Cost, Supply Chain, and Manufacturing Competitiveness Issues Related to SiC-based Variable Frequency Drives for Industrial Motor Applications

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Abstract

A significant fraction of industrial energy use is attributable to motor-driven systems. The use of silicon carbide (SiC) in industrial motor drives can improve efficiency and, in certain applications footprint, balance-of-system cost, and other performance metrics compared to systems using traditional silicon (Si) devices. However, adoption of these drives is currently low. Barriers to adoption include the conservative nature of the market, a lack of public sources quantifying the value proposition of technology, and supply chain issues. We present a regional bottom-up cost analysis of SiC-based power modules and variable frequency drives, as well as an analysis of the global supply chain and current status of manufacturing. These results highlight possible opportunities and challenges for potential adopters of this technology, manufacturers currently in the SiC power electronics space or looking to expand into it, and policymakers seeking to understand how to increase the adoption of these energy-efficient systems or influence where they are manufactured.

Introduction

Machine drives have historically constituted the single largest end use of electricity in the manufacturing sector (Unruh 2003). A significant fraction of the electricity is consumed by medium-voltage, high-power electric motor drives, which are used in the chemical, oil, gas, mining, and manufacturing industries (Wolk 2014). The use of power electronics-based variable frequency drives (VFDs) in these applications—rather than systems employing relatively the inefficient gearboxes and mechanical throttles typically used today—can improve the efficiency of these systems. Replacing traditional silicon (Si) electronics in the VFD with silicon carbide (SiC)—a wide bandgap semiconductor—provides additional efficiency gains, as well as allow for more efficient operation at higher voltages, powers, temperatures, and switching frequencies. Because of reduced cooling requirements, lower part counts, and the possibility of using smaller passive components, SiC-based power electronics can additionally reduce the footprint and potentially the system cost of VFDs. Medium and high voltage VFDs are particularly well suited to benefit from the use of SiC power electronics.

The current SiC market is small, comprising less than 2% of the total power semiconductor market, and to our knowledge no fully-SiC VFDs are commercially available or used in industry today. However, the industry is maturing, and the SiC power electronics market share will grow steadily over the next 5 to 10 years, with pronounced growth in motor drive applications (Yole Développement 2016; IHS 2016). In addition to the potential for industrial energy savings, increasing market penetration of this technology also presents an opportunity for manufacturing along the supply chain for SiC power electronics components. This work provides insights into the current state of global manufacturing along the value chain for SiC components and medium-voltage VFDs that may be of interest to industry members looking to either adopt or manufacture SiC power electronics. Additionally, we present a bottom-up regional cost analysis of SiC power electronics and medium-voltage VFDs that provides insights into the cost drivers for this technology and the potential benefits at the system level.

Current Status of the Supply Chain and Global Manufacturing

A simplified diagram of the value chain for manufacturing SiC power electronics in VFDs is shown in Figure 1. SiC boules (crystals) are grown, machined into ingots, and then sliced into substrates, which are subsequently polished. A thin SiC epitaxial layer is then grown on top of this substrate to create an epi-wafer. The epi-wafer is processed to make SiC semiconductor devices—transistors or diodes (individually referred to as die). The chips (diodes and/or transistors) are then either integrated into a power module or discretely packaged. These power electronic components can then be integrated into the VFD along with other low-voltage circuitry (e.g., gate drivers and control circuit boards).

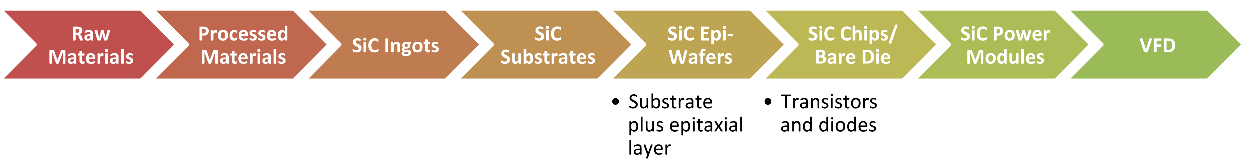

Figure 1. Simplified value diagram for SiC-based VFDs.

