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Wide Bandgap Semiconductor Opportunities in Power Electronics

Kristina Armstrong
Sujit Das
Laura Marlino

November 2017

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OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division

WIDE BANDGAP SEMICONDUCTOR OPPORTUNITIES IN POWER ELECTRONICS

Kristina Armstrong
Oak Ridge Institute for Science & Education

Sujit Das
Laura Marlino
Oak Ridge National Laboratory

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The report objective is to explore the Wide Bandgap (WBG) Power Electronics (PE) market, applications, and potential energy savings in order to identify key areas where further resources and investments of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE EERE) would have the most impact on U.S. competiveness. After considering the current market, several potential near-term application areas were identified as having significant market and energy savings potential with respect to clean energy applications: (1) data centers (uninterruptible power supplies and server power supplies); (2) renewable energy generation (photovoltaic-solar and wind); (3) motor drives (industrial, commercial and residential); (4) rail traction; and, (5) hybrid and electric vehicles (traction and charging). After the initial explorative analyses, it became clear that, SiC, not GaN, would be the principal WBG power device material for the chosen markets in the near future. Therefore, while GaN is discussed when appropriate, this report focuses on SiC devices, other WBG applications (e.g., solid-state transformers, combined heat and power, medical, and wireless power), the GaN market, and GaN specific applications (e.g., LiDAR, 5G) will be explored at a later date. In addition to the market, supply and value chain analyses addressed in Section 1 of this report, a SWOT (Strength, Weakness, Opportunity, Threat) analysis and potential energy savings analysis was conducted for each application area to identify the major potential WBG application area(s) with a U.S. competitiveness opportunity in the future.

As U.S. energy demands rise, methods to increase system efficiency are highly sought after to curb the growing energy demand. WBG power electronics can reduce the energy lost during power conversion and do so with a smaller footprint and lighter weight. The specific benefits of WBG devices differ for each application area, as do the challenges associated with greater WBG-integration. For each of the application areas, the report identifies current practices and energy losses during power conversion. Additionally, it identifies the application-specific requirements of power conversion circuitry, current WBG usage and market, as well as potential cost and energy impact of WBG power electronics. Market reports, peer-reviewed journals, government reports, manufacturers' webpages, and product specifications were used to inform the analyses. Potential energy savings were calculated by determining the application's energy use/generation and the energy lost by power conversion, comparing it to the established lower losses of WBG power conversion devices. To evaluate the full potential in each application area, energy use and market data were analyzed for current standings (2014-2016) and future predictions (2025).

The WBG PE market is currently small: \$160M out of the \$16B power electronics market (Eden 2016; Fodale and Eden 2015). The size of the market can largely be attributed to the relative age of WBG technology compared to conventional Silicon (Si). As a less mature field, WBG devices are more expensive, have a low manufacturing level and demand, and have not yet been proven reliable to the level demanded by the application areas. These constraints lead final product manufacturers to be hesitant to begin integration and WBG device manufacturers hesitant to increase production levels to reduce the cost, resulting in a stalemate between the two. Government-sponsored research institutes, such as PowerAmerica in the United States, aim to bridge the gap between laboratory and production environments and help the WBG become competitive in the PE industry. By funding projects to design WBG-inclusive products with the help of university researchers and manufacturers, research institutes can move WBG devices from laboratory prototypes to working demonstration models and, finally, commercialized products.

In addition to government-sponsored research initiatives, the United States has significant wafer and device manufacturing capacity, though some of it belongs to foreign headquartered companies (e.g., X-Fab and Infineon). The United States faces competition from Europe, China, and Japan. Including final product manufacturers who are in the research and development stage, the United States has a strong position in WBG-inclusive final products. Manufacturers such as General Electric, Eaton, and John Deere are developing products like motor drives and PV inverters with WBG. Others, like Enphase and Avogy, have released products with WBG power electronics included. Of the different application areas, WBG devices for hybrid/ electric vehicles have the highest expected market potential, but this potential is highly dependent on future production of electric and hybrid electric vehicles.

Presently, Si-PE devices usually range between 85 – 97% efficient; WBG-PE reduces losses by half or more, raising efficiencies to between 95 – 99%. While a few of the potential application areas considered here benefit from reduced energy losses and will have a share in the WBG market in years to come, some have more benefits than others. Due to the large amount of electricity used by motors, WBG-integration into motor drives stands to have the largest energy impact. Motor drives have been estimated to potentially save between 150 – 410 PJ of primary energy for electricity in 2025, depending on the fraction of motors with drives (and assuming 100% penetration of WBG into motor drives). In order, data centers, renewable generation, and hybrid/electric vehicles follow in savings potential and are far more dependent on the general future of the application, which in turn could be affected by changing energy policies. Rail, due to the very low level of electrification in the United States, has by far the lowest energy potential. It is estimated here that in 2025 the WBG use in the five application areas could, at maximum, save the United States between 1.1 – 2.2% of its total electricity use and 0.3 – 1.1% of the gasoline use (from HEVs and PHEVs).

Major opportunities for WBG-integration lie in the expected increases in demand for the application areas or expected increases in the demand for more energy accountability (either by increasing system efficiency or by adding renewable energy generation). The relative immaturity of WBG that affects cost and perceived reliability, the necessity of system redesigns to adopt WBG and shortage of knowledgeable engineers to do so, the risk aversion of manufacturers, and changing demands for energy accountability continue to remain as major challenges being faced by the industry.

1. POWER SEMICONDUCTOR MARKET OVERVIEW

Power Electronics (PE) are a subset of solid-state electronics that act as switches to transform alternating and direct current (AC and DC). They are used for the conversion (i.e., AC to DC, DC to AC, DC to DC), control and processing of electricity. As in most solid-state electronics, the semiconductor material in PE is usually silicon (Si). However, as Si semiconductors get closer to the theoretical thermal and voltage handling limits of Si, other materials are gaining more attention (B Ozpineci and Tolbert 2003). Wide bandgap semiconductors (WBG) such as silicon carbide (SiC) and gallium nitride (GaN) can, in theory, withstand higher voltages, temperatures and electromagnetic radiation before breaking down and have been shown to be more efficient at power conversion and to reduce the size of the power conversion (Burak Ozpineci and Tolbert 2011).

Currently, WBG power electronics are a very small segment of PE, and PE is a very small share of total semiconductor use today (Figure 1-1). The U.S. has a strong foothold in both the SiC and GaN markets, but there exists an increasing threat to competition from Europe, Japan, and China. The White House has declared that maintaining manufacturing strength is a priority for the U.S., and President Obama launched a competition for new manufacturing innovation institutes. One of the winners was PowerAmerica (the Next Generation Power Electronics National Network for Manufacturing Innovation Institute, led by North Carolina State University and the Department of Energy's Advanced Manufacturing Office), a government, academic, and industrial partnership dedicated to growing U.S. manufacturing and lowering the cost of WBG semiconductors (White House 2014).

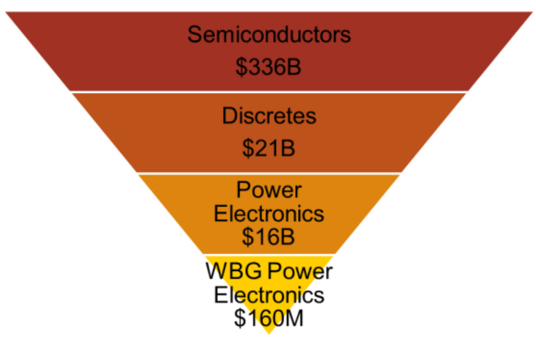


Figure 1-1. WBG power electronics within the semiconductor industry. (Semiconductor Industry Association (SIA) 2016; IHS Technology 2016; Fodale and Eden 2015; Eden 2016)

1.1. SEMICONDUCTOR AND POWER ELECTRONICS MARKET

1.1.1 General Semiconductor Overview

The semiconductor industry is vast and diverse, with products able to store data, act as logic circuits, condition electricity, and emit electromagnetic waves. The 2015 semiconductor market was nearly $336 billion, split amongst wide-ranging device types and application areas (Figure

1-2a). The largest market of semiconductor devices is integrated circuits (IC) which are electronic circuits built onto a single semiconductor chip. ICs can be made very tiny with billions of components per chip and hundreds of chips per wafer. ICs can be digital (discrete high/low voltage level) or analog (continuous voltage scale). Approximately two-thirds of semiconductors are digital IC, including memory (23%), microcomponents (e.g., microprocessors) (17%) and logic (27%). Analog ICs are the next largest segment with 13% of the market. In contrast to ICs, there are discrete semiconductors (6%); devices not manufactured as circuits. The largest subcategory of discrete semiconductors is power electronics (76%, see section 1.1.3 Power Electronics Overview), but radio frequency (RF) and microwave (MW) electronics are also considered discretes. In addition to ICs and discretes, there are optoelectronics (10%), including photoelectric and light emitting (LED) devices and sensors (3%). Nearly two-thirds of semiconductors are used for communications (e.g., cell phone, transmission equipment, etc.) and PC/computers (Figure 1-2b). The remainder is used for automotive, consumer (e.g., TVs, HVAC power conversion) and industrial (e.g., motor drives) applications (Fodale and Eden 2015; Semiconductor Industry Association (SIA) 2016).

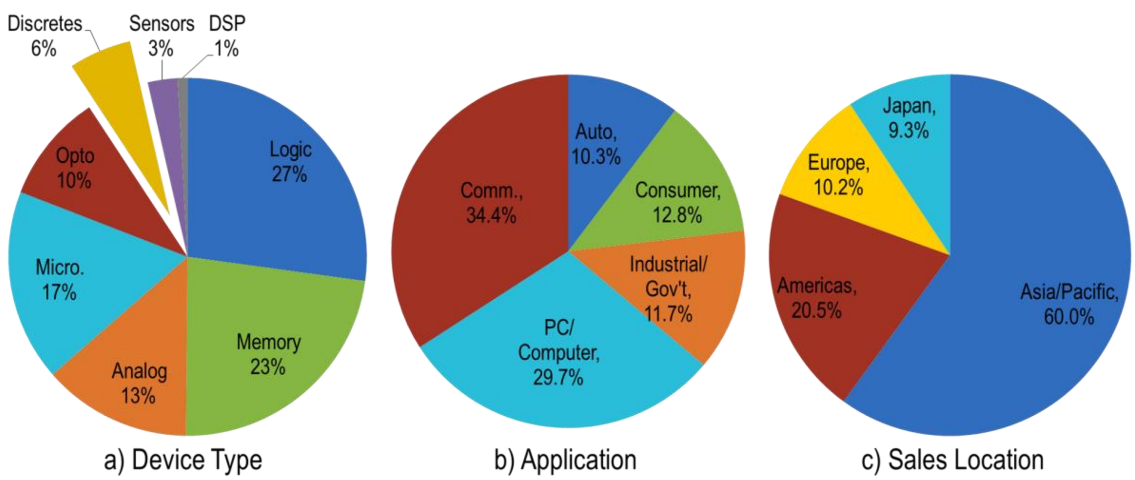


Figure 1-2. Total semiconductor 2015 market share by a) device type, b) applications and c) sales location. (Semiconductor Industry Association (SIA) 2016)

1.1.2 U.S. Standing in the Semiconductor Industry

Historically, the U.S. has been a leader in semiconductor manufacturing, and currently U.S. headquartered companies hold half (50%) of the worldwide market (Figure 1-3). Over half of U.S. companies' wafer manufacturing capacity is located in the United States, and about 86% of U.S. wafer manufacturing capacity is accounted for by U.S. headquartered companies, suggesting that a significant portion of wafer fabrication occurs in the United States (Semiconductor Industry Association (SIA) 2016). However, most semiconductor end-use products (e.g., computers, communication equipment, automotive electronics) are made in the Asia/Pacific region (excluding Japan) (58%), with the Americas coming in second (21%) followed by Europe and Japan (Figure 1-2c) (IHS Technology 2016).

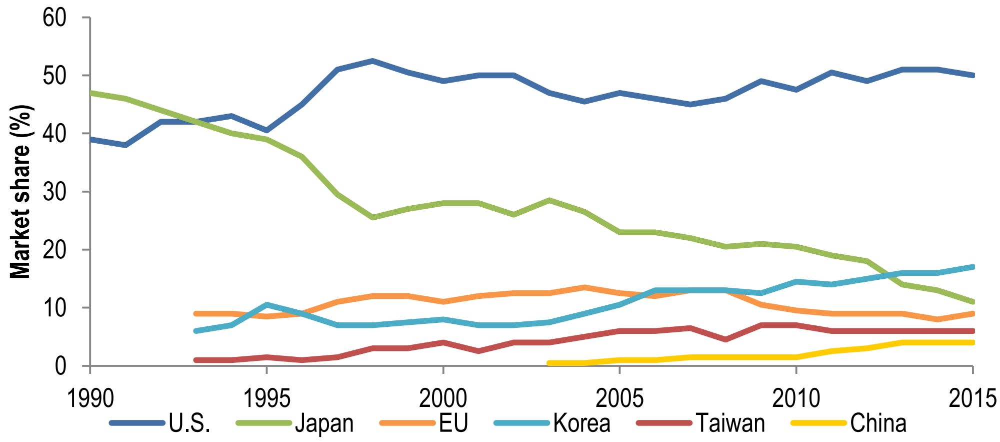


Figure 1-3. Relative semiconductor device market share based on company HQ. (Semiconductor Industry Association (SIA) 2016)

1.1.3 Power Electronics Overview

Although PE is only a small share of the total 2015 semiconductor market ($16B / $ 335B (Gueguen 2016)) (Figure 1-2a), it plays an important part of the world's electrical infrastructure, with approximately 70% of the world's electricity managed by power electronics, creating a $50 billion market for power conversion equipment (Iannuzzo and Ciappa 2016; Gueguen 2016). Power electronics condition and control the conversion and flow of electricity. Power semiconductors are the devices utilized in these electronics.

There are two general categories of PE devices, discretes, and modules. When referring to PE, discretes are power semiconductor devices that are not arranged and packaged together in a module (similar to the previous definition of not being packaged as an IC). Discretes include rectifiers (diodes), thyristors, and transistors, including bipolar junction (BJTs), metal–oxide–semiconductor field-effect (MOSFETs) and insulated gate bipolar (IGBTs) transistors. Modules are often several discrete chips, packaged together, sometimes with the control and protection circuitry included (Figure 1-4a).

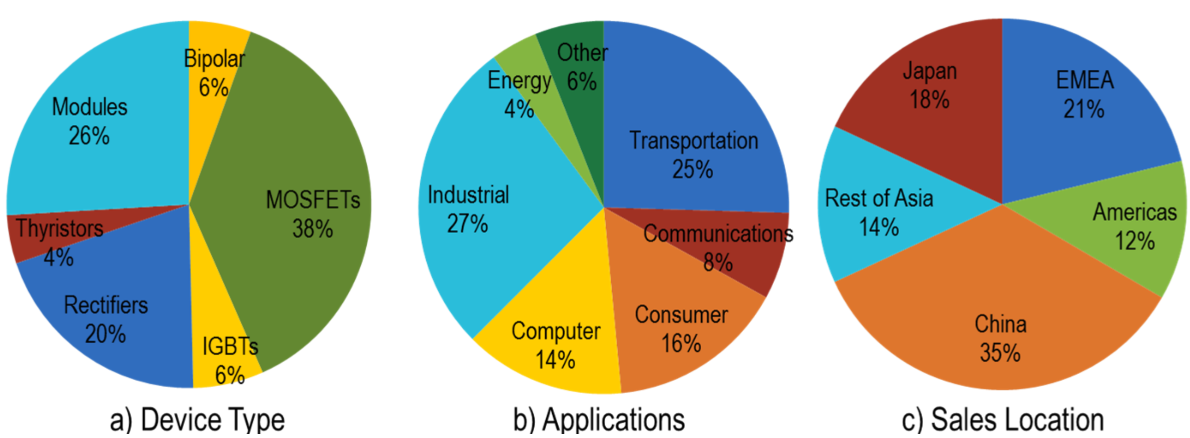


Figure 1-4. Power semiconductor 2014 market share by a) device type, b) applications and c) sales location. (Fodale and Eden 2015)

Power conversion is required for many sectors (Figure 1-4b), the largest two being industrial (27%, e.g., motor drives) and transportation (25%, e.g., electric traction drives, converters and vehicle charging). The consumer sector is the next largest (16%), containing power supplies for televisions and major home appliances. Computer and office equipment, the next largest, is a closely related sector (14%), including power supplies for computers and office equipment. Power conversion for renewable energy generation is a smaller segment now (4%) but is expected to grow more rapidly than many others will. Like the rest of the semiconductor industry, end use manufacturing most often occurs in Asia (China, Japan or the rest of Asia), with some in the United States and the rest of the world (Figure 1-4c) (Fodale and Eden 2015).

Power conversion works via several different conversion methods (Figure 1-5). Rectifiers convert sinusoidal AC electricity into linear DC via one-way switches (e.g., diodes) or transistors by only allowing one direction of current to pass through. This creates pulses of current that can be smoothed into constant current with more complex topologies and passive components (i.e., inductors and capacitors). A cell phone or laptop charger is an example of a common rectifier circuit. Inverters convert linear DC into near-sinusoidal AC by flowing electricity though several devices switching on and off to approximate a sinusoidal output; this can be further smoothed into a sinusoidal waveform (Figure 1-5 and Figure 1-6). Inverters are required to transform the DC current generated by solar panels into AC current for grid integration. Converters change DC voltage using switches and passives to higher or lower voltage levels; these circuits are often found in conjunction with the other two circuit types. While each of these processes has a high efficiency, come greater than 95%, when several of them must be used, the system efficiency can be dramatically reduced.

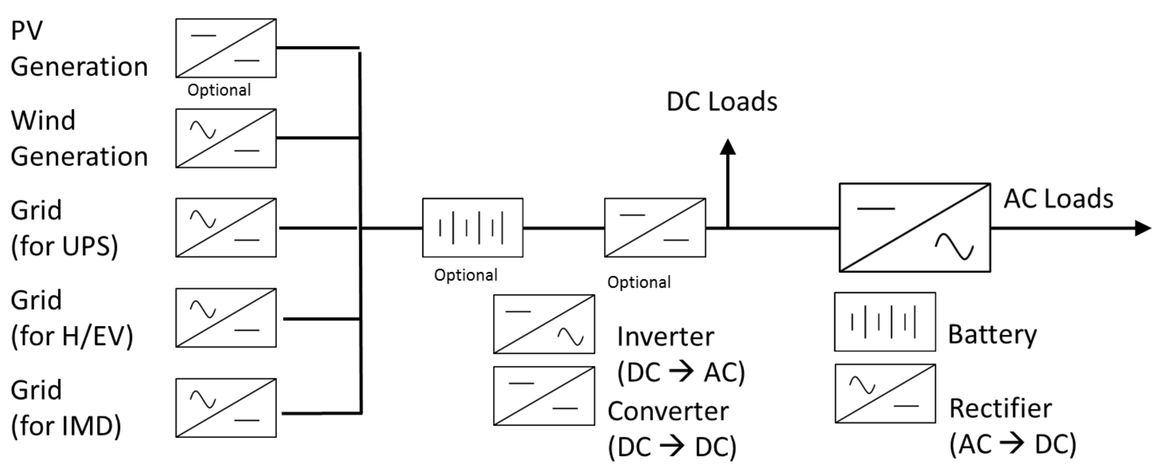


Figure 1-5. Power electronics for power conversion.

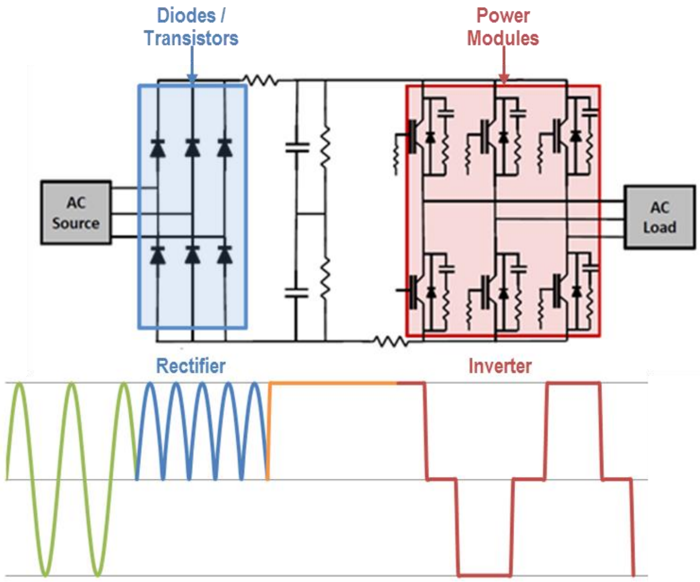


Figure 1-6. Standard power conversion topology (top) with current waveform (bottom).

1.2. WIDE BANDGAP POWER ELECTRONICS MARKET

1.2.1 Benefits of WBG Utilization

Wide bandgap semiconductors are a sub-class of semiconductor materials, defined by their larger-than-Si bandgap, typically between two and four electron volts (eV). There are several wide bandgap materials currently being explored for power conversion: silicon carbide (SiC), gallium nitride (GaN), gallium oxide (Ga_2O_3) aluminum nitride (AlN), and diamond. Of these, diamond-based devices are considered by many to hold the most promise but are hindered by small wafer size, scalability issues, and cost (Burak Ozpineci, Chinthavali, and Tolbert 2006). While SiC and GaN also have more crystal growth problems than Si, manufacturers have been able to grow large crystals of these materials. Because of this, Ga_2O_3, AlN and diamond power devices are all extremely primitive in development, while SiC and GaN-on-Si are both on the market and bulk GaN is in development today. Figure 1-7 compares properties of SiC and GaN to Si.

Wide bandgap power electronics are a small but growing segment of PE (Figure 1-8). in 2015, the technology information company IHS estimated that the market for PE will be nearly $18 billion in 2016 (Fodale and Eden 2015) while the market for WBG devices is expected to be less than $300 million (Eden 2016), or less than 2% of the PE market. Assuming the PE market continues its current growth rate however, WBG devices can be expected to comprise over 12% of the PE market by 2025. This growth is being driven by demand for smaller packaged electronics with increased power density and higher efficiency. Replacing Si with a WBG semiconductor can yield higher breakdown voltages, faster switching, lower switching losses, and higher operating temperatures. Through careful design, all of the attributes and trade-offs can lead to power conversion products that have higher power density (more efficient and smaller), weigh less and may even cost less. Figure 1-9 and Figure 1-10 illustrate how some of the fundamental material properties of SiC and GaN semiconductors can lead to WBG's end-use benefits.

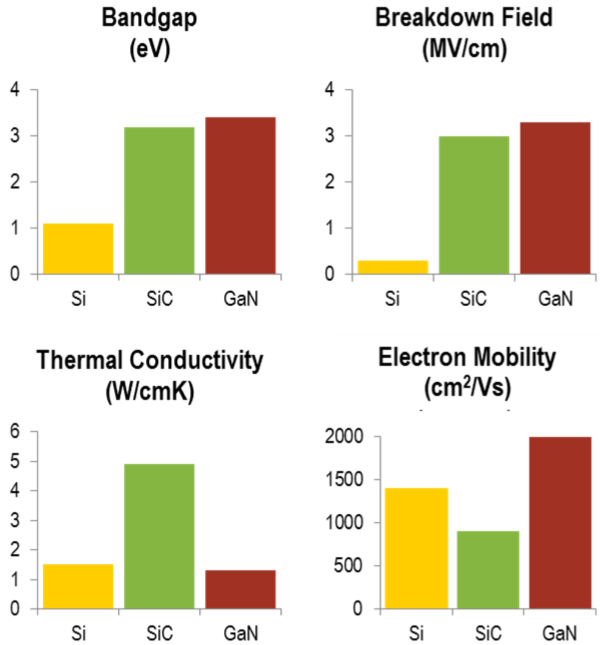


Figure 1-7. Relative key properties of semiconductor materials (adapted from Rohm Semiconductor 2013; Misra, Ramanan, and Lee 2015; Meneghesso et al. 2016; Evans et al. 2016)**).**

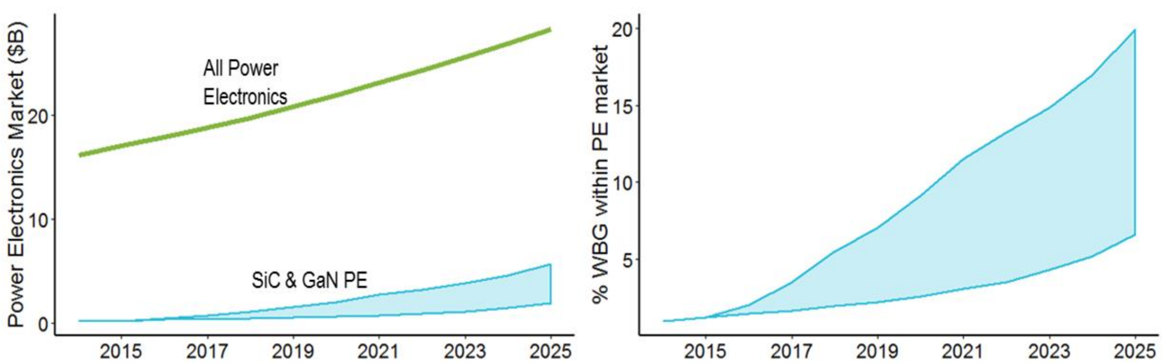


Figure 1-8. WBG semiconductors within the power electronics market by revenue, left (a) and percent, right (b) (Fodale and Eden 2015; Eden 2016)**.**

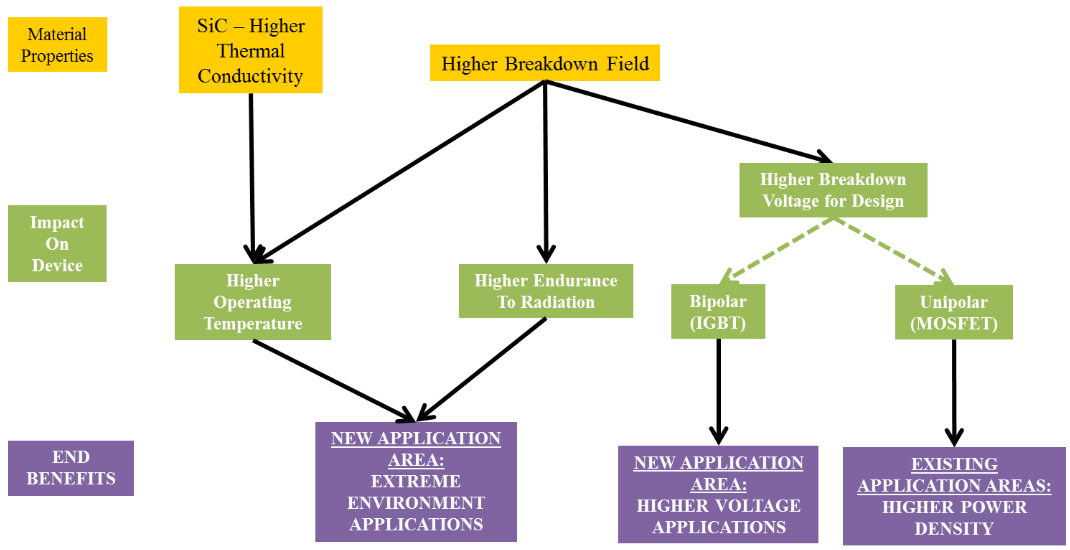


Figure 1-9. WBG's fundamental material properties lead to new application areas and improve existing areas.

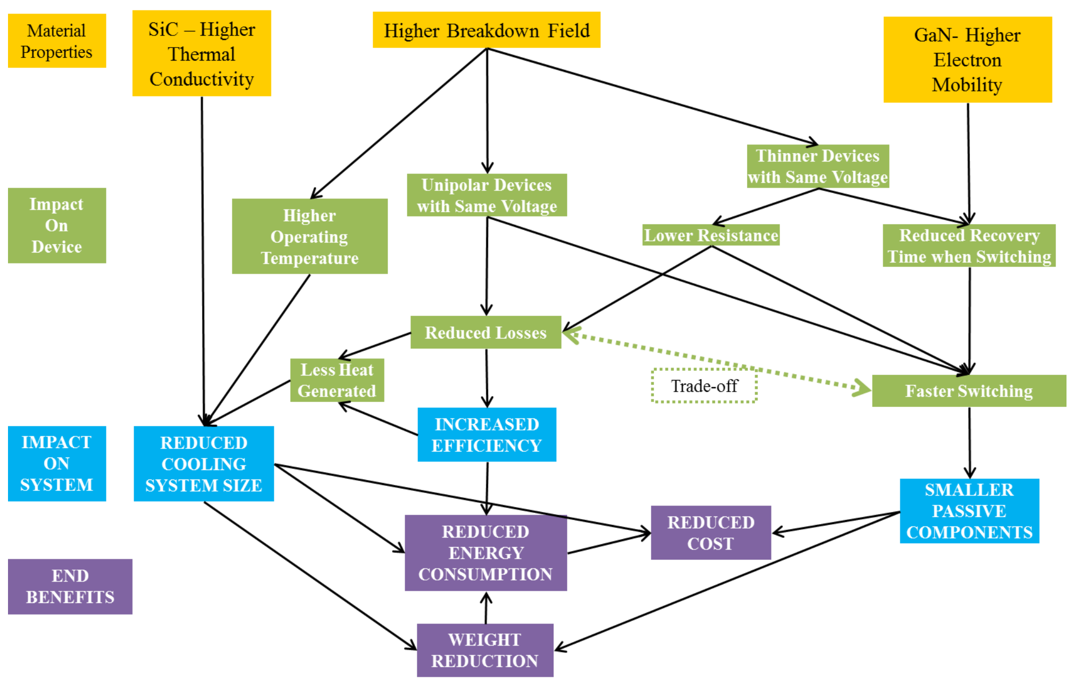


Figure 1-10. WBG's fundamental material properties lead to improved operation.

Compared to Si, SiC has a higher breakdown field and thermal conductivity, whereas GaN has a higher breakdown field and electron mobility. These key material properties lead to higher operating temperatures, higher endurance to electromagnetic radiation, and a higher operational voltage for a given design (Figure 1-9). Devices able to withstand high temperatures and radiation hold significant promise for extreme environmental conditions such as space exploration, deep well drilling, and proximity to high temperature engines. The higher breakdown voltage leads to two potential application areas: high voltage applications (grid) and increasing the efficiency of existing power conversion. The use of high voltage bipolar devices (e.g., IGBTs or BJTs) enables extreme high voltage applications, such as solid-state transformers and other smart grid applications. Using a unipolar device (e.g., MOSFET and JFET) for low to medium voltage applications (e.g., PV solar or industrial motor drives) can lead to significant reduction in losses compared to bipolar Si devices. This is because unipolar devices use only electrons as carriers whereas bipolar devices use both "holes" and electrons. This means that bipolar devices can move more current at higher voltages, but when switched off, there are more charge carriers that must be recombined. When engaged in rapid switching, bipolar devices have an overlap where the leftover carriers are exposed to a high voltage and lost as heat. Being able to use unipolar devices will allow for faster switching, reduced device size and increased efficiency and power density (Burak Ozpineci and Tolbert 2011). However, it is not just the ability to use unipolar devices that contributes to WBG's potential. The different material properties can work together to reduce system cooling requirements, and the size of passive components, resulting in greatly reduced system size, weight and even cost (Figure 1-10).

Compared to Si IGBTs, analogous WBG devices can significantly reduce losses leading to an increase in circuit efficiency, usually from around 95% to 98% or higher, depending on the PE configuration and application (Go Solar California 2016; Teschler 2015; Advanced Energy, n.d.; Roggensack, Tschudi, and Fortenbery 2008; Toshiba International Corporation 2015; Han et al. 2014; Rabkowski, Peftitsis, and Nee 2013). When applied to an entire application sector, like uninterruptible power supplies (UPS) in data centers or renewable energy applications, terawatt-hours of energy can be saved at current usage rates.

Currently, most of the market is focused on SiC. Production of SiC devices began over 15 years ago (Burak Ozpineci and Tolbert 2011), making SiC a more mature technology than GaN. Also, SiC is available at higher breakdown voltages and current handling capabilities (SiC MOSFETs are commercially available up to 1.7 kV and a thyristor up to 6.5 kV). GaN has seen rapid development over the last 15 years, due to GaN's use as a light emitting diode in Blue-Ray discs. GaN devices are currently available at 600V and lower. The cost savings enabled by Si wafers and very high switching frequency make it very possible for GaN to overtake Si SuperJunction MOSFETs in future low voltage applications (Eden 2016). Additionally there are several SiC wafer and device manufacturers in the U.S (e.g., Cree/Wolfspeed, Dow Corning, GeneSiC) and more abroad (e.g., Infineon, Fuji) (see Section 1.4: SiC and GaN Supply Chain). There are fewer U.S. power GaN wafer or device manufacturers (e.g., Texas Instruments, Transphorm), although the power GaN supply chain is still growing (Eden 2016).
The high bandgap and breakdown fields of SiC and GaN is leading researchers to push for even higher voltages. Wolfspeed is reliability testing 10 kV SiC MOSFETs and have developed SiC MOSFETs up to 15 kV (J. W. Palmour et al. 2014). Bipolar SiC IGBTs have been developed up to 27 kV (van Brunt et al. 2015) and maximum voltages are potentially higher. Most GaN devices sold today are on Si substrates (due to their low cost and availability) and are lateral devices, meaning current does not flow vertically though the device like most PE devices, resulting in large area devices, low voltage capabilities, and poor thermal handling. Vertical GaN holds potential for higher breakdown voltages, but requires GaN substrates, which are much less mature than Si or SiC, with material issues (e.g., high defect densities) and high costs, though this is improving.

1.2.2 Challenges for WBG Integration

While there are several benefits to adopting WBG power electronics, several engineering design and economic challenges still exist. One of the most common issues with WBG adoption is cost; it is often cited by both academia and industry as one of the largest barriers to overcome (Burak Ozpineci and Tolbert 2011; Agarwal 2014; US Department of Energy 2015). Figure 1-11a shows the average selling price of WBG discretes decreasing, with bumps likely due to the introduction of higher voltage or current handling devices by IHS (Eden 2016). The range between IHS's conservative and optimistic forecasts is shown by the shaded area. This can also be seen in Figure 1-11b, where the average price per amp is shown decreasing more smoothly with time. GaN transistors are currently lower priced than SiC, likely due to the much lower voltage capabilities of GaN; the highest rated GaN transistor is 650 V compared to SiC's 1.7 kV (Eden 2016). In 2015, the average PE device selling price with Si was much lower than SiC or GaN; rectifiers/diodes were around $0.06, MOSFETs, $0.14 and IGBTs, $0.61 (Fodale and Eden 2015). This puts SiC diodes at about 10 times the price of Si diodes; the price difference is greater for Si transistors. (For more information on WBG devices, see Section 1.4.2: WBG Devices: Discretes and Modules.)

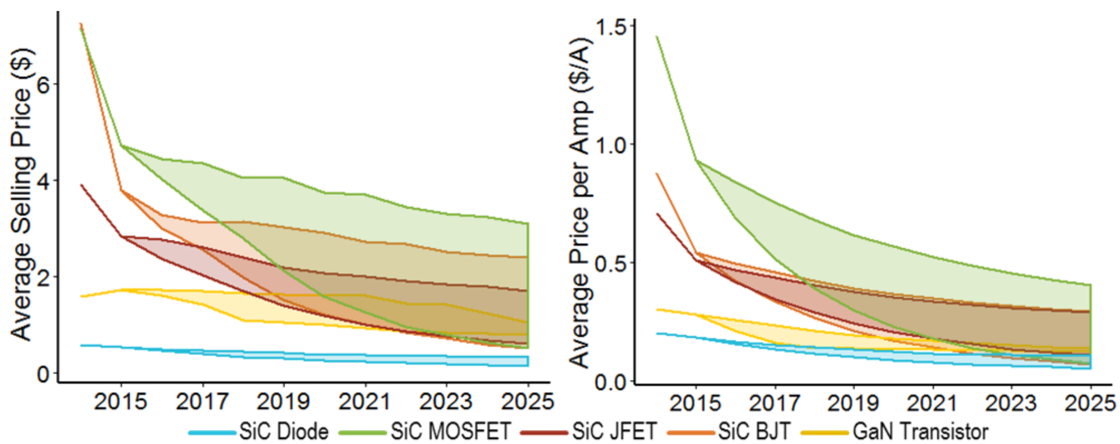


Figure 1-11. WBG discretes' average selling price, left (a), and price per amp, right (b) (Eden 2016)**.**

Figure 1-12 shows the same for WBG modules, with the average price mostly decreasing and the projected price per amp smoothly declining over the next 10 years. WBG device costs are expected to decrease as manufacturers improve manufacturing technologies and increase production volume and wafer size (150 mm SiC wafers are currently being adopted over 100 mm SiC, see Figure 1-13, and GaN on SiC is already manufactured on 150 mm wafers (Eden 2016). Additionally, SiC and GaN device costs may not require cost parity with Si devices to begin adoption. Several studies have shown that the reduced cooling and passives costs, in addition to the increased efficiency, can be enough that WBG inclusive system costs are less than Si systems, making device costs less of a challenge than WBG module price suggests (Schwarzer, Buschhorn, and Vogel 2014; Yole Development 2013a; Abbatelli et al. 2014). However, price is still a big hurdle; if the price is not less than twice Si or lower, then it is likely many manufacturers will not switch from Si (Agarwal et al. 2016; Evans et al. 2016).

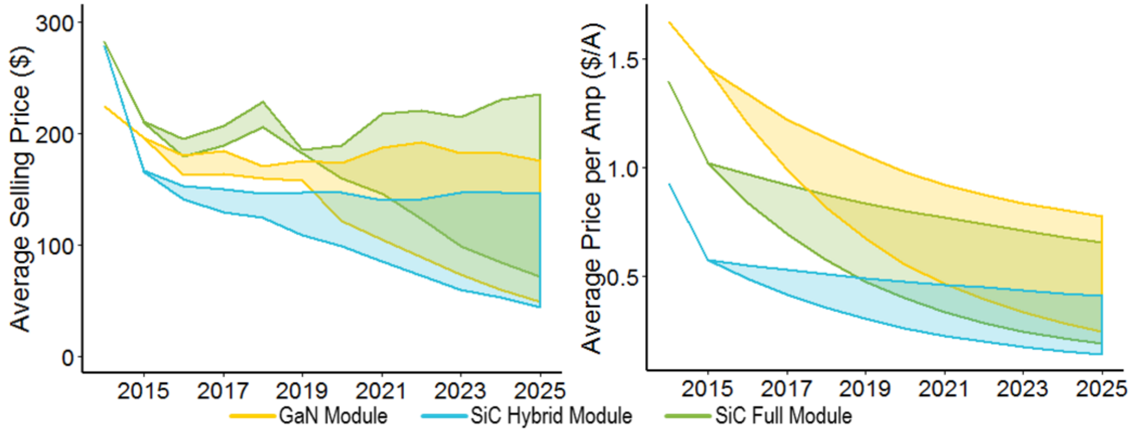


Figure 1-12. WBG modules average selling price, left (a), and price per amp, right (b) (Eden 2016)**.**

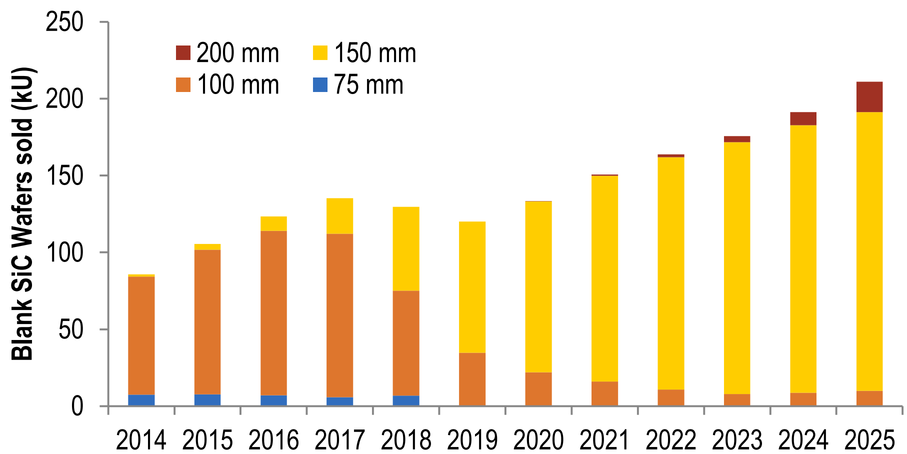


Figure 1-13. Production of various sized SiC substrate wafers (Eden 2016)**.**

Another challenge, specifically for SiC, has been material defects in the semiconductor crystal; as recently as five years ago, micropipes were a major problem for SiC manufacturing. However, with continuous improvements in crystal growth, wafer manufacturers have largely removed micropipes from their products and this is no longer considered a hindrance for SiC (Burak Ozpineci and Tolbert 2011). However, the high dislocation density remains a challenge for GaN/Si material which leads to high leakage currents and long-term reliability issues. In addition to cost and material issues, another major hurdle is the need to prove, promote, and develop WBG-specific standards for reliability (Evans et al. 2016). JEDEC, a global microelectronics standards leader that develops open reliability standards for power electronics and other semiconductor devices, is currently working on developing WBG-PE standards (Keller 2016), and PowerAmerica is hoping to establish an independent reliability center. A major SiC manufacturer, Wolfspeed, claims that its devices have worked over 972 billion cumulative hours (as of March 2014) with 0.12 failures per billion hours (3.5 fail/109 hours for MOSFETS), 10 times lower than Si (Casady and Palmour 2014). Additionally, GeneSiC claims that, as of November 2013, none of their devices had failed any reliability tests (GeneSiC Semiconductor

2013, 2014). Other manufacturers have shown the reliability of WBG devices as well, but there are still additional device and packaging reliability issues to be addressed, as well as addition time in the field to prove reliability to the satisfaction of final product manufacturers(Henshall 2015; Chow 2015; Weimer 2015; M. Johnson 2015; Evans et al. 2016).

Another major barrier is "design inertia." PE and power conversion equipment manufacturers design their products similarly to how it has been done for years, however WBG power electronics have specific benefits and challenges compared to Si that require special attention to properly utilize and avoid. It has been repeatedly stated in the industry that WBG devices are not best used as drop in replacements for Si; new passives, packaging, gate drives and EMI short circuit protections need to be developed to fully take advantage of and utilize SiC (M. Johnson 2015; Liu, Tuttle, and Dhar 2015). This is potentially an even larger problem for GaN, for which special care must be taken in designing a circuit to best take advantage of its benefits (Scott et al. 2013; Reusch 2015). GaN is also not readily available on GaN substrates (bulk GaN), leading to potential crystal mismatch faults but cheaper wafers. It is also not readily available in a vertical current flow configuration, resulting in larger devices or lower current and voltage handling capabilities. To encourage using GaN to its full potential and compensate for its physical design, manufacturers do not often package in standard Si packaging, unlike SiC. Some GaN manufacturers package in modified Si packages; others use completely new systems; this makes it more difficult to use it as a drop in replacement for Si (Scott et al. 2013). Additionally, there is a need for a sophisticated low inductance packaging innovation to better utilize the high frequency operation of GaN devices.

1.3. WBG GROWING MARKET AND MARKET DRIVERS

One of the major market drivers for the increase in WBG utilization is the growing demand for energy accountability including efficiency and generation sources. As energy demand and environmental awareness grows, there has been an increase in regulations relating to energy efficiency and growing incentives for increasing renewable energy generation, alternative transportation energy, and further increasing energy efficiency. Other application-specific drivers include the reduction in power converter size and the growing evidence of decreased system cost.

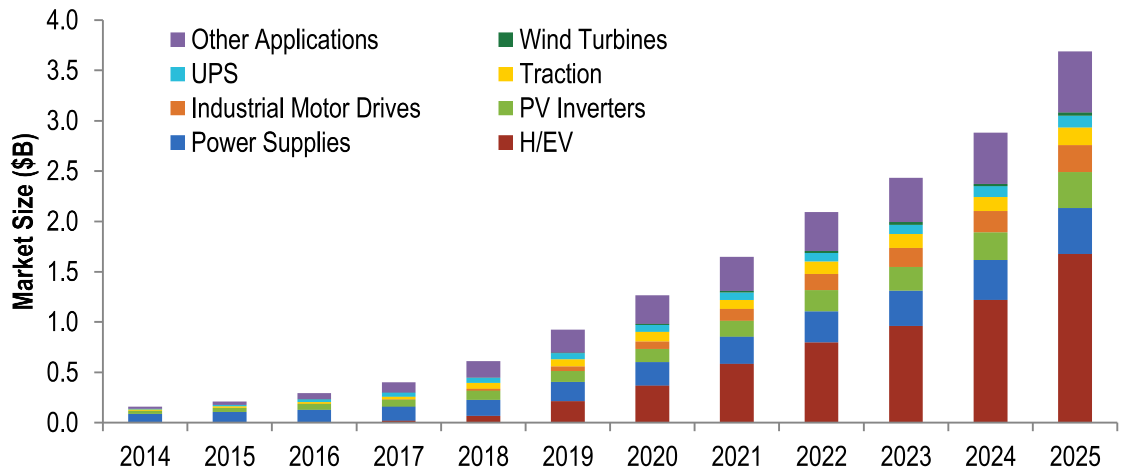


Figure 1-14. Annual growth of WBG market by application (Eden 2016)

There are several potential application areas for WBG power electronics. Specifically of interest are applications that place a high value on small size/weight or high operating temperatures, switching frequency and efficiency (Table 1-1 and Table 1-2). For example, the potential increases in inverter operating temperature are highly advantageous to electric vehicles and well logging while relatively unimportant to UPS applications. Figure 1-14 illustrates the current WBG future market sizes for each potential application area. Currently, the major WBG market is power supplies; all AC-DC power supplies rated at 75W and above must use power factor correction (PFC). PFC is used in power supplies for home electronics, telecommunications, servers and industrial three-phase mains power supplies (e.g., for motors) to reduce harmonics and correct voltage and current waveform misalignment caused by inductive loads (such as transformers or induction motors/generators) (PowerStudies n.d.). Industrial PFC greatly benefits from the increased switching speed enabled by WBG devices and is the current largest market for SiC Schottky barrier diodes. Smaller/lower-voltage power supplies (for consumer and office supplies) may be an opportunity for GaN, but at this point, market analysists expect the power supply market to stay with Si for these smaller, single-phase applications (Eden 2016). Within the next few years however, it is expected that the market for WBG in hybrid and electric vehicles (H/EV) will surpass power supplies, as use in PV inverters and industrial motor drives significantly increases. WBG power devices are well suited for H/EV chargers, DC-DC voltage conversion, and the traction drivetrain. The weight loss enabled by faster switching and reduced cooling systems will have a major impact on the overall vehicle efficiency (vehicle acceleration and range). Additionally, the environmental benefits of H/EVs over petroleum-based vehicles are expected to greatly increase the H/EV market size (Eden 2016).

Table 1-1. Market drivers for major potential WBG applications

	Power Supply	UPS	PV Solar	Wind	Motor Drives	Rail	H/ EV	Key
Efficiency	High	Medium	High	High	High	Medium	High	High
Weight/ Size	Medium	Low	Low	Medium	Medium	High	High	Medium
Operating Temperature	Low	Medium	Low	Low	High	Medium	High	Low
Switching Frequency	Low	Low	Low	Low	Medium	Medium	High	
Cost	Medium	High	High	Medium	Medium	Low	High	

Table 1-2. Market drivers for advanced WBG applications

	Sensors	Process Heating	Medical	Well Logging	Wireless Charging	Key
Efficiency	High	High	Medium	Medium	High	High
Weight/ Size	Low	Medium	High	Medium	Medium	Medium
Operating Temperature	High	High	Low	High	Low	Low
Switching Frequency	n/a	Medium	High	Low	Medium	

The estimated uptake of WBG devices is based primarily on when the device price drops to a point where it becomes advantageous to the system to adopt them (usually assumed to be between 2-3 times that of Si). It should be noted however, that IHS and other forecasters have predicted the rapid growth of WBG devices for several years; IHS predicted in 2012 that by 2016, the WBG market would be near $1.0 billion, but now the market is less than $300 million and reaching the $1.0 billion mark is not expected until after 2019 (Eden 2016). Yole's 2016 forecast (SiC only) is closer in line to IHS's 2016 conservative forecast for SiC. The lack of WBG market expansion is likely due to the delay of the expected price drop, which did not happen until 2015 (see Figure 1-15) (Eden 2016).

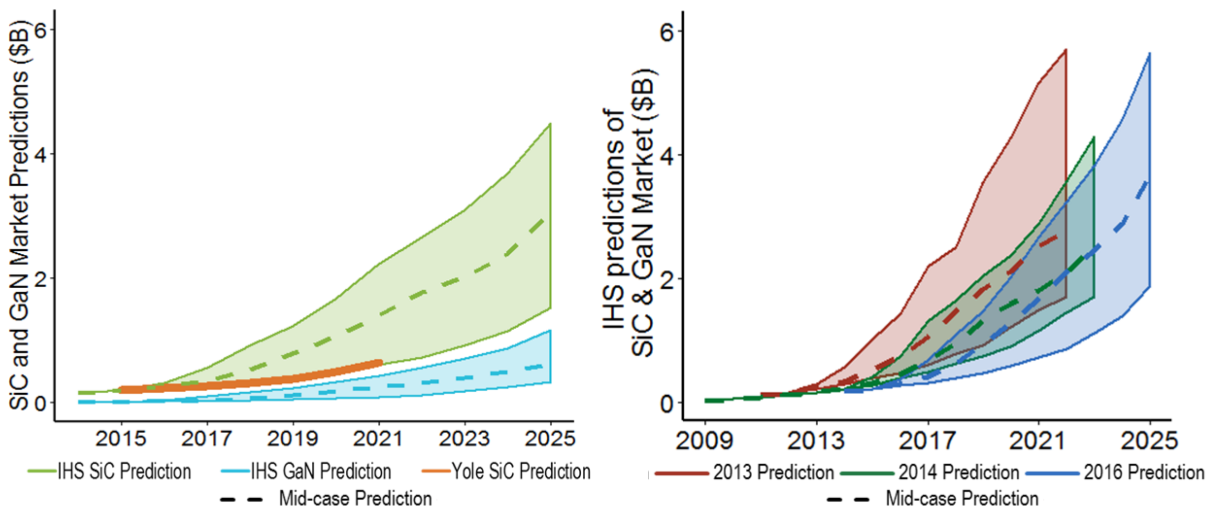


Figure 1-15. IHS and Yole forecast variance (left) and variation in IHS forecast by prediction year (right) (Eden 2016)**.**

1.4. SIC AND GAN SUPPLY CHAINS AND MANUFACTURERS

Currently, SiC is the leading WBG semiconductor material, globally outselling GaN by nearly a factor of 25 in 2014 (Eden 2016). Given the current market and the lack of GaN devices with the current or voltage handling capabilities needed for most of the applications considered in this report, the majority of the report will be focused on SiC. Unlike Si, there is no stoichiometric liquid phase of SiC; therefore, it must be grown via seeded sublimation using the modified Lely method. This involves heating ultra-pure SiC powder in a crucible at over 2000°C, past the sublimation temperature, then condensing on a cooler seed crystal. After ingot growth, SiC production is similar to Si, wafers are cut and polished before epitaxial growth, however, SiC is much harder than Si, meaning the cutting of wafers from ingots is much more difficult (Kimoto and Cooper 2014). After epitaxial deposition, the dies undergo several front-end and initial back-end processes (e.g., etching, backgrinding, and dicing). The bare dies then are subjected to further back-end processing (e.g., packaging and housing) to turn them into either discrete packaged devices or packaged modules. These can then be assimilated into power conversion circuits for integration into the final product (Strenger 2010) (Figure 1-16).

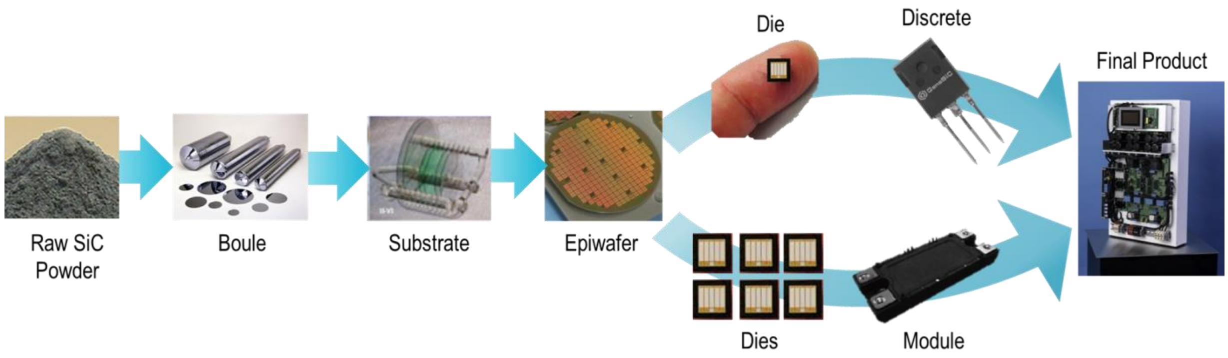


Figure 1-16. SiC product manufacturing chain.

Figure 1-18, Figure 1-19 and Table 10-1 to Table 10-4 (located in Chapter 10), show that there are many semiconductor companies expanding into WBG power electronic. There are several companies that handle one segment of the chain (e.g., device manufacturing), and others that are integrated throughout several segments, (e.g., substrate to end-product manufacturing) (see Figure 1-17). Japanese companies tend toward full vertical integration (Mitsubishi) whereas European and American companies are more mixed, with some partially vertically integrated (Cree/Wolfspeed) and some only operate under a single tier (such as device manufacturer, X-Fab or wafer provider, SiCC). There are also several companies that have supply deals, selling epitaxy wafers (epi-wafer) at cost to device manufacturers, effectively simulating vertical integration (II – VI and Global Power Technologies Group). Table 10-1 - Table 10-4 describe where WBG companies' HQs are located, what materials and sub-sections of the supply chain they provide and how many U.S. patents they hold in the areas of silicon carbide and gallium nitride[1], to illustrate current location of WBG innovation.

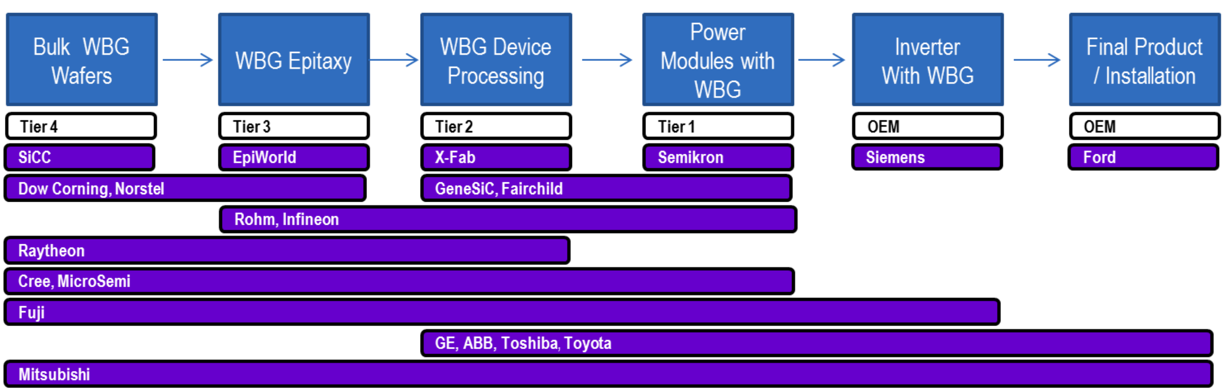


Figure 1-17. Examples of variety of integration levels by major WBG-inclusive manufacturers.

[1] The number of patents was determined via a patent key word search on the USPTO website (U.S. Patent and Trademark Office n.d.) by using the following search criteria: AN/("company name") AND "Semiconductor" AND ("silicon carbide" OR "gallium nitride")). This returns any patents assigned to the specified company that contain the words "semiconductor" and "silicon carbide" or "gallium nitride" in the body of the patent. The results include patents that are not used, are not specifically about WBG materials or are about a different semiconductor product (LEDs) and, thus may not reflect the true innovation within WBG power wafers and semiconductors and does not reflect current ownership of IP.

Color coded by company headquarters location, Figure 1-18 and Figure 1-19 illustrate the position of several OEMs within the WBG PE supply chain. The box holding some OEM's names are immediately adjacent to another, filling the gap between supply chain segments, indicating that those companies have some form of purchase deal or similar connection. Companies that are working on WBG products, but do not yet have a WBG commercial offering (e.g., Monolith) (or WBG inverter systems, but do produce Si inverter systems, e.g., Toshiba) are indicated by a lighter color fill. Companies with an announced prototype have the lighter fill, but also a darker border (e.g., GE).

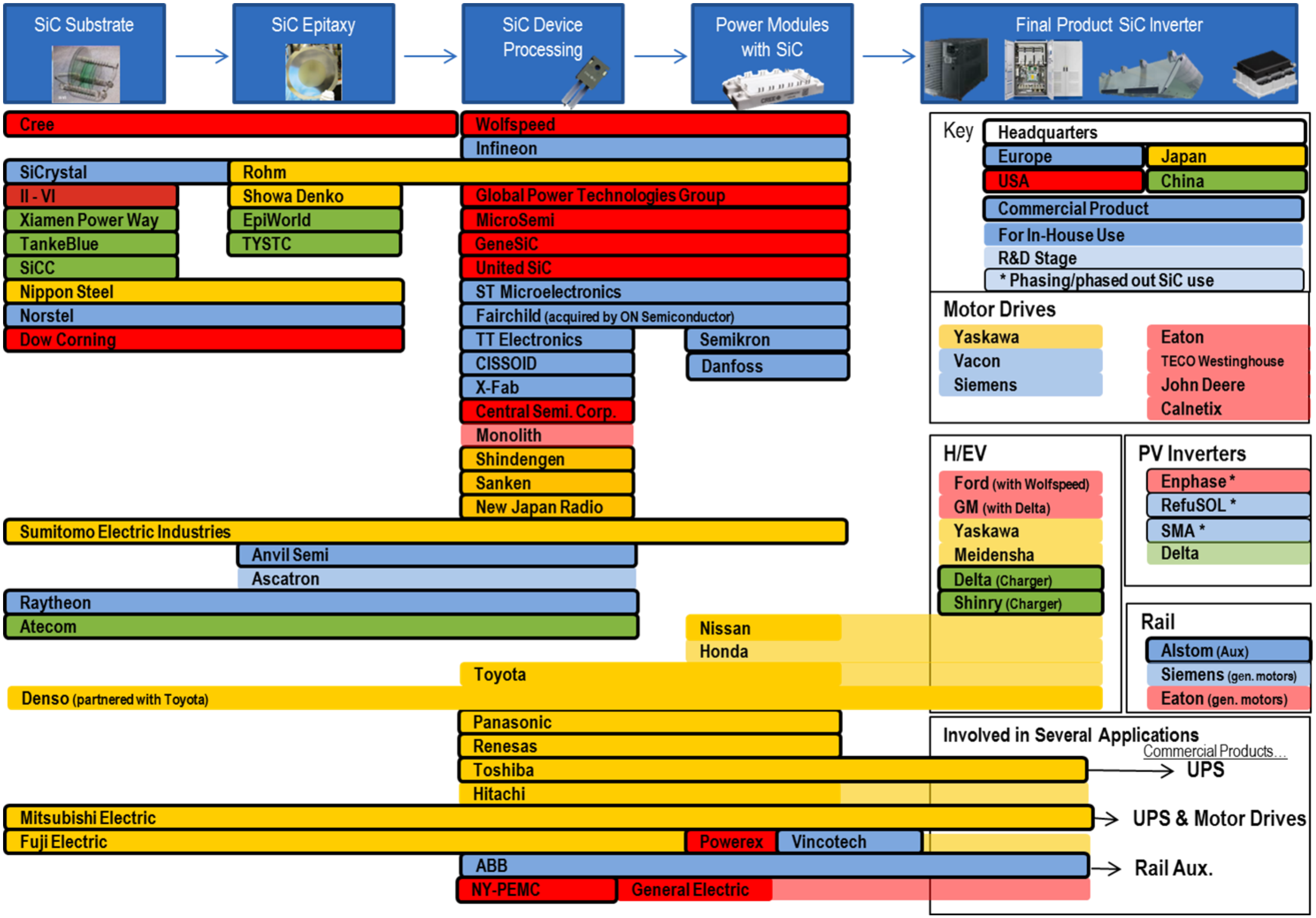


Figure 1-18. SiC electronics manufacturers and their role on the supply chain.

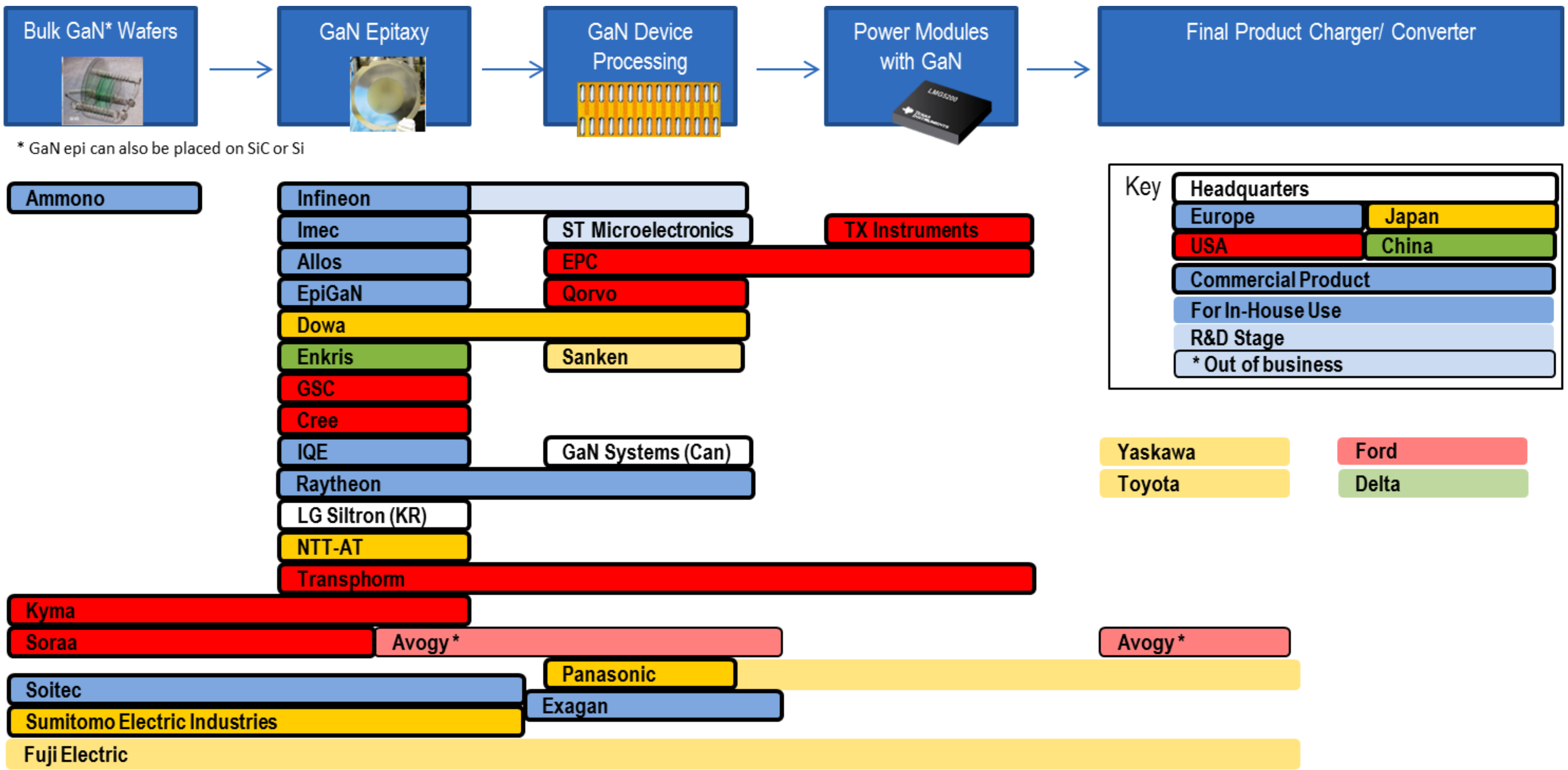


Figure 1-19. GaN electronics manufacturers and their role on the supply chain.

Overall, the number of WBG companies is nearly equal between Asia, Europe, and America, though Japanese companies hold the most U.S. patents, followed by American and European (see Table 1-3). However, there exists no direct correlation between number of companies in a region and patents for a company to revenues.

Table 1-3. Number of WBG companies and U.S. patents by region (as of June 2016) (U.S. Patent and Trademark Office n.d.)

	WBG Companies	SiC Companies	GaN Companies	U.S. WBG Patents
Asia	25	17	9	3935
Europe	24	17	9	1066
America	25	16	10	2695

As of 2014, Infineon and Cree (European and American, respectively) held 68% of the SiC device market, while all other companies, regardless of location, held the remaining 32% (Yole Development 2015b). This fraction has decreased to slightly above 50% (Wolfspeed/Cree with 27% and Infineon with 23%) in the past few years (Figure 1-20). In July 2016 Cree announced the sale of its power electronics division, Wolfspeed, to Infineon (Yole Development 2016f), however this fell through in February 2017 due to the Committee on Foreign Investment in the United States (CFIUS) likely blocking the sale due to national security risks (Infineon 2017). Until 2008 the United States (led by Cree), held the majority of the SiC market; during this time Europe (led by Infineon) ramped up production to eventually surpass the U.S. in 2009. Japan entered the market about six years after Europe and is expected to be near equal to both the U.S. and Europe by 2017 (Figure 1-21), based on 2013 Yole projections (Yole Development 2013b)). China is just entering the WBG PE market with several wafer manufacturers but few device manufacturers at this time, and have significant government funding (Yole Development 2016c). While U.S. SiC revenues are expected to increase over the next few years with the overall projected market increase, the U.S. market share likely will continue decreasing due to the continued Japanese and Chinese device manufacture ramp up. GaN follows a similar pattern: the U.S is expected to hold the majority of market share for a few years while losing shares to Japan, Europe, and Asian countries (Figure 1-22) (Yole Development 2014).

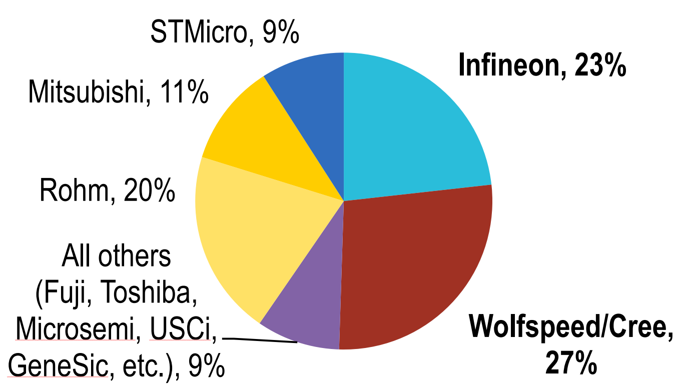


Figure 1-20. 2015 company market shares of SiC devices (Yole Development 2016c)**.**

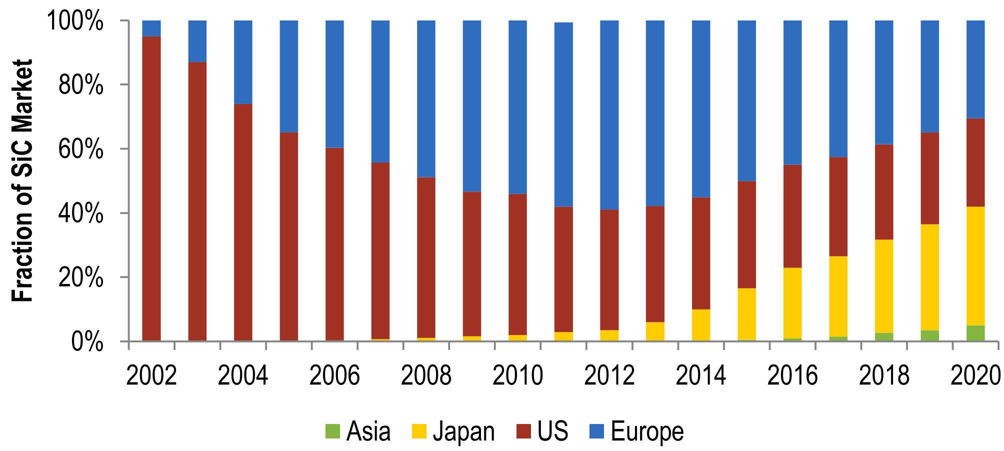
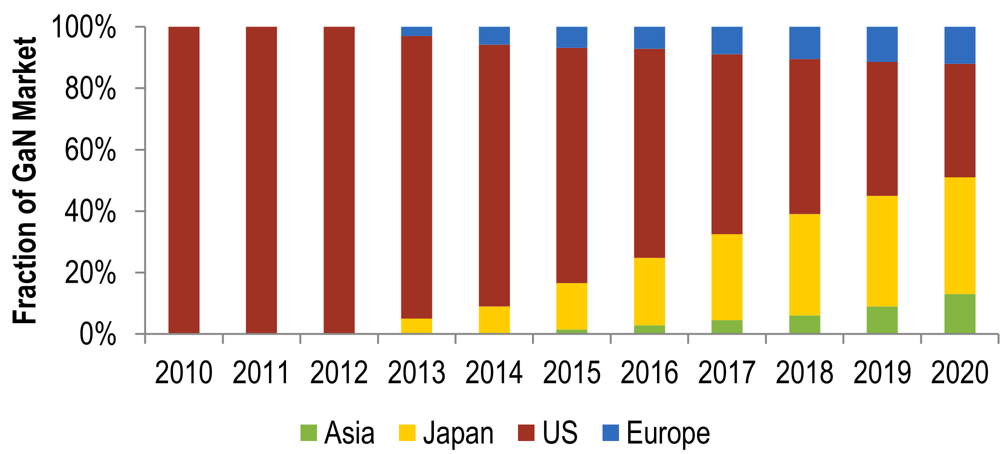


Figure 1-21. Percentage of SiC revenues by company HQ location (2013 projections) (Yole Development 2013b)**.**



.Figure 1-22. Percentage of GaN revenues by company HQ location (2014 projections) (Yole Development 2014)**.**

1.4.1 WBG Wafers: Substrate and Epitaxy

WBG semiconductor wafers (substrate) and epitaxies are less mature technologies than silicon; silicon has had access to 200 mm and larger wafers for several years now, and they comprise about one-third of the Si power electronics market, though the majority is still held by 150 mm (Yole Development 2015d). WBG wafers are also increasing in size, for SiC, 100 mm is beginning to lose market share to 150 mm (Figure 1-13). Most GaN for PE, however, is actually deposited onto Si substrates instead of GaN, with some GaN epitaxy on SiC and a small amount of bulk GaN. Because of GaN-on-Si, GaN is actually able to take advantage of Si's larger substrate size and there is expected to be more GaN on 150 mm Si wafers than any other substrate (Figure 1-23) (Eden 2016).

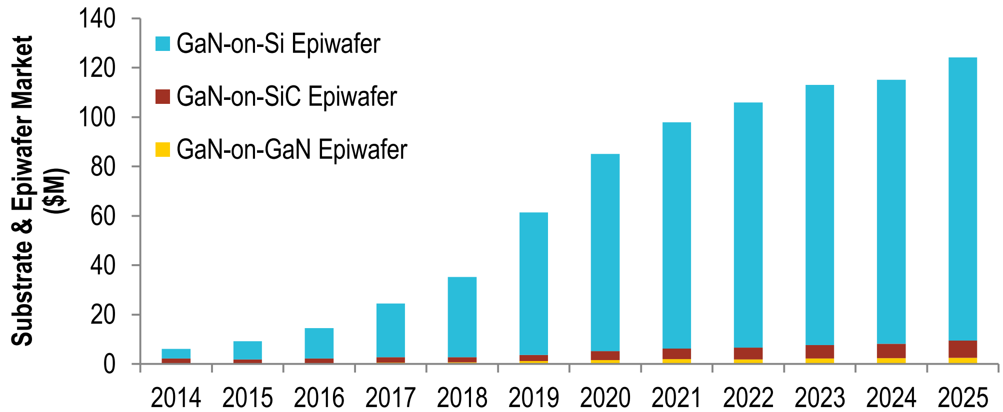


Figure 1-23. GaN epi-wafer revenues breakdown by substrate material(Eden 2016)**.**

Table 10-1 (located in Section 10.1: Appendix A) provides details on substrate and epitaxy manufacturers' products and number of U.S. WBG patents held. There are eight substrate and/or epi-wafer companies headquartered in the United States; together they hold approximately 1,410 U.S. WBG patents. Of those eight, four provide SiC substrates and three of those have SiC epitaxy services; there are four manufacturers providing either bulk GaN or GaN epitaxy. In Europe, 12 companies collectively hold about 880 U.S. patents (six providing SiC products, eight GaN epitaxy products) while the 15 Asia headquartered wafer manufacturers (11 SiC, five GaN epitaxy) hold 1,900 patents. Additionally, there are other companies, e.g., General Electric, producing SiC or GaN wafers for in-house purposes (without selling them commercially).

1.4.2 WBG Devices: Discretes and Modules

The Schottky diode (SBD) is the most common SiC device sold now and is likely to continue to be (see Figure 1-24a). Beyond diodes, GeneSiC also makes SiC PiN rectifiers and thyristors for ultra-high voltage bipolar applications. The most popular transistor is the SiC MOSFETs; there are also SiC BJTs (GeneSiC) and JFETs (United SiC and Infineon). Some discrete and module manufacturers also incorporate SiC SBD into Si-IGBT modules (hybrid SiC modules) as a free-wheeling diode to reduce switching losses by about 30% while still maintaining a low cost compared to a full SiC module. There are also some JFET and MOSFET modules on the market; these are expected to become a major segment of the market along with hybrid modules as the price of SiC drops (see Figure 1-24 b) (Eden 2016).

GaN power electronics are less mature than SiC and similar discretes are not available; most commercial GaN power devices are transistors (FETs or HEMTs) (Eden 2016). Table 10-3 outlines a sampling of suppliers and developers of SiC and GaN power devices, separated by region, and what devices they currently have on the market or in development.

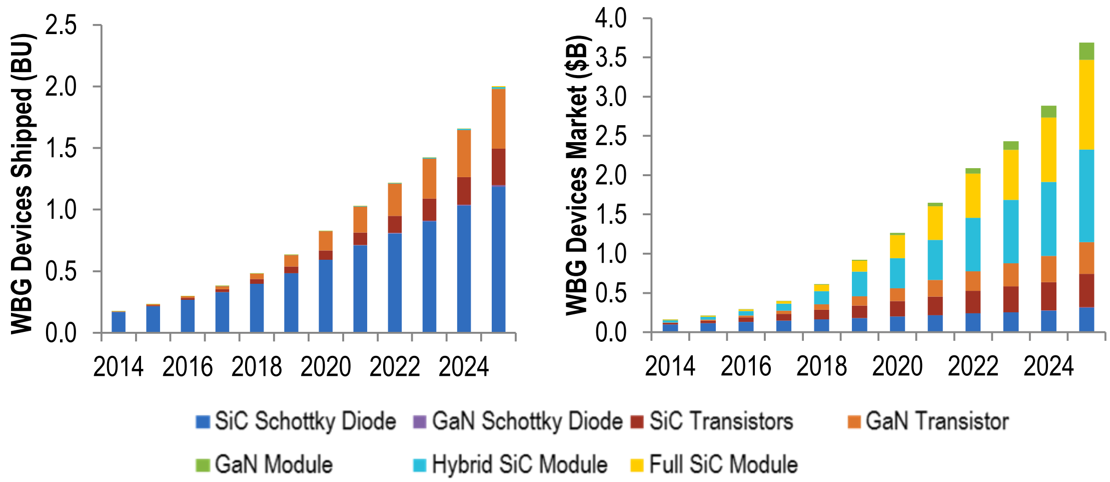


Figure 1-24. WBG devices market size by unit sales, left (a) and revenue, right (b) (Eden 2016).

Sixteen of the device manufacturers listed in Table 10-2 have U.S. or Canadian headquarters and hold 2,350 U.S. patents[2], whereas Europe houses 11 companies and 910 patents and Japan has 12 companies and 3,700 patents (Table 10-2, located in Section 10.1: Appendix A). The origins of these companies vary; several are long time Si semiconductor or electronic product manufacturers (e.g., Fairchild), others began in optoelectronics (e.g., Cree/Wolfspeed) or are new companies devoted to WBG power electronics (e.g., EPC).

1.4.3 WBG Inclusive Products

WBG inclusive power electronics have been on the market for a few years now, though limited to power supplies, small PV inverters, and vehicle battery chargers. Enphase, SMA and RefuSOL PV inverters, as well as Delta's EV charger for the Chevrolet Volt, all utilize SiC diodes ("Personal Communication with Michael Mahon (SMA-America) 04/08/2016" 2016; Advanced Energy, n.d.; "Personal Communication with Martin Fornage (Enphase) 04/05/2016" 2016). There has been a significant amount of research with a final application in mind for SiC and GaN, and this is leading to more WBG final products available. Recently, Toshiba released a SiC inclusive UPS (Toshiba International Corporation 2015), and Fuji has released SiC inverters for air-conditioning units and is testing one for rail traction. Fuji and GE are both working on large PV inverters (1 MW) with SiC and Yaskawa has developed a microinverter using GaN. Toyota has also begun work in SiC and has tested SiC inverters in the Camry Hybrid and a hybrid bus. SiC inverters may be included in the upcoming 2017 Prius (Toyota Motor Corporation 2016).

End-product manufacturers are also evenly distributed across the major manufacturing regions, with Japan and Europe each having six and the United States having five manufacturers. However, Japan has a firm hold on intellectual property with 1,756 of the SiC- or GaN-related U.S. patents (though given Japan's tendency toward vertical integration, many of these may be wafer or device related and not end product/inverter related2). U.S. and European manufacturers

[2] Since some companies fill multiple spots along the value chain, patents may be counted multiple times between the wafer, device and end-product stages.

hold 470 and 55 patents, respectively (see Table 10-4). Additionally, it should be noted that many foreign end-product manufactures (e.g., Siemens, ABB) also have manufacturing in the United States and countries other than their headquarters' location to take advantage of tax benefits and increased local sales that come with being locally made (Clover 2014).

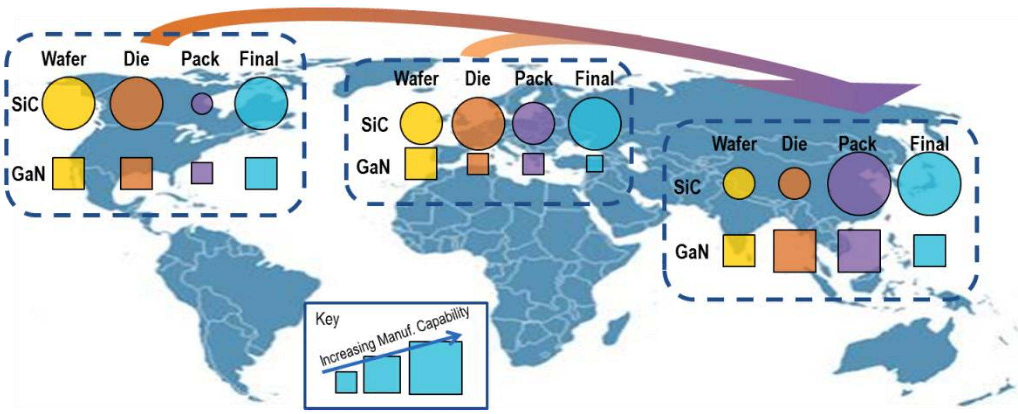


Figure 1-25. Relative manufacturing capacity and material flows of WBG semiconductor manufacturing by major region.

Figure 1-25 illustrates the three major regions' (America, Europe, and Asia) relative strength along the expanded supply chain. Overall, the United States is currently strong in SiC and GaN wafer and device manufacturing, but losing ground to both Europe and Asia. As production increases, it is expected that more semiconductor dies will be sent to Asia for packaging (as illustrated by the orange to purple arrow in Figure 1-25), similar to Si dies, and most passive devices (capacitors and magnetics) originate there, even if the device is packaged elsewhere (Hurst 2016; Agarwal et al. 2016; Evans et al. 2016). While the U.S. is strong in conventional electronics product manufacturing, overall it is not as strong as Asia and specific to WBG, there are few companies, foreign or domestic, with WBG-inclusive final products currently on the market (Hurst 2016; Evans et al. 2016).

However, WBG devices could be a special opportunity for U.S. semiconductor packaging. WBG devices are best utilized with specialized packaging (to reduce parasitic inductance and thermal impedance, and for higher temperature operation), as this has not been fully developed and if packaging moves toward automation, there is little benefit to sending dies to Asia for packaging. If the U.S. can develop WBG packaging technology and facilities, either from the ground up or repurposing Si facilities, this will provide the U.S. an opportunity for innovation and manufacturing (Agarwal et al. 2016).

While the future of WBG looks promising, the U.S. standing in the global WBG market is uncertain. The competitiveness of WBG manufacturing in the U.S. faces threats from Europe's and Japan's increasing device manufacturing capabilities and willingness to begin integrating WBG into power conversion products (e.g., uninterruptible power supplies, rail operations, and H/EVs). Some of the challenges faced by WBG in the U.S. are being tackled head on by PowerAmerica and NY- PEMC. PowerAmerica is focused on reducing the cost of SiC devices (by partially converting Si foundries to produce SiC devices), support WBG workforce development, WBG demonstration projects, and developing and improving WBG packaging. Another research partnership is the New York Power Electronics Manufacturing Consortium

(NY- PEMC), a partnership between State University of New York (SUNY), General Electric (GE), and New York state, as well as smaller partners. NY-PEMC is currently devoting its efforts to building SiC PE and passives manufacturing in the NY area and allows all partners access to their SiC manufacturing facility (Moniz 2014; "Governor Cuomo Announces 100 Businesses Led by GE to Join $ 500 Million Partnership with State to Develop Next-Generation Power Electronics, Creating Thousands of Jobs in Capital Region and Upstate" 2014).However, these initiatives are not unique to the U.S., both Japan and Europe have strong government/industry research initiatives(e.g., New Generation Power Electronics & System Research Consortium Japan, NPERC-J, and the European Center for Power Electronics, EPEC) working, separately and even together, to further their manufacturing capabilities (European Center for Power Electronics 2016).

1.5. SIC DISCRETE AND MODULE VALUE CHAINS

Value chains were developed for three representative SiC devices:

- 600 V, 4 A Schottky Barrier Diode (SBD)
- 1.2 kV, 20 A MOSFET
- 1.2 kV, 200A half-bridge MOSFET module composed of two 100A MOSFET dies
-

These three devices were chosen as representative samples of their device type (diode, transistor and module) due to their commercial availability and are representative of the average selling price (ASP) of their device type (e.g., the 2016 ASP of a SiC SBD was $0.49, the estimated 2016 price of a 4 A SiC SBD was $0.69 (Eden 2016)). The configuration of the chosen module (i.e., a two 100 A MOSFET die half-bridge) was selected to conform to the common configuration of high current modules as opposed to a three-phase, six-pack module (currently lower current capabilities and 6 dies per module).

Each layer of the value chain triangle represents what the manufacturers in the layer above would have to pay if they did not supply that layer themselves (see Figure 1-26). Discrete and module price data was obtained from the latest IHS market report (Eden 2016). Bare dies (finished but unpackaged devices) were assumed to be 73% of a packaged device cost (independent of device type or size), removing the costs of packaging/assembly (19%), testing (5%) and scrap (3%) (Yole Development 2017); the first two are accounted for in the final device costs, the latter in the assumed die yield. Pricing information for the 100 mm epiwafer ($73.4 / micron, 1 micron per 100 V), substrate ($380), and boule ($8,000) were obtained from Dow Corning [16] and raw SiC powder price ($5,440/kg) from American Elements [17].

Approximately 89% of blank wafers and epiwafers sold in 2015 were 100 mm wafers (Eden 2016) (see Figure 1-13), making the choice of 100 mm for this analysis reasonable. The epiwafers were assumed to have a standard 5 mm exclusion area and 90% surface packing (Agarwal 2014), producing 5730 mm^2 of useable epiwafer. The fraction of wafer used for each device was the basis for the epiwafer, substrate, boule, and raw materials calculations. This was determined by the die size required for the specified current, obtained from Wolfspeed power device datasheets (Wolfspeed n.d.) and a 60% die yield was assumed (Agarwal 2014) (see Table

1-4). While higher devices yields have been observed, 60% was chosen to reflect the current state of immature manufacturing.

Table 1-4. Details for diode, MOSFET and module value chain (Eden 2016; Wolfspeed n.d.; Mouser Electronics n.d.)

	Voltage V	Current A	Die Area mm^2	IHS Projected Selling Price $	Surveyed Selling Price $
SBD	600	4	1.3	0.62	1.94 – 3.01
MOSFET	1200	20	6.3	11.1	7.61 – 15.5
Module	1200	200	---	169	507
MOSFET bare dies	1200	100	26	46.6[3]	---

For all three value chains, value added per step increases when moving further along the value chain, with the final step incurred the most value added (see Figure 1-26). This suggests much of the final price is in device design, front and back end processing, and packaging, with very little in raw SiC material. Even at the ingot formation stage, the SiC material price of the approximately 500 gram ingot is only $2,700, or 34% of the ingot price.

The expected selling price for diodes and modules of the chosen sizes were much less than what can be found on a distributer's webpage. The 2015 IHS report predicted the price of 600 V, 4 A SiC diodes to be $0.62 in 2016, which lies outside the range of $1.94-$ 3.01 on Mouser (as of Jan. 2017 (Mouser Electronics n.d.)). More extreme is the 200 A MOSFET module: the IHS report predicted $169 whereas an approximately 200 A module ranges between $395 - $ 507 on Mouser (as of Jan. 2017 (Mouser Electronics n.d.)). The IHS price of 1.2 kV, 20 A MOSFETs ($11.10) was within the range of similar devices sold on Mouser ($7.61 – $15.50, as of Jan. 2017 (Mouser Electronics n.d.)). The larger value added between epiwafer (estimated including its components down the value chain here) and final device market price may, to some extent, indicate the premium paid due to low-volume and immature technology today.

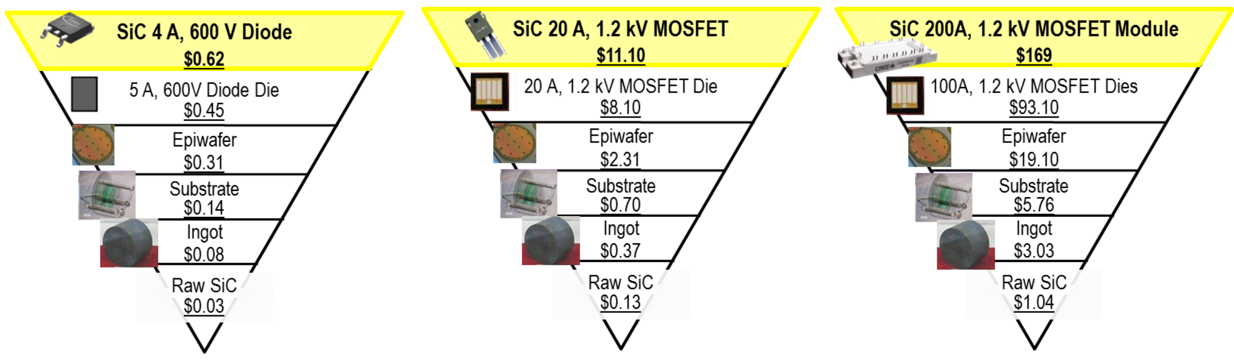


Figure 1-26. Calculated value chains for SiC diode (left), MOSFET (middle), and module (right).

[3] Calculated from linear relationship between MOSFET price and current (Eden 2016) and assuming 73% of final MOSFET price is attributable to the bare die (Yole Development 2017).

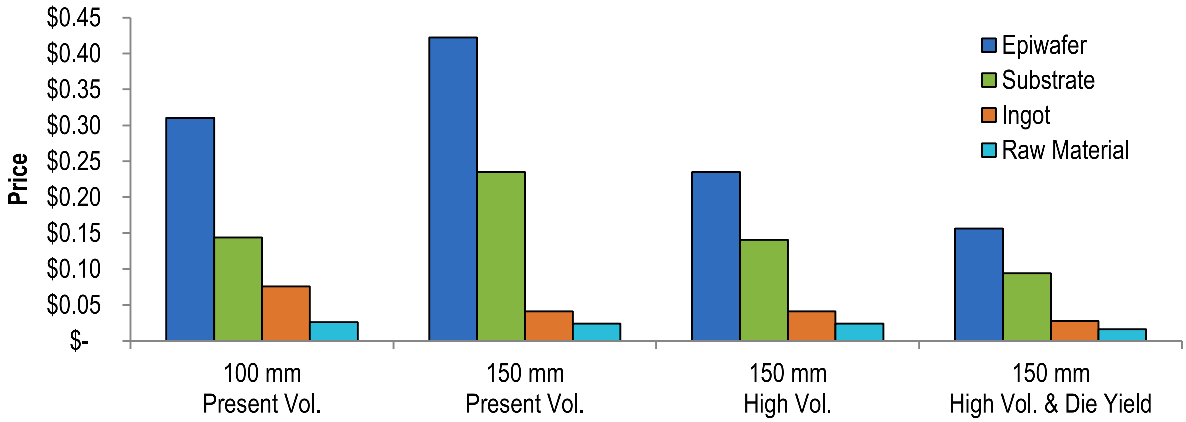


Figure 1-27. Price of diode manufacturing stages with different wafer sizes and manufacturing volumes.

Calculated prices (epiwafer, substrate, boule and raw material) are strongly tied to manufacturing assumptions (wafer size, production volume, die yield). The costs for boule, blank substrate and epitaxy are higher for 150 mm wafers ($10,500; $1,500; and $200/micron) but the blank substrate and epitaxy prices are expected to decrease as production volume increases ($900 and $100/micron). Additionally, the assumption of 60% die yield is low and is likely to be as high as 90% in a dedicated foundry ("Personal Communication to Pablo Cassorla from Andy Wilson (X-Fab) 09/02/2016" 2016). As device manufacturing moves toward 150 mm wafers and high-volume productivity, the prices at each manufacturing stage will go down; though, at present volumes, transitioning to 150 mm wafers will temporarily increase epiwafer and substrate prices (see Figure 1-27).

1.6. MARKET OVERVIEW CONCLUSION

WBG semiconductors have many benefits in power conversion over traditional silicon semiconductors; they allow faster switching, yield higher power densities and are likely to reduce system costs. While they still have many challenges, especially high costs, the WBG power device market is growing and expected to continue to do so, especially in electric vehicles and power supplies. Currently the United States has a strong position along the direct semiconductor market chain but may lose ground to Asia, especially with respect to peripherals (passives and packaging) and final products. As WBG devices increase in voltage and current handling capacity and decrease in price, it is expected that more WBG products will enter the market and establish their utility in multiple power conversion applications.

2. DATA CENTERS

A data center is a building that houses networked computer servers for electronic data storage, processing and distribution, as well as the essential building infrastructure. Servers are the core of a data center; they store the data and provide the processing power for company intranets, independent data clouds, and the internet. Close to 2.5 billion people are online around the world and 70% of them use the internet. Every minute, 204 million emails are sent, 5 million Google searches are run, and $272K is spent on Amazon; all of these emails, searches and transactions move through data centers (Delforge and Whitney 2014). These numbers and thus data centers are growing, prompting concerns about electricity usage and equipment efficiency, and providing the motivation for new energy efficient power conversion technologies, such as those provided by WBG power devices. This section explores the benefits and potential energy savings from converting silicon power electronics within power conversion equipment to SiC or GaN.

2.1. DATA CENTERS OVERVIEW

The focus of this study is data centers that are most likely to have substantial power conversion and cooling systems: localized, mid-tier and enterprise. Table 2-1 illustrates several types of data centers from very small (server closet) to very large (enterprise). The smaller two (server closets and rooms) tend to have less than 10 servers and only occasionally a UPS; this allows them to utilize the building's existing HVAC systems instead of a dedicated server building with its own systems. The larger three comprise the bulk of the data center electricity use due to their larger number of servers and dedicated backup power (UPS) and cooling systems (Brown et al. 2007).

Table 2-1. 2007 U.S. data center size distribution (Brown et al. 2007)

Space Type	Area (ft^2)	# Servers	UPS?	Cooling?	% Electricity
Server Closet	< 200	1 – 2	No	Office HVAC	13%
Server Room	< 500	2- 10s	Few	Office HVAC	16%
Localized	< 1000	10s-100s	Yes	Dedicated	18%
Mid-tier	< 5000	100s	Yes	Dedicated	16%
Enterprise	+ 5000	100s-1000s	Yes	Dedicated	37%

2.1.1 Electricity Use within Data Centers

Data center electricity use first came under scrutiny in 1999 after an article in Forbes suggested unbelievably high electricity use (Huber and Mills 1999). This resulted in many peer reviewed reports and a 2006 Act from Congress to commission a report on data center energy usage (Koomey 2011). The 2007 Report to Congress, filed by the Environmental Protection Agency (EPA) found that data center electricity use was very high, though not as high as the Forbes article would suggest (60 TWh in 2006), and was expected to double by 2011 (Brown et al. 2007).

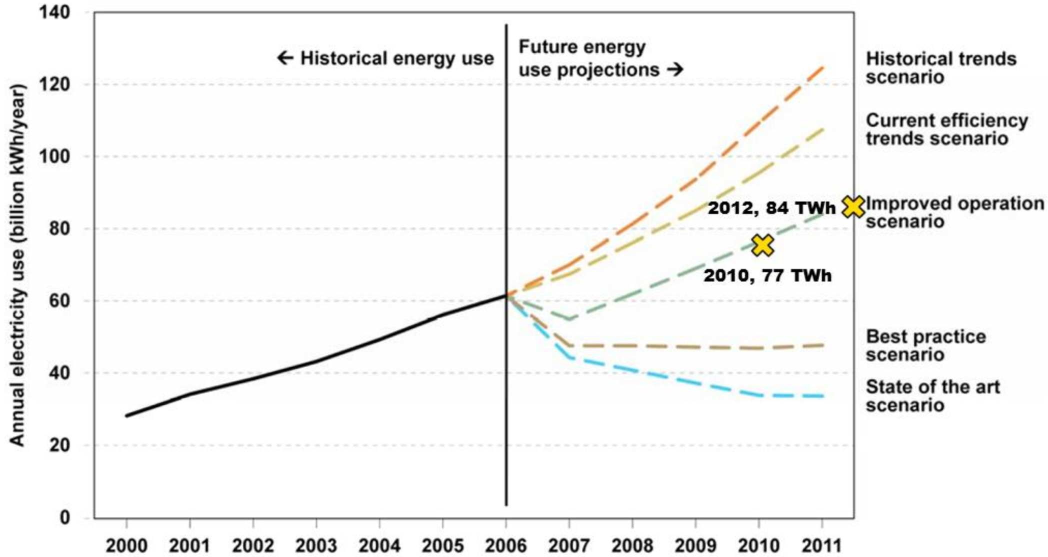


Figure 2-1. Annual data center electricity use, adapted from (Brown et al. 2007; J. Miller et al. 2015; US Department of Energy 2015)**.**

Figure 2-1 shows data centers' historical energy use, expected trends as of 2007, as well as two updated energy use values for 2010 (Delforge and Whitney 2014; J. Miller et al. 2015) and 2012 (US Department of Energy 2015). These values fall far below the expected "historical trends" and "current efficiency trends" scenarios, but still above the potential "best practices" or "state of the art" scenarios. The Natural Resources Defense Council (NDRC) estimated that in 2013, data centers used approximately 2.4% of U.S. electricity demand or 91 TWh (Delforge and Whitney 2014). The three larger classifications of data centers (as shown in Table 2-1) were estimated to consume 72% of total data center electricity use (18%, 16% and 38% respectively) (Brown et al. 2007), which was estimated to be approximately 69.4 TWh in 2015 (Delforge and Whitney 2014; Yole Development 2016a).

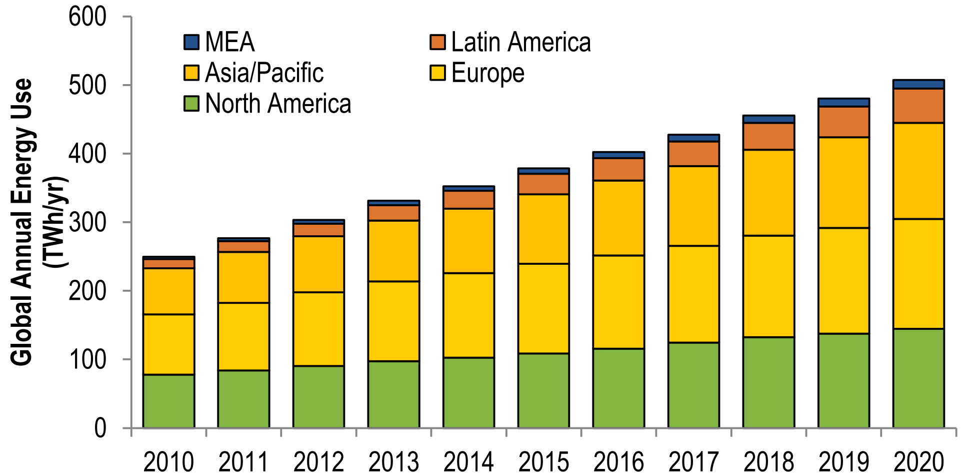


Figure 2-2. Global data center electricity use, projection after 2015 (adapted from Yole Development 2016a)**).**

Figure 2-2 shows a more recent Yole forecast of world-wide data center electricity use (Yole Development 2016a), disaggregated by region; this suggests that U.S. data center electricity use could be approximately 130 TWh by 2020[4]. If growth continues at the same rate, by 2025 the total usage could be greater than 160 TWh. These trends have led several world governments to begin introducing regulations and efficiency standards targeting data centers. In the United States, the Energy Independence Security Act of 2007 mandated Energy Star and other efficiency programs of the DOE and EPA include provisions for data centers (U.S. Congress 2007). There was also an executive order in 2015 that declared all existing federal data centers must become more efficient and new data centers must fit stricter efficiency guidelines (Obama 2015). In addition to growing governmental pressure, data center companies have begun self-regulating their efficiencies and energy use (EBay 2013; Facebook 2016; Google 2016) in an effort to reduce costs and improve their "green position." A 2007 study found that nearly 10% of data center annual costs were for energy use (Koomey et al. 2009), and savings from increased efficiency could have a significant impact on the operating cost of a data center.

2.1.2 Data Center Systems

The most important component of a data center energy use is the information technology (IT) load (Figure 2-3, upper right). The IT load includes the servers, data storage, network devices, and the server power supply unit (PSU). Together, they generally use about half the electricity for a data center, the remainder is used for additional power conversion (e.g., UPS, transformers) and cooling (Figure 2-4) (Emerson 2009; Brown et al. 2007; Greenberg, Sartor, and Tschudi 2015; Scheihing 2009; Masanet et al. 2011).

[4] Reported U.S data center electricity was 93% what Yole reports for North America in 2013, so 93% of the North American forecast for 2020 was assumed.

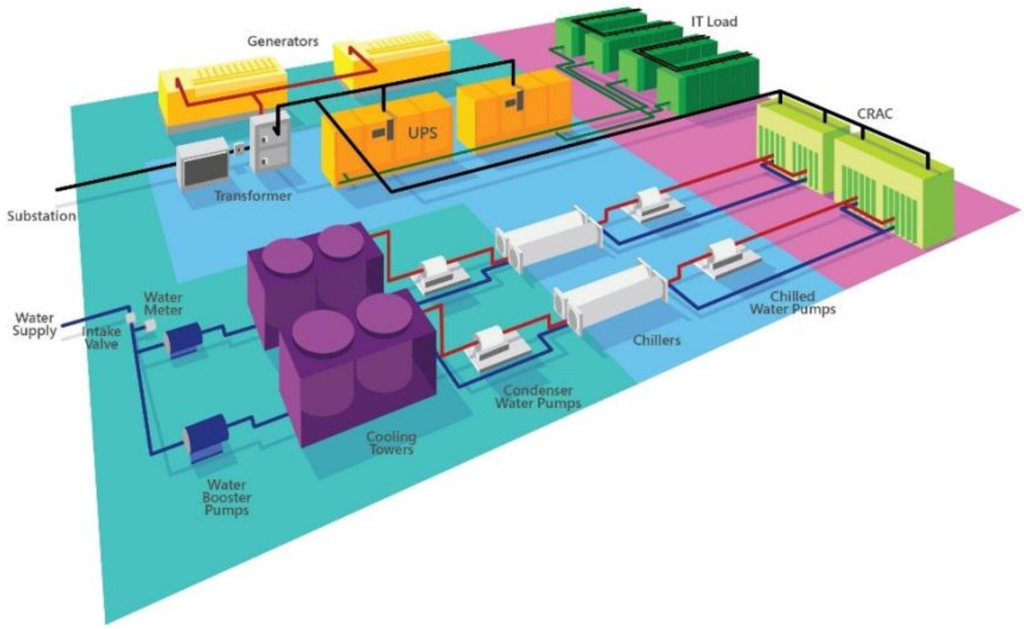


Figure 2-3. Illustration of a data center (Harris 2015)**.**

Power conversion is the system that takes the electricity provided by the utility (the grid) and transforms it into a form that can be transported safely and efficiently across the data center to be used by the servers and emergency power supplies (Figure 2-3, upper center). It includes power backup, uninterruptible power supplies (UPS) and generators, and distribution and power distribution units (PDU). Power losses from conversion constitute another significant portion of data center energy use, ranging between 5-10% (Figure 2-4) (Emerson 2009; Brown et al. 2007; Greenberg, Sartor, and Tschudi 2015; Scheihing 2009; Masanet et al. 2011).

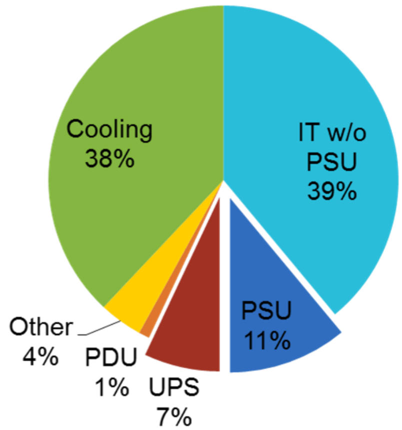


Figure 2-4. Average data center energy use breakdown.

Data center cooling is a complex system consisting of not only airflow and heat exchange systems, but also server layout and partitioning (Figure 2-3, lower half). Many data centers are laid out such that the rows separating servers are either cold or hot, depending on whether all servers or its exhausts are facing the row, respectively. Using computer room air conditioning

(CRAC) units, many data centers maintain cold row temperatures between 68 and 72°F, with some using as low as 55°F (R. Miller 2008). Google, however, recommends 80°F or higher to reduce energy use, with proper hot/cold aisle separation (R. Miller 2008; Google 2016). On average, cooling electricity requirements range between 35 and 50% of the total energy usage of the data center (Figure 2-4) (Emerson 2009; Brown et al. 2007; Greenberg, Sartor, and Tschudi 2015; Scheihing 2009; Masanet et al. 2011).

2.1.3 Data Center Efficiency

Data center efficiency is often measured with the power usage effectiveness (PUE) metric. The PUE was developed by The Green Grid as a standard way to compare data center energy use (Avelar, Azevedo, and French 2012). It is defined as the ratio of overall data center energy use to the IT energy use (Equation 1 and Figure 2-5).

$$PUE = \frac{Data\ Center\ Electricity\ Use}{IT\ Equipment\ Electricity\ Use} \qquad \text{(Equation 1)}$$

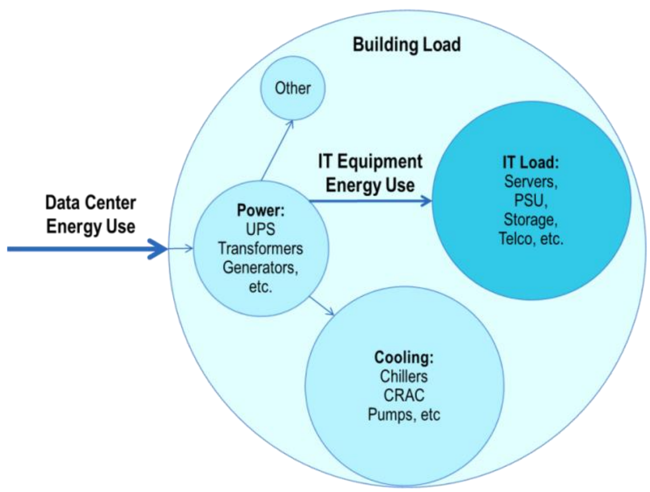


Figure 2-5. Illustration of energy use in data centers.

While not a perfect metric, the PUE metric has become an industry standard (Avelar, Azevedo, and French 2012) and is a simple enough metric for evaluating areas for improvements. Ideally, the PUE should be near unity (the data center only uses electricity for the IT load), in reality, the average is closer to 1.9 (Sullivan 2010) with a lot of variation as shown in Table 2-2.

Table 2-2. PUEs from various data centers

Data Center	PUE	Source
LBNL, Agency X (2015)	2.27	(Greenberg, Sartor, and Tschudi 2015)
EPA, Energy Star ave.	1.91	(Sartor 2015; Sullivan 2010)
Uptime Institute survey ave. (2014)	1.65	(Sartor 2015)
eBay (2013)	1.57	(EBay 2013)
Intel, Jones Farm	1.41	(Sartor 2015)
Google, average (2016)	1.12	(Google 2016)
Facebook, average (2014)	1.08	(Facebook 2016)
NREL	1.06	(Sartor 2015)

There are many causes for a high PUE: zombie servers and UPS (equipment that is turned on, but not fully utilized), inefficient backup/cooling strategies, and data center focus (Sartor 2015; Delforge and Whitney 2014; Brown et al. 2007; Emerson 2009; Greenberg, Sartor, and Tschudi 2015). If a data center is more focused on reliability than efficiency, they may have more cooling, power backups, and extra servers, reducing the load and thus the efficiency of the equipment. Common and lower cost PUE reduction strategies include reducing the number of UPS and servers and adding variable frequency drives (VFD) to cooling fans (Energy Star 2012; Greenberg 2013) (also see Section 4.1 Motor Drive Overview). More costly efficiency strategies include replacing standard power conversion equipment with more efficient power supplies, such as those that use WBG semiconductors instead of silicon and converting to a direct current (DC) data center.

Power conversion equipment for data centers (including those used in VFD) usually consists of all three of the major PE equipment types: rectifiers, inverters, and converters. Each of these range between 70 and 95% efficient using standard silicon PE; replacing the diodes and transistors with the WBG equivalents could reduce losses by half (US Department of Energy 2015). Figure 8-1 (located in Chapter 8) shows the power and voltage ranges required for the semiconductors within data center WBG application areas compared to other applications to be further discussed in the corresponding sections of this report.

2.2. UNINTERRUPTIBLE POWER SUPPLIES

Uninterruptible Power Supplies (UPS) are systems that connect the load with the incoming grid electricity or backup generators and monitors power status at any given moment. UPS are very important for data centers; any loss of power could have a major impact on the stored data and the reputation of the data center. They also often include an additional power supply (either battery bank or flywheel) to smoothly transition between grid and generators. A double conversion UPS, such as the type often in local and larger data centers, consists of a rectifier/charger connected to the battery and inverter to supply AC power to the rest of the system. While this insures the load always has access to power, it can create significant losses when transforming the power from AC to DC for the battery and then back to AC for transmission across the data center, and eventual conversion to DC by the power distribution units (PDU) or server power supply units (PSU) (Eubank et al. 2003).

2.2.1 UPS Power Electronics

As stated, a UPS consists of a rectifier and inverter and, for data centers, are usually rated to convert input voltages between 246 V and 480 V, depending on the electricity source, and power ratings depending on the load demand. The diodes and transistors within the rectifier and inverter should be rated significantly higher to protect against any potential surges; at this range, it is recommended that the discrete devices be 1.2 kV (Fuji Electric Co. Ltd 2013b). Devices with this voltage rating are currently available for SiC diodes and MOSFETs from several companies based in the U.S. and abroad.

Not only are SiC discrete devices at the appropriate voltage rating commercially available, there is a series of UPS from Toshiba (G2020) utilizing SiC power electronics currently on the market (Toshiba International Corporation 2015) and another from Mitsubishi (Summit Series) was recently announced (Morrow 2015). Toshiba’s G2020 series is available in 500 kVA and soon to be released in 750 kVA; it is rated as 98.2% efficient at 30% to full load. Compared to Toshiba’s similarly sized silicon-based UPS series (less than 95% efficient at 20% load and 97% at full load for the 500 kVA model), the SiC-inclusive G2020 series is smaller, has higher operating temperature, half the losses and is only 10% more expensive (Toshiba International Corporation 2015).

UPS are also used in hospitals and industry to ensure continuous power in case of an outage in addition to smoothing out the transition from grid to backup generators or provide enough power to safely shutdown machinery. Hospital UPS are likely to have similar or smaller power demand and use similar input voltages (between 240 V and 480 V) as data centers (USAID n.d.), implying that present commercially available SiC devices would be suitable for hospital UPS.. Industrial UPS range from smaller to much larger than data centers, and if placed with higher incoming voltages will require correspondingly higher voltage power electronics.

2.2.2 UPS Market

The global UPS market is approximately $10 billion with little change in the past few years (Yole Development 2012b; Gueguen 2016). Power semiconductors account for about $241 million of that (Yole Development 2012b), with WBG power semiconductors accounting for an even smaller segment, $6.7 million(Eden 2016) (Figure 2-6). UPS for data centers only accounted for about $3.7 billion of the market in 2014, with about 35% devoted to North America (Radiant Insights 2015). Despite the lack of change in the global UPS market, data centers are growing; $143 billion was invested in new data center projects in 2014, in addition to $40 billion invested annually by content and application providers for network hosting infrastructure (existing data centers) (Yole Development 2016a). Yole also estimates a time-to-market of 3-5 years for WBG devices in data centers due to the distinct advantages of smaller and reduced heat generating power supplies (Yole Development 2016a).

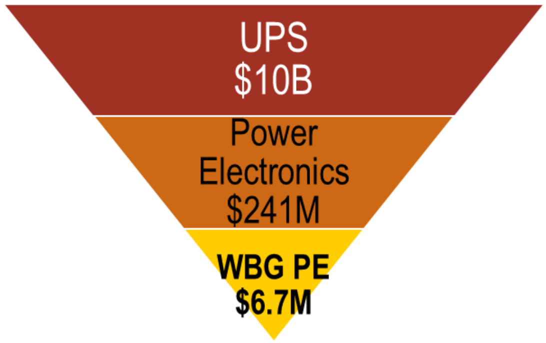


Figure 2-6. 2014 global UPS market (Gueguen 2016; Eden 2016; Yole Development 2012b)**.**

For WBG devices in UPS, IHS expects a small market for diodes; instead, most of the market will be focused on SiC transistors. They also expect most of the WBG inclusion in UPS to be for smaller, single phase UPS (<5.1 kVA for discretes and 5.1 kVA – 250 kVA for modules). As the smallest of this group is normally for backing up personal computers and use of PCs are declining, this segment is likely to decrease whereas the larger size UPS market is expected to increase. This contrasts with the fact that the only advertised SiC-inclusive UPS are a 500 – 750 kVA 3-phase series from Toshiba and a 500 kVA model from Mitsubishi (Toshiba International Corporation 2015; Morrow 2015).

While there are several UPS manufacturers (e.g., Siemens, America Power Conversion, Emerson, Eaton, GE, Toshiba and Mitsubishi) only a few (Siemens, GE, Toshiba and Mitsubishi) are known to be working with WBG power electronics and only the latter two companies have announced any WBG-inclusive UPS (Toshiba International Corporation 2015; Morrow 2015). Overall, much of the SiC-UPS supply chain is identical to other SiC applications, with only two Japanese UPS manufacturers using SiC devices and two other UPS manufacturers (ABB and GE) having interest in WBG devices.

2.3. SERVER POWER SUPPLIES

The server Power Supply Unit (PSU) converts power from the UPS, via the power distribution unit (PDU), into lower voltage DC power for the individual server loads. It consists of a transformer, a rectifier, and a DC-DC converter which transforms the current from higher AC to the 12 VDC used by the servers. Like a UPS, power losses of the rectifier diodes and switches can be reduced by replacing them WBG diodes and transistors (Cui et al. 2014; W. Zhang et al. 2014). The individual device ratings depends on the incoming voltage; for most data centers, voltages into the PSU will range from between 200 and 480 V depending on the system, so discrete devices need to be 1.2 kV for the converter.

Unlike a UPS, the PSU does not have an inverter, but a power conversation (to DC) and a step down in voltage is achieved by a AC-DC rectifier and DC-DC converter using low voltage diodes (40 V) and higher voltage switches (600 V - 1.2 kV). This can be done with SiC diodes and MOSFETs (1.2 kV) and GaN FETs and HEMTs (600 V) (W. Zhang et al. 2014). A SiC-based data center rectifier has been demonstrated with an efficiency of 98.8% (at 28 kHz). A

GaN-based data center converter has also been demonstrated, with an efficiency of 96.3% (at 1 MHz) and reduction of the transformer winding losses, and thus further reducing the heat produced by the converter (Cui et al. 2014; W. Zhang et al. 2014). The diodes and transistors recommended for use in PSU rectifiers and converters are available commercially from several different vendors (see Table 10-3). For smaller power supplies (residential grid to electronic device), there are WBG based power converters on the market (Avogy n.d.), but at this time, there are none for industrial sized data centers (Eden 2016).

2.3.1 Power Supply Unit Market

For WBG markets, IHS includes server power supplies with "Power supplies for computing and servers"; this category also includes commodity AC-DC power supplies such as computer and office equipment. Since over 99% of non-commodity AC-DC power supplies (for servers and data storage) employs PFC and less than 1% of commodity power supplies employs PFC and most of WBG use in server power supplies could be considered PFC, therefore, it is likely that this data reflects the WBG market for data center power supplies. IHS predicts that most of the market for computing and server power supplies will be SiC diodes or GaN transistors with a small market for SiC transistors and very little for modules. While the revenues for Schottky diodes are expected to decrease, the number sold is actually expected to increase with a projected significant decrease in the average selling price (Eden 2016).

2.4. ENERGY SAVINGS ESTIMATION

With the increased efficiencies of the UPS and PSU from the inclusion of WBG power electronics, the overall power system efficiency can be increased from 75% to over 90% with a resulting PUE reduction from the assumed initial PUE of 2.0 to 1.89 (see Section 10.2.1 in Appendix B). Figure 2-7 shows the change in IT load losses to the rest of the system. Specifically, losses from the PSU are reduced from 11% to 6% while UPS drops from 7% to 3%. The IT load (blues) increases from half the use to slightly more than half. Since some of the IT load reduces in addition to non-IT load, the PUE reduction is less impressive than other efficiency measures, but this simply illustrates an issue with PUE as an efficiency metric. Direct losses from the two systems combined are greater than 12.0 TWh per year (2015); with the inclusion of WBG power electronics, this can drop to 4.4 TWh, a 7.6 TWh annual savings. If the reduced cooling demand is taken into account, savings are 12.1 TWh, which is the equivalent to the electricity use of 1.1 million homes and could avoid 6.3 million tonnes of carbon dioxide and 2.3 million tonnes of coal (see Section 10.2: Appendix B and Table 2-3).

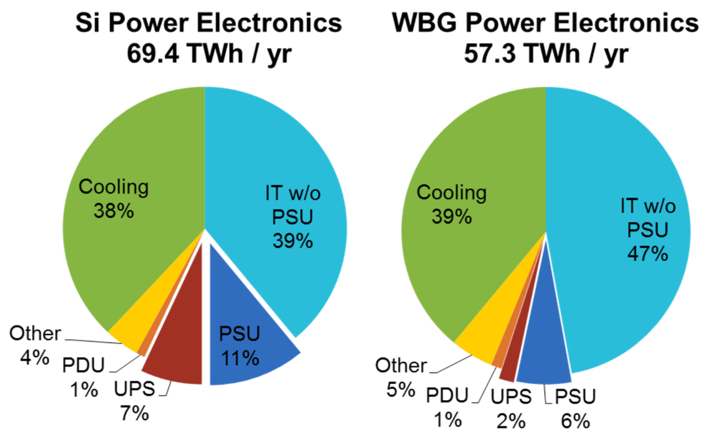


Figure 2-7. Relative electricity use of data center equipment with Si (a) and WBG power electronics (b).

Table 2-3 Estimated 2015 electricity use of Si and WBG power conversion equipment within data centers

System	Expected Annual Electricity Use (TWh / yr)		Estimated Annual WBG Savings			
	As Is	WBG	TWh	Millions Homes	Coal avoided (M tonne)	CO_2 avoided (M tonne)
PSU	7.6	3.3	4.4	0.40	0.8	2.3
UPS	4.9	1.2	3.7	0.34	0.7	1.9
Cooling Load	26.4	22.3	4.0	0.37	0.8	2.1
Total	**69.4**	**57.3**	**12.1**	**1.1**	**2.3**	**6.3**

With the expected increase in data centers and data center electricity use, the yearly savings potential increases greatly. Given Yole Development's projected growth for data center electricity use (Yole Development 2016a), data center energy use in 2025 is estimated to be 160 TWh of which 114 TWh is for large data centers; the large data center energy use could drop to 93.7 with WBG power conversion equipment. Assuming the same energy use breakdown in data centers and same efficiency increase from WBG devices, direct losses from PSU and UPS could be 20.5 TWh annually, which could be reduced by up to 19.9 TWh per year in 2025, when cooling is included (Table 2-4).

Table 2-4. Estimated 2025 electricity use of Si and WBG power conversion equipment within data centers [5]

System	Expected Annual Electricity Use (TWh / yr)		Estimated Annual WBG Savings			
	As Is	WBG	TWh	Millions Homes	Coal avoided (M tonne)	CO_2 avoided (M tonne)
PSU	12.5	5.3	7.2	0.64	1.3	3.7
UPS	8.0	1.9	6.1	0.56	1.1	3.1
Cooling Load	43.2	36.5	6.6	0.60	1.2	3.4
Total	**114**	**93.7**	**19.9**	**1.8**	**3.6**	**10.2**

Whether in 2015 or 2025, WBG power electronics can help reduce the energy use of data centers by **up to 17% annually**. There are other potentially more cost-effective methods of energy reduction, such as reducing zombie servers and UPS, switching to DC power, or improving cooling efficiency, but even some of those could still benefit from the inclusion of WBG power electronics.

2.5. DC POWER

The current power conversion architecture for data centers involves five power conversion steps, outlined in Figure 2-8:

- AC to DC (UPS rectifier)
- DC to AC (UPS inverter)
- AC to AC (PDU transformer)
- AC to DC (PSU rectifier)

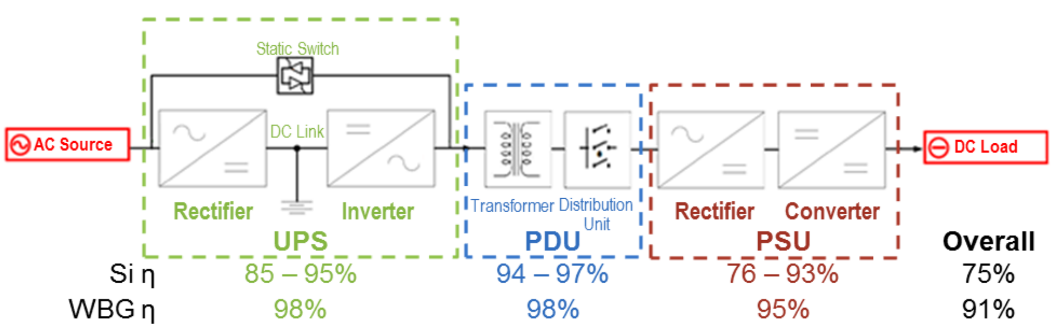


Figure 2-8. AC data center architecture (Toshiba International Corporation 2015; Liu, Tuttle, and Dhar 2015; H. Zhang and Tolbert 2011; Cui et al. 2014; Han et al. 2014; Mansoor and Griffith 2004; Energy Star n.d.; Loeffler and Spears 2011; Prabhala, Baddipadiga, and Ferdowsi 2014; W. Zhang et al. 2014)**.**

Each step has power losses that are significant to the overall data center energy use, and, given data centers' high electricity use, also significant to the U.S. and world energy use. It has been

[5] Determined via linear regression of Yole Development data (Yole Development 2016a).

suggested that several of these conversion steps are unnecessary (W. Zhang et al. 2014; Ton, Fortenbery, and Tschudi 2008; Pratt, Kumar, and Aldridge 2007): is there a reason for the UPS to convert back to AC beyond the fact that the PSU accepts AC?

DC power data centers have been suggested as a power saving setup, similar to that described in Figure 2-9. Converting to DC power allows for the removal of the UPS inverter, PDU transformer and PSU rectifier and can be high voltage DC (PSU incoming voltage is around 400 V) or low voltage DC (PSU incoming voltage is around 48 V), via different topologies depending on data center preference.

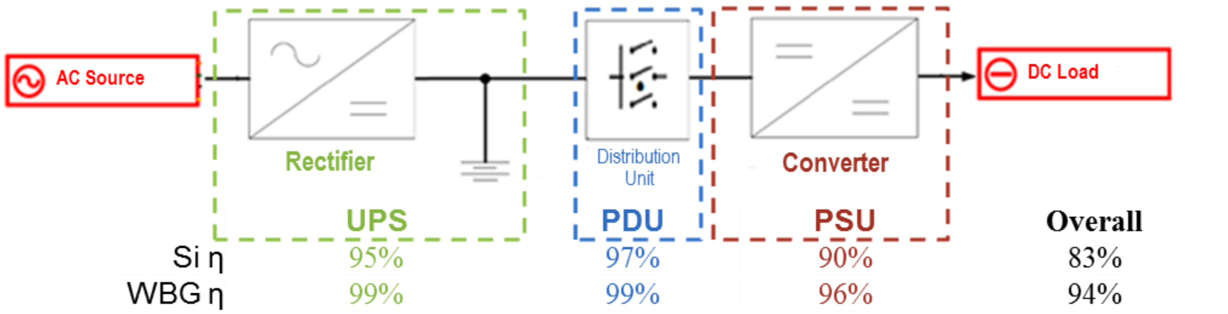


Figure 2-9. DC data center architecture (Cui et al. 2014; F. Xu et al. 2013; Liu, Tuttle, and Dhar 2015; H. Zhang and Tolbert 2011)**.**

Low voltage DC has been used in telecommunications and data networks for a while (Ton, Fortenbery, and Tschudi 2008), but high voltage DC was slower to permeate due to fears of higher voltage DC (HVDC), lack of equipment with appropriate voltage ratings, and a lack of standards and regulations. With time, studies have shown that there is little more to fear from HVDC data centers compared to AC data centers, and they may even be safer (Ton, Fortenbery, and Tschudi 2008; Doughty and Watts 2015). Also, DC equipment is on the market (ABB 2012b; B. Davis 2015), and DC power standards have been developed (B. Davis 2015). While still a newer efficiency solution, there are several DC-powered data centers (Park 2011; ABB 2012b; Stark 2015; B. Davis 2015). In addition to efficiency gains, DC data centers have smaller footprints (less bulky equipment) and inherently reduced harmonics; they can be powered directly by solar or wind power, eliminating the need for the initial rectifier as well. However, they are not the best for all situations, if a data center is already high efficiency using AC power and running at higher loads, then there is little improvement to be gained from switching to Si-based DC (The Green Grid 2008). While not inherently a WBG technology, HVDC is pushing the limits of Si. SiC switches faster, has lower conduction losses and higher junction temps than Si IGBTs (Wu et al. 2012).

2.5.1 Energy Savings Estimation for DC Data Centers

As with UPS, energy savings estimates are based on the data center energy usage, fraction of losses from UPS, PSU and PDU as well as the change in efficiencies from AC to DC and Si to SiC. Energy use for large data centers (71% of data center electricity (Brown et al. 2007)), in 2015, was still 69.4 TWh (Yole Development 2016a). As discussed in an earlier section, the average AC data center's power conversion system is around 75% efficient and a WBG AC data center could be over 90% (Figure 2-8). Conversely, a silicon based DC data center's power conversion could be near 83% efficient or higher and a WBG DC data center would be around 94% (Figure 2-9).

Each of these increases in efficiency can lead to significant savings over the baseline average AC data center (Figure 2-8, Figure 2-9), up to nearly 15B kWh per year for a WBG DC data center including reduced cooling load (Table 2-5).

Table 2-5. 2015 AC and DC Energy Savings Potential (from Si-AC baseline)

System	WBG AC	Si DC	WBG DC
		TWh/yr	
PSU	4.4	2.0	5.5
UPS	3.7	2.1	4.3
PDU	- -	0.2	0.2
Cooling Load	4.0	2.1	5.0
Total	**12.1**	**6.4**	**15.0**

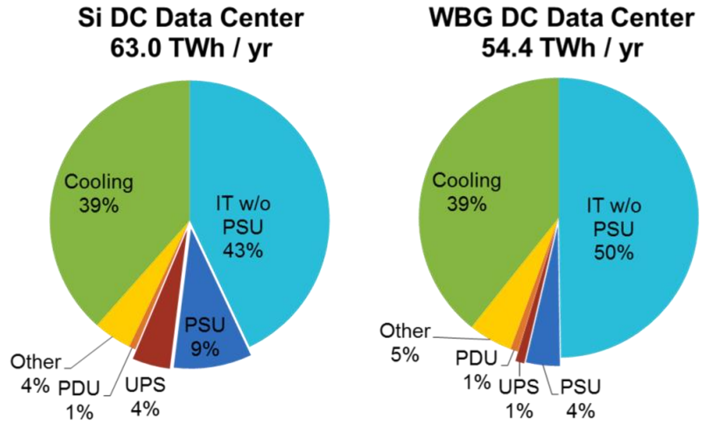


Figure 2-10. Relative electricity use of DC data center equipment with Si (a) and WBG power electronics (b).

Figure 2-10 shows the relative distribution of electricity use in a data center with conversion to DC power. Specifically, losses from the PSU are reduced from 11% (AC) to 9% (Si- DC) to 4% (WBG-DC) while UPS drops from 7% (AC) to 5% (Si-DC) to 1% (WBG-DC). The IT load (blues) change from half the use of slightly more than half, reducing PUE to 1.85. While increasing power conversion efficiency from 75% to 90% or 94% would be very significant, power conversion losses are only a small part of the data center energy use; there is still significant savings to be gained by other efficiency improvement strategies to be implemented.

2.6. DATA CENTER CONCLUSION

2.6.1 Strengths

Data centers will benefit from all of the strengths granted by WBG utilization (see Section 1.2.1: Benefits of WBG Utilization). Data center UPS, as well as UPS for hospitals and industrial facilities, will benefit most from the increased efficiency, higher frequency, and temperature operation, resulting in reduced passives and lower cooling requirements. These benefits will be reflected in decreased system costs. The PSU, like general power supplies, will benefit most from the efficiency improvements; SiC's current adoption into general power supplies illustrates the reduced influence of cost on power supply uptake of WBG. Utilization of WBG for cooling fan VFDs will also benefit from all of the advantages of WBG PE, and the decreased size (via decreased cooling needs and decreased passives) can reduce the physical footprint imposed by adding a VFD (see Section 4.1 Motor Drive Overview).

Most WBG device manufacturers produce WBG devices within the required voltage ranges of data center equipment (40 and 600 V, GaN and 1200 V SiC). Additionally, there are also several UPS and motor drive manufacturers in the U.S. (Eaton, Emerson, GE, etc.), one of which, GE, has announced plans to begin transitioning all of their power electronics to SiC (Willis 2015). SiC Schottky are already present in high-end power supplies, so while it is likely that some PSU already include WBG devices, none are currently marketed as such. It is possible that having existing WBG and end-use manufacturers in the U.S. will encourage more WBG-inclusive data center products.

2.6.2 Weaknesses

There are no data-center-specific weaknesses for the integration of WBG devices. The biggest deterrents for WBG integration are the same as other applications (see Section 1.2.2: Challenges for WBG Integration). As the voltage and current requirements of data center WBG-inclusive devices are satisfied, WBG integration into data centers is likely to suffer most from cost and reliability issues associated with WBG integration.

2.6.3 Opportunities

Almost the entire world uses the internet; data centers are a necessary component to this and will continue to grow and use more electricity (Figure 2-4). Without significant increases in energy production or data center efficiency, data centers will grow to consume a significant fraction of the world's electricity. This makes data centers a very attractive opportunity space for WBG power electronics. If WBG devices are adopted by data center equipment manufacturers (UPS and PSU), data center energy use could be reduced by 17%, nearly 20 TWh per year by 2025. However, replacing PSUs and UPSs in existing data centers would likely need to wait until a replacement system was required. Increasing numbers of data centers implies the need for new PE systems that could be WBG-inclusive, reducing the cost of WBG-integration from the price of the equipment to the price difference of Si and WBG systems. Additionally, WBG-UPS efficiency does not reduce significantly with reduced load, reducing the pressure to increase the load on the UPS at the risk of reliability (i.e., eliminating zombie UPS). There are also potential energy savings from incorporated WBG variable frequency drives (VFDs) into cooling systems, such as fan motors and coolant pumps (see Chapter 4).

In 2007 the U.S. Congress passed the Energy Independence and Security Act (U.S. Congress 2007) which included a section on the formation of government efficiency standards for data center equipment via Energy Star. Additionally, there has recently been an Executive Order calling for existing federal data centers to reduce their PUE to below 1.5 and new data centers to have PUE less than 1.4, preferably closer to 1.2 (Obama 2015). These standards, as well as standards from Europe, are another excellent opportunity for WBG power electronics. Silicon power electronics is struggling to achieve the efficiencies required to meet these standards, and WBG could potentially to do so.

Power supplies and UPS are used for many applications beyond data centers, and WBG-integration would still be beneficial. For example, UPSs are also extensively used by medical facilities, and the reduced size of SiC-inclusive UPS would be extremely attractive for hospitals where space has a high premium. The WBG power supply market is expected to be a major portion of the overall WBG market, comprising nearly 23% of the market by 2025; the WBG market for UPS is smaller, nearly 6%, but still a significant potential market.

Beyond the growth of the data center industry, many of the opportunities for WBG inclusion in data centers are the same as other applications: established U.S. supply chains from wafer to end-product manufacturing and a strong governmental desire to increase the United States' strength in the field of WBG power electronics and decrease our energy usage.

2.6.4 Threats

In addition to threats that could hinder all U.S. WBG manufacturing (e.g., strong foreign WBG supply chains and loss of U.S. manufacturers to foreign companies), there are several data center specific threats. One of the major threats to WBG-data center integration is the variety of alternate energy savings techniques with more savings per investment (Masanet et al. 2011; Emerson 2009; Delforge and Whitney 2014; Sartor 2015). For example, simply eliminating zombie servers and UPS can create significant energy savings at no cost. Additionally, there are other thermal management and system architectures that could be used instead of WBG power electronics (Figure 2-11).

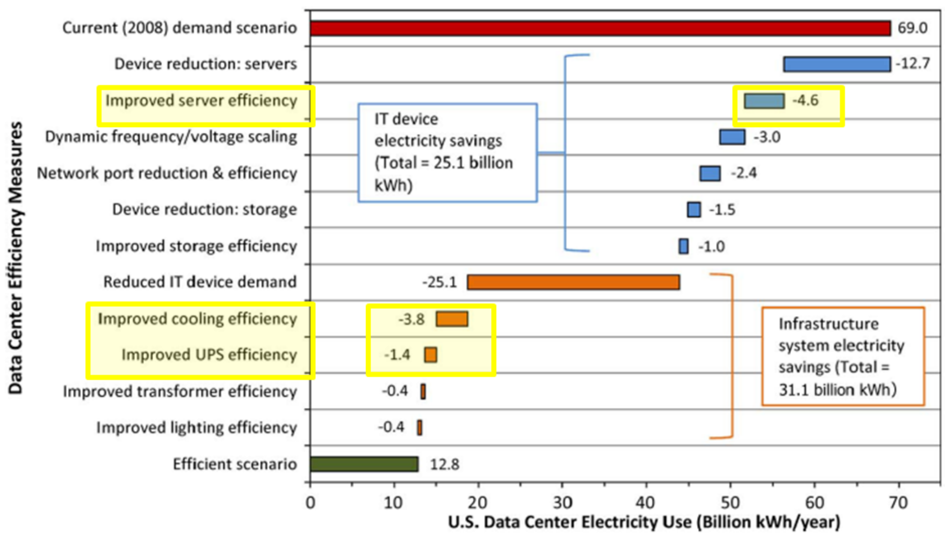


Figure 2-11. Data center efficiency measures with discussed techniques highlighted (Masanet et al. 2011)**.**

Additionally, while the United States has the potential to produce WBG data center equipment, Japan already is doing so. Toshiba & Mitsubishi have announced and begun distribution of SiC-UPS systems (Toshiba International Corporation 2015; Morrow 2015).

Strengths

- WBG strengths lead to reduced energy use and system cost
  - Faster switching
  - Higher operating temperature
  - Smaller footprint
- Commercial SiC devices with required breakdown voltage for several applications available in US
  - SiC- 1.2 kV
  - GaN– 40, 600 V

Weaknesses

- Immature technology compared to Si
  - Higher cost
  - "Unproven reliability"
  - Low manufacturing level
  - "Design Inertia"
    - Redesign for thermal benefits
    - Redesign for high frequency switching

Opportunities

- Increasing data center growth trend
- Increasing demand for reducing energy use
- Increasing government efficiency standards (U.S. & Europe)
  - EISA
  - EO: Federal data center PUE reduction
- Growing U.S. supply chain
  - Wafer & Discrete Manufacturing
  - GE switching PE to SiC

Threats

- Non-WBG based data center eff. improvements
  - Eliminate zombies (servers & UPS), thermal mgmt., DC Power
- Non – U.S. WBG technology advances
  - Toshiba & Mitsubishi have SiC UPS
- Global WBG Market
  - Competition from Europe, China & Japan
  - Asian vertical integration
  - U.S. company buyouts (IR → Infineon)

Figure 2-12. SWOT matrix for WBG power electronic in U.S. data centers.

Data centers are integral to the internet, which is becoming equally integral to society. As data centers are inherently considerable energy users, it is becoming essential to reduce data center energy consumption. The combination of energy use awareness, potential for cost savings and government regulations is fueling a drive for more efficient data centers, providing a growing opportunity for wide bandgap semiconductor devices.

Overall, while there are lower cost strategies for improving data center efficiency, utilizing WBG devices in data center power conversion could save a significant percentage of energy use while we head into a future of increased data center electricity use.

3. RENEWABLE ENERGY GENERATION

As the energy demand throughout the world increases, there is a push to incorporate more renewable energies into our energy portfolio (Clean Power Plan (Environmental Protection Agency 2016), EERE Mission (U.S. Department of Energy n.d.)). Renewable energies are energy generation methods that replenish naturally on a short time scale. They can be directly (photovoltaics) or powered by the sun or other natural forces (wind, geothermal, and tidal); they do not come from fossil fuels or waste products (Ellabban, Abu-Rub, and Blaabjerg 2014). In 2014, the U.S. used 98 quadrillion BTU of energy, 13 quadrillion BTU (4100 TWh) was electricity generated nationally. Of that total electricity generation, 550 TWh (14%) was generated from renewable resources. The fraction of renewables is expected to rise to 27% by 2040 (U.S. Energy Information Administration 2016a).

Renewable energy generation is increasing, but work still must be done to insure it grows at the expected rate or higher, by decreasing cost of installation and operation and increasing efficiency and usability while maintaining safety. This provides the motivation for new energy efficient power conversion technologies, such as WBG power devices.

3.1. RENEWABLE ENERGY GENERATION OVERVIEW

Photovoltaic solar energy (PV) is generated by photovoltaic semiconductors producing current when exposed to solar radiation, compared to wind energy, where energy is produced by the wind pushing blades on the hub connected to a generator. Both of these are considered renewable energies because they rely on natural forces that are always present and cannot be "used up" and have little to no long-term effect on the climate (Millstein and Menon 2011; Pryor and Barthelmie 2010).

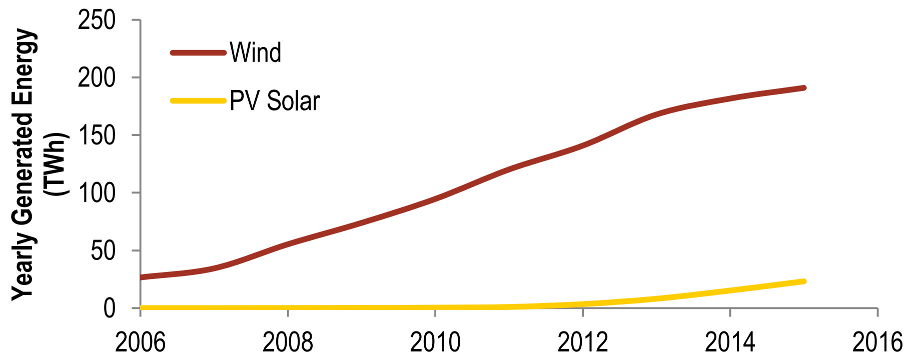


Figure 3-1. Renewable electricity generation onto U.S. grid
(U.S. Energy Information Administration 2016c).

3.1.1 Demand for Renewables

The 2015 installed PV and capacities were 220 GW and 430 GW, respectively. Europe and Asia are leading the world in installed solar capacity (the potential amount of energy that could be generated from existing installations); the top four countries are China, Germany, Japan and the U.S. (International Energy Agency 2016). China, U.S., Germany and India are leading the world for cumulate wind capacity (Figure 3-2) (Global Wind Energy Council 2016).

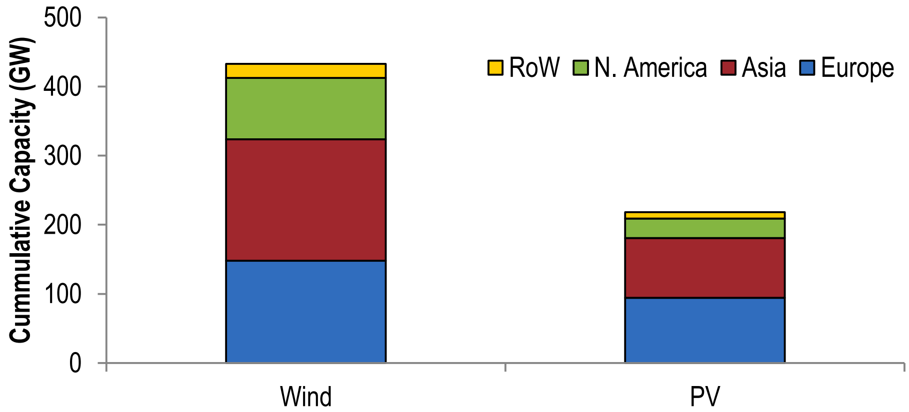


Figure 3-2. Geographic breakdown of installed renewable generation capacity (adapted from Global Wind Energy Council 2016; International Energy Agency 2016)**.**

In 2014, solar and wind comprised 5% and 33% of U.S. renewable energy generation (554 TWh) (Figure 3-1), with solar approximately equal to biomass combustion, municipal waste and geothermal but both less than hydroelectric generation. According to the 2016 Energy Information Administration (EIA) Annual Energy Outlook (AEO) projection, both are expected to surpass hydroelectric by 2040 with 35% and 34%, respectively, of the total renewable generation capacity of 1374 TWh (U.S. Energy Information Administration 2016a). In 2015 the EIA projection for total renewable generation was projected to be 909 TWh with 35% wind and 12% solar by 2040 (U.S. Energy Information Administration 2015). Several factors seem to have contributed to this change in expectations, a major one being the announcement of the Clean Power Plan (Environmental Protection Agency 2016), calling for a reduction in carbon dioxide based electricity generation along with an increase in non-emitting renewable energies. Additionally, the underlying assumptions of expiration/renewal of tax credits and reduction in capital costs contribute to forecast variation and actual new installations (U.S. Energy Information Administration 2016d).

3.1.1.1 Tax Credits/Policies

Tax credits have a significant impact on new renewable installations and cause substantial variations in past & projected growth (Investment Tax Credit & Production Tax Credit). Wind projects under construction before 2020 will receive a production tax credit; when this expires, it is expected to cause a sharp decline in new wind growth after 2022. Solar installations are eligible to receive an Investment Tax Credit, which provides a credit of 30% for new installations until 2019. The credit reduces every few years to a permanent 10% for commercial businesses and utilities with nothing for residential consumers by 2023 (U.S. Energy Information

Administration 2016h). Also, the expiration of the Production Tax Credit (PTC) in 2003 caused a dramatic decrease in new wind installations in 2004. Additional credits and incentives vary between states, given each state's different energy portfolio goals.

3.1.1.2 Capital Costs

Variation in actual capital costs can also affect the number of new installations and can cause significant variation in projections as well. Over the past several years the costs of both PV and wind power installations have been decreasing. PV is expected to continue cost reductions; a government program, Sunshot, hopes to reach the goal of reducing cost to $60/MWh by 2020 (U.S. Department of Energy 2012). Similarly, Wind Vision is working to reduce costs and encourage new installations of wind power by funding research and development, partnering with industry to provide turbine testing and certification, exploring the impacts of wind energy on the surrounding environment and society, among other key activities (U.S. Department of Energy n.d.).

3.1.2 Energy Losses in Generation

Solar generates electricity in the form of direct current (DC), what most electronic devices use, but unfortunately not what is provided by the electrical grid. The grid is alternating current (AC), where the voltage and current vary sinusoidally. While wind generation can be made to produce either DC or AC current, it still must be conditioned. The grid is very carefully monitored and maintained and all electricity that is fed back to the grid must meet very specific standards for voltage and frequency (Figure 1-5)(Kramer et al. 2008; U.S.-Canada Power System Outage Task Force 2004).

Whether a generation farm or rooftop/neighborhood systems, grid connected distributed energy resources (DER) must match the voltage, phase, frequency, and sine wave profile of the grid at the point of connection. A DC-AC inverter for grid connection must monitor the grid and the DER output (the inverter input) then adjust the inverter output to match the grid, or disconnect the two if there is something wrong with the grid connection. Generally, even if not connected to the grid, DER generated electricity must be matched to the end use voltage, often done with a dc-dc boost converter if the DER output is DC (solar, some wind). If the DER output is AC (such as with a microturbine for combined heat and power or wind) a rectifier would be before the converter to switch to DC power (Blaabjerg, Chen, and Kjaer 2004; Kramer et al. 2008). Whether a DER is regenerating onto the grid or suppling end-user electricity, anytime there is an electrical conversion, some energy is lost, and these inefficiencies in conversion add up. If there is to be a large fraction of renewable energy on the grid, actions must be taken to account for the variability in renewable supply and match the total supply to the electrical demand. While the solutions to this problem may involve WBG power electronics, they are still in the early stages of development due to the unavailability of significantly higher voltage and amperage devices as such, this report will not include them.

WBG power electronics reduce losses in PE, in the case of renewables, this leads directly to increased electricity on the grid without the addition of more power plants, renewable or fossil fueled. The PE required for PV and on-shore wind applications are on the higher boundary of low-voltage devices (600 V - 1.7 kV) and will condition between 10 kW and 10 MW of power (see Figure 8-1). Most of this can be handled by commercial WBG devices, as of now, commercial SiC devices top out at 1.7 kV and GaN at 900 V, though for higher power wind, WBG current ratings are still below what would be required.

3.2. PHOTOVOLTAIC SOLAR ELECTRICITY GENERATION

3.2.1 PV Generation Systems

PV generation systems are expensive, though that price is reducing via a concentrated effort from programs like SunShot. The solar collection panel is the most expensive (38% – 51%) of the installed system price (Goodrich, James, and Woodhouse 2012); it is what "collects" the sunlight and turns that energy into DC electricity via photovoltaic semiconductors (U.S. Department of Energy 2012). This electricity is then transformed into AC grid compatible current by the inverter (7 – 10% of the installed system price) (Goodrich, James, and Woodhouse 2012; Jones-Albertus et al. 2016), as shown in Figure 3-3.

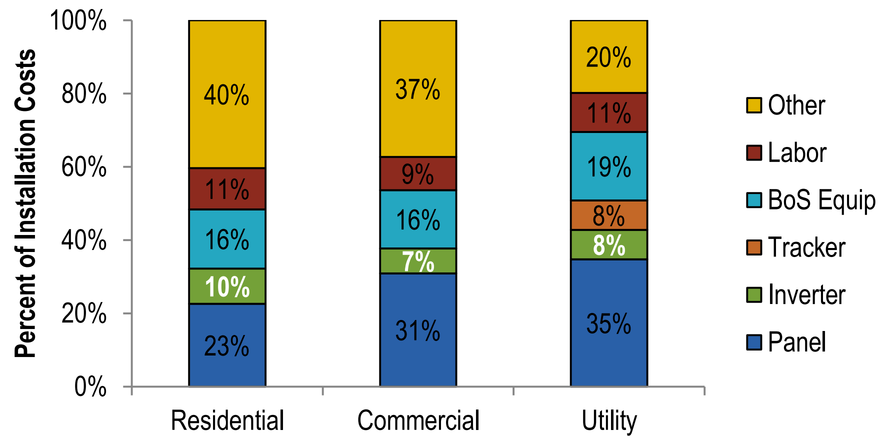


Figure 3-3. Breakdown of 2015 benchmark installation costs of PV systems (adapted from Jones-Albertus et al. 2016).

The inverter size depends on the size of the generation system and falls under three different size categories, i.e., micro-inverters, string, and central inverters (Table 3-1). Small home rooftop systems often use micro-inverters; this is the smallest market (2%),can generally only condition up to 1 kW of power and are directly integrated with the solar panel (Rogalla 2013). They are the least efficient and the least cost effective, but are ideal for smaller systems. Their PEs are simpler, using smaller voltage discretes, and could use either SiC or GaN. A major micro-inverter supplier, Enphase, was a large user of SiC diodes until a recent design change prompted the move to Si transistors (Gueguen 2016; "Personal Communication with Martin Fornage (Enphase) 04/05/2016" 2016). String inverters comprise 37% of the market. These are used in large residential (neighborhood) or commercial sized systems or small utility scale systems and generally handle less than 30 kW each (Rogalla 2013). String inverters use modules instead discretes, but could potentially still use either GaN or SiC, depending on the system voltage. The largest in terms of market (61%) and power (30 kW or more) are central inverters for utility scale systems (Rogalla 2013). These are the most expensive, have the highest efficiency, and require the larger, 1.2 kV or higher modules.

Table 3-1. Comparison of PV inverter sizes

	Micro	String	Central	
				
Size Install	Single Panel	Residential	Utility	(Rogalla 2013)
$/W (2015)	$0.30	$0.15	$0.11	(Jones-Albertus et al. 2016; Fu et al. 2015)
$/W (2010)	$0.42	$0.37	$0.29	(Goodrich, James, and Woodhouse 2012)
Est. Mkt Size	2%	37%	61%	(Fraunhofer Institute for Solar Energy Systems 2016)
Power Rating	< 1 kW	< 100 kW	> 100 kW	(Fraunhofer Institute for Solar Energy Systems 2016)
Input Voltage	< 100 V	150 – 1000 V	450 – 1500 V	(Rogalla 2013)
PE Voltage (kV)	0.6 – 1.2 discretes	1.2 – 1.7 modules	1.2 – 3.3 modules	(Fuji Electric Co. Ltd 2015a; Yole Development 2013a)
WBG Material	GaN/SiC	GaN / SiC	SiC	
WBG Available?	Y	Y	Some	
Max Eff	96%	98%	98.5%	(Fraunhofer Institute for Solar Energy Systems 2016; Rogalla 2013)
CA SB1 Ave Eff	95.1%	95.9%	96.7%	(Go Solar California 2016)

3.2.2 PV Generation Power Electronics

Historically, the cost of PV systems (i.e., the light collection panel or module) was high and production volume low. Most research in this area was focused on increasing the system efficiency, to decrease the payback period. More recently, great strides have been made in improving panel efficiency, now shifting focus on reducing system costs (U.S. Department of Energy 2012). The drive for higher efficiency(Gueguen 2016) has been responsible for an early uptake of WBG materials. Enphase micro-inverters have used SiC diodes alongside Si transistors for several years and are one of the top solar manufacturers. However, with recent focus shifting to cost and other considerations (such as allowing bidirectional power flow), they are changing the topology of their inverter to better fit customer requirements, and will be using additional silicon transistors instead of SiC diodes until the price of SiC transistors drops to acceptable levels, when they might consider transitioning to SiC ("Personal Communication with Martin Fornage (Enphase) 04/05/2016" 2016). There were several string inverters that used SiC devices, including ones from REFUsol (020K-SCI) (Advanced Energy, n.d.), SMA (STP 20000TLHE-10) ("Personal Communication with Michael Mahon (SMA-America) 04/08/2016" 2016; Yole Development 2013a) and PowerOne (Yole Development 2013a). However, these models are no longer available on the market and no others advertising SiC use have taken their place. While it may seem that the reintroduction of price as the major market driver may kill WBG in solar, further advances have shown that WBG still has much to offer. Beyond the increased efficiency, a full SiC MOSFET PV inverter system has been projected to be less expensive than a Si system within a few years (Yole Development 2013a; Burger, Kranzer, and Stalter 2008; Sintamarean et al. 2014; Schupbach 2015). PV inverter systems also often include a DC-DC converter, to boost the voltage generated by the solar panel, before transforming into AC, unlike wind inverters. In general, WBG devices have higher efficiencies at higher switching frequencies, compared to Si. This allows for smaller inductors, transformers, and capacitors, producing a smaller inverter and a much smaller converter. The reduced losses coupled with higher operating temperatures also allow for smaller heat sinks and cooling systems. Additionally for PV, SiC MOSFETs can operate at higher voltages than their Si counterparts, leading to systems with simpler topologies and thereby fewer devices and gate drivers (Sintamarean et al. 2014). All of this together leads to a much smaller system (reduced 50% by volume (Pushpakaran et al. 2016)) that has the potential to cost as much or less than a Si system. Several manufacturers have developed WBG PE prototypes and products (Table 3-2), encouraged by potential system level benefits and ongoing reduction of WBG device prices. Recently Fuji (PVI1000AJ-3/1000) (Oshima, Maeda, and Muratsu 2015) and Mitsubishi (PV-PN44KX) (Mitsubishi Electric n.d.) have announced new 1.0 kV SiC PV systems to be released at 1 MW (SiC only in the DC boost converter) and 4.4 kW respectively; Yaskawa has announced a GaN 4.5 kW inverter (Teschler 2015; Gueguen 2016). SMA and Delta have also prototyped new SiC solar string inverters (Gueguen 2016). Additionally GE has built a hybrid power plant in Germany with a 1 MW, 1.5 kV, SiC inverter that is 40% smaller than its silicon equivalent (Kellner 2015). The system 1.5 kV DC link is less common than typical 1000 V, or lower, voltages; higher DC link voltages reduce the system current (reducing the size of cabling, connections, etc.), providing lower line losses, simpler systems and reduced installation costs (by reducing the number of stings per installation). The 1500 V link will require a breakdown voltage higher than most available Si MOSFETs or a multi-level topology (meaning more discrete devices) (Crowell 2016; Nunez 2016), making these systems an attractive opportunity for SiC MOSFETs, which, due to the higher breakdown voltage, would not need as complex of topologies as Si.

Table 3-2. A sample of solar inverter prototypes announced

Company	Model	Year Announced	η	Device	System Voltