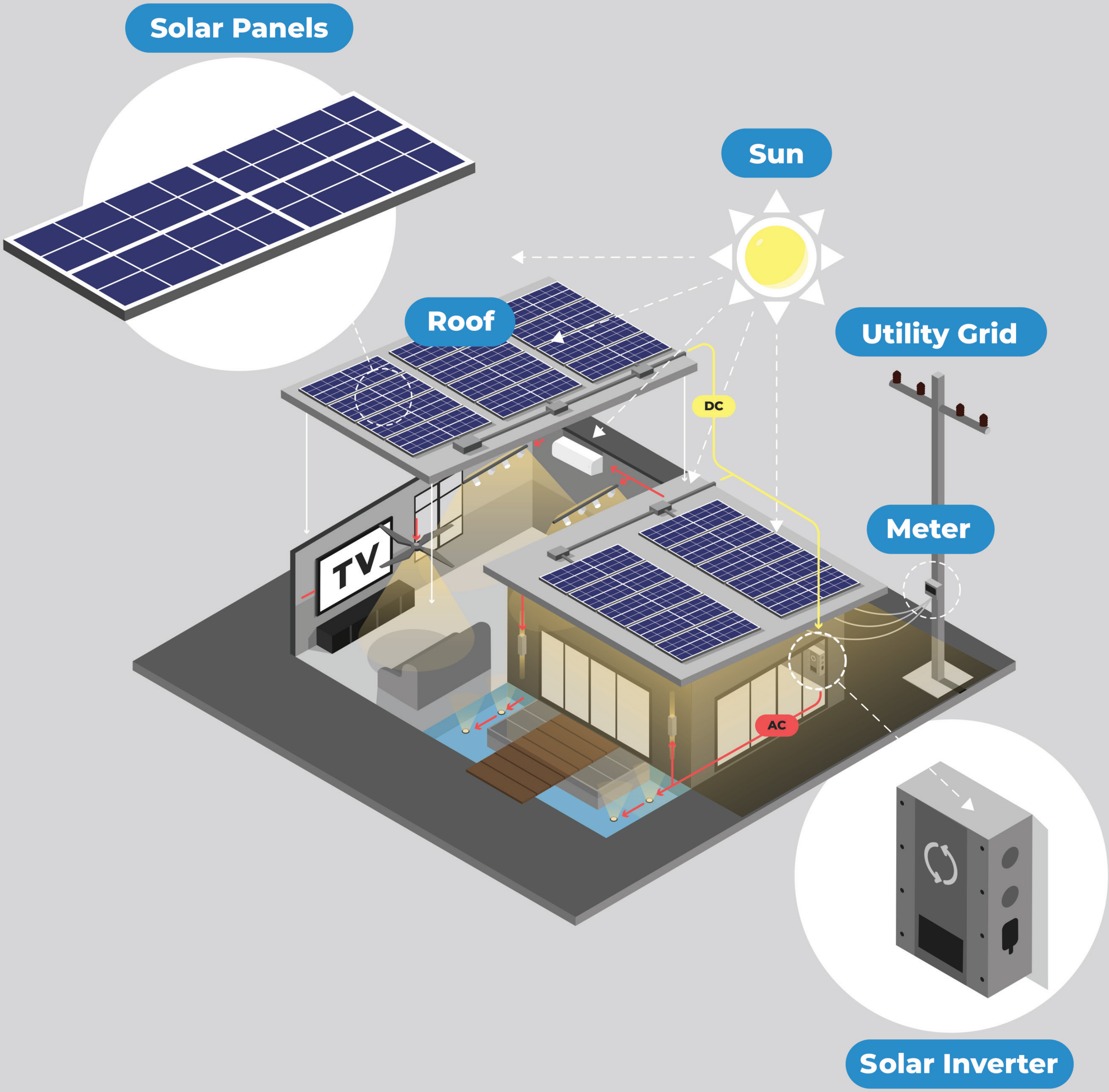

DOE

MARKET RESEARCH STUDY

SiC POWER ELECTRONICS FOR SOLAR

September 2022

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1.0 Introduction

Wide band gap (WBG) materials hold great promise to significantly outperform and eventually replace traditional silicon. Silicon carbide (SiC) and gallium nitride (GaN) have reached a level of maturity that allows use in power electronics applications. SiC is regarded as a stronger candidate for power electronic applications above1.2kV, while GaN is ideal for high-frequency applications in applications below 1200V. Existing 200 mm silicon wafer semiconductor fabrication plant (commonly called a fab or foundry) can be used for SiC manufacturing.

Table 1: WBG Materials

Materials	Chemical Symbol	E_g (eV)
Silicon Carbide	SiC	3.3
Gallium Nitride	GaN	3.4
Zinc Oxide	ZnO	3.4
Gallium Oxide	β-Ga_2O_3	4.8-4.9
Diamond	C	5.5
Aluminum Nitride	AlN	6.0

Source: MarketsandMarkets. "Silicon Carbide Market – Global Forecast to 2025." (February 2020).

The growing market demand for SiC-based power electronics is driven by the rising adoption of SiC devices by original equipment manufacturers (OEMs) of electric vehicles and hybrid vehicles (EVs) in the power electronics market. Market consulting firm, Frost & Sullivan believes that the majority of OEMs will transition to SiC in advanced power electronics by the end of the decade. SiC technology is being used in EV low power applications such as battery chargers, auxiliary DC- DC converters and solid-state circuit breakers as well as EV inverters. Market consulting firm, Yole Développement (Yole) sees a "prospering" EV market holding more than 60% of total device market share in 2025. Another consulting firm, IHS Markit, expects the annual global SiC revenues to reach over $5 billion by 2027, with electric and hybrid vehicles making up the majority of the sales.

With respect to solar, the reduction in price makes it possible to potentially produce inverters and transformers (the systems that would use these chips) in the U.S. This report provides an overview of the silicon carbide device market, the benefits of SIC for solar inverters, as well as the supply chain and key players.

2.0 Silicon Carbide Device Market

After a brief introduction to SiC- based power electronics in the automotive industry, this section explores the possibilities with solar applications.

2.1 Trends – Inverter Market is Led by Automotive Industry

The growing demand for SiC-based power electronics is driven by the rising adoption of SiC devices by OEMs of electric vehicles (EVs). According to market consulting firm Yole Développment, the inverter market is driving the overall SiC-based EV market and is expected to remain the sector with the highest potential for the overall power SiC market.[1] Some EV applications are using SiC technology, primarily for low power applications, such as battery chargers, auxiliary DC-DC converters, and solid-state circuit breakers. SiC devices are also used in EV inverters. Frost & Sullivan anticipates SiC to increase its penetration in EV powertrain from about 4% in 2021 to about 20%–25% in 2026.[2]

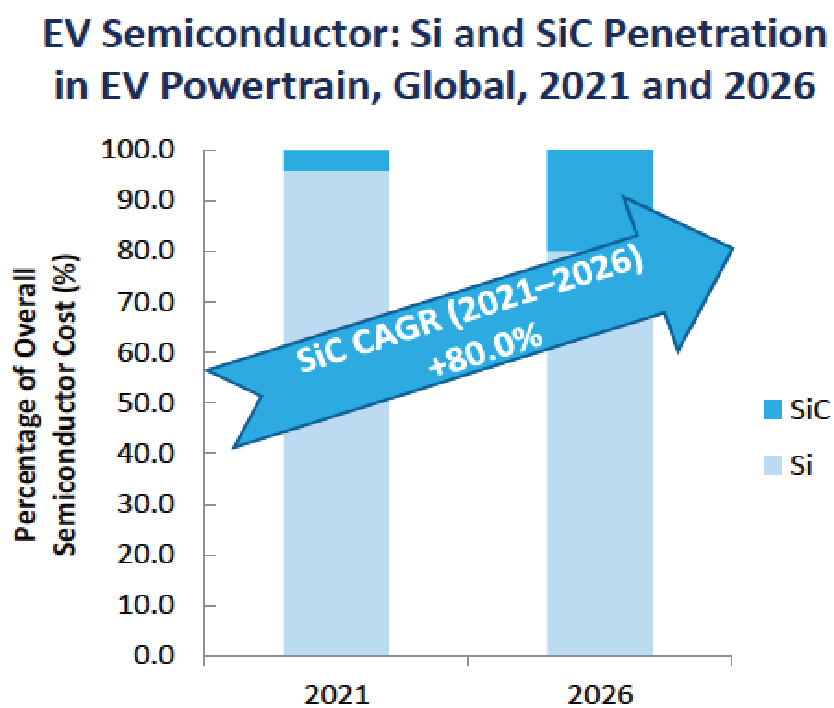

Figure 1: SiC Penetration in EV powertrain
Reprinted with permission of Frost & Sullivan. [3]

After EVs, the next largest use case for SiC is expected to be in photovoltaics, specifically in storage, where efficiency improvements can reduce the size of a battery, both in residential and larger installations.[4] Figure 2 provides a roadmap for SiC modules and MOSFETs as proposed by Yole Group, a firm which specializes in market research, technology and strategy analysis, and photonics module performance evaluation, focused on the semiconductor industry and related fields.

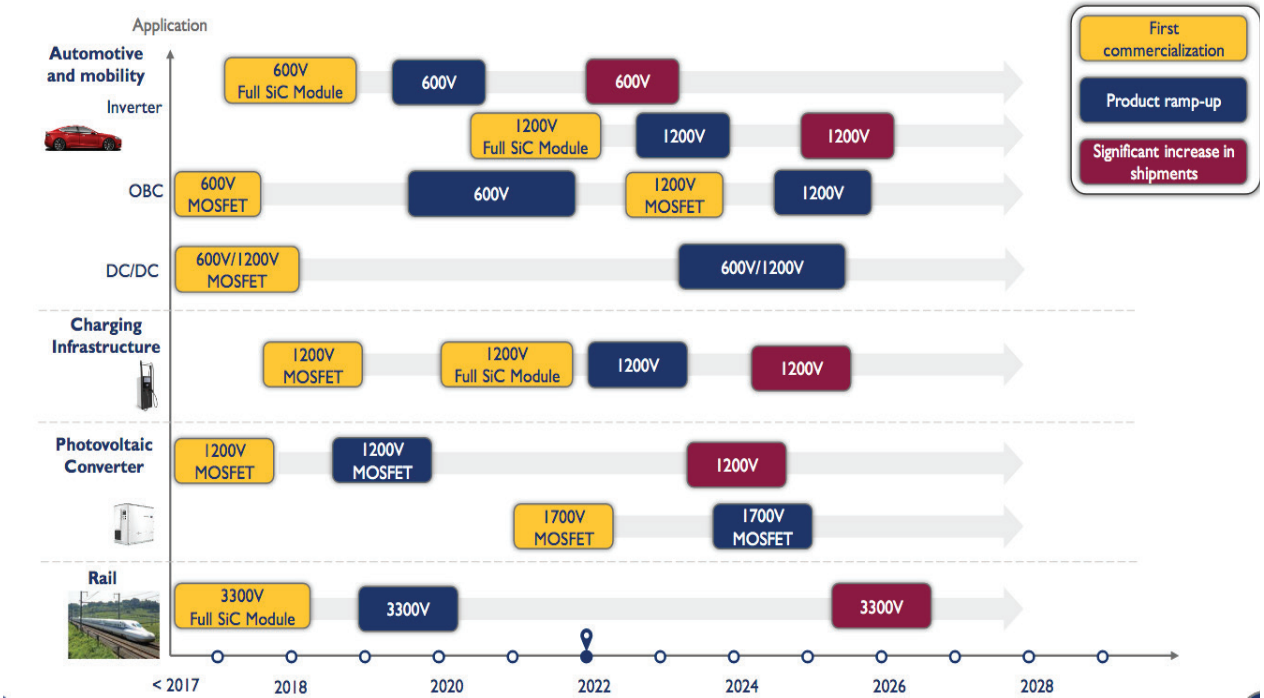

Figure 2: SiC Power application Roadmap
Source: Yole Développement. (2022).[5]

The trend towards EVs is creating a need for fast DC charging. In this application, SiC-based components can provide better performance than traditional Si and insulated-gate bipolar transistor (IGBT) components due to their improved operating temperature, better conduction losses, lower leakage currents, higher surge capacity and max voltage ratings, and overall better power density.[6] The 800V, which fills this need is expected to drive the SiC market and eventually become the standard in EVs.[7] Renewable energy, specifically photovoltaics with the benefit of decarbonization is also driving the market.[8]

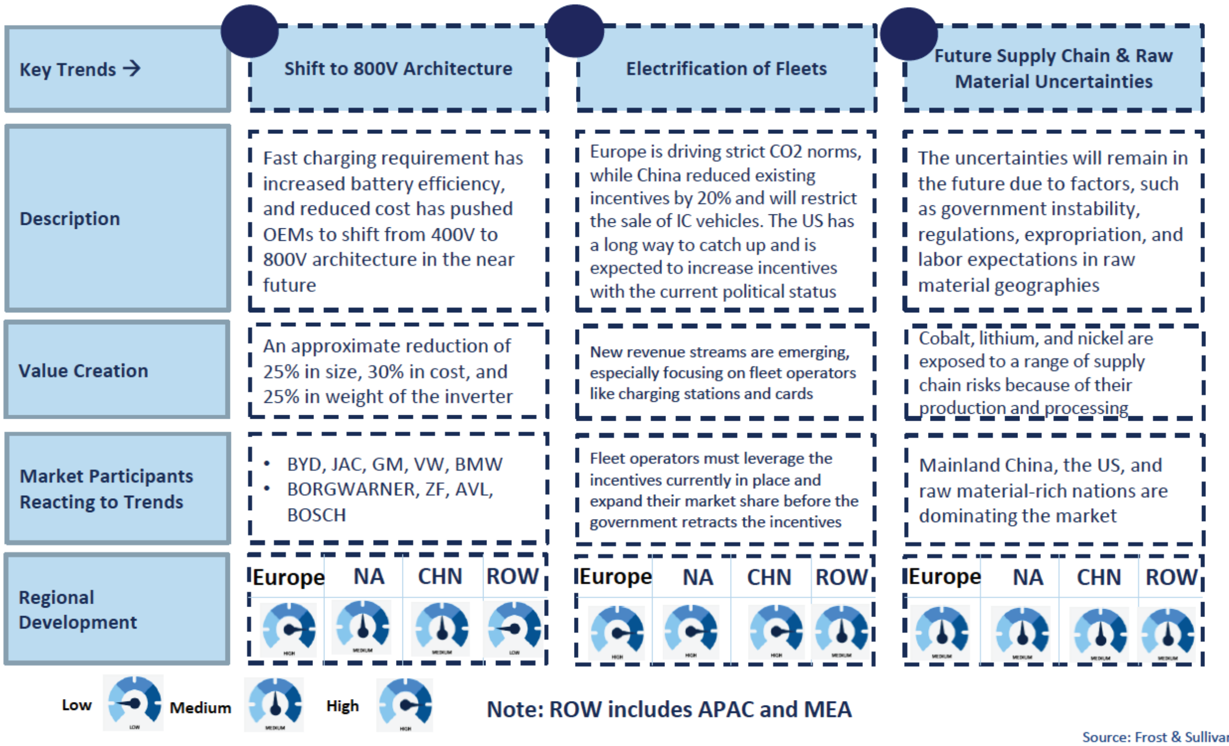

Figure 3: 800V architecture benefits in EVs.
Reprinted with permission of Frost & Sullivan.[9]

Automotive OEMs are expected to shift to 800V architecture due to cost, size, and weight, higher power density and efficiency advantages. Examples include:

- **Inverters**: The transition from silicon-based IGBTs and fast-recovery diodes to Wide-bandgap semiconductors such as SiC MOSFETs enables higher switching frequencies up to 20kHz with power outputs up to 200kW.
- **Onboard chargers**: While Si-MOS/IGBT and SiC Schottky barrier diodes (SiC-SBDs) are the most prevalent currently, the industry is already on the way to adopting SiC-SBD/ SiC-MOSFETs for power outputs up to 20kW.
- **DC-DC and DC-AC converters**: SiC-MOSFETs is fast becoming the preferred choice for converters, with power outputs up to 50kW for DC-DC converters and up to 4kW for DC-AC converters.
- **800V architecture**: 800V systems using SiC materials are a key enabler for fast charging, gaining significance for increased EV penetration.[10]

Figure 4 is an automotive inverter roadmap (2022-2035) prepared by market research firm Frost & Sullivan. This figure shows their predicted timeline for the replacement of optimized Si semiconductor devices with SiC and GaN devices. This Figure also highlights anticipated improved performance of inverters.[11]

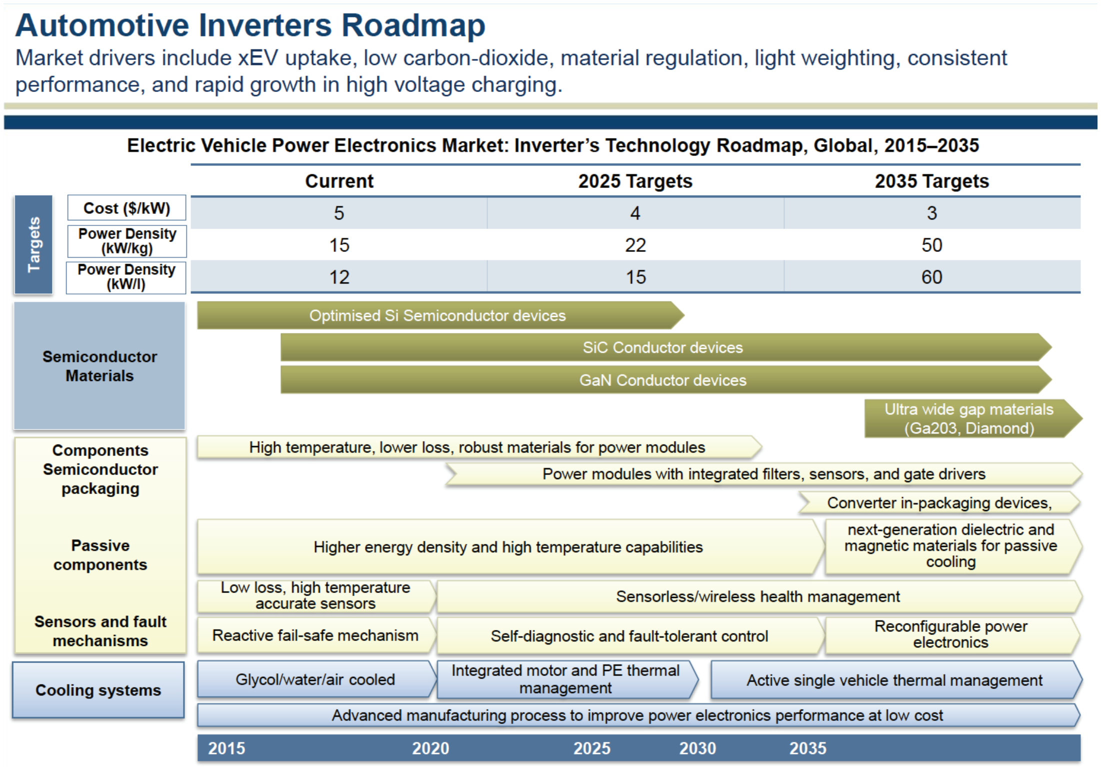

Figure 4: Roadmap for Automotive Power SiC / GAN Devices
Reprinted with permission of Frost & Sullivan.[12]

Below is a summary of selected partnerships which demonstrates the extent to which manufacturers are collaborating with SiC device vendors. Tesla structured its SiC supply chain with its own module-design intellectual property that was codeveloped with STMicroelectronics and Boschman – with STMicroelectronics manufacturing the devices.[13]

Table 1: Summary of Selected SiC EV Inverters

Year	Developer/ Manufacturer*	Specifications	SiC Device Supplier
May 2022	Nio, Inc.	NIO Inc. chose the latest VE-Trac™ Direct SiC power modules from onsemi for its EVs. "The VE-Trac Direct SiC is an integrated single side direct cooling (SSDC) power module in a six-pack configuration with a low turn on resistance of 1.7 mohm."[14]	onsemi

April 2022	Lucid Motors	SiC MOSFET – "with low switching losses, minimal resistance, and high-power density, the XM3 power modules contribute to the efficiency and power density of Lucid's 163-lb, 670-hp (74kg 500kW) electric motor."[15]	Wolfspeed
March 2022	Semikron	"ST and Semikron cooperated to integrate STPOWER SiC MOSFETs, which control power switching in the main EV traction inverter, with Semikron's innovative fully sintered Direct Pressed Die (DPD) assembly process. DPD enhances module performance and reliability and enables cost-effective power and voltage scaling. Leveraging the parameters of ST's SiC MOSFETs, supplied as bare dice, Semikron has established 750V and 1200V eMPack platforms, addressing applications from 100kW to 750kW and battery systems from 400V to 800V."	
November 2021	BorgWarner	BorgWarner won a supply order, scheduled to start in 2023 for 400-volt silicon carbide inverter for various BEV models from a European OEM. The 400-volt silicon inverter as part of BorgWarner's iDM integrated drive module, whose customers include Hyundai and an unnamed "leading Chinese luxury electric vehicle brand."[16]	NA
2021	Vitesco Technologies, the Spin-off of Automotive Supplier Continental	Vitesco is supplying an 800-volt SiC inverter for Hyundai Motor Group's electric vehicle platform. The order volume is in the "three-digit million € range, and the quantities are likely to be correspondingly high. …. Vitesco Technologies uses semiconductors made of silicon carbide for the 800-volt inverter, which significantly increase the energy efficiency."[17]	NA
2020	VisIC Technologies (Israel)	GaN for 800V power-bus motor inverter, which can be used for an EV motor drive.[18]	NA
2020	Delphi Technologies (Now BorgWarner)	The company announced it has volume production of SiC inverters,enabling electrical systems up to 800 V.[19] Delphi also secured a $2.7 billion customer win for volume production of SiC over eight years with a firm it described as a "premier global OEM." Launchis expected in 2022, initially "for a high-performance vehicle operating at up to 800 V." Delphi is supplying 800-Volt inverters to 3 of top 4 global premium OEMs.[20]	Wolfspeed SiC MOSFETs.

2020	Karma Automotive, Irvine, CA	"Karma Automotive, founded in 2014, is a southern California based producer of luxury electric vehicles, headquartered in Irvine, CA with an assembly plant located in Moreno Valley. Karma sells vehicles via its dealer network in North America, Europe, South America and the Middle East."[21] SiC traction inverters are engineered in-house by Karma's Powertrain Power Electronics team, in collaboration with the Power Electronic System Laboratory at University of Arkansas.[22]	Not disclosed
2021	Vitesco Technologies, the spin-off of automotive supplier Continental	Vitesco is supplying an 800-volt SiC inverter for Hyundai Motor Group's electric vehicle platform. The order volume is in the "three-digit million € range, and the quantities are likely to be correspondingly high. .... Vitesco Technologies uses semiconductors made of silicon carbide for the 800-volt inverter, which significantly increase the energy efficiency."[23]	Not disclosed

**Not an exhaustive list*

2.2 Market Size for Power Electronics by Vertical

A report by consulting firm MarketsandMarkets forecasts that the global SiC device market will grow beyond $2 billion by 2026 from a $899 million business in 2021. Although the market is driven by automotive applications, MarketsandMarkets believes that renewable **energy applications have a higher than 16 percent growth rate over the five years 2021 - 2026**. SiC market for power electronics is projected to hold the largest market share during the same period.[24]

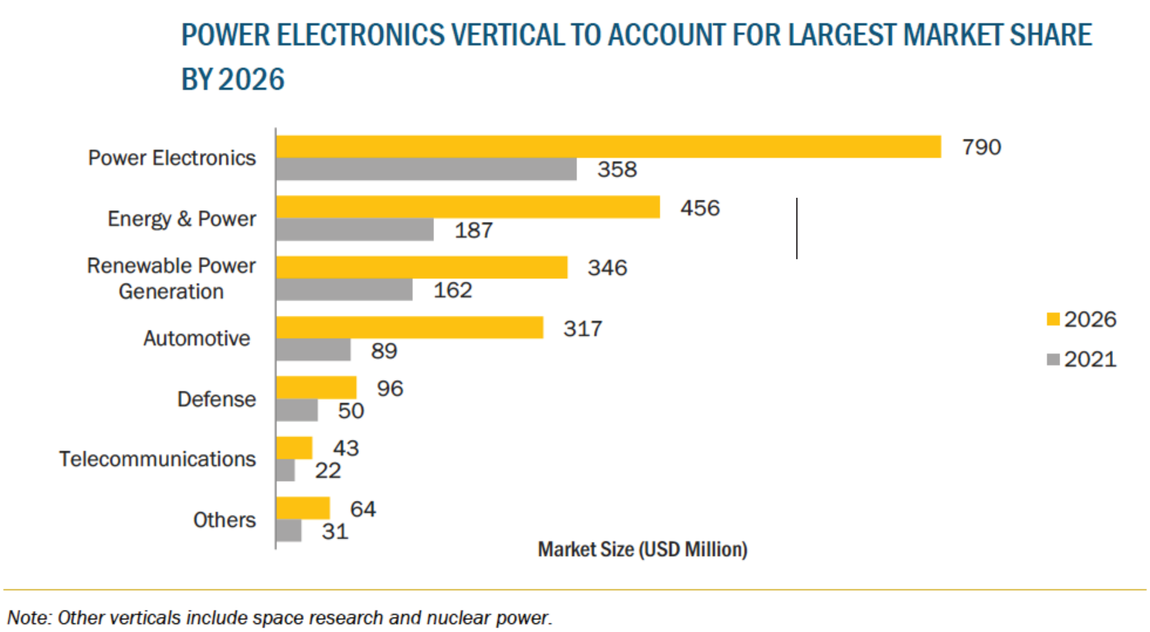

Figure 5: SiC Market devices split by segment
Reprinted with permission of MarketsandMarkets

MarketsandMarkets segments the market by device type (discrete, bare die and module). SiC discrete devices (SiC diodes and SiC MOSFETS), also known as wide-bandgap devices held the largest share of the market. Growth is attributed to the increasing demand for SiC discrete devices for use in numerous applications, including radio frequency and cellular base station applications, as well as in power supplies and inverters.

Table 2: Global SiC for Solar by Device Market, 2021-2026 (USD Million)

Device	2021	2022	2023	2024	2025	2026	CAGR (2021–2026)
SiC Discrete Device	755	906	1,072	1,251	1,442	1,643	16.8%
SiC Bare Die	112	149	195	250	315	390	28.4%
SiC Module	32	39	48	58	68	80	20.3%
Total	**899**	**1,095**	**1,315**	**1,559**	**1,826**	**2,113**	**18.7%**

Source: MarketsandMarkets. (September 2021).[25]

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SiC is of great interest for solar PV and energy storage systems. Various SiC devices such as power modules, diodes, and inverters are used in PV systems, among which, SiC diodes and MOSFET are viewed as the ideal solutions. SiC diodes for solar are projected to grow steadily through 2026, however, the SiC MOSFET segment is projected to grow more than 40%from $82 million in 2021 to $103 million in 2026.

Table 3: Global SiC Market for Solar Power Systems by Discrete Device, 2021-2026 (USD Million)

Device Type	2021	2022	2023	2024	2025	2026	CAGR (2021–2026)
SiC Diode	53	58	61	63	65	65	4.0%
SiC MOSFET	29	39	52	67	84	103	29.1%
Total	**82**	**97**	**113**	**130**	**149**	**168**	**15.4%**

Reprinted with the permission of MarketsandMarkets[26]

The North American SiC market was valued at $234.7 million in 2021, and is expected to reach $538.9 million by 2026, growing at a CAGR of 18.1% from 2021 to 2026.[27] The solar power systems market is expected to grow from $27.3M in 2021 to $60.4 by 2026.

Table 4: North American SiC Market by Application 2021-2026 (USD Million)

Application	2021	2022	2023	2024	2025	2026	CAGR (2021–2026)
Power Grid Devices	32.6	40.7	50.2	60.5	71.8	84.3	20.9%
Flexible AC Transmission Systems	19.3	22.6	26.1	30.0	34.1	38.2	14.6%
High-Voltage Direct Current Systems	9.0	11.0	13.2	15.6	18.2	21.0	18.3%
Power Supplies & Inverters	40.0	47.8	56.4	66.5	77.3	88.9	17.3%
RF Devices & Cellular Base Stations	2.1	2.4	2.7	3.0	3.3	3.5	11.0%
Lighting Control Systems	20.6	23.9	27.3	31.1	35.1	39.0	13.6%
Industrial Motor Drives	20.6	25.1	30.1	35.7	41.7	48.1	18.5%
Flame Detectors	8.5	10.5	12.7	15.1	17.8	20.7	19.5%
EV Motor Drives	8.4	12.8	19.5	26.0	33.7	42.7	38.5%
EV Charging Stations	17.7	21.2	23.6	27.0	30.5	34.0	14.0%
Electronic Combat Systems	13.7	15.9	18.2	20.5	22.8	25.0	12.8%
Wind Turbines	9.6	11.8	14.1	16.7	19.6	22.6	18.6%
Solar Power Systems	27.3	32.9	39.0	45.7	52.8	60.4	17.2%
Others	5.2	6.1	7.1	8.2	9.4	10.5	15.3%
Total	**234.7**	**284.7**	**340.3**	**401.5**	**467.9**	**538.9**	**18.1%**

Note: The market size is represented up to one decimal to exhibit the difference.

Reprinted with permission of MarketsandMarkets [28]

2.3 Market Drivers

MarketsandMarkets identifies the following market drivers: [29]

1. Power electronics continues to evolve as it is the key enabler for solving the future electricity demands. Emerging applications include renewable energy generation, such as solar (mainly photovoltaics); and electrified automobile systems including electric vehicles, trains, and buses; charging infrastructure; uninterruptible power supplies; and motor drives.
2. The market has seen continuous developments in the fabrication of SiC semiconductor power devices such as power MOSFETs, and other discrete devices.
3. New opportunities for innovative designs have resulted from progress made in SiC device technologies as well as advanced manufacturing and packaging techniques, which has enabled higher efficiency, higher power density, and improved equipment reliability.

Research institutions are conducting research in SiC advancements for solar power development. For example, in 2021, Germany's Fraunhofer Institute for Solar Energy Systems reported it had successfully developed a 250-kW SiC inverter that can be used in utility-scale PV projects. Compared to a standard PV inverter using silicon transistors, the SiC inverter eliminates the need for a 50 Hz.

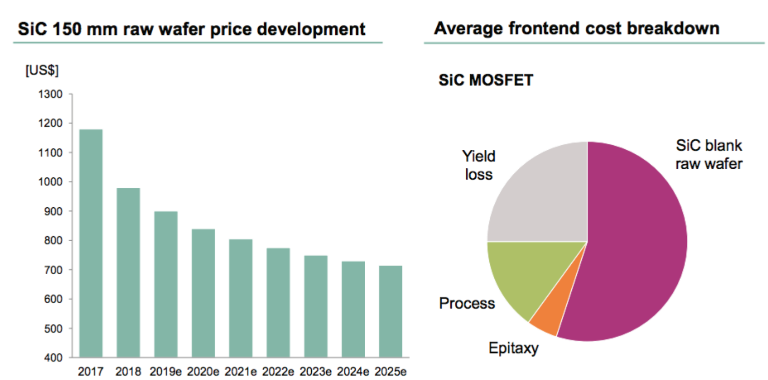
2.4 Market Barriers

Although SiC has gone beyond the period when SiC power devices were deemed as the "next-generation devices", the number of applications continues to increase. However, barriers to the widespread adoption of SiC power electronics, especially in applications such as solar, remain. Yole identifies various market barriers including: "*SiC transistors still have some technical and commercial challenges to face, despite the value they add. These include the wafer price and the complexity of some process steps, specifically SiC etching and high temperature implantation. These challenges still hinder SiC adoption on a large commercial scale.*" [30] The following table summarizes barriers seen by various sources.

Table 5: SiC Power Electronics Barriers

Barrier	Description
Cost	"Over the past 10-20 years, the main challenges of SiC have shifted significantly from performance (demonstrating clear advantages over Si devices), to reliability (passing industrial and automotive qualification, identifying, and mitigating special failure modes), to cost (from serving a niche market to achieving cost-effectiveness for a wide range of applications). At this time, cost is the main remaining barrier for many potential applications that could have adopted SiC to improve system performance and power density. But this is getting better every year, especially after SiC has proven to offer great system value for EV power converters (onboard chargers and traction inverters). As global market demand increases rapidly, SiC device production efficiency is vastly improved through larger wafer diameters and other supply chain advantages. This momentum will eventually enable SiC to overtake Si for 600V+ power devices in a much wider application space, step by step."[31]
High cost of substrates	Substrate materials used in fabrication of SiC semiconductors are expensive unlike silicon. Hence, the challenge here is to develop a commercially viable foundry model for high volume processing of wafer substrates for WBG semiconductors.[32]
Slow growth rates and limitations to crystal size	According to GT Advanced Technologies, a SiC crystal grower, "**Differences in the processes used for SiC and silicon boule growth are behind differences in the cost, size, and availability of substrates**. For silicon, ingots produced in state-of-the-art crystal growth equipment have a diameter of 450 mm and a length exceeding 2 m and are **realized at a growth rate of around 100 mm/hour**. Growth is initiated using a thin seed with a 10 mm by 10 mm cross section. In contrast, SiC crystals are grown with a diameter of 150 mm, and have a length up to 50 mm, with growth proceeding far more slowly – **it occurs at 100-300 µm/hour**. This process begins with a starting seed that has a diameter of 150 mm or more and a thickness of 1-2 mm."[33]
Manufactur-ing issues	One of the biggest challenges of widespread adoption of SiC devices is due to higher manufacturing process cost and a lack of volume production. "Mass production of SiC devices imposes challenges that require a robust and well-thought-out infrastructure and manufacturing processes. This includes wafer testing, which requires the test of smaller devices that work at higher current and voltage ranges."[34]

Barrier	Description
Quality of SiC Crystals	GT Advanced Technologies has publicly reported that, "the quality of SiC lags behind that of silicon. The latter can be grown free of defects, while SiC suffers from fundamental issues associated with vapor-phase growth, multiple polytypes and a spiral growth mechanism. Part of the problem is that the stacking fault energy needed for the atoms to migrate to, and sit in, the right place is far lower in SiC than silicon. This introduces a wide range of defects, including micropipes, carbon inclusions, and extended crystal defects, such as threading screw dislocations, threading edge dislocations, basal planar defects and stacking faults. Mitigating these defects is not easy, requiring a combination of equipment expertise and process knowhow. Just one without the other is insufficient for delivering the results demanded by high-growth markets."[35]
Production Capacity	With demand for SiC-based power electronics increasing, limited SiC production capacity could be a barrier to entry for players considering entering the market.[36] However, progress is being made regarding the wafer quality of silicon carbide. In the current scenario, SiC wafers are manufactured in 100 mm and 150 mm, with 200-mm SiC wafers expected to penetrate the market in the future.[37]
Processing Costs	SiC is not available as a natural mineral processing costs have remained high given that SiC doping is a difficult process, resulting in challenges in producing larger SiC wafers with fewer defects.[38]
Defects	SiC-based inverters are known for having higher power density, less need for cooling and lower overall system costs than traditional inverters.[39] Defects at the interface between the SiC and the insulating silicon dioxide material still represent a big hurdle to bringing the technology to mass production. For example, in 2019, Fraunhofer Institute for Solar Energy Systems scientists found evidence indicating the defects affecting the heat resistance of SiCs are attributable to "nanometer-sized carbon clusters which are formed during the oxidation of silicon carbide to silicon dioxide under high temperatures."[40] According to the study, "although SiC offers great potential for reducing weight and improving the electric conductivity and thermal properties in next generation solar inverters, the defects studied – which occur at the interface between silicon carbide and the insulating material silicon dioxide – are considered a major obstacle to commercial adoption. Inverter makers have thus far developed silicon carbide devices only as prototypes or in small-scale production runs."[41]
Design and Integration issues	Orlando Esparza, strategic marketing manager for the Discrete and Power Management business unit at Microchip Technology, identifies design and integration issues,[42] *"SiC power devices are not commoditized, and there are real differences in performance, reliability, and ruggedness. It is unlikely that the lowest-cost devices will satisfy the high-reliability requirements for mission-critical applications given the various design, development, and manufacturing [circumstances] from different vendors. Designers need to ensure they carefully evaluate — on their own bench and systems — device performance, reliability, and degradation in performance under stringent conditions."*[43] The "complex design and integration process" is a restraint for the overall power electronics market. The players "operating in the power electronics industry are focusing on integrating multiple functionalities in a single chip, which results in complex designing. The designing and integration of complex devices require special skillsets, robust methodology, and toolset, which increase the overall cost of the devices. The high cost of the devices is expected to hamper the switching process toward advanced technological devices."[44]

Barrier	Description
Cost of SIC vs Competition	SiC cost is often cited by both academia and industry as one of the largest barriers to overcome. The issue of cost is discussed below by semiconductors leaders (STMicroelectronics, ON-Semiconductor and ROHM Semiconductor) in April 2019:[45] *"**STMicroelectronic**s: ST is among the few suppliers of SiC devices and the only one with automotive grade SiC in production. From this, it's easy to see that the biggest inhibitor to the growth of SiC today is capacity. As the industry addresses its capacity limitations — and you may recall that ST announced a supply agreement for SiC wafers with Wolfspeed in January, we announced the acquisition of a majority stake in wafer-manufacturer Norstel, and we're expanding our SiC manufacturing capacity. All of these efforts are consistent with our goal of sustaining an important share of the SiC market into the future.* ***Toshiba Electronic Devices & Storage Corporation**: The cost of Silicon Carbide semiconductors is still higher than that of Silicon ones. We continue to develop technologies for reducing the production cost – for improving its yield rate, for example.* ***onsemi** : SiC is now well proven across multiple market segments and applications. Although there are always new applications with associated reliability and design challenges, how to appropriately incorporate SiC into new systems and platforms is well understood. The biggest factor hindering growth is cost. Today SiC provides savings at the system level with the electric vehicle transformation creating a catalyst for dramatic growth over the next 3-5 years. However, even greater growth will be realized when SiC can be provided with a lower cost than silicon based IGBTs at the device level. In order for this to occur, sub $500 SiC substrate costs must be achieved which could potentially occur within the next 3-years."*
Wafer Cost	In a presentation dated May 7, 2020, Infineon's Peter Mawr (President, Industrial Power Control) and Peter Friedrichs (Silicon Carbide Senor Director) indicated that SiC raw wafer remains a cost driver.  1. **Source:** Infineon. "Industrial Power Control Business Update." (May 7, 2020).[46]

According to "[PowerAmerica's Strategic Roadmap for Next Generation Wide Bandgap Power Electronics](https://)," the future is promising for wide bandgap power electronic technologies. Driving adoption of WBG power electronics are SiC and GaN's proven technical advantages over Si, as well as decreasing prices.[47] Power America has more than 35 members, including large companies whose focus is SiC such as Wolfspeed, Infineon, and XFAB.[48] The PowerAmerica Roadmap identifies the following four challenges that need to be overcome in order to advance SiC and GaN technologies for power electronics:[49]

1. **Reducing cost**
2. **Improving reliability**
3. **Enhancing performance capabilities**
4. **Strengthening** the power electronics ecosystem—are intimately connected to form an integrated, collaborative strategy.

Table 6: Power America - SiC Power Electronics for Energy Challenges

Application	Challenge
1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection.	• High cost
1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection.	• Lack of good reliability testing data that demonstrates device performance in different situations over long periods of time
1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection	• Need for AEC-like qualifications, short circuit rating, and/or optimized gate driver. • Lack of good high-temperature packaging (e.g., for down hole) • Need for package standardization with dual sourcing. • Need for reduced parasites
1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection.	• Need for improved material quality for 100-200A single chips

Source: Power America, Inc. "PowerAmerica Strategic Roadmap for Next Generation Wide Bandgap Power Electronics." (February 2018).[50]

2.5 SiC Device Manufacturers

There are nearly two-dozen SiC device suppliers that compete in this market. SiC chip production is currently split among the United States, Japan, China, and Europe**. Suppliers of SiC devices include Fuji Electric, Infineon, onsemi, STMicroelectronics, Rohm, and Wolfspeed / Wolfspeed.**[51] Other SiC device manufacturers in the US include:[52]

- Littelfuse
- Microchip
- GeneSiC Semiconductor, Inc.
- United Silicon (UnitedSiC)

Device makers sell SiC power MOSFETs and diodes, which are used in 600-volt to 10-kilovolt applications. SiC power module manufacturing and manufacturing of power modules in general currently fall into two categories: 1) vertically integrated approaches, where companies have in-house manufacturing facilities, particularly in cases where highly customized modules are required; and 2) the use of contract manufacturers. Vertically integrated companies include Infineon Technologies AG (Munich, Germany), Wolfspeed, Inc. (Durham, NC), ROHM Co., Ltd. (Kyoto, Japan), STMicroelectronics N.V. (Geneva, Switzerland), and Fuji Electric Co., Ltd. (Tokyo, Japan) are involved at this stage.[53]Other supplies using contract facilities includes suppliers include ABB, GeneSiC, Global Power, Microchip, Monolith, and UnitedSiC. For example, UnitedSiC is a fabless SiC device supplier.[54]

2.6 Movement Toward Vertical Integration is Shaping the Landscape

Companies including STMicroelectronics, Wolfspeed, onsemi, and Infineon Technologies, announced their revenue objectives for SiC that includes an **integrated device manufacturer (IDM) business model**.[1] The IDM business model is the one chosen by leading players to supply devices, especially power modules.

Table 7: Companies with Integrated Device Manufacturer Model

onsemi	SiC modules contain SiC MOSFETs and SiC diodes. onsemi introduced a pair of1200 V SiC MOSFET2-PACK modules for the EV market.
Infineon AG	Silicon carbide MOSFET; MOSFET Discrete; MOSFET Modules; SiC Schottky Diode; CoolSiC Hybrid Modules; SiC Diodes; and SiC Transistors
Wolfspeed, Inc.	SiC MOSFETs; SiC Schottky Diodes; SiC Power Modules; SiC Substrates; and SiC Epitaxy
Rohm Co., Ltd.	SiC Schottky Barrier Diodes (SBDs); SiC MOSFET; SiC Power Modules; SiC Schottky Barrier Diodes Bare Die; and SiC MOSFET Bare Die
STMicroelectronics NV	SiC Diodes; Automotive SiC Diodes; Automotive grade SiC Diodes; SiC Schottky Diodes; and SiC Power MOSFETs
FUJI Electric	SiC Devices SiC Schottky-Barrier Diodes; SiC Modules; and Hybrid SiC Modules

Major SiC players are migrating along the supply chain toward the module level with STMicroelectronics having the largest share of SiC power devices market.

1 **An integrated device manufacturer (IDM)** is a large-scale semiconductor company that designs, manufactures and sells integrated circuit products.

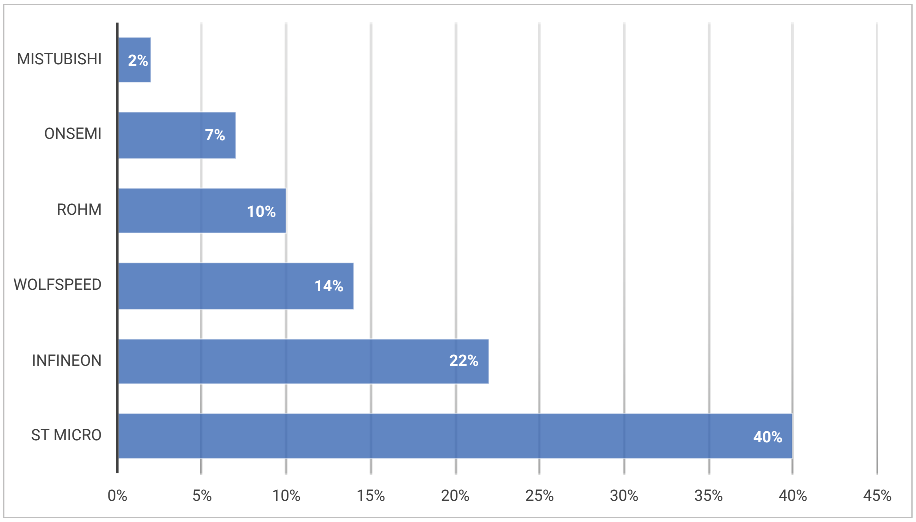


Figure 6: SiC power devices market share of key players
Source: Infineon AG. (May 11, 2022).[55]

3.0 Silicon Carbide and Photovoltaics

This section provides an overview of the different types of inverters used in solar applications and introduces companies that are using SiC devices in solar applications. Also included is a discussion of the overall inverter market.

3.1 Solar Inverters

Inverters account for about 5% of total solar PV system costs. Growth of the solar PV inverter market is directly proportional to the increase in solar PV power installments. As noted previously, the SiC market is being driven by both PV and electric vehicles. Frost & Sullivan forecast a total of $2 billion to be invested in solar PV through 2030, with half going to utility-scale projects and the rest going to commercial, industrial, and residential PV systems. Frost & Sullivan believe project costs will continue to decline during the forecast period, 2020-2030. In tandem, technology costs will also continue to decline although costs will decrease more slowly than during the last decade (2010-2020).[56]

Innovations in solar are also occurring in siting and location of the solar panels. Land scarcity, country-level carbon neutrality targets and falling prices are expected to contribute to the growth. Dual use examples include:

1. The deployment of rooftop solar PV systems has increased significantly in recent years. **Rooftop solar PV market is expected to reach $124.36 Billion by 2028, growing at a CAGR of 6.01% between 2021 and 2028.**[57]
2. Floating solar is promising, representing ~1% of global solar demand in 2021.[58] **The market, estimated at 1.6 thousand MW in 2021 is projected to reach 4.8 thousand MW by 2026.** China is expected to dominate floating solar installations over the next five years, with India and South Korea trailing close behind.[59]

3. **Interest is rising around dual use solar or agrivoltaics, the simultaneous use of land bo**th for crop production as well as energy production using photovoltaics.[60]

3.1.1 *Types of Inverters*

There are three primary types of solar inverters: (1) **Central inverters** which are used in large scale installations and large commercial buildings; (2) **String inverters** – used in medium-sized installations such as commercial and residential establishments; and (3) **microinverters** which are mostly used in residential installations with some installations in the commercial field.[61]

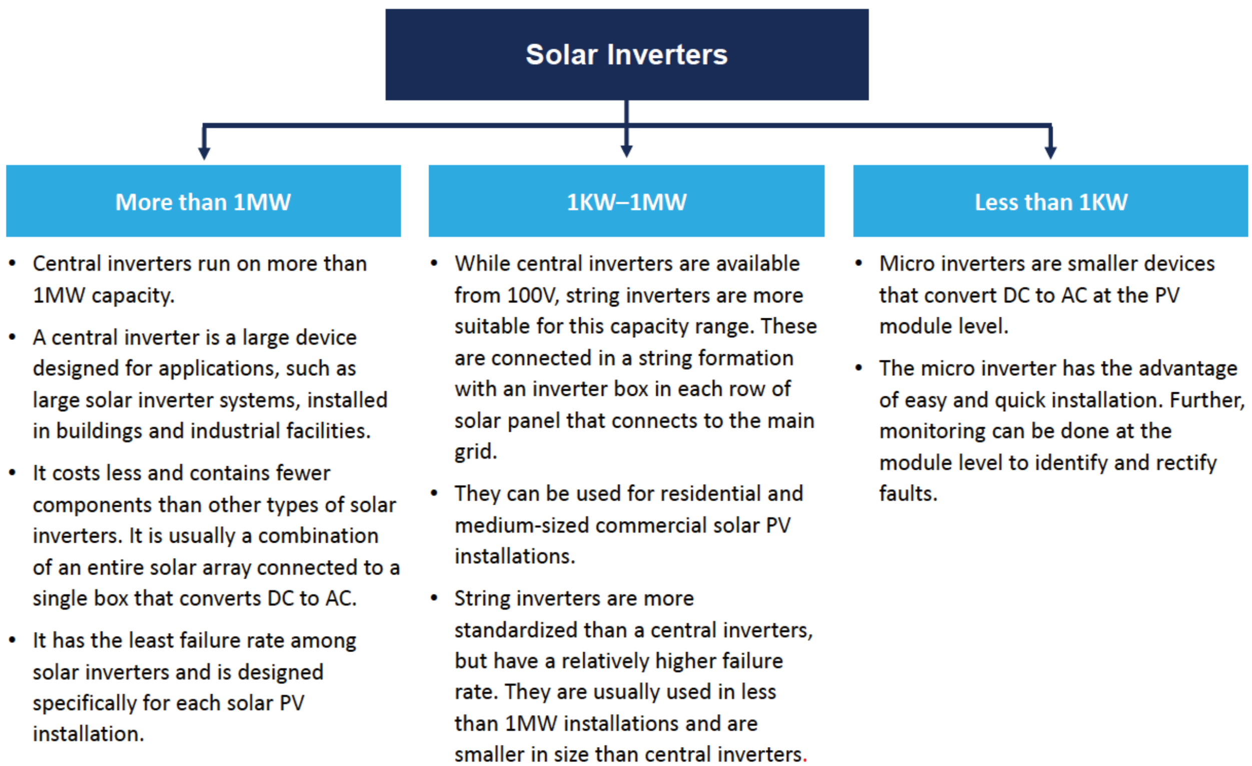


Figure 8: Inverters Market Segmentation.
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Each inverter type has its own unique distribution setup as follows:[63]

- **Central inverters** are usually not held in stock by most manufacturers and are built to order for customers. The main distribution channel for central inverters is direct sales as these devices need to be customized as per project requirements.
- **String Inverters** are more standardized/commoditized products and can be held in stock. Manufacturers rely heavily on distributors for the sale of string inverters and microinverters due to the standardized nature of these products. System integrators and engineering, procurement and construction firms are other important distribution channels for string inverters used in large-scale projects.

- **Microinverters** are sold mostly through direct sales. Sales through online portals contribute to the sale of microinverters. In addition, manufacturers of solar PV inverters also sell to solar module manufacturers who bundle inverters with their modules to sell as complete solar PV solutions.

With **string inverters, the benefit of SiC is greater because weight, and volume are much more important than in the central inverter**. Currently, SiC devices for solar inverters are still expensive, but they have other advantages:[64]

> Although the SiC MOSFET unit cost is generally not yet lower than that of an IGBT for similar headline ratings, system hardware costs are lower due to maintained high efficiency at higher switching frequencies. This allows smaller and cheaper magnetic components and heat sinks to be implemented.

Although a "switch from IGBTs to SiC MOSFETs is a net system benefit at increasing power level," this should not be considered as a "a simple swap-out" and "will not give good results – optimum performance requires a re-evaluation of gate drive arrangements, layout and EMI filtering."[65]

3.3 SiC Inverters for PV

SiC devices can replace existing silicon switching technologies, enabling designers to achieve significantly better performance in applications such as solar inverters, EV on-board chargers, server power supply units, telecoms, as well as uninterruptible power supplies.[66] SiC as a semiconductor performs better than Si when it comes to a mix of high power and higher switching frequencies. This is especially the case for the conversion from DC to DC in inverters, where it creates a significant advantage. By eliminating switching losses for example, a SIC inverter is able to achieve higher switching frequencies without increasing semiconductor losses and hence temperatures.[67] Another advantage is its current handling ability at higher voltage levels.

SiC devices can enable 98% efficiency in solar power systems. Beyond increased efficiency, research has shown that using SiC power components instead of Si for solar inverters enables solar inverters to be lighter, smaller, and more efficient. It can save 10 megawatts for each gigawatt, and 500 watts/sec in operations, which leads to significant energy savings. These benefits can be used for a wide range of applications from utility-scale solar to residential solar panels.[68]

SiC inverters can improve the efficiency of the grid-tie, shrink the cooling system, and reduce overall system costs. String solar inverters are expected to benefit from SiC:

> "The rise in the use of string inverters in large solar plants has been another critical factor. … as installations moved from small installations towards enormous plants reaching the gigawatt range, so did the philosophy; from central inverters towards string inverters. With string inverters, the benefit of SiC is even bigger because weight, and volume are much more important than in the central inverter – basically because you need somebody to install it. And if you are below a certain weight for

> the PV inverter, you can do it by one or two people. To achieve the same power rating with silicon in the newest inverters would double the weight. It's a simple driving post to use SiC in PV string inverters."[69]

The **next big thing for SiC in solar is predicted to be in storage**:[70]

> *"The next big SiC use case will be in storage, where efficiency improvements can reduce the necessary size of a battery, both in residential and larger installations. In every PV system now you have storage, and in the storage system, you can save with the higher efficiency enabled by SiC. Between the panels and battery, you need a DC-DC stage, and you usually have different voltage levels, and you need to convert what comes out of the panel."*

Frost & Sullivan expects inverters with SiC/GaN switching devices, 210 mm module compatible inverters, 1,500 V inverters, and string inverters to gain traction. Several points should be noted:[71]

- **Utility-scale 210 mm modules starting from 550 W capacities offer several benefits**, including **reduced project costs**, due to reduced foundations for installation and fewer trackers and cables. In tandem, the leading PV inverter suppliers have announced production of inverters that are compatible with 210 mm modules.
- Inverters with 1**,500 V minimize capital expenditures and operating expenses** by reducing labor and, thereby, decreasing levelized cost of electricity and improving return on investment. They enable longer strings and require fewer combiner boxes and less wiring and trenching, which effectively closes the price gap with central inverters. Frost & Sullivan believe that 1,500 V will reduce system losses at the direct current end, and these systems are poised to garner a major share in the global market. The market is shifting toward string inverters. Decision makers prefer modular, highly reliable string inverters over central inverters, which were the conventional choice for large-scale PV systems. The inverter industry is also shifting to SiC/GaN converters for improved conversion efficiency. Significant cost pressures and competition have resulted in the consolidation of the inverters market during recent years.
- While many countries produce PV inverters, such as Japan, South Korea, Australia, the United States, Canada, Germany, Spain, Austria, Switzerland, Italy and Thailand, China is the leading supplier with more than 60% (approximately 75 GW) of the global PV inverter market share.

There have been some interesting announcements with respect to SiC solar inverters. For instance, in 2021, Germany's Fraunhofer Institute for Solar Energy Systems showcased a 250-kW SiC inverter that can be used in utility-scale PV projects for medium-voltage grid. **"The inverter runs at 98.4% efficiency and can be installed in a modular interconnection of multiple inverter stacks, which makes it ideal, according to its creators, for the deployment of systems at megawatt scale."**[72]

3.4 SiC Device-based Solar Inverter Manufacturers

The demand for SiC components is increasing for renewable energy applications, especially for solar power. Several manufacturers are developing SiC devices compatible with solar energy applications. For instance, Hillcrest Energy Technologies achieved proof of concept for the Hillcrest ZVS inverter in 2022. By eliminating switching losses, the company was able to achieve higher switching frequencies without increasing semiconductor losses.[73] Table 8 provides examples of SiC-based devices for solar currently on the market.

Table 8: Summary of Selected **SiC-based Devices** for Solar Applications

Developer / Manufacturer	Location / Manufacturing	Device / Trade Name	Remarks
onsemi	onsemi has 5 manufacturing locations in the U.S. SiC epiwafers are manufactured at the Maine Manufacturing Facility (85k sq. ft of clean room space, located on a 20-acre campus with 371k sq. ft of building)[74]	200V silicon carbideSiC MOSFETs	The 1200V devices are rated at up to103 A (ID Max.), while 900V devicescarry ratings as high as 118 A.[75]

onsemi	Designs and manufactures semiconductor chips, sensors, power management devices and other electronic components at 20 sites, most in the Asia-Pacific region.[76]	900V N-channel SiCMOSFETs 900V N-channel SiCMOSFETs	onsemi markets a range ofSiC devices for solar converters including:[77] • Discrete MOSFETs and diodes ina variety of packages for flexibility • Hybrid IGBTs with a SiC freewheel diode for cost optimization. • SiC Hybrid modules and full SiCmodules for compact designs. In July 2020, onsemi introduced NXH40B120MNQ family of full SiC power modules integrate a 1200V, 40mΩ SiC MOSFET and 1200V, 40 A SiC boost diode with dual boost stage.
GeneSiC Semiconductor	Dulles, VA	1700V 450mΩ TO-247-3 SiC MOSFET 50V G3R™SiC MOSFETs 1700V 450mΩ TO-263-7 SiC MOSFET[78]	Devices are available from the followingdistributors: • Digi-Key Electronics • Newark Farnell • Mouser Electronics • Arrow Electronics
		1700V 450mΩ TO-247-3 SiC MOSFET 50V G3R™SiC MOSFETs 1700V 450mΩ TO-263-7 SiC MOSFET[79]	

Infineon Technologies AG	Germany	TRENCHSTOPIGBT and a Cool SiC MOSFET	CoolSiC MOSFETs 650V devices that are rated from 27 mΩ to 107 mΩ, which the company states have usefulness in telecom, industrial, EV, and solar powerapplications, among others. The Active Neutral-Point Clamped topology allows system voltages up to 1500V maximumto be switched with switches designed for 1200V.[80]
Wolfspeed, Inc.	Durham, NC	Various products including 650V SiC MOSFET	Wolfspeed (formerly Wolfspeed Inc.) is a public company and operates in the Asia-Pacific, Europe-an and North American regions.
Rohm Semiconductor	Kyoto (Japan)	SiC power module portfolio with the addition of new 1200V/400A & 600A models.	ROHM Semiconductor's primary products comprise discrete semiconductors, ICs, modules, opto-devices, commercial products, and passive and power devices.
United Silicon Carbide, Inc.	Monmouth Junction, NJ	UF3C family of 650 V and 1200V SiC FETs Alow $RDS_{(on)}$ for solar power inverters. [81]	UnitedSiC was founded in 1997. The company develops silicon carbide FETand diode power semiconductors. Products that UnitedSiC offers includes:SiC FETs, SiC JFETs, and SiC Schottky Diodes.
Littelfuse, Inc.	Chicago, IL	1200V silicon carbide Schottky diodes series	In March 2018 1200V SiC MOSFETs was introduced
Microchip Technology Incorporated	Chandler, AZ	Products include 700-V and 1,200-V SiC Schottky barrier diodes and 700-V SiCMOSFETs.[82]	Microchip through its Microsemi division offers a comprehensive product portfolio.

Toshiba Electronic Devices & Storage Corporation	Tokyo, Japan	Toshiba provides a range of SiC power device lineup including1200V SiC MOSFETs, 650-V SiC Schottky Barrier diodes and SiC MOSFET Modules.[83]	MG800FXF2YMS3, a SiC MOSFET module integrating a developed dual channel SiC MOSFET chips with ratings of 3300V and 800A designed for industrial and renewable energy applications was recently introduced. Volume production started in May 2021.[84]

3.5 Bill of Materials – SiC Solar Inverters

Cost information for SiC Solar inverters on the basis of volume is documented in the research paper by Akanksha Singh, Samantha Reese, and Sertac Akar (National Renewable Energy Laboratory), "Performance and Techno-Economic Evaluation of a Three-Phase, 50-kW SiC-Based PV Inverter." Benchmark commercial system cost was calculated for the U.S. Department of Energy Solar Energy Technologies Office's SunShot program.[85] According to the authors, the main driver in the manufacturing cost is economies of scale from parts procurement.

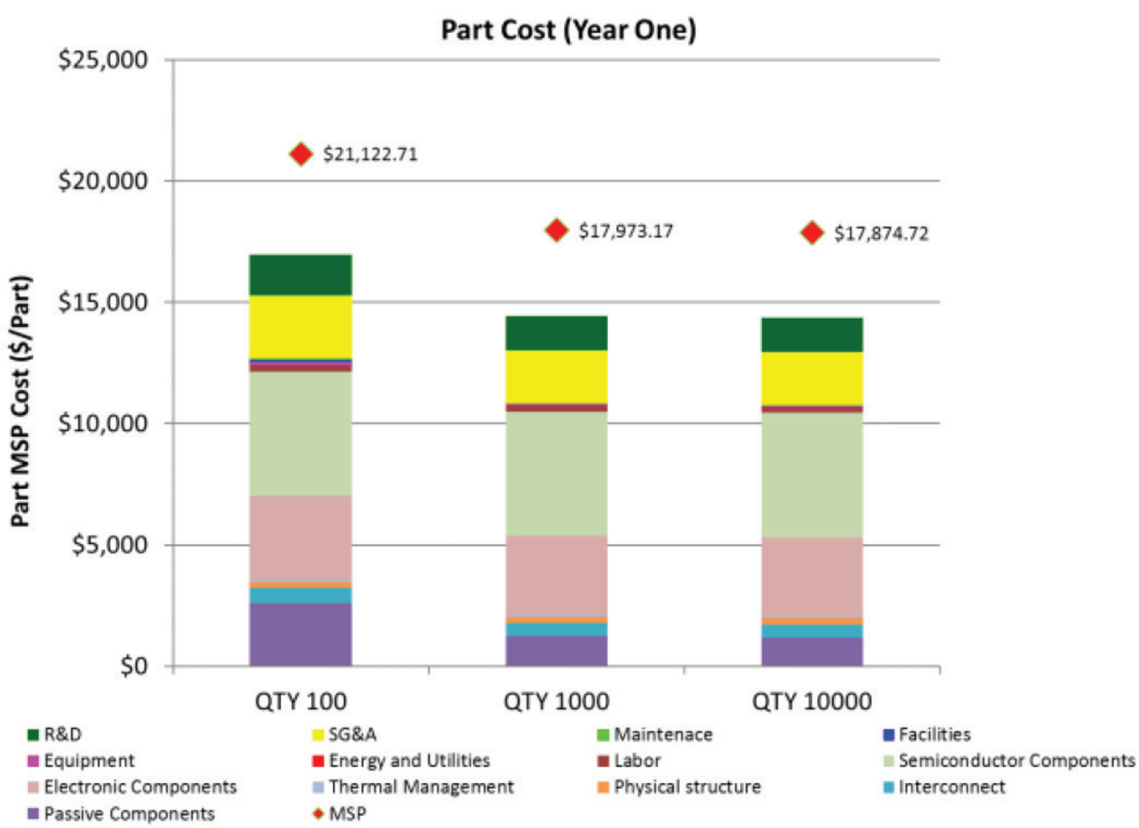

Figure 9: Modeled factory gate pricing of Alpha SiC inverter
Source: Akanksha Singh et al. (National Renewable Energy Laboratory).[86]

In Table 9 below, the individual inverter parts are all treated as purchased parts in the model except for the power block made from SiC devices.

Table 9: 50kW SiC Inverter Bill of Materials

50kW SiC Inverter		
	$/Watt	% Total
Module	$0.35	16%
Inverter	$0.19	9%
Structural BOS	$0.15	7%
Electrical BOS	$0.20	9%
Install Labor & Equipment	$0.26	12%
EPC Overhead	$0.22	10%
PII	$0.17	8%
Sales Tax	$0.05	3%
Contingency %	$0.05	2%
Developer Overhead	$0.40	18%
EPPC/Developer Net Profit	$0.14	6%
∑ Total Cost	$2.17	

Source: Akanksha Singh et al. (National Renewable Energy Laboratory).[87]

Figure 10 presents the minimum sustainable price for the NREL-developed 50-kW SiC Gamma inverter using the cost of power blocks with current die pricing. The Gamma inverter used 1700-V SiC devices. The 10,000 per year manufacturing level yields an inverter price of $9,457/inverter. This translates to a $0.19/W price point. The researchers determined the majority of the cost is in the wafer.

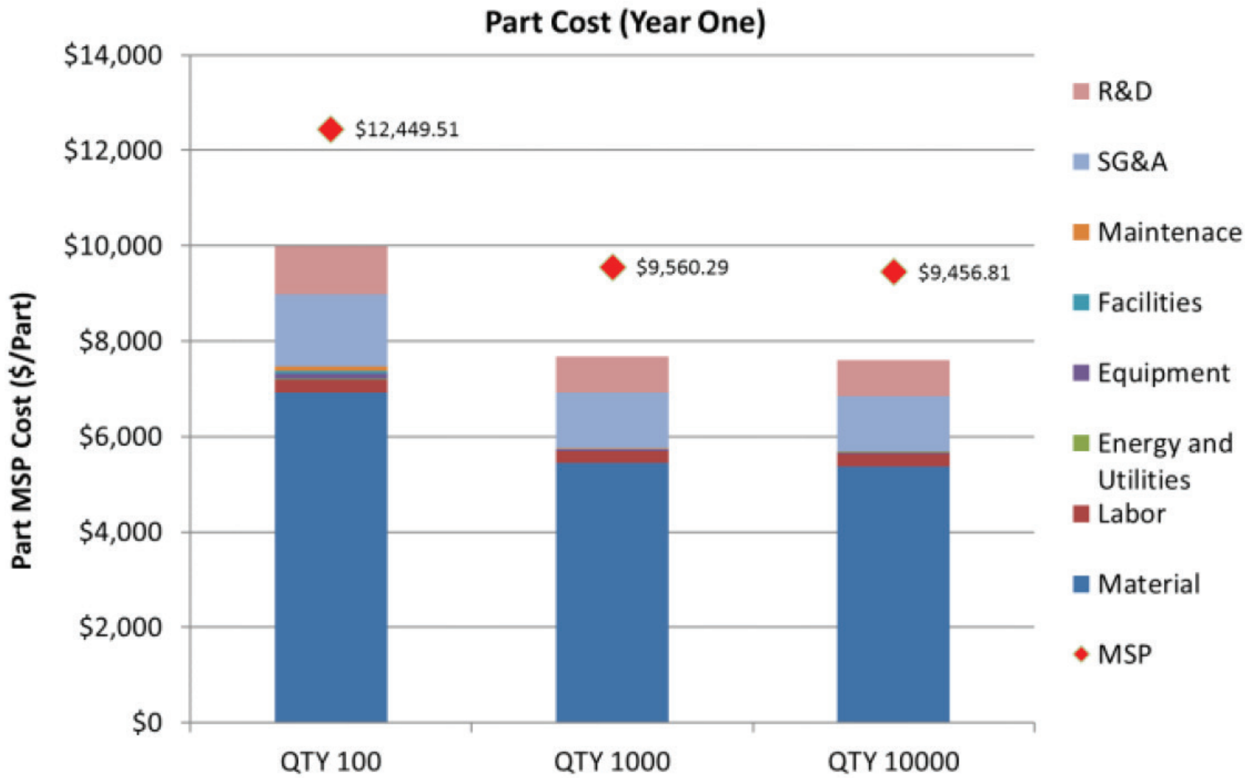

Figure 10: Modeled factory gate pricing of Gamma SiC inverter using current die pricing.
Source: Akanksha Singh et al. (National Renewable Energy Laboratory, 2017).[88]

Kelsey Horowitz, et al. of NREL modeled the minimum sustainable price of each SiC component per variable frequency drive.[89] Table X below shows the minimum sustainable price per component.

Table 10: Minimum Sustainable Price of Each SiC Component Per Variable Frequency Drive

Raw Materials	NA
Wafers	$1,598
Chips	$3,594
Modules	$13,109
Variable Frequency Drive	$176,355

Source: Akanksha Singh et al. (National Renewable Energy Laboratory, 2017).[90]

3.6 Global Inverter Market

The global inverter market is projected to reach $33.8 billion by 2027 from an estimated $16.3 billion in 2022, at a CAGR of 15.7% during the five years 2022–2027.[91] The market is made up of mostly Si-based inverters with the solar inverter segment projected to account for the highest share of 65.5% in 2022. The trend is expected to continue during the forecast period due to the increasing demand for inverters in solar PV plants and the residential and commercial sectors. [92]

Table 11: Global Inverter Market, by Type, 2020 and 2027 (USD Million)

Type	2020	2021	2022-e	2023-p	2024-p	2025-p	2026-p	2027-p	CAGR (2022–2027)
Solar Inverter	8,110	9,305	10,716	12,397	14,322	16,597	19,290	22,469	16.0%
Vehicle Inverter	3,175	3,666	4,249	4,948	5,754	6,713	7,855	9,212	16.7%
Others	1,163	1,271	1,390	1,524	1,664	1,816	1,982	2,159	9.2%
Total	**12,447**	**14,242**	**16,355**	**18,868**	**21,739**	**25,126**	**29,127**	**33,840**	**15.7%**

Note: e – Estimated; p – Projected

Other types include battery and UPS inverters.

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The string inverter type is projected to reach $7,921 million by 2027, increasing from an estimated $3,391 million in 2022, at a CAGR of 16.1% between 2022-2027.

Table 12: Global Solar Inverter Market, by Type, 2020 – 2027 (USD Million)

Type	2020	2021	2022-e	2023-p	2024-p	2025-p	2026-p	2027-p	CAGR (2022–2027)
Central Inverter	2,543	2,851	3,206	3,620	4,078	4,606	5,214	5,911	13.0%
String Inverter	2,834	3,256	3,754	4,349	5,030	5,837	6,792	7,921	16.1%
Micro-inverter	2,470	2,889	3,391	3,997	4,702	5,548	6,563	7,778	18.1%
Hybrid Inverter	262	309	364	432	511	606	720	858	18.7%
Total	**8,110**	**9,305**	**10,716**	**12,397**	**14,322**	**16,597**	**19,290**	**22,469**	**16.0%**

Note: e – Estimated; p – Projected.

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Inverters are sold in various power ranges including: <10 kW, 10–50 kW, 50–100 kW and >100 kW. These power ranges address the needs of the residential, commercial, and utility segments of the solar inverter market (Table 13). The <10 kW segment accounted for the largest share (~35%) of the inverter market in 2021. Inverters with output power ratings below 10 kW are suitable for use in the residential and commercial sectors. Installation of solar PV systems in the residential sector is increasing significantly worldwide. Apart from residential inverters, string inverters, micro-inverters, and vehicle inverters also have an output voltage rating below 10 kW.[32]

Table 13: Global Inverter Market, by Output Power Rating, 2020 – 2027 (USD Million)

Output Power Rating	2020	2021	2022-e	2023-p	2024-p	2025-p	2026-p	2027-p	CAGR (2022–2027)
Below 10 kW	4,409	5,038	5,777	6,655	7,657	8,838	10,232	11,871	15.5%
10–50 kW	2,691	3,025	3,412	3,865	4,371	4,956	5,636	6,419	13.5%
50–100 kW	2,227	2,556	2,944	3,406	3,935	4,561	5,303	6,178	16.0%
Above 100 kW	3,120	3,623	4,223	4,943	5,776	6,770	7,957	9,371	17.3%
Total	**12,447**	**14,242**	**16,355**	**18,868**	**21,739**	**25,126**	**29,127**	**33,840**	**15.7%**

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North America held a 26.5% share of the global inverter market in 2021. The US is one of the major contributors to the market growth in this region. North America includes the United States, Canada, and Mexico in this report.

Table 14: North America Inverter Market, by Type 2020 – 2027 (USD Million)

Type	2020	2021	2022-e	2023-p	2024-p	2025-p	2026-p	2027-p	CAGR (2022–2027)
Solar Inverter	2,086	2,386	2,738	3,156	3,647	4,226	4,909	5,712	15.8%
Vehicle Inverter	861	993	1,149	1,336	1,557	1,819	2,131	2,499	16.8%
Others	364	399	439	483	533	587	648	714	10.2%
Total	**3,311**	**3,779**	**4,326**	**4,976**	**5,737**	**6,633**	**7,688**	**8,926**	**15.6%**

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3.6.1 Solar PV Key Suppliers

The figure below shows the solar PV key suppliers. Inverter supplies are for the most part, non-United States based companies.

PV Cells	PV Modules	PV Inverters	O&M
• TONGWEI	• LONGI	• HUAWEI	• SOLV
• AIKO	• TRINA SOLAR	• SUNGROW	• STERLING AND WILSON
• RUNERGY	• JA SOLAR	• SMA	• ENEL ENERGY
• SHANXI LU'AN	• JINKO SOLAR	• POWER ELECTRIC	• SONNEDIX
• SOLAR SPACE	• CANADIAN SOLAR	• FIMER	• NOVASOURCE
	• HANWHA Q CELLS	• SINENG	• SCATEC SOLAR
	• RISEN	• SOLAREDGE	• BAYWA RE
	• FIRST SOLAR	• GROWATT	• ENERPAC
	• SUNTECH	• TMEIC	• METKA EGN
	• ASTROENERGY	• GINLONG SOLIS	• CANADIAN SOLAR
		• GOODWE	• MAHINDRA SUSTEN
		• TBEA SUNOASIS	• VIKRAM SOLAR
		• INGETEAM	• GRUPOTEC
		• FRONIUS	• EDF ENERGIES
		• KSTAR	• GRUPO ORTIZ
		• CHINT	• IB VOGT SOLR
			• IBC SOLAR
			• KYUDENKO CORP
			• BRITISH SOLAR
			• BELECTRIC

Figure 11: Players in the PV Value Chain
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The global competitive landscape for inverters remains relatively consolidated. The major players in the inverter market are **Huawei Technologies** (China), **Sungrow Power Supply** (China), **SMA Solar Technology** (Germany), **Power Electronics** (Spain), **FIMER** (Italy), **SolarEdge Technologies** (Israel), **Fronius International** (Austria), **Altenergy Power System** (U.S.), **Enphase Energy** (U.S.), **Darfon Electronics Corporation** (China), **Schneider Electric** (France). The top 10 suppliers accounted for more than 70% of global PV inverter shipments. The increasing focus on the use of renewable power sources across the globe is driving the market for power electronics for renewable energy applications.[98]

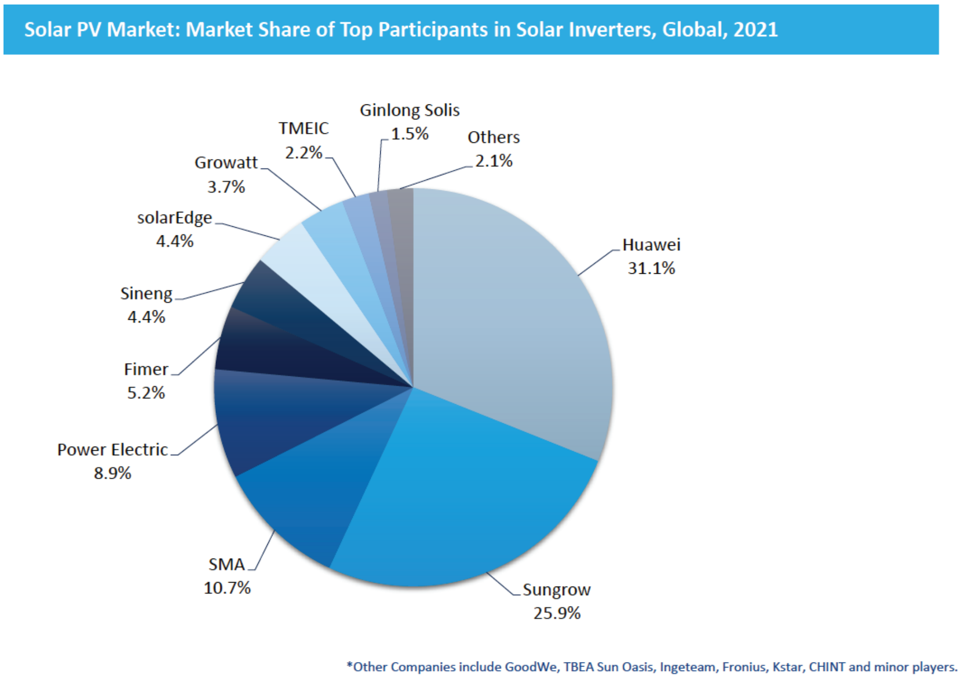

Figure 12: Solar Inverter Manufacturers Market Share
Reprinted with permission of Frost & Sulivan.[99]

4.0 Silicon Carbide Supply Chain and Key Players

In this section, an overview is provided of the current supply chain and key SiC chip manufacturers. The silicon carbide value chain is made up of companies at each point in the chain, namely: (1) material suppliers (2) SiC crystal growers (boule); (3) wafer manufacturers and (4) device manufacturers.

4.1 Supply Chain

Silicon carbide is rarely found in nature and, therefore, it is more commonly produced synthetically. Figure 13 illustrates the production steps, starting at crystal growth and ending up as devices and circuits.

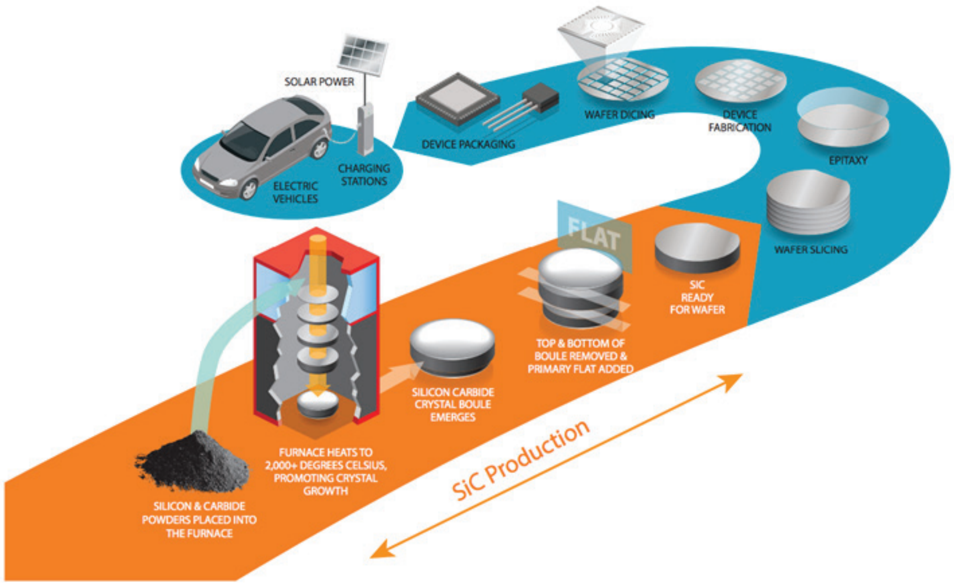

Figure 13: Steps Involved in Making SiC
Source: GT Advanced Technologies. (September 2019).[100]

"The SiC substrate production starts with silicon and carbon materials, which are inserted in a crucible. In the crucible, a boule is formed and then sliced into SiC substrates. Following the SiC wafer process, an epi layer is grown on the substrate. Then the wafer is processed in the fab, resulting in a SiC device. In the SiC flow, a vendor obtains a SiC wafer, which is then processed in a 100mm (4-inch), 150mm (6-inch) or 200 mm fab. This, in turn, creates a SiC power device."[101] SiC for power electronics is ramping up and suppliers of SiC devices are putting supply chain infrastructure in place to handle the anticipated aggressive forecast ramp up.[102]

4.1.1 SiC Materials Suppliers

High purity SiC powder, which can be used to grow SiC boules, is available from a small number of global suppliers, and is relatively expensive. SiC powder is used to grow SiC boules. SiC powder is produced by large, multinational companies such as **Dow Chemical Co.**, (US) **ESD-SIC b.v**. (Netherlands), Carborundum Universal Limited (India), **Saint Gobain Ceramic Materials GmbH** (Malvern, PA) and **ESK-SIC GmbH** (Germany).[103]

Another ingredient, high purity silane is a critical precursor for growing SiC layers in chips and is typically produced by large, multinational industrial gas companies such as Linde, Messer, REC Silicon, Air Liquide, Taiyo Nippon Sanso (Matheson), Air Products, Henan Silane Technology, Shaanxi Non-ferrous Tian Hong REC Silicon Materials, Shin-Etsu. Firms headquartered in the United States, Asia (China, Japan, Hong Kong, South Korea, and Taiwan), and Europe (Germany and France).[104]

High purity silane is a critical precursor for growing SiC layers in chips and is typically produced by large, multinational industrial gas companies.

4.2 SiC Crystal Growers

The SiC supply chain still has some rough spots to iron out. This is partly due to reliability issues that are yet to be fully solved, and partly due to volume manufacturing ramp-up issues for any new material or changes in the size of wafers. A key challenge is to lower the defectivity, or dislocations, and for SiC substrates this is trickier than for standard silicon. Manufacturers have continued to increase SiC crystal quality.

Typically, companies that grow SiC boules also machine them into ingots and slice them to create substrates. A few of the companies that manufacture ingots and substrates also provide epi-layer growth and sell epi-wafers.[105] The following companies are vertically integrated from crystal growth through device manufacturing: SiCrystal (owned by Rohm Semiconductor, German manufacturing), Nippon Steel (Japan), Norstel (Sweden), and SICC (China). onsemi, Wolfspeed, ROHM, STMicroelectronics, II-VI and SK Siltron.

Wolfspeed is a vertically integrated company, growing SiC crystals, manufacture wafers, and also supplies other SiC device competitors. With respect to growing SiC crystals, Wolfspeed estimates that the company holds about 60% of the merchant market for SiC crystals (they also grow SiC crystals for in house use).[106] II-VI Advanced Materials is another notable crystal grower, that probably has ~15% market share.[107]

Table 14: Notable U.S. SiC Crystal Growers

Company*	Location(s)	Description
Wolfspeed	Durham NC Research Triangle Park (Durham NC) Mohawk Valley, NY	Vertically integrated
II-VI Advanced Materials	Saxonburg, PA	Manufactures crystals and substrates
onsemi	Has SiC manufacturing facility in Hudson, New Hampshire.	The company markets CrystX® SiC, form factor for the product is 150mm (6") diameter. Resistivity is 20 mΩ-cm ±5. Upon request, this can be tuned to a 2 mΩ-cm range.[108]

**Not an exhaustive list*

Brief profiles of these two companies are provided in the next section.

4.2.1.1 onsemi Corporation / GT Advanced Technologies, Inc

In November 2021 onsemi, acquired GT Advanced Technologies, a SiC boule supplier for $415 million. GT Advanced Technologies manufactures SiC crystals in its Hudson

Hampshire facility.[109] onsemi is working on the expanding GTAT's manufacturing facilities, supporting research and development efforts to advance 150mm and 200mm SiC crystal growth technology, while also investing in the broader SiC supply chain, including Fab capacity and packaging.[110] As listed in the following table, GT Advanced Technologies has several SiC crystal supply agreements in place.

Table 15: GT Advanced Technologies – SiC Crystal Supply Agreements

Date	Partner	Description
November 2020	Infineon Technologies	A supply agreement for SiC boules. The contract has an initial term of five years.[111]
March 2020	ON Semiconductor	A five-year agreement valued at a potential of $50 million. GTAT will produce and supply its CrystX™ SiC material to ON Semiconductor. ON Semiconductor will use GTAT's proprietary 150mm SiC crystal to make its SiC wafers.[112]
August 2019	GlobalWafers Co., Ltd.	Long-term agreement, GlobalWafers will add 150mm SiC to its offering, manufactured from bulk SiC crystal produced by GTAT.[113]

4.2.1.2 II-VI, Inc

II-VI, Inc., located in Saxonburg, PA manufactures SiC substrates and is positioning itself as a vertically integrated SiC player.[114] In February 2022, II-VI demonstrated an automotive-qualified 1200V silicon carbide MOSFET platform on its high quality SiC substrates. II-VI, Inc. also extended its partnership with General Electric and signed a three-year access agreement with GE Research.[115] With this qualification, II-VI plans to ramp up activities for devices in the industrial motor and renewable-energy markets, while in parallel, initiating longer-term design-in activities in the electric vehicle market.[116] Long term vision is to invest $1 billion in capacity and innovation for its SiC platform over the next ten years starting in 2022.[117] In 2020, II-VI, Inc. made two acquisitions:[118]

- Ascatron AB (Kista, Stockholm, Sweden) – Ascatron produces SiC epitaxial wafers and devices that enable a wide range of high-voltage power electronics applications.
- INNOViON Corp (Colorado Springs, CO) – provides ion implantation technology for silicon and compound semiconductor devices. "INNOViON is said to be the world's largest provider of ion implantation services, with 30 implanters across a global footprint supporting capabilities in semiconductor materials processing for up to 300mm wafers. The firm's processes enable doping in a wide range of semiconductors, including silicon carbide, gallium arsenide, indium phosphide and silicon."

II-VI's strategy is to secure new business in the growing SiC module market.[119] In April 2021, the company expanded its silicon SiC wafer finishing manufacturing footprint in China.[120]

In June 2020, II-VI licensed General Electric's technology for manufacturing SiC devices and modules for power electronics. II-VI "intends to remain focused on executing announced plan to scale capacity of 150mm SiC materials by 5–10x while scaling volume production of a differentiated 200mm materials technology to meet the anticipated growing demand over the next five years."[121] II-VI has five manufacturing locations in the U.S.[122] II-VI plans to double capacity every 18–24 months through 2025.[123]

4.3 Silicon Carbide Wafers

Key silicon carbide wafer manufacturers include **Rohm, Wolfspeed, onsemi, II-IV, SK Siltron, KISAB, DISCO, Infineon, Soitec and others.**

4.3.1 SiC Wafer Capacity Expansion Announcements

Among the top SiC device players, STMicroelectronics, Wolfspeed, Infineon Technologies and onsemi have plans to increase capacity. Table X below provides a summary of planned capacity increases. It is anticipated that considerable capacity will come online in 2022.[124]

Table 16: Global SiC Capacity Expansion

Company	Expansion	Finished
Wolfspeed	30x Capacity expansion	2022
STMicroelectronics	2.75X Capacity expansion	2022
NXP Semiconductor	(100m investment)	2020
Rohm/SiCrystal	16x Capacity expansion	2025
Others		
X-fab	26,000 wafer per month	2020
Clas-SiC	Entered recently	-
Episil	Entered recently	-
Sanan	Entered recently	-
Yes Power Technix	Entered recently	-
II-VI	"Scale capacity of 150mm SiC materials by 5-10x while scaling volume production of a differentiated 200mm materials technology to meet the anticipated growing demand over the next five years."[125]	2025

Source: Seeking Alpha. "Wolfspeed: The winner of EV adoption, but too many uncertainties." (November 30, 2020).

4.3.1.1 X-Fab Texas, Inc. – An Example of a US Fab

The X-FAB Silicon Foundries is a German group of semiconductor foundries, with headquarters in Erfurt (Germany) and a foundry in Lubbock, Texas. X-FAB is a pure-play foundry that provide processing technologies for WBG materials, SiC and GaN. The company offers foundry services using the existing silicon manufacturing lines:[126]

- Processing GaN-on-Si wafers in the 8” fab in Dresden, Germany
- SiC wafers in 6” fab in Lubbock, Texas.

X-FAB has positioned itself as the first foundry to offer high-volume manufacturing to meet the growing SiC demands. In 2020, the company added SiC epitaxy capabilities to its offering. X-FAB also announced its intention to expand its SiC capacity and, with the 26k wafers per month capacity at its Lubbock facility, can meet its customers’ needs.[127]

Working with PowerAmerica, X-Fab devised process kits and other technologies for making SiC devices. The X-Fab foundry operates under a collaborative model, providing companies that lack their own silicon carbide fabrication capabilities with access to a shared production and R&D facility.[128] For example, UnitedSiC has its 150mm products made by X-Fab. It also uses an undisclosed vendor for 100mm capacity.[129]

4.3.2 Progress to 8” Wafers

With SiC wafer as the basis for SiC devices, the industry has been working on the supply by expanding wafer capacity. However, there are still many issues to solve in order to have high-quality wafers and to further improve the challenges of yield loss. Companies are working on ways to solve these issues.

Major wafer suppliers are manufacturing 8” wafers. As of July 2022, 8” wafers have been qualified. 8” SiC wafers are considered as the critical step to scaling up production. The objective is to increase yield. Major IDMs are developing their own manufacturing capability of 8” SiC wafers; already, some wafer suppliers are shipping samples as of 2022.

- In March 2022, Tokyo-based wafer manufacturer Showa Denko K.K. launched the mass production of 6-inch (150mm)-diameter SiC single-crystal wafers, for processing into SiC epitaxial wafers for power semiconductor devices as demand rises rapidly in fields including electric vehicles, railcars, and industrial equipment.[130] And in May 2022, Showa Denko was funded by the Japan’s New Energy and Industrial Technology Development Organization for its 8-inch SiC wafer development project.[131]
- In July 2021, STMicroelectronics announced it has manufactured the first 200mm (8-inch) SiC bulk wafers for prototyping next-generation power devices from its facility in Norrköping, Sweden. “ST’s initial 200mm SiC wafers are also very high quality, with minimal yield-impacting and crystal-dislocation defects. The low defectivity was achieved by building on know-how and expertise in SiC ingot growth technology developed by STMicroelectronics Silicon Carbide A.B.”[132]

- In April 2022, Wolfspeed opened its 200mm SiC fab in Marcy, N.Y.[133]
- Another vertically integrated semiconductor manufacturer, Rohm opened Apollo fab in Japan in 2021.[134] The fab also begun 200mm wafer based SiC power chip evaluation. The company is aiming to begin mass production of SiC power chips in 2024. It is aiming for a global market share of 30%.
- Infineon Technologies is spending over €2 billion to expand its capacity for and GAN power chips, converting its 200mm and 150mm silicon lines in Villach to these wide bandgaps and adding a third fab at its site in Malaysia. Infineon also opened its 300mm power chip fab at Austria in September 2021.[135] Infineon is targeting revenues of $1billion with SiC-based power semiconductors by the middle of the decade.[136]

4.3.3 Innovations in SiC Wafer Manufacturing

SiC raw wafer cost represents more than 60% of the epi-wafer cost for 1200V SiC MOSFETs. Even though SiC wafer capacity has been expanding, there is a strong motivation for improving quality, throughput, and reducing cost. Some of the solutions proposed to improve the quality include new wafer manufacturing processes, and the new format of SiC wafers. For example, to produce uniform wafers with the high quality surfaces, Applied Materials has developed the Mirra Durum CMP system, which integrates polishing, measurement of material removal, cleaning and drying in a single system. "The new system has demonstrated a 50X reduction in finished wafer surface roughness as compared with mechanically grinded SiC wafers and a 3X reduction in roughness compared to batch CMP processing systems."[137]

To optimize the wafer manufacturing process and thus produce more wafers from one single SiC boule is another approach. Equipment suppliers such as DISCO Corporation (Tokyo, Japan) has developed a laser cutting system to increase the SiC wafer throughput. The laser wafer slicing method called key amorphous-black repetitive absorption achieves high-speed production of SiC wafers. "The process increases the number of wafers produced from a single ingot, and dramatically improves productivity."[138]

In 2018, Infineon acquired Siltectra GmbH, a start-up (Dresden Germany) bringing Cold Split technology into its fold. Siltectra developed the Cold Split, which processes crystal material efficiently and with minimal loss of material. Using the Cold Split technology to split SiC wafers doubles the number of chips out of one wafer.[139] Infineon Technologies has qualified their Cold Split technology.[140]

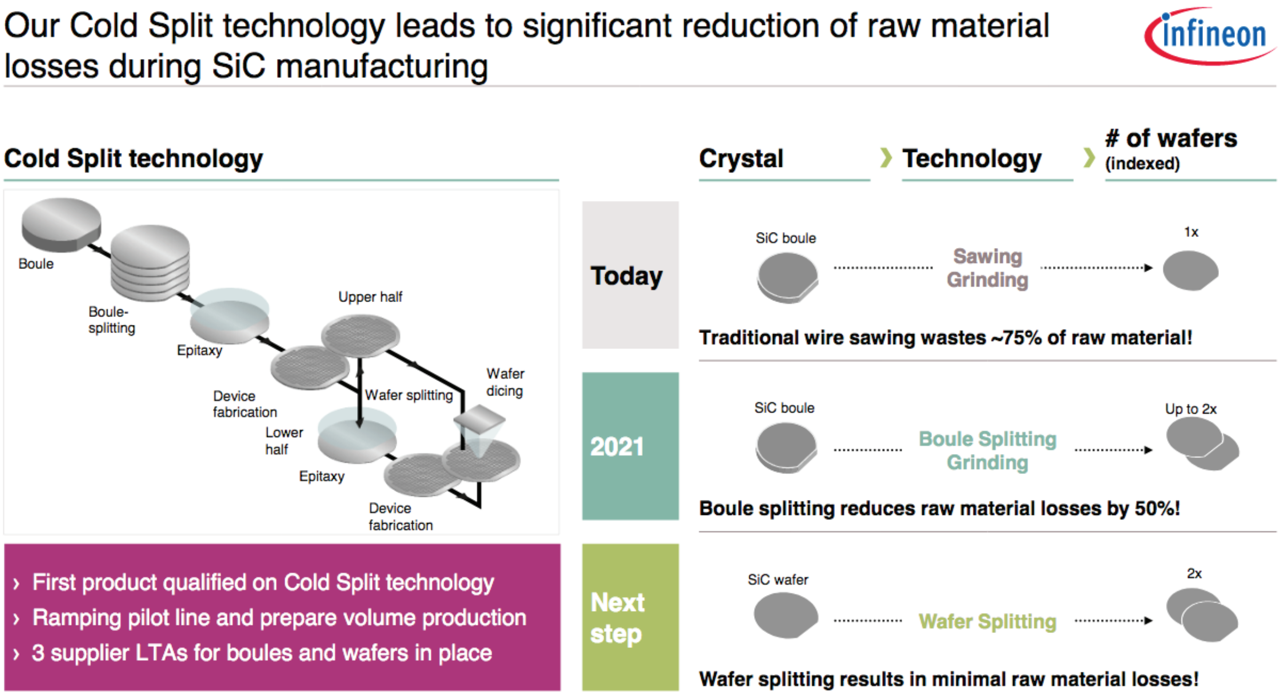

Figure 12: Infineon Cold Split technology
Source: Infineon. (2021).[141]

Soitec uses their Smart Cut technology to produce SiC wafer with a thin layer with a lower defect rate and a handle wafer with lower resistivity. "Smart Cut™ technology makes use of both implantation of light ions and wafer bonding to define and transfer a thin single-crystal layer from one substrate to another. It works like an atomic scalpel and allows to generate active layers of our structures independently from the supporting mechanical substrate, and its optional functional layers that can be inserted in the stack."[142]

4.3.4 Key Players

The SiC foundry business is still small. There are two types of SiC wafer suppliers — (1) vertically integrated and (2) third party:[143]

- **Wolfspeed, STMicroelectonics and Rohm** are vertically integrated. Wolfspeed not only supplies SiC wafers for its own power semiconductors, but it also sells them to others. Rohm sells power devices and has an internal SiC wafer manufacturing unit.
- **Infineon and STMicroelectronics** have signed long-term wafer supply agreements with Wolfspeed.
- **STMicroelectronics** acquired a majority share in Norstel AB (Sweden), a supplier of SiC wafers.
- Third-party foundry vendors are entering or expanding their efforts the SiC market, including **II-VI (U.S.), Showa Denko K.K., and Sumitomo (Japan)**.

- SK Siltron acquired DuPont's Silicon Carbide Wafer (SiC Wafer) unit in March 2020. The primary site for the business is in Auburn, Michigan.[144] In February 2021, SK Siltron started to produce a small amount of SiC wafers in South Korea. SK Siltron acquired DuPont's SiC wafer division for $450 million in February 2020.[145]

Wolfspeed is the market leader with an estimated ~60% market share, with the remaining (40%) by the rest of the world.[146]

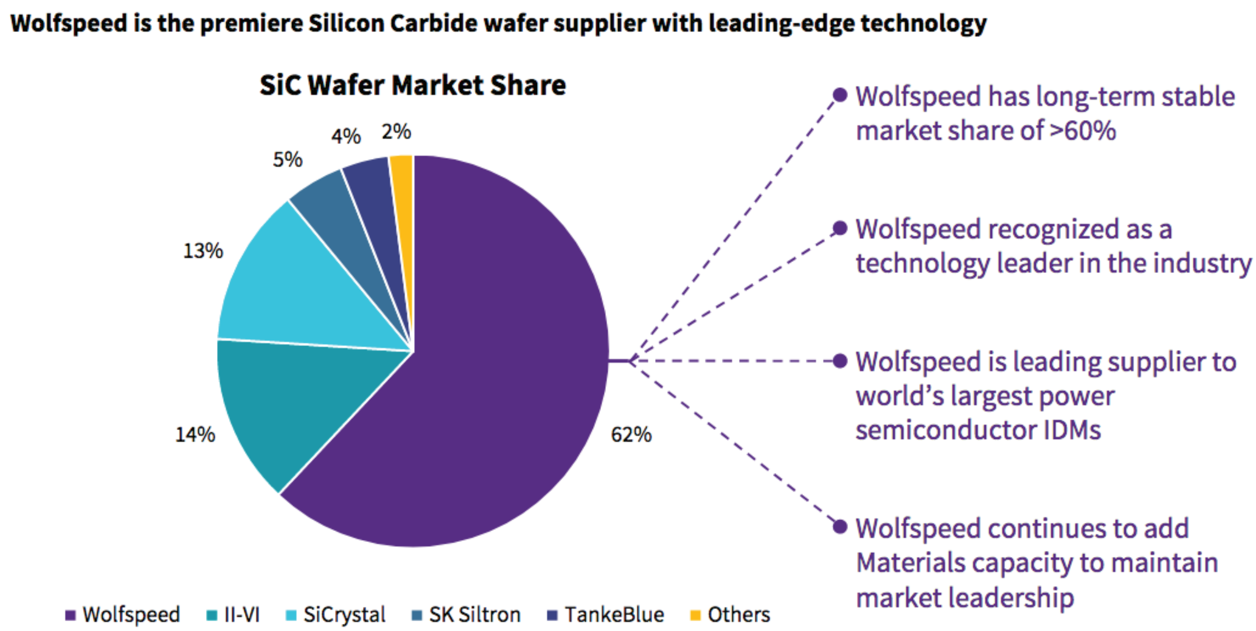

Figure 13: Global Market Participants
Source: Wolfspeed. (November 2021).[147]

4.3.4.1 Chinese SiC Manufacturers Entering Market

Chinese SiC chip manufacturers have begun to enter the market and are looking to scale up production. Typically, Chinese SiC chip manufacturers (as well as Chinese manufacturers of SiC substrates, epi-wafers, and systems) are not vertically integrated. While the share of Chinese firms in the SiC substrate, market was only 3% - 4% in 2015, several Chinese firms have made investments in SiC substrate and epi-wafer manufacturing, increasing capacity. More than $2 billion were invested by Sanan, TankeBlue, SICC and other Chinese suppliers covering wafer and epiwafer fabs and packaging. The following table provides an overview of the semiconductor players from China.[148]

Table 17: Chinese SiC Semiconductor Player

Company	Description
Sanan Integrated Circuit Co., Ltd	Sanan Integrated Circuit Co., Ltd. is a compound semiconductor wafer foundry, serving the microelectronics and photonics markets worldwide. The company was founded in 2014 and is based in Xiamen City, China, operating as a subsidiary of Sanan Optoelectronics Co., Ltd. The company develops and provides GaAs, GaN, SiC, and InP foundry services with its III-V compound semiconductor fabrication facilities.[149] Sanan is mainly focuses on III-V compound semiconductor materials' R&D and applications. Its core businesses are wafer's and chip's new semiconductor materials, including GaAs, GaN, SiC, InP, AlN, and sapphire. In 2017, Sanan invested RMB 33.3 billion in III-V compound semiconductor materials' facilities. All projects are planned to be put into mass production in five years and reach their design capacities in seven years.[150] In 2018, Sanan, a pure-play wafer foundry with its advanced compound semiconductor technology platform, announced that it had achieved process qualification for commercial release of its 6-inch SiC technology to add to its foundry services portfolio. Sanan IC's SiC process technology offers device structures for 650V, 1200V and higher-rated Schottky Barrier Diodes, to be followed by a SiC MOSFET process for 900V, 1200V, and higher. SiC SBDs and SiC MOSFETs.[151] In 2020, Sanan announced its growing portfolio of advanced, wide bandgap power electronics foundry services for 650V and 1200V SiC devices, and 650V GaN power high-electron-mobility-transistors.[152]
TanKeBlue Semiconductor	TanKeBlue Semiconductor, a wholly owned subsidiary of Xinjiang Tianfu Energy, is the first and largest supplier of SiC mono-crystal products in China. Currently, the company has developed 2-inch, 3-inch, 4-inch, and 6-inch SiC wafers, with its annual capacity of 70,000 pieces.[153]
EpiWorld International	Pure-play SiC epitaxial wafer foundry EpiWorld International Co Ltd in Xiamen, China (a privately owned joint venture with investors in the USA, Japan, and China). In 2019, the company installed an AIX G5 WW C high-volume manufacturing system SiC epitaxial wafer foundry. With this addition, annual capacity was expected to be increased to 60,000 wafers in 2019. The company also completed phase I expansion of an 18,000m^2 facility.[154] Production lines for 4- and 6-inch SiC epi-wafers for making 650 Volt-, 1,200 Volt- and 1,700 Volt-power devices are complete. The company completed manufacturing center provides space for rapid expansion to 400,000 6-inch epi wafers per year in 2020. EpiWorld currently has a capacity of over 60,000 pc/yr.[155]
Dongguan Tianyu Semiconductor	Dongguan Tianyu Semiconductor Technology Co., Ltd. was established in 2009. It specializes in R&D, production, and sales of third-generation semiconductor silicon carbide epitaxial wafers.
Global Power Technology	Global Power Technology, a leader in China in industrialization of SiC power devices, has China's only SiC device production line. In 2014, the company succeeded in mass producing SiC Schottky Barrier Diode, but the scale was still at the starting stage, with the current capacity of only 4,000 pieces.[156]
SICC Science & Technology Co., Ltd.	In 2018, the company funded a SiC material project, funded with a 3 billion yuan ($431.6 million).[157]

Company	Description
Beijing Century Goldray Semiconductor Co., Ltd.	Century Goldray Semiconductor was founded in 2010 in Beijing with registered capital of RMB 234 million. The company's focus is on the R&D, manufacture, and sales of the second and three generation of semiconductor powder, wafer, epitaxial, substrates and appliances. Main products include 3-4 SiC wafers, GaN wafers, InP wafers, GaSb wafers, SiC powder, SiC-SiC epitaxial.[158]
Yangzhou Yangjie Electronic Technology Co., Ltd.	Yangzhou Yangjie Electronic is an integrated device manufacturer in China, which integrates discrete semiconductor chip design and production, semiconductor component assembly and test as well as market sales & services.[159]
Semiconductor Business Unit of Zhuzhou CRRC Times Electric Co., Ltd.	Zhuzhou is a prominent maker of traction systems for locomotives and for electric multiple units and urban transit train applications.[160] In 2017, Shandong Tianyue developed a new high purity SiC. Currently, the mass production products are mainly 4 inches. In addition, its 4H conductive SiC substrate materials are mainly 2 inches, 3 inches and 4 inches. And 6 inches. Shandong Tianyue also developed a 6-inch N-type silicon carbide substrate material.[161]
Dongguan Tianyu Semiconductor Technology Co., Ltd.	Shandong Tianyue is a leading enterprise in my country's third-generation semiconductor material silicon carbide.
Xiamen Xinguangrunze Technology Co., Ltd.	In September 2018, Xiamen Xinguang Runze Technology Co., Ltd started an intelligent power module production line, marking another important breakthrough in China's strategic emerging industry of silicon carbide chips.[162]
CISRI-Zhongke Energy Conservation and Technology Co., Ltd.	In July 2017, Zhongke Energy signed a cooperation agreement with Qingdao Laixi City and Guohong Zhongjing to invest in the construction of a SiC crystal growth line project. After completion, it can produce 50,000 6-inch N-type silicon carbide crystal substrate sheets and 5,000 pieces of 4-inch high-purity semi-insulating type.[163]
Tianke Heda	Tianke Heda has developed four products: 4-inch silicon carbide wafer production (6-inch unproduced, ready); silicon carbide single crystal growth equipment; silicon carbide crystal cutting, wafer processing and clear return service; silicon carbide gemstone crystal. Tianke Heda has more than 100 furnaces and can produce 20,000 pieces of 4-inch conductive silicon carbide wafers a year.[164]
Hebei Tongguang	Hebei Tongguang's main products include 4-inch and 6-inch conductive, semi-insulating silicon carbide substrates, of which 4-inch substrates have reached the world's advanced level.[165]

4.4 Company Profiles

This section provides brief profiles of key companies.

4.4.1 Wolfspeed, Inc.

The Wolfspeed (Durham, NC) was founded in 1987 and is a manufacturer and marketer of power products, products for radio frequency (RF) applications, lighting components and semiconductor chips. "Wolfspeed has historically been a company with a presence in Lighting, LED, and SiC and GaN semiconductors. After Gregg Lowe joined Wolfspeed as CEO in September 2017, the company has divested its Lighting and LED segment and "transformed Wolfspeed from a lighting and LED company to a semiconductor powerhouse."[166]

Wolfspeed is one of the leaders in semiconductor chips that use SiC and GaN technologies, with an estimated 60% of the market.[167] The company provides SiC silicon materials for RF and power applications as well as MOSFETs, GaN dies and high-electron-mobility transistor, among other products. Wolfspeed's earnings statements also reflect its role in driving the SiC market. According to Wolfspeed's financial results for fiscal year 2020, Wolfspeed gross profit (which includes SiC) from June 2019 to June 2020 was $186.4 million, registering gross margin of 39%.[168] Wolfspeed's Wolfspeed business is a global leader with 60%+ share in substrates for SiC.[169] Wolfspeed management believe the company has market leadership for several reasons:[170]

- Silicon carbide extremely difficult to grow with high difficult to grow with high quality.
- Wolfspeed has by far the most experience and learning in manufacturing of manufacturing of SiC crystals.
- Wolfspeed has a tremendous head tremendous head start over competitors in terms high volume production silicon carbide boules.

In the November 2019 "Wolfspeed Investor Day" slide deck,[171] Wolfspeed reaffirmed its market leadership in the SiC market, highlighting the benefit of leveraging its experience in growing SiC crystals. Wolfspeed had ~62% market share if you include all the SiC that has been shipped over the past 22 years, including in LEDs and RF, Wolfspeed estimated that it has shipped over 95% of the total SiC during this time. It appears that Wolfspeed has a clear advantage in its manufacturing capabilities. While competition in the market is increasing, Wolfspeed has been able to maintain its competitive advantage.

As part of its $1 billion capex plans over the five years, 2019 -2024, Wolfspeed is expanding its SiC fab capacity by up to 30X by 2024 amid what the company believes is increasing demand.

To meet the expected increase in SiC demand, Wolfspeed is increasing its fab and/or wafer capacities.[172] As part of its $1 billion capex plans over the five years, 2019 -2024, Wolfspeed is expanding its SiC fab capacity by up to 30X by 2024 amid what the company believes is increasing demand.[173] This includes investment in the Durham (NC) production plant to ramp up production of SiC materials.[174] Wolfspeed is also moving forward with the next SiC wafer size—200mm from its 150mm fab capacity. In September 2019, Wolfspeed announced expansion for an automated 200mm silicon carbide fabrication facility in Mohawk Valley (NY), after getting $500 million worth of incentives from the State of New York. Work at the Utica facility started in 2020.[175]

Table 18: Wolfspeed, Wafer Fab Strategy

Location	Sq. Foot	Wafer Diameter	Tool Lay Out	Automation
Durham, NC	99K sq. ft	100 – 150 mm	Bay and Chase	Manual
Research Triangle Park (Durham, NC)	99K sq. ft.	100 – 150 mm	Bay and Chase	Manual
Mohawk Valley Fab, NY	115k sq. ft	100 – 150 mm	Ball room	Automated

Source: Wolfspeed. "Investor Day" slide deck. (November 20, 2019).[176]

At an investor conference in October 2020, CEO Gregg Lowe stated the company's strategy is to be a "pure-play global semiconductor powerhouse for silicon carbide and gallium nitride devices, as well as materials."[177] Wolfspeed also presented its silicon carbide strategy in the February 2018 Investors' Day. The strategy for becoming a more streamlined supplier of SiC and GaN chips includes: (1) ensuring a new source of revenue, (2) expand activities towards new sectors and more. In this presentation, Wolfspeed reiterated its commitment to the development of SiC and GaN to gear up for the "large multi-decade growth opportunities in electric vehicles, solar energy, telecommunications, industrial, and military/aerospace."[178] In line with the strategy, Wolfspeed strengthened its wireless RF portfolio solutions with the acquisition of Infineon's RF business in 2018.[179] Wolfspeed divested its lighting business for $310 million in 2019[180] and LED business in March 2021.[181]

Wolfspeed believes the next generation power electronics will be powered by SiC, with half of the pipeline dedicated to electric vehicles. Beyond the automotive market, Wolfspeed is targeting broad markets including solar, aerospace, defense and industrials

Wolfspeed believes the next generation power electronics will be powered by SiC, with half of the pipeline dedicated to electric vehicles.[182] Wolfspeed's SiC-based devices are produced in a fab, where the company continues to make a wafer size transition. "SiC is available on both 4- or 6-inch. Wolfspeed has made the transition from 4 - (100mm) to 6-inch (150mm) wafers.[183] Wolfspeed has high optimism for the SiC business.[184] Beyond the automotive market, Wolfspeed is targeting broad markets including solar, aerospace and defense and industrials. Wolfspeed is bracing for a major uptick in SiC inverters for automotive and industrial applications in the few years to come.[185]

Wolfspeed's strategy for SiC adoption includes: (1) Selling bare and epitaxial chip wafers to third-party chipmakers and (2) selling internally designed chips. Wolfspeed has long-term agreements totaling more than $1B to produce and supply its SiC wafers.[186] Strategic partners are listed in table 19.

Table 19: Wolfspeed SiC Partnerships

Application	Partner	Description
Automotive	onsemi	Wolfspeed signed a long-term strategic agreement ON Semiconductor valued at more than $85 million. Wolfspeed will supply of 150mm SiC bare and epitaxial wafers to ON Semiconductor for use in "high-growth markets" such as EVs and industrial applications.[187]
Automotive	Delphi Technologies	A partnership with Delphi Technologies in which Wolfspeed supplies SiC semiconductor devices to improve the driving range and charging times of Delphi's electric vehicles. The Wolfspeed SiC MOSFETs will initially be used in Delphi Technologies' 800 Volt inverters for a "premium global automaker." Production will ramp in 2022.[188]
SiC Wafers	STMicroelectronics	Wolfspeed expanded a long-term SiC wafer supply agreement to more than $500 million with STMicroelectronics. The extended agreement is a doubling in value of the original agreement for the supply of Wolfspeed's advanced 150mm silicon carbide bare and epitaxial wafers to STMicroelectronics over the next several years.[189]
Automotive	ABB	ABB will use SiC devices in the EVs. ABB's strategy in developing energy-efficient silicon carbide semiconductors in the automotive, power grid, and industrial sectors.[190]
Automotive	StarPower Semiconductor	StarPower is using Wolfspeed 1200V silicon carbide devices in power modules for powertrain systems for electric buses.[191]
Automotive	ZF Friedrichshafen AG	Create electric drivetrains for EVs to advance the electric powertrain with SiC-based Inverter. ZF expects to make silicon carbide electric drivelines available in the market by 2022.[192]

4.4.2 Fuji Electric Corporation

Fuji Electric Corp. of America is a wholly owned subsidiary of Fuji Electric Co., Ltd., and has been responsible for sales and distribution of the company's products since 1970. Fuji Electric is one of the leading players across the power electronics system industry. Incorporated in 1923 as a capital and technology alliance between Japan's Furukawa Electric Co., Ltd. and Germany's Siemens AG, Fuji Electric has established their presence across the semiconductor market. Fuji Electric manufactures and sells power semiconductor devices that contribute to high power conversion efficiency and energy-saving across industrial, automotive, and consumer electronics applications.[193]

Fuji Electric manufactures various power products including SiC power devices. Approximately 30% of its products ship to the automotive industry. In 2013, Fuji built a new SiC line at its Matsumoto plant that includes both wafer process and packaging facilities. Fuji Electric manufactures SiC devices on 150mm SiC wafer technology. The "all-SiC modules" with SiC MOSFETs were introduced in 2014 and has applications in power conditioners in solar power.[194]

Fuji Electric's all-SiC modules with SiC MOSFETs were introduced in 2014 and have applications in power conditioners in solar power applications.

Fuji Electric has been developing SiC technologies and products for the next generation power semiconductor business:

> *"As Fuji's first SiC products, the 600V and 1200V hybrid power integrated modules (PIMs) included silicon IGBTs with SiC diodes. The modules were used in inverters for air conditioners in internet data centers beginning in 2012. Another product is a 1700V/400A hybrid module for 690V inverters called the "FRENIC-VG Stack Series," which started sales in 2014. In 2015, Fuji developed a 3.3kV/1.2kA hybrid module, which was applied in the next generation Shinkansen, the high speed train in Japan. Fuji also developed all-SiC modules with SiC MOSFETs in 2014 and applied them in power conditioners in solar power applications. Regarding mass-production facilities, Fuji has built a 6-inch front-end factory, whose production line has been operating since 2013, followed by an automated back-end factory, which has been operating since 2014. Fuji plans to expand its all-SiC module range, offering Type 1, 2 and 3L with voltage classes of 1200V (15 to 300A and higher) in 2016 and 2017, and 1700V (25 to 200A)."*[195]

Fuji has made a strong push into SiC power materials, devices, components, and modules, particularly in the traction drive market. Fuji Electric 2.0 strategy's entails developing its global power electronics systems business and India has been identified as one of the key markets in Fuji's global growth plan. In February 2020, Fuji Electric India, the 100 per cent subsidiary of Fuji Electric, announced interest in expanding into the solar inverters and batteries business in India. A Fuji press release reported, "Fuji Electric is currently focusing on expanding its three existing product segments – Un-interrupted Power Supply systems, Variable Frequency Drives that boost energy efficiency and automation products. .... The plan is to launch solar inverter business first along with setting up a facility for manufacturing and assembly of different components into Megawatt-scale solar inverters."[196] In January 2022, Fuji stated it would make capital investments in its semiconductor manufacturing – includes silicon and SiC:[197]

> "In the Five-Year Medium-Term Management Plan ending in fiscal 2023 (fiscal 2019 - fiscal 2023), FE announced that it will carry out capital investments totaling 120 billion yen toward power semiconductors. Although our capital investments currently focus on front-end process production lines for 8-inch Si (silicon) wafers, our amount of investments in power semiconductors, including this investment in SiC power semiconductors, is expected to expand to 190 billion yen, set against conditions of increased demand for electrified vehicles and renewable energy.
>
> FE has developed and applied SiC power semiconductors for equipment such as inverters for railcars and power conditioning systems used for power conversion in photovoltaic power plants. We intend to widen the scope of their application to electrified vehicles, whose market is expected to expand, and contribute to the realization of a decarbonized society."

Table 19: Fuji – SiC Modules for Power Electronics Products

Device Type	New products	Configuration	Series	VCES (V)	IC(A)	Package	Width (mm)	Length (mm)
1MSI1200XAGF330-03		1-pack	Hybrid	3.300	1.200	M155	140	130
1MSI1800XAEF330-03		1-pack	Hybrid	3.300	1.800	M156	140	190
2MSI200VAB-120-53	New	2-pack	Hybrid	1.200	200	M274	45	92
2MSI300VAH-120C-53	New	2-pack	Hybrid	1.200	300	M276	62	108
2MSI300VAN-120-53	New	2-pack	Hybrid	1.200	300	M254	62	150
2MSI400VAE-170-53	New	2-pack	Hybrid	1.700	400	M277	80	110
2MSI450VAN-120-53	New	2-pack	Hybrid	1.200	450	M254	62	150
2MSI600VAN-120-53	New	2-pack	Hybrid	1.200	600	M254	62	150
2SI900AGF330-03		2-pack	SiC-SBD	3.300	900	M289	140	130
7MBR100VB060S-50	New	PIM	Hybrid	600	100	M712	62	122

Source: Fuji Electric. "SiC Devices."[198]

4.4.3 Infineon Technologies AG

Headquartered in Munich, Germany, Infineon Technologies AG was founded in 1999. The company is a manufacturer, designer, and developer of semiconductors. The company specializes in energy efficiency, mobility and security products and solutions. Products offered by Infineon Technologies AG include power sensors, microcontrollers, transistors and diodes, and RF and wireless controls, among others.

Infineon offers the CoolSiC MOSFETs. These 650V devices, which are rated from 27 mΩ to 107 mΩ, have stated usefulness in telecom, industrial, EV, and solar power applications, among others.[199] Infineon's business is dominated by industrial applications and additional potential in the automotive.[200]

With respect to solar, Infineon's product portfolio "comprises a broad selection of inverters ranging from just a few watts and kilowatts for residential use to several megawatts for the commercial and utility-scale markets. It includes discrete OptiMOS™, CoolMOS™ and CoolSiC™ MOSFETs and IGBTs as well as highly integrated 3-level Easy 1B/2B modules, functionally integrated EiceDRIVER™ gate driver ICs and XMC™ controllers." Infineon claims a maximum efficiency of over 99% by using CoolSiC™ MOSFET solutions from Infineon.[201]

<table>
<tr><th></th><th>Optimizer
250-750 W</th><th>Single/dual/quad microinverter
250-1200 W</th><th>Single phase multilevel inverter
<10 kW</th><th>Single phase string inverter standard
<10 kW</th></tr>
<tr><td>MOSFETs</td><td>OptiMOS™
SuperSO8/DirectFET™ | 75-150 V</td><td>OptiMOS™
SuperSO8 | 60-200 V</td><td>OptiMOS™
SuperSO8/D^{2}PAK | 150 V</td><td></td></tr>
<tr><td></td><td></td><td>CoolMOS™
D^{2}PAK/ThinPAK | 600-800 V</td><td>CoolMOS™
TO-247/D^{2}PAK | 600 V</td><td>CoolMOS™
TO-247 | 600/650 V</td></tr>
<tr><td></td><td></td><td></td><td></td><td>CoolSiC™ MOSFET
TO-247-3/TO-247-4 | 650/1200 V</td></tr>
<tr><td>SiC diodes</td><td></td><td>CoolSiC™ Schottky diodes
DPAK/TO-220 | 600 V/1200 V
D^{2}PAK | 650 V</td><td>CoolSiC™ Schottky diodes
TO-247 | 600 V/1200 V
D^{2}PAK | 650 V</td><td>CoolSiC™ Schottky diodes
TO-220/TO-247 | 600 V/1200 V
D^{2}PAK | 650 V</td></tr>
<tr><td>IGBTs</td><td></td><td></td><td></td><td>TRENCHSTOP™ 5 / TRENCHSTOP™ IGBT6
TO-247-3/TO-247-4 | 600/650/1200 V</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Easy 1B/2B</td></tr>
<tr><td>Gate driver ICs</td><td></td><td>2EDN EiceDRIVER™</td><td>2EDN EiceDRIVER™</td><td>EiceDRIVER™ 1ED Compact
EiceDRIVER™ Enhanced</td></tr>
<tr><td>Schottky diode</td><td></td><td></td><td></td><td>BA165 Schottky diode</td></tr>
<tr><td>Auxiliary power supply</td><td></td><td></td><td></td><td>CoolSET™
800 V</td></tr>
<tr><td>Microcontrollers</td><td>XMC1xxx ARM® Cortex®-M0</td><td>XMC1xxx ARM® Cortex®-M0</td><td>XMC1xxx ARM® Cortex®-M0</td><td>XMC1xxx ARM® Cortex®-M0</td></tr>
<tr><td></td><td>XMC45xx ARM® Cortex®-M4</td><td>XMC45xx ARM® Cortex®-M4</td><td>XMC45xx ARM® Cortex®-M4</td><td>XMC45xx ARM® Cortex®-M4</td></tr>
</table>

Figure 15: Infineon – SiC Solutions for Solar
Source: Infineon Technologies AG. (2019).[202]

Infineon is not completely vertically integrated and has supply agreements with Wolfspeed for 150 mm SiC wafers.[203] Infineon produces SiC devices in a 150mm line. Infineon sees growing interest in SiC-based power devices, with growth well above the expected general market level. Although 150mm is sufficient in the short- and medium-term, Infineon believes long-term, 200mm will be needed to advance the technology. Infineon's manufacturing lines are capable of processing 200mm.[204] Infineon has further publicly disclosed "SiC line resides within its 300mm fab, which produces silicon-based power semiconductors. Because Infineon integrates SiC production into high-volume silicon line, Infineon can benefit from a high-volume flexibility. Therefore, production expansion can be managed based on actual demand without requiring significant investments."[205]

Table 20: Infineon Technology – Solar Partnerships

Company	Description
Sungrow	Sungrow teamed with Infineon to manufacture a 250kW solar inverter, which uses custom SiC power modules from Infineon. The SG250HX uses the SiC module with high voltage 1500Vdc and 800Vac operation to give the string inverter a maximum of 99 percent efficiency and a power density of 1kW/l.[206]
SMA Solar Technology	Germany-based SMA Solar Technology teamed up with Infineon to use SiC power devices in its solar inverter designs. Infineon developed a custom solar inverter power module that included both a classic TRENCHSTOPIGBT and a CoolSiC MOSFET with body diode. The Active Neutral-Point Clamped topology allows system voltages up to 1500 V maximum to be switched with switches designed for 1200 V.[207]
Fronius International GmbH (Austria)	In November 2020, Fronius International launched the Symo GEN24 Plus solar inverter, which is suitable for a wide range of applications supporting energy self-sufficiency. Using CoolSiC MOSFETs from Infineon Technologies AG, the Symo GEN24 Plus “achieved a record value in the System Performance Index (SPI) of 94 percent in the 10 kW class. It was the only one in this combination to achieve Class A energy efficiency.” The inverter weighs only 24 kg and has a small volume (HWD 594 x 527 x 180 mm 3). Its active air-cooling can reduce the temperature of the power electronics parts, and thus extend service life. The inverter is available in the power classes 6, 8, and 10 kW. Fronius supplies this inverter primarily in Europe, South America, and Australia.[208]

4.4.4 ROHM Semiconductor

Headquartered in Kyoto, Japan, ROHM Semiconductor was established in 1958. The company was previously known as Toyo Electronics Industry Corp. and was rechristened as ROHM Co. Ltd. in 1981, and to ROHM Semiconductor in 2009. ROHM Semiconductor is a public company and is listed on the Tokyo Stock Exchange. ROHM is at the forefront in the development of SiC power devices and modules that offer improved power-savings in applications across several industries. In 2009, Rohm acquired a German SiC wafer maker, SiCrystal, which started supplying 150mm wafers to Rohm in 2013. Rohm also acquired Renesas Electronics’ Shiga plan, Japan (200mm line) in 2016 to manufacture SiC power and other discrete devices.[209]

ROHM’s portfolio is bare chips and discrete products of SiC Schottky barrier diodes and SiC MOSFET and Full SiC power modules incorporating both the company’s SiC Schottky barrier and SiC MOSFETs. [210]

Table 21: Rohm Semiconductor – Solar Power Electronics Products

Products	Applications
1200V 400A/600A rated full SiC power modules BSM400D12P3G002 /BSM600D12P3G001	Optimized for inverters and converters in solar power conditioners, UPS, and power supplies for industrial equipment
1200V/300A	SiC power module designed for inverters and converters in solar power conditioners and industrial equipment. The 300A rated current makes the BSM300D12P2E001 suitable for high power applications such as large-capacity power supplies for industrial equipment.[211]

In 2018, Rohm announced a 150mm fab expansion plan within a new building. Rohm has plans to increase its SiC production capacity by 16X at a total investment of approximately $546.1 million by 2025. In June 2018, Rohm announced plans to establish a SiC production facility at Apollo Plant in Chikugo Japan (completed in 2021) to meet the growing demand for SiC power devices. In addition to this facility, SiCrystal GmbH, a Rohm Group company manufactures SiC wafers.[212] In 2021, Zhenghai Group and Rohm formed a joint venture agreement (Zhenghai Group will own 80% and Rohm 20%). The JV, HAIMOSIC will develop, design, manufacture, and sell power modules employing silicon SiC power devices, with the aim of creating a power module business suitable for traction inverters and other applications in new energy vehicles.[213]

ROHM's silicon carbide MOSFETs are being used by Midnite Solar (Arlington, WA) in its solar products.

Rohm is "pushing hard in the automotive and industrial markets." Rohm has publicly disclosed SiC technology is evolving in electric vehicles and industrial equipment and Rohm is continuing to invest in this area. Rohm is working to improve manufacturing efficiency by increasing wafer size diameter and using the latest equipment to reduce the environmental impact of manufacturing.[214] With respect to automotive applications, the company is "addressing the key applications to the electrification of vehicles with common devices such as the traction inverter and on-board chargers."[215] Rohm is also targeting solar power electronics.[216] Rohm's silicon carbide MOSFETs are being used in Midnite Solar (Arlington, WA) solar products.[217] However, no other solar partners have been publicly announced making it difficult to determine if the SiC MOSFETs are being manufactured in large quantities.

Rohm is also looking at 200mm. Rohm also expects 8-inch wafer production soon. The company has decided that 8-inch equipment shall be installed in the new building, which the company can use for the production line for either 6- or 8-inch based on the technology and market situation.[218]

Table 22: Rohm Semiconductor – Partnerships

Application	Partner	Description
Solar	**Midnite Solar**	Midnite Solar (Arlington, WA) is utilizing ROHM's silicon carbide MOSFETs. Four products new to the US market – the Hawkes Bay 600VDC to 48VDC 6000W MPPT solar charge controller, powerful Barcelona dual MPPT charge controller, MNB17 advanced battery-based charger/inverter, and 120/240V Rosie inverter/charger. Midnite Solar incorporates ROHM's 60mΩ RDS(on) SiC devices and newer 30mΩ RDS(on) products in its new solar product ranges.[219]
Electric Vehicles	**Vitesco Technologies**	Vitesco Technologies will use SiC components in its power electronics for EVs. ROHM and Vitesco Technologies will work on creating the optimum combination of ROHM's SiC technology for high-volume manufacturing. Vitesco Technology plans the start of production of the first SiC inverter in 2025.[220]
SiC Devices	**STMicroelectronics**	SiCrystal AG signed a multi-year agreement to supply more than $120m of 150mm SiC wafers to STMicroelectronics "during what is described as this current period of demand ramp-up for silicon carbide power devices."[221] SiCrystal owns all processing stages from the production of the original material to packaging the epi-ready substrate in an in-house clean-room environment.

4.4.5 STMicroelectronics N.V.

STMicroelectronics (Amsterdam, Netherlands) is one of the leading providers of semiconductor solutions. STMicroelectronics started working with SiC in 1996, producing its first SiC diodes in 2004. In 2009 ST started to produce its first SiC MOSFETs and power Schottky diodes. ST's 150mm SiC wafer production started in 2017. Some of the power electronics products offered by the company include power modules, IGBT, power MOSFETS, wide bandgap transistors, power management devices, silicon carbide diodes, automotive-grade diodes, Schottky barrier diodes, and field-effect rectifiers. STMicroelectronics has two SiC manufacturing sites. ST's portfolio of SiC MOSFETs includes devices from 650V to 1200V and SiC diodes ranging from 600V to 1200V that feature negligible switching losses and 15% lower forward voltage than standard silicon diodes."[222]

The company's strategy of targeting $1B SiC in revenue by 2025 is by having >40% production with inhouse substrate by 2024.[223] Striving for SiC market domination, ST has made some moves in the market, for example:

- In November 2019, STMicroelectronics entered long-term SiC wafer supply agreement with Wolfspeed, Inc worth more than $500 million.[224]
- ST acquired various players in SiC and GaN ecosystem to broaden its portfolio and expand its market presence. Some of the recent acquisitions include Exagan[225] and Norstel AB, which develops and manufactures advanced 150mm silicon carbide bare and epitaxial wafers.[226]

With these acquisitions, ST intends to ramp up production of 150 mm SiC wafers as well as increase research and development activities on 200 mm wafer production. Activity on 200 mm R&D wafer preparation has already started and ST" intends to be ready with the technology when the market requires wafer migration." [227] In a 2019 press conference, Marco Monti, President of ST's Automotive and Discrete group provided insights into the company's strategy and the need to control the supply chain stating that,[228]

> *50% of the power semiconductors market in 30 years will be based on SiC. While ST currently outsources the supply of ingots and substrates (with the epitaxy and wafer processing carried out in Catania), ST wants to have more control of the supply chain and bring it internal. … ST already has plans to further integrate Norstel into its supply chain … the ambition is to be more vertically integrated. While its SiC is currently on 6-inch wafers, it intends to use its Norstel and local research links to push to 8-inch slices, probably by 2025.*

In February 2022, STMicroelectronics announced it will start bringing its supply chain for SiC in house, from substrates to end products. ST is building a SiC substrate 300mm wafer fab in Agrate, Italy that will supply about 40 per cent of its SiC substrates internally by 2024. In its "billion-dollar revenue" objectives, STMicroelectronics has stated its annual revenues from the semiconductor, used in electric cars and applications will be in the ten figures within the next couple of years. As part of a roughly $3.6 billion CapEx spending program, STMicroelectronics is investing in SiC for power management and analog circuitry ST estimates its annual revenue from these SiC products will hit $1billion by 2024.[229] ST has also moved along the module level. Their modules have been used in the Tesla Model 3. STMicroelectronics demonstrated their in-house 8" SiC wafer in 2021.

STMicroelectronics is building a SiC substrate 300mm wafer fab in Agrate, Italy that will supply 40% of its SiC substrates internally by 2024.

With respect to applications, although ST is targeting the automotive market, while automotive markets get much of the attention for SiC MOSFETs and diodes, ST also sees a "significant opportunity for SiC, and GaN, in high-end industrial applications, including power supplies, renewable generation and industrial motor drives." ST is an established supplier to the solar PV market providing hybrid power integrated modules using 1200V SiC diodes and will soon provide full SiC modules that incorporate 1200V SiC MOSFETs.[230] STMicroelectronics is a leading global supplier for SIC with >50% market share for SiC MOSFETs in automotive and industrial markets.[231]

4.5 Other Notable U.S. Companies

4.5.1 onsemi

onsemi (Phoenix, AZ) is a semiconductors supplier company. The company has a market capitalization of $16 billion. Products include power and signal management, logic, discrete, and custom devices for automotive, communications, computing, consumer, industrial, LED lighting, medical, military/aerospace and power applications. onsemi designs and manufactures semiconductor chips, sensors, power management devices and other electronic components at 20 sites, most in the Asia-Pacific region. The company added the South Portland operations in its 2016 acquisition of Fairchild Semiconductor International Inc. for $2.4 billion. At the time, the plant and offices employed about 700.[232] The company's goal is to be "a top tier SiC supplier with complete vertical integration from boule growth to finished goods inclusive of die only, discrete devices, and modules for both the industrial and automotive markets."[233]

onsemi offers products for solar. For instance, in June 2020, ON Semiconductor introduced the NXH40B120MNQ family of full SiC power modules (1200 V, 40mΩ SiC MOSFET and 1200 V, 40 A SiC boost diode with dual boost stage) for solar inverter applications.[234]

Table 23: onsemi SiC Products

Product	Description
200V Silicon Carbide SiC MOSFETs	900 V N-channel SiC MOSFETs include a fast intrinsic diode with low reverse recovery charge that reduces power losses and boosts operating frequencies. A small chip size also leads to a lower device capacitance and reduced gate charge (Qg) down to 220 nC) and on resistance of 20, 40 and 80mΩ, reducing switching losses when operating at high frequencies.
900V Silicon Carbide SiC MOSFETs	The 1200 V devices are rated at up to 103 A (ID Max.), while 900 V devices carry ratings as high as 118 A. For applications requiring higher currents, the ON Semiconductor MOSFETs can be easily operated in parallel, due to their positive temperature coefficient and temperature independence.

4.5.2 UnitedSiC

UnitedSiC (Princeton, NJ) develops silicon carbide FET and diode power semiconductors for solar PV inverters, as well as for electric vehicle (EV) chargers, DC-DC converters and traction drives, and telecom/server power supplies variable speed motor drives. Products that UnitedSiC offers includes: SiC FETs, SiC JFETs, and SiC Schottky Diodes.

According to company claims, the UnitedSiC product portfolio was expanding in 2020 at a rapid rate. The company currently offers a wide range of voltages, with RDS(on) levels starting at an industry-best 7mohms, as well as packages ranging from D2PAK, TO-220, TO-247, and more. UnitedSiC introduced its Generation 4 SiC technology in 2020, which enabling the introduction of new FETs at 750V. These performance levels are designed to accelerate WBG adoption in automotive and industrial charging, in addition to telecom rectifiers, and datacenter PFC DC-DC conversion, as well as renewable energy and energy storage applications. Worldwide customers are using UnitedSiC FET, JFET, and Schottky diode devices in solar PV inverters, EV chargers, AC-DC and DC-DC power supplies, and solid-state circuit breakers, as well as variable speed motor drives.[235]

For solar applications, UnitedSiC offers the UF3C family of 650 V and 1200 V SiC FETs. A low $R_{DS(on)}$ for solar power inverters is a vital factor affecting inverter longevity, as heat is destructive.[236]

4.5.3 Microchip Technology

Microchip Technology Inc., via its Microsemi subsidiary, announced in 2019 the production release of a family of SiC power devices. The new products include 700-V and 1,200-V SiC Schottky barrier diodes (SBDs) and 700-V SiC MOSFETs. Totaling more than 35 discrete products, Microchip's SiC power product portfolio consists of SiC discrete, die, and power modules across various voltages, current ratings, and package sizes.[237] Microchip Technology is seeing interest and applications in silicon carbide technology across various industries including industrial, automotive, computing, medical, aviation, defense, space, and others. [238]

4.5.4 Genesic Semiconductor, Inc.

Headquartered in Dulles, Va., GeneSiC Semiconductor Inc. was established in 2004. The company operates through two business segments, namely silicon carbide, and silicon-based high-power semiconductor products. The SiC product segment includes SiC MOSFETs, SiC Merged PiN Schottky, SiC PiN, SiC junction transistors, and customized products. The silicon products segment comprises modules, bridges, and studs. GeneSiC Semiconductor caters to the aerospace, commercial, industrial, alternative energy, and military industries. Moreover, the company specializes in gallium nitride, JFETs, IGBT modules, thyristors, and wide-bandgap semiconductors.

The company offers silicon carbide products and silicon products. Under silicon carbide product segments, GeneSiC offers SiC junction transistors, SiC PiN, SiC MOSFETs, SiC Schottky diodes, and customized products. Under silicon products, the company provides bridges, modules, and studs.

4.5.5 Littelfuse, Inc.

Headquartered in Chicago, IL. manufactures electronics and electrical devices. Founded in 1927, Littelfuse is a public company and is traded on the NASDAQ. The company engages in the development and manufacturing of silicon carbide diodes and SiC MOSFETs. The company further specializes in manufacturing thyristors, varistors, power distribution equipment, transient voltage protection, and zener diodes. The products in this segment comprise silicon carbide, SiC diodes, MOSFETs, transient-voltage-suppression diode arrays, and IGBTs. Littelfuse Inc.'s electronic segment products are used in automotive electronics, consumer electronics, medical, information technology, lighting products, and telecommunication equipment applications. As of December 2017, Littelfuse Inc. had over 10,000 employees.

In November 2018, Littelfuse acquired Monolith Semiconductors Inc., a startup company developing SiC power devices technology. Littelfuse began partnering with Monolith from 2015 and gradually increased its ownership in recent years. Also in 2018, Littelfuse announced the launch of its 1700V, 1 Ohm SiC MOSFET, which enables increased efficiency and power density. This new expanded Littelfuse's SiC MOSFET device portfolio. Electric and hybrid vehicles, induction heating and solar inverters are among the applications of the 1700V SiC MOSFET.

4.5.6 Powerex, Inc

Mitsubishi holds 50% ownership in Powerex, Inc. The company supplies discrete devices, modules, and integrated high-power semiconductor solutions. The company's product portfolio consists of IGBTs, rectifiers, thyristors, custom power modules, and assemblies. It offers SiC MOSFET, and hybrid Si/SiC IGBT modules. These products have in applications such as boost converters, inverters, high-frequency power supplies, medical imaging amplifiers, electric vehicles, energy-saving power systems (fans, pumps, and consumer appliances), and high-temperature power systems. The company has its manufacturing facility in the US and sales representatives in Europe, APAC, and MEA.

5.0 Summary

The purpose of this report is to provide insight into factors that affect the availability of SiC for the U.S. solar inverter market. For the next five years, SiC is forecast to be the option for power electronic devices within certain voltage ranges, and will continue to displace their silicon based counterparts in some applications.[239] The growing market demand for SiC-based power electronics is driven by the rising adoption of SiC devices by OEMs of EV, which is expected to create growth opportunities for the power electronics market.[240] Market consulting firm, Frost & Sullivan believes the majority of EV OEMs will transition to SiC by the end of the decade for advanced power electronics.[241] The next big SiC use case is expected to be in PV for storage, where efficiency improvements can reduce the size of a battery, both in residential and larger installations.[242]

Though inverters account for around 5% of total solar PV system costs, these devices are indispensable. The growth of the solar PV inverter segment is directly proportional to the increase in solar PV power installments.[243] Solar inverters are of three types – (1) Central inverters are used in large scale installations and large commercial buildings; (2) String inverters are used in medium-sized installations such as commercial and residential establishments; and (3) microinverters are mostly used in residential installations with some installations in the commercial field. Each inverter type has a unique distribution channel:

- The main distribution channel for central inverters is direct sales as these devices need to be customized as per project requirements.
- Manufacturers rely heavily on distributors for the sale of string inverters and

microinverters due to the standardized nature of these products. System integrators and engineering, procurement and construction (EPC) firms are other important distribution channels for string inverters used in large-scale projects.

- Direct sales through online portals contribute to the sale of microinverters. In addition, manufacturers of solar PV inverters also sell to solar module manufacturers who bundle inverters with their modules to sell as complete solar PV solutions.

With respect the global solar inverter market, the top 5 participants account for a little less than 50% of the market: **Huawei Technologies (China); Power Supply (China); SMA Solar Technology (Germany);** and **SolarEdge Technologies (Israel)**. However, when it comes to SiC-based solar inverters, the U.S. does not appear to have a large share of the market. SiC-based solar inverter manufacturing is dominated by European and Asian companies such as: **Delta Electronics; Sungrow; KACO Energy (Siemens AG); SMA Solar Technology AG;** and **Fronius International GmbH**. These companies customize products for the U.S. market.

The supply chain itself still has a few bottlenecks. With respect to the supply chain, crystal growth requires expertise, equipment and factory design, and a mature supply chain which are fundamental to enable industry leading capacity expansion. The supply chain appears to still be evolving, although crystal growing is difficult, the crystal quality is good and continues to evolve. Therefore, there have been multi-million-dollar supply deals signed in the last two years.

The U.S. leads in crystal growing segment, with Wolfspeed and II-IV commanding the majority of the market share. The U.S. leads in wafer manufacturing with Wolfspeed leading the market. With respect to solar inverters, the European and Asian companies appear to have an edge.

APPENDIX A: Summary Tables of Selected Sic-based Inverters and Inverter Products

Table 24: Summary of Selected SiC-based Inverters for Solar

Developer/ Manufacturer	Country	Manufacturing Locations	Description
Delta Electronics, Inc.	Taipei, Taiwan US HQ: Fremont, CA	Various	Delta Electronics (Taoyuan, Taiwan) is one of the leading global players in the field of power electronics, industrial and building automation, information and communications technology, and energy infrastructure. The company offers single-phase and three-phase string inverters, central inverters, energy storage systems, and related accessories. The single-phase inverters offered by the company are mainly used in houses and small factories. The three-phase inverters are used in large-scale industrial and commercial applications, as well as in power plants. In 2013, Delta Energy Systems introduced solar inverters, which utilized SiC power MOSFETs from Wolfspeed. The use of SiC MOSFETs in the next-generation PV inverters can enable significant new milestones in power density, efficiency and weight.[244]

Developer/ Manufacturer	Country	Manufacturing Locations	Description
Kaco energy Systems (Siemens AG	Neckarsulm, Germany	KACO has a plant in San Antonio Texas.	SiC string inverters, blueplanet 155 TL3 and 165 TL3 inverters, designed for the large-scale PV projects.[245] In November 2019, KACO extended its range of string inverters for 1,500 Volt projects by five SiC devices. The blueplanet 87.0 TL3 and blueplanet 92.0 TL3 are suitable for solar power plants on commercial and industrial roofs. Inverters comply with protection class NEMA 4X and thus meet the highest requirements for outdoor installation.[246] In November 2020, KACO introduced 125-kW SiC inverters for U.S. market. The line voltage of 400 V makes it possible to connect the blueplanet 105 TL3 to an existing transformer at no additional cost.[247]
EnphaseEnergy	California, United States	Enphase micro-inverters have used SiC diodes for several. In 2016, Enphase reported it had shipped 20 million SiC 1200V diodes, thereby making up a large part of the market.[248]	Enphase designs, develops, and sells micro inverter systems for residential and commercial markets in the U.S. and internationally. With respect to WBG materials, Enphase seems to favor GaN over SiC:[249]

Table 25 summarizes examples of SiC-based inverters introduced on the market during the last year.

Table 25: Summary of Selected New SiC Solar Inverter Products

Commercial Year	Developer/ Manufacturer	Specifications	SiC Device Supplier
March 2021	Sungrow Power Supply Co., Ltd	The SG250HX 250kW solar inverter, uses the SiC module with high voltage 1500Vdc and 800Vac operation to give the string inverter a maximum of 99 percent efficiency and a power density of 1kW/l.[250]	Infineon Technologies
2020	Delta Electronics, Inc.	Three-phase PV string inverter incorporating NXH40B120MNQ family of SiC power modules integrate a 1200 V, 40mΩ SiC MOSFET and 1200 V, 40 A SiC [251]	ON Semiconductor
2020	Kaco Energy (Siemens AG)	(1) The 155 TL3 inverter measures 719 x 699 x 460 mm and weighs 78.2 kg. It offers a reported efficiency of 99.1% – for a European rating of 98.9%. The device also features 1500 V (DC) technology, a voltage range maximum power point of 875-1,450 V, and an ambient operating temperature ranging from -25 C to 60 C. (2) The 165 TL3 device has the same efficiency, size, weight, and operating temperature as the 155 TL3 inverter, but a higher European efficiency of 99.0%.[252]	Infineon Technologies
2020	Sungrow Power Supply Co., Ltd	250kW solar inverter, which uses custom SiC power modules from Infineon. The SG250HX uses the SiC module with high voltage 1500Vdc and 800Vac operation to give the string inverter a maximum of 99 percent efficiency and a power density of 1kW/l.[253]	Infineon Technologies
2020	SMA Solar Technology AG	SMA Solar Technology teamed up with Infineon to use SiC power devices in its solar inverter designs.	SiC CoolSiC MOSFETs from Infineon[254]
2020	Fronius International GmbH	Symo GEN24 Plus solar inverter weighs 24 kg and has a small volume (HWD 594 x 527 x 180 mm 3). Its active air-cooling can reduce the temperature of the power electronics parts, and thus extend service life. The inverter is available in the power classes 6, 8, and 10 kW. Fronius supplies this inverter primarily in Europe, South America, and Australia. [255]	SiC CoolSiC MOSFETs from Infineon Technologies[256]
2021	Midnight Solar, Inc. (U.S)	Hawkes Bay 600VDC to 48VDC 6000W MPPT solar charge controller, Barcelona dual MPPT charge controller, MNB17 battery-based charger/inverter, and 120/240V Rosie inverter/ charge[257]	ROHM's silicon carbide MOSFET

Commercial Year	Developer/ Manufacturer	Specifications	SiC Device Supplier
February 2021	Toshiba Electronic Devices & Storage Corporation	1200V SiC MOSFETs, 650-V SiC Schottky barrier diodes and SiC MOSFET Modules.[258] The MG800FXF2YMS3, a SiC MOSFET module integrating dual channel SiC MOSFET chips with ratings of 3300V and 800A designed for industrial and renewable energy applications. Volume production started in May 2021.[259]	NA

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256 "Infineon's CoolSiC used in Fronius' solar inverter," Semiconductor Today, November 23, 2020.
257 Rohm Semiconductor, "ROHM SiC MOSFETs Solve Design Challenges for Leading Solar Energy Company Midnite Solar," February 3, 2021.
258 "SiC Power Devices," Toshiba Electronic Devices, 2022.
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Assignee	Title	Method	PEMFC/MEA processed whole?
Audi Aktiengesellschaft	Method for operating a motor vehicle with a fuel cell device and a motor vehicle	chemical	Process PEMFC/fuel cell stack as whole
Basf Catalysts Llc	Simplified process for leaching precious metals from fuel cell membrane electrode assemblies	mechanical/chemical	MEA pulverized to form powder
Basf Catalysts Llc	Efficient process for previous metal recovery from fuel cell membrane electrode assemblies	mechanical/chemical	MEA ground to powder
Basf Catalysts Llc	Process for recycling components of a PEM fuel cell membrane electrode assembly	chemical/heat	MEA as whole, chemical and heat processing
Basf Catalysts Llc	Method for Recovering Catalytic Elements from Fuel Cell Membrane Electrode Assemblies	mechanical/chemical	MEA converted to particulate, by grinding or granulating
Chengdu Guangming Paite Precious Metals Co., Ltd., Chengdu Guangming Optoelectronics Co., Ltd.	Method for recovering noble metal platinum from proton exchange membrane of hydrogen fuel cell	chemical	MEA dissolved
Daimler Ag	Method for recycling membrane electrode unit of fuel cell for use as alternative energy source for vehicle, involves performing filtration of laden with solvent to obtain filter material, and recovering metals from filter material	ultrasound/mechanical/chemical	MEA crushed into chips, flocs or flakes
Datasi Nantong Information Technology Co	Method for recovering metal platinum from platinum-carbon catalyst/microporous polymer composite membrane	drying/chemical	Disassembling PEMFC, drying MEA, chemical processing of MEA as whole
Datasi Nantong Information Technology Co., Ltd. OR Datax Nantong Information Technology Co., Ltd.	Method for recovering metal platinum from platinum-carbon catalyst	drying/mechanical/chemical	disassembling PEMFC, grinding MEA, chemical processing

Link	Assignee	Comments re: HF emissions/treatment
US7255798B2	Ion Power	In certain embodiments, the disclosure includes processes that allow for the re-manufacture of new catalyst coated membranes (CCMs) from used CCMs extracted from failed fuel cell stacks. This may be accomplished by removing the CCM from the stack, decontaminating the CCM to remove impurities, and then **dissolving the ionomer component of the CCM to form a slurry of dissolved PFSA™ together with the Pt/C catalyst particles**. The dissolution may, in certain embodiments, be done at increased pressure in an autoclave, for example. Preferred embodiments include a pressure of from 500 to 2000 psi. These two valuable ingredients are then separated, allowing the PFSA™ solution to be reprocessed into a new fuel cell membrane. Ideally the recovered catalyst (Pt/C) is redeposited on the re-manufactured membrane so that a completely re-manufactured CCM is the final result. The same process would be used for an end-of-life Chlor-alkali membrane where the separation of the fiber reinforcement and other solids are separated by similar methods.
US8101304B2	Umicore	The hydrogen fluoride formed during the heat treatment of fluorine-containing components is **bound by an inorganic additive so that no harmful hydrogen fluoride emissions occur**.
US7713502B2	Umicore	a process for recycling fuel cell components containing fluorine-containing and precious metal-containing constituents: in this process, **the fluorine-containing constituents are separated off** from the precious metal-containing constituents by treatment with a medium present in the supercritical state. Preference is given to using water as supercritical medium. After the fluorine-containing constituents have been separated off, the precious metal-containing residues can be recovered in a recycling process without harmful fluorine or hydrogen fluoride emissions. The fluorine-containing constituents can likewise be recovered.
US7635534B2	BASF Catalysts	The bulk of the membrane electrode assembly is carbon-based; therefore, a standard method to recycle precious metals, including platinum, involves a combustion step to remove carbon material. However, membrane electrode assemblies have high fluorine content due to polytetrafluoroethylene (PTFE) impregnated on the carbon fibers and from common polymer electrolyte membrane materials, such as Nafion® (DuPont Co., Wilmington, Del.), which results in a large, undesirable discharge of HF upon combustion. **Removal of HF gas involves scrubbing and dedicated equipment that can withstand the corrosive nature of HF gas.** Isolating the combustion from existing infrastructure is recommended to localize maintenance needs caused by the effects of HF gas.
US7709135B2	BASF Catalysts	Regardless which vessel or apparatus is used to filter the solids from the leachate solution, the corrosive nature of the slurry requires materials of construction that can withstand corrosion. FIG. 6 illustrates the corrosion of various materials, in percent weight loss, when exposed to chlorine. A Hastelloy C276 metal coupon was tested and corroded badly. Glass lined vessels, such as those fabricated by De Ditrich and Pfaudler, have been shown to fare better when exposed to acid, but such vessels are typically limited to pressures of less than about 10 bar (150 PSIG). For example, according to vessel manufacturer data, a 20% HCl mixture at 160° C. corrodes away about 20 mils per year from a glass liner. However, trace HF from the degraded perfluoropolymer membrane could attack the glass liner. The addition of **dispersed silica acts as a fluorine getter** to protect the glass liner, and testing has shown that 100 ppm of SiO_2 added to the mixture reduces the glass liner corrosion to about 2 mils per year at 160° C. Boric acid can also be used as a fluorine getter.
US8206682B2	BASF Corp	to optimize the recovery of catalytic elements from a fuel cell MEA, the efficiency of the **leaching process** can be improved based on parameters including, but not limited to, the leach medium, the concentration and quantity of leach medium per weight of catalytic element sought to be recovered, and the temperature, pressure, and cycle time of the leach step or steps. In the experiments discussed herein, leaches have been performed in several reactor vessels, including open glass beakers and **sealed fluorinated polymer vessels.**
KR102284348B1	Korea Institute of Geoscience and Mineral Resources	As a recycling method of a waste electrode of a phosphoric acid type fuel cell that **recovers phosphoric acid by wet method**, recovers platinum group elements and silicon carbide (SiC), and does not emit waste, leaching the waste electrode of the phosphoric acid type fuel cell to wet-recover the phosphoric acid; an oxidation step of removing carbon by oxidizing the waste electrode of the phosphoric acid type fuel cell obtained by wet recovery of the phosphoric acid; and Leaching the oxidized phosphoric acid type fuel cell waste electrode with a mixture of an acid compound and a halogen gas to separate the silicon carbide (SiC) and the platinum group element, and to recover the silicon carbide (SiC) and the platinum group element
KR102284346B1	Korea Institute of Geoscience and Mineral Resources	As a recycling method of a waste electrode of a phosphoric acid type fuel cell that **recovers phosphoric acid by dry method**, recovers platinum group elements and silicon carbide (SiC), and does not emit waste, dry-recovering the phosphoric acid by heat-treating the waste electrode of the phosphoric acid type fuel cell at a low temperature; an oxidation step of removing carbon by oxidizing the waste electrode of the phosphoric acid type fuel cell obtained by dry recovery of the phosphoric acid; and Leaching the oxidized phosphoric acid type fuel cell waste electrode with a mixture of an acid compound and a halogen gas to separate the silicon carbide (SiC) and the platinum group element, and to recover the silicon carbide (SiC) and the platinum group element
CN112421067B	JIANGSU YAOYANG NEW ENERGY TECHNOLOGY CO LTD	Since the fluorine proton exchange membrane releases hydrofluoric acid harmful to human body during combustion, **calcium oxide must be used for adsorption to remove fluorine**, thereby increasing the complexity of the process.
JP2005289001A	Toyota Motor Co	To efficiently recover a precious metal and a fluorine-containing polymer without using a solvent or the like from a membrane-electrode bonded element (MEA) of a used solid polymer electrolyte fuel cell. SOLUTION: The membrane-electrode bonded element (MEA) is constituted of an electrolyte membrane comprising the fluorine-containing polymer having a sulfonic acid group, a conductive carrier which is bonded to the electrolyte membrane and carries a catalyst metal, and a gas diffusing electrode (b) of which the major constituent material is a catalyst layer comprising a proton conductive polymer. The precious metal and/or the fluorine-containing polymer having the sulfonic acid group are recovered from the membrane-electrode assembly (MEA) by this recycling method. The recycling method has two processes, (1) a process in which the membrane-electrode assembly (MEA) is solidified, and the electrolyte is expanded to a degree wherein the plastic deformation of the catalyst layer after the solidification becomes easier, (2) a process in which the membrane-electrode assembly (MEA) after the electrolyte has been expanded is solidified while imparting a stress. By these processes, the electrolyte membrane comprising **the fluorine-containing polymer having the sulfonic acid group, and the catalyst layer comprising the conductive carrier carrying the catalyst metal and the proton conductive polymer are made easily separable**.
US20140056786A1	Heraeus Precious Metals GmbH	Ashing plant for enriching noble metals from fluorine-containing materials, comprising a thermal treatment chamber (1) having a refractory insulating lining on the inside of the thermal treatment chamber (1), and an exhaust gas cleaning system, whereby the insulating lining is resistant to hydrofluoric acid and the **exhaust gas cleaning system comprises at least one or more acid scrubber(s)** (3, 4) and at least one alkaline scrubber (5).
US20210047708A1	Battelle Energy Alliance LLC - NOTE, funded by DOE	a method of recovering palladium from a palladium-containing material includes exposing the palladium-containing material to a **leaching solution** including an acid, an oxidizer, and iron ions (e.g., ferric ions (Fe^{3+}), ferrous ions (Fe^{2+})) dissolved therein. The acid may include a source of halide ions. For example, the acid may include one or more of hydrochloric acid, hydrofluoric acid, hydrobromic acid, or hydroiodic acid.
US10964967B2	Johnson Matthey Hydrogen Technologies	A process for the **recovery of a perfluorosulphonic acid ionomer** from a component comprising a perfluorosulphonic acid ionomer is disclosed, the process comprising immersing the component comprising the perfluorosulphonic acid ionomer in a solvent comprising an aliphatic diol and heating. Also disclosed is the use of the recovered perfluorosulphonic acid ionomer, for example in to prepared a proton conducting membrane or a catalyst ink.