In this section, we provide an overview of global manufacturing and supply chain issues for each of these value chain links. Additional discussion on these topics can be found in (Horowitz, Remo, and Reese 2017).

Supply Chain Analysis Methodology

In this section, we provide an overview of the current supply chain for most prevalent commercial designs and manufacturing processes associated with each link in the value chain for SiC-based VFDs (Fig. 1). These designs and processes, as well as the materials associated with them, were determined via interviews with members of industry and/or subject experts, literature and market reports (where available), and product datasheets. We then selected a sub-set of these materials for each value chain link for discussion based on the criteria outlined in (Horowitz, Remo, and Reese 2017). We evaluated whether a given material meets these criteria was evaluated using three sources: interviews with industry members and subject experts; data from the U.S. Geological Survey (USGS), the U.S. International Trade Commission (USITC), the International Trade Center, and literature/market reports (where available); and common knowledge (e.g., that carbon is not a fundamentally constrained material). Details of sources for the analysis of each supply chain element are provided in the following subsections.

Because we focused on the designs and processes that are most prevalent in industry today, our analysis does not necessarily apply to all designs in the market or to emerging designs. Additionally, the SiC industry is relatively new and not widely tracked, and some of the supply chain data were available from only a limited number of sources. We attempted to mitigate any data limitations by having industry representatives and other experts review the data and provide feedback, but some uncertainty in this information should be assumed.

Raw Materials

Silver and gold are often used as part of the metal contacts to SiC transistors or diodes. The supply of these materials is spread globally, reducing the risk associated with any import or export tariffs that may be placed on them. According to USGS, the largest producers of mined silver in 2014 and 2015 were China, Mexico, and Peru, but significant amounts were also produced in other countries around the world; gold was also mined globally during these years, with top producers being China, Russia, Australia, and the United States. The second exception is diamond, which is used in the wire used to slice SiC ingots into wafers, as well as in the slurry used for polishing wafers. Diamond is required for these processing steps because of the hardness of SiC. Both natural and synthetic diamond are used for industrial purposes, including cutting and polishing in other semiconductor applications. Currently, 95% of the U.S. industrial diamond market uses synthetic diamond (U.S. Geological Survey 2016). At least 15 countries have the technology to produce synthetic diamond, including the United States, whose primary and secondary production in 2015 are estimated at 111 million carats and 38.3 million carats respectively (U.S. Geological Survey 2016). China is currently the world's leading producer of synthetic industrial diamond, exceeding four billion carats of production in 2015 (U.S. Geological Survey 2016). Mine production of diamond is led by Australia, Botswana, Congo (Kinshasa), Russia, South Africa, and Zimbabwe.

Si and carbon (C) are the raw materials used in the greatest volume in SiC chips. These materials are earth-abundant, available globally, and do not pose a supply chain constraint.

Processed Materials

Two key processed materials used in the manufacture of SiC power electronics are high-purity SiC powder, which is often used to grow SiC boules, and high purity silane (SiH_4), which is a critical precursor for growing SiC layers in the chips (Wijesundara 2011). Our primary interviews with three manufacturers of SiC substrates, one manufacturer of SiC crystal growth equipment, and four manufacturers of SiC materials, and Yole Développement indicate that high purity SiC powder is currently available from a limited number of suppliers and is relatively expensive. Bridgestone (United States), Washington Mills (United States), LGInnotek (Korea), and Pallidus (United States) currently manufacture high purity SiC materials. High purity silane is typically produced by large multinational industrial gas companies. Firms headquartered in the United States, Asia (China, Japan, Hong Kong, South Korea, and Taiwan), and Europe (Germany and France) currently produce silane (ENF 2017).

Other processed materials are used in the manufacturing along the value chain for SiC-based VFDs, but these are not discussed further here as they are widely available and not critical to cost, can be substituted with other materials if necessary, and/or are traded globally and do not pose a supply chain challenge. This determination was based on NREL interviews, a review of USGS data, and company websites.

SiC Substrates and Wafers

Figure 2 shows the percent of global wafer production by region/country. The locations shown correspond to where the wafers are manufactured, not the location of company headquarters. In Europe, wafer production facilities are located in Germany, Sweden, and

Russia. In Asia, production is located in Japan, China, and South Korea. In 2015, SiC wafer manufacturing capacity exceeded demand (Yole Développement 2016).

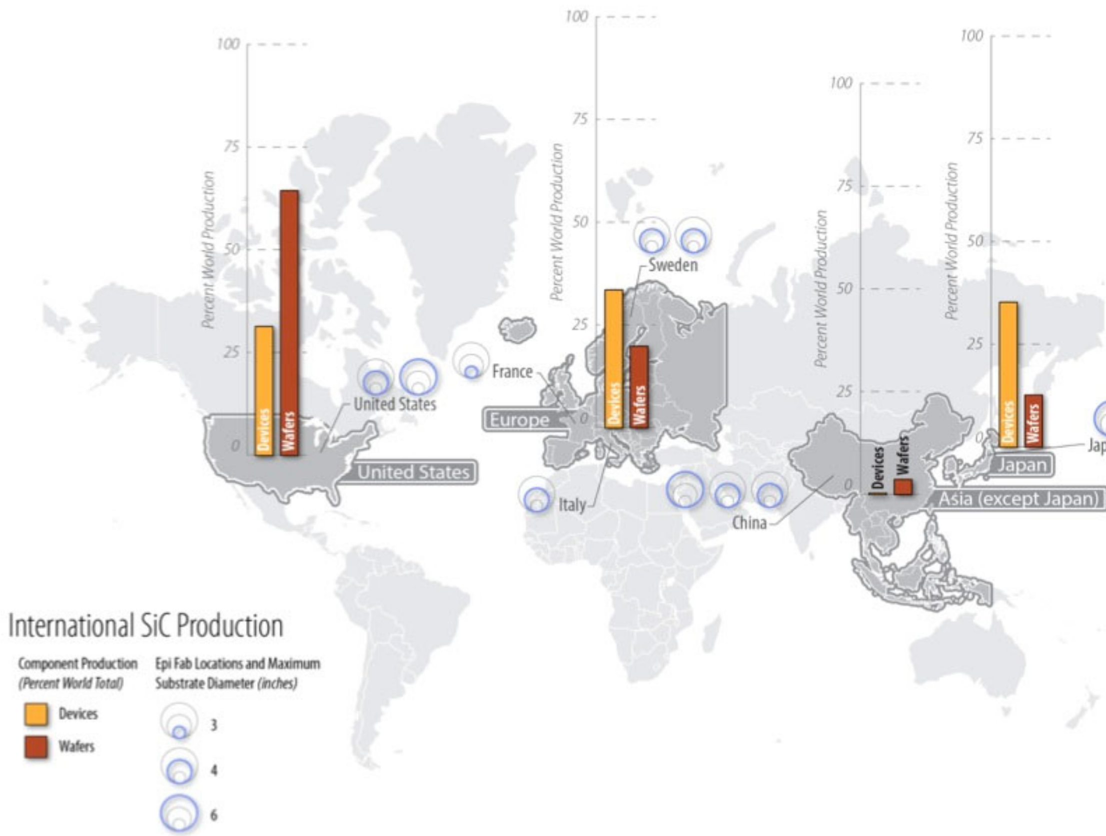

Figure 2. Map of global production of SiC wafers (substrates and epi-wafers) and devices with locations of SiC epi-fab facilities in 2016. Data source: Power SiC 2016: Materials, Devices, Modules, and Applications Report, Yole Developpement (2016).

Typically, the companies that grow SiC boules also machine them into ingots and slice them to create substrates. According to Yole Developpement and company websites, few of the companies that manufacture ingots and substrates also provide epi-layer growth or sell epi-wafers; these include Cree (United States), Dow Corning (United States), SiCrystal (Japanese-owned, German manufacturing), Nippon Steel (Japan), Norstel (Sweden), and SICC (China). The blue circles in Figure 2 indicate which countries have facilities for epitaxial growth and what wafer sizes can be produced by companies located within each country.

As can be seen from Figure 2, the United States is currently the global leader in production of SiC substrates and wafers, followed by Europe and Japan. The quality of the SiC substrate is critical to achieving high-quality chips, and the SiC substrate constitutes a major portion of the chip cost. Thus, the distribution of SiC substrate and epi-wafer manufacturing has mostly been driven by where the companies that are able to achieve high-quality wafers with good yields are located. Interviews with five leading SiC firms indicate that the choice to locate plants in certain locations has been driven largely by the existence of existing facilities and capabilities in that location. Some companies (like Dow Corning) have leveraged their own facility space, while others have acquired companies with existing SiC substrate manufacturing facilities and expertise (e.g., ROHM's acquisition of SiCrystal in 2010). Cree already produces

SiC substrates in relatively high volumes for the light-emitting diode market, allowing it to build expertise and realize additional economies of scale that would not be possible given the level of current demand for SiC power electronics. Cree previously spun off the portions of its business related to power electronics and radio frequency electronics into Wolfspeed, although Wolfspeed never went public. German company Infineon planned to acquire Wolfspeed, but the deal was recently canceled because Cree could not sufficiently address national security concerns from the Committee on Foreign Investment in the United States (McGrath 2017). The U.S. government has blocked other deals in the semiconductor space in the past over similar concerns (Inverardi 2016).

The cost of epi-growth and chips can also be reduced by using larger-area substrates, so manufacturers that are able to successfully fabricate six-inch (150-mm) diameter substrates with acceptable quality also have an advantage, which will be reinforced as six-inch wafers gain market share in the coming years. Cree, II-VI, and Dow Corning—all companies with U.S. manufacturing facilities—currently dominate the supply of 6-inch SiC wafers; however, the volume of 6-inch wafers sold and the number of devices manufactured on six-inch substrates is currently very small.

While Chinese firms are not currently major suppliers of SiC wafers globally, several Chinese firms have recently made significant investments in SiC substrate and epi-wafer manufacturing capacity, and additional expansions for coming years have been announced (Yole Développement 2016). The Chinese government has supported the development of this industry by providing subsidies for equipment, and new plants have been financed with a combination of local government funding and private investment. However, most of these firms have demonstrated only four-inch-diameter wafers and are still developing the ability to produce high-quality substrates and/or epi-layers, and they are working to improve yields (Yole Développement 2016).

SiC Chips

SiC chip production is currently split roughly equally among the United States, Japan, and Europe (Figure 2). The top seven SiC chip manufacturers, which combined have over 95% of the market share, are large multinational companies that were already established in the Si power electronic device space, and all have vertically integrated a significant portion of the value chain, including final systems integration/applications.

The limited number of high-quality suppliers for SiC substrates, epi-wafers, and chips has made it difficult to multi-source components and thus increased supply risk for downstream manufacturers. NREL discussions with several motor drive manufacturers indicate this supply chain risk has been a barrier to adoption for SiC technology in the past; cost, the newness of the industry and conservative nature of drive manufacturers, and need to better define the value proposition for SiC compared to Si were also cited as key barriers to adoption. However, a number of new players have recently entered the market or have announced plans to do so, and this issue is expected to be somewhat mitigated in the coming years. Many new entrants in chip manufacturing are SiC pure-players, producing only SiC materials, and they are focused on processing devices, which represent a single piece of the value chain.

Over the last several years, China has also made significant investments in developing a local semiconductor industry. SiC has been included in this, with the government providing significant funding for development of SiC chip manufacturing. Chinese chip manufacturers have begun to enter the market and are looking to scale up production. Chinese SiC chip manufacturers (and Chinese manufacturers of SiC substrates, epi-wafers, and systems) are not vertically integrated (Yole Développement 2016).

SiC Power Modules

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 used; and 2) the use of contract manufacturers, which are overwhelmingly located in Asia. Interviews with leading SiC manufacturers indicate that contract manufacturing is more commonly used for higher-volume production, where economies of scale can be realized by tapping existing facilities and supply chains for manufacturing Si power modules without needing significant upfront capital investments. Contract manufacturing of power modules takes place primarily in China and Southeast Asia.

Medium-Voltage VFDs

Medium-voltage motor drives are usually defined as those with voltages between 2 kilovolts (kV) and 15 kV and powers between 0.2 megawatt (MW) and 40 MW. Due to the physically large size of medium-voltage VFDs, economically shipping the completed drive requires transport by ocean freighter. Many VFDs are semi-customized, and locating manufacturing facilities close to the end customer allows for more rapid response to customers, reduced lead times, and decreased uncertainty in lead times. While manufacturing production and capacity information for any medium-voltage VFDs is sparse, and trade codes are insufficient to determine how these specific types of drives are shipped globally, our interviews with members of industry indicate that for these reasons, VFDs are primarily assembled close to the end customer. Many leading manufacturers of medium-voltage VFDs are large multinational companies that have assembly plants throughout the globe and thus are able to respond to local markets. In 2015, the United States was the largest market for medium-voltage drives by revenue (30.0%), followed closely by China (28.6%). Europe, Middle East, and Africa (24.7%), Japan (4.7%), and the rest of Asia, excluding China and Japan 11.9% accounted for the remainder of the 2015 market (IHS 2016).

The total number of medium-voltage VFDs sold each year is very small; only 12,000 units were sold in 2015 (IHS 2016). To our knowledge, no full-SiC VFDs are produced commercially for use in industry today. Reliability and downtime are very important for VFD customers, as unexpected downtime can result in significant lost revenue. Thus, potential customers are very conservative, require quantitative field data of performance and lifetime expectancy, and are typically slow adopters of new technology like SiC. More data field data on the performance and reliability of SiC-based systems has begun to emerge in recent years, and multiple efforts are underway to collect additional data.

The Cost of SiC-Based VFDs

In this paper, we include the regional cost breakdowns for manufacturing SiC power modules and SiC-based VFDs. The VFD we examine is a 1-MW drive; costs will vary depending multiple factors discussed below. We assume the power modules have a voltage rating of 3.3 kV, which would be suitable for use in many medium-voltage VFD applications.

SiC transistors and power modules are only commercially available for voltages up to 1.7 kV today. However, 3.3-kV components have been developed by several companies, are available as engineering samples, and are expected to become more widely available in the coming years.

The SiC industry is rapidly evolving, and costs are expected to decrease along the value chain. This work provides a snapshot of costs under a set of assumptions at the time of analysis; thus, these results do not reflect the potential cost reduction that may be achieved in the future.

Cost Analysis Methodology

Regional cost analysis was performed using the Clean Energy Manufacturing Analysis Center's (CEMAC's) established bottom-up cost modeling approach. This approach involves first creating a representative manufacturing process flow for each component based on a literature review, interviews with industry and subject experts, and other secondary sources (e.g., company websites, news articles, and market reports) and then computing the materials, labor, utilities, facilities, equipment, and equipment maintenance cost associated with each step in the process. Most data from industry members and equipment manufacturers are collected via interview, and data from material suppliers are obtained via request for quotes or interviews. The ability of NREL to collect these input data relies on our ability to build trust with industry and protect proprietary or business-sensitive information from individual companies; therefore, detailed information on data sources as well as some input data for our cost models cannot be disclosed. For this reason, we collect data from as many different sources as possible and provide only aggregated anonymized information. In general, we received between one and five data points for each input; in some cases, the number of data points was limited because there were few suppliers of a given material or piece of equipment. Several subject experts with the U.S. Department of Energy (DOE), its national laboratories, and industry have previously reviewed results generated by our cost model, and their feedback has been incorporated.

Country-specific input data, including labor rates for different types of labor and electricity prices, are taken from a CEMAC database of country costs. Labor and electricity costs are taken from the U.S. Bureau of Labor Statistics and the Energy Information Administration respectively; if data are unavailable from these sources, supplemental data was obtained from interviews and reports. The costs assume that all equipment is purchased new.

In addition to computing manufacturing costs using the methodology described above, we also compute a minimum sustainable price (MSP). The MSP corresponds to the price at which the net present value of the investment in the manufacturing plant is equal to zero, and the internal rate of return is set equal to the weighted average cost of capital. The MSP represents the minimum price that, at a specific instance in time, would be required to cover all variable and fixed costs and repay investors at their expected rate of return. MSP is different from market price and does not reflect the effects of economic factors such as supply and demand. The MSP may be above or below market prices. The MSP is calculated using a *pro forma* discounted cash flow. Research and development (R&D) and sales, general, and administrative (SG&A) costs used in this model are typically input as a percent of revenue. For all cases and components, we use a 20-year cash flow analysis period.

While not discussed further in this paper, this bottom-up cost analysis methodology was also applied to model the cost and MSP associated with SiC substrates, epi-wafers, and chips. Outputs from these cost models are used as inputs to the power module cost model. Detailed results of our SiC substrate, epi-wafer, and chip cost models, along with a deeper discussion of regional drivers of manufacturing costs, are included in Horowitz, Remo, and Reese (2017). Detailed information on the input assumptions and methodology for all bottom-up cost analysis and MSP calculation are also provided in Horowitz, Remo, and Reese (2017).

Regional Manufacturing Costs for SiC Power Modules and VFDs

Figure 3 shows the MSP breakdown by country for the SiC power module, assuming that all countries are able to produce the power modules in equal volumes (one million packages/year) and with equal yields. The SiC chips are the largest contributors to overall cost, making up 46% of materials costs. We assume chips used in the power modules are sourced locally, and we assume the chip costs for each region are equal to our modeled MSPs for those countries. The difference in regional MSP for the power modules is primarily due to these differences in chip costs. However, in reality, chips can be sourced from other locations as well, and eventually, as the industry scales, a global chip price could emerge. Many companies use contract manufacturing for SiC module production; equipment and facilities that already exist for manufacturing Si power modules can be used for SiC production. This means that SiC module manufacturing firms can take advantage of the economies of scale enjoyed by Si module manufacturing firms, reducing overall equipment, facilities, and non-chip material costs.

Differences in effective corporate tax rates, labor costs, and electricity costs play a minor role in the regional cost differences as shown in Figure 3.

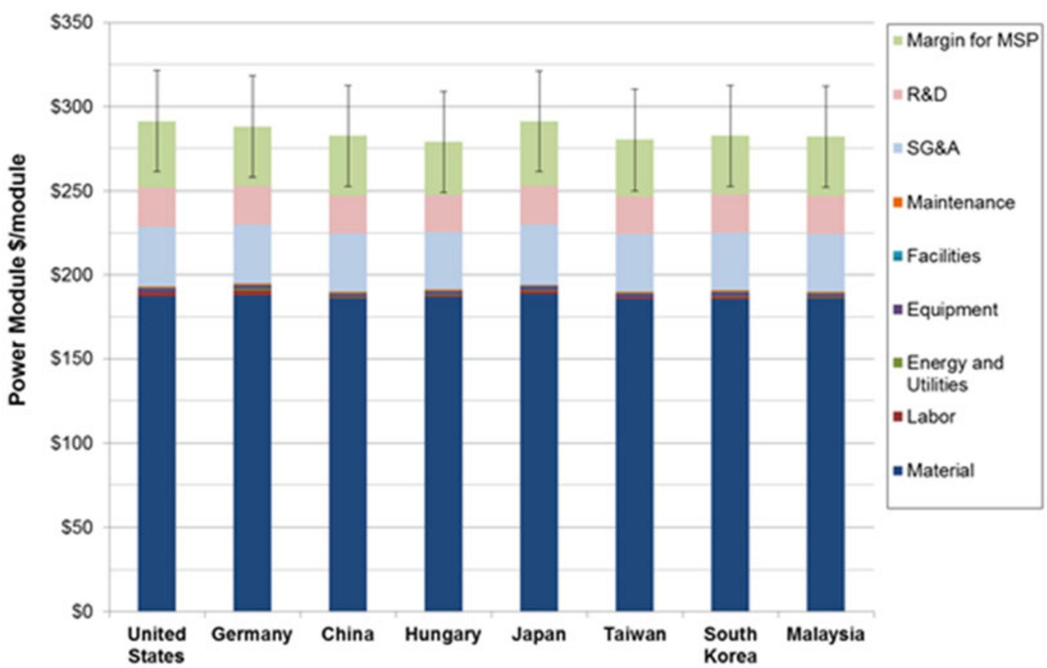

Figure 3. Breakdown of regional manufacturing costs for a 3.3-kV SiC power module. In this case, we assume the capabilities and production volumes for all countries are equal; in practice, they vary.

Figure 4 shows the cost breakdown for the 1-MW VFD using SiC power modules. As can be seen from the figure, the total cost is dominated by the materials costs, which include the SiC power modules, VFD housing and cooling, the transformer, the SiC power modules, and other electronic components (e.g., gate drivers and filters). For the modeled VFD design, the use of 3.3-kV SiC power modules enabled a significant reduction in balance-of-system part counts (e.g., housing and cooling) and an associated balance-of-system cost reduction. However, the cost of the transformer, which was not mitigated by the use of SiC in this case, was very high—over half the materials cost was for the transformers (Figure 5). Transformers costs will vary by VFD/system design as well as by the voltage of the distribution line. Eventually, medium- or high-voltage SiC power electronics could allow for the elimination of the transformer in some cases, providing a substantial additional balance-of-system cost benefit. The smaller footprint that results from the reduce part count (described above) and the elimination of the transformer could also drive adoption of VFDs in areas that were previously unable to utilize this technology due to footprint constraints.

Nevertheless, the cost of SiC power modules compared to incumbent Si technology is still high, and this has historically been another barrier to adoption for potential customers who are able to use Si alternatives. As previously mentioned, the cost of the SiC power module is dominated by the cost of the SiC chips, which is in turn dominated by the cost of the substrate and epi-layer. Our cost models for the substrates, epi-wafers, and chips assume designs and production processes associated with best-in-class performance expected in the near-term, and so many firms may currently have higher costs than those shown here. However, the cost of all of these components is anticipated to decrease still further in the future as the wafer diameters increase, manufacturing yields improve, and production volumes increase.

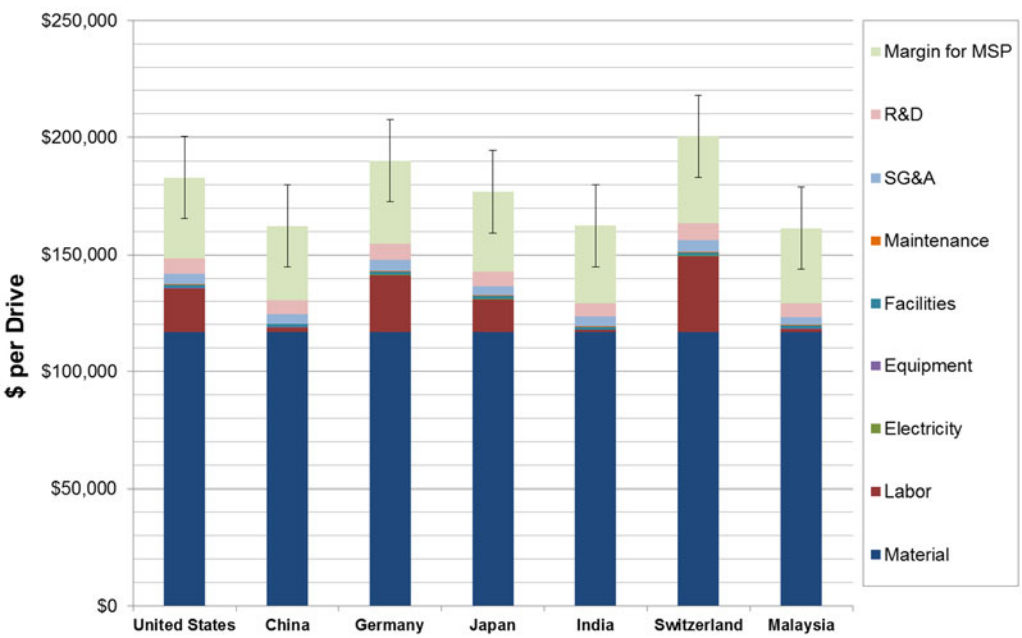

Figure 4. Breakdown of regional manufacturing costs for a 1MW VFD using SiC power modules.

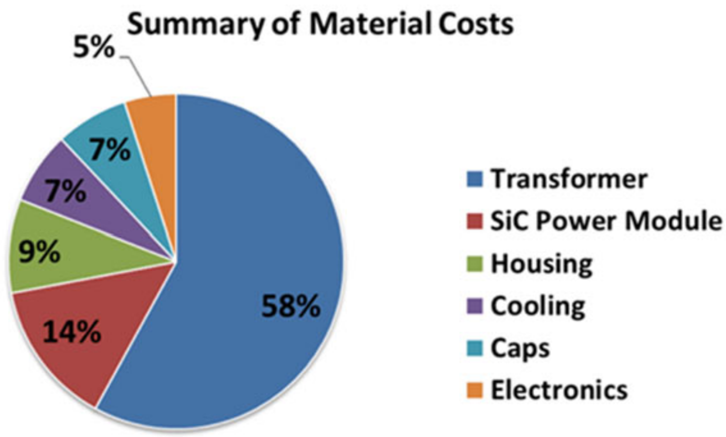

Figure 5. Breakdown of the SiC-based 1-MW VFD material costs by category.

Regional cost differences are driven by differences in labor rates and can be significant. This is because the VFD is manually assembled. However, we found that assembly of medium-voltage VFDs is sited near the end customer (demand) despite these differences in costs because of the lead time and expense involved with shipping these very large drives, as well as the benefit manufacturers derive from being able to quickly respond to customer needs.

Summary: Insights for Practitioners and Energy Efficiency Program Managers

VFDs in general have a significant upfront cost and are best utilized in applications with varying load or speed. SiC power electronics can be used in medium-voltage VFDs to increase efficiency—particularly for those operating at high power levels and high temperatures—compared to existing Si-based VFDs. In some cases, SiC power electronics can also reduce part counts and thus potentially overall system cost. Our analysis demonstrates that VFD costs could be reduced significantly if the transformer could be reduced or eliminated. Because SiC has a wide bandgap, SiC based VFDs could enable the use of smaller, higher frequency transformers. Additionally, the use of SiC-based VFDs could provide a return on investment associated with energy savings; this should be evaluated on a case-by-case basis.

The quality of upstream SiC components is an important factor in achieving a high performance VFD. While there are currently a limited number of suppliers who can produce high quality SiC devices, the supply chain has matured and expanded in recent years. Costs are expected to come down over the next 5 years as the industry scales and transitions to 150mm wafer fabrication. Increased availability of fully-SiC and hybrid Si/SiC VFDs is also anticipated in the next 5 years. SiC power electronics components that can be used in VFDs are currently available with voltages up to 1.7kV in volume; engineering samples of 3.3kV, 10kV, and 15kV devices are also available.

Despite the potential benefits, a key barrier to adoption of SiC-based VFDs in the industrial motor drive market is the perceived risk associated with the use of a relatively new technology. Unreliable or poorly designed parts and associated downtime can mean significant lost revenue. Continued investment in demonstrations of reliability and field performance is key to penetrating this conservative market. VFD manufacturers located near their end users may also be able to respond more rapidly to customer needs and reduce lead times, easing adoption.

Research is needed on the potential for innovations throughout the supply chain to drive down costs of SiC technology, increase adoption, and affect global manufacturing. Additional research and analysis is also required to understand the potential energy savings that can be achieved by SiC VFDs for specific industries and regions. Application of these cost models to other end applications is also of interest for evaluating the requirements for SiC to compete with Si power electronics, enabling increased energy efficiency throughout industry.

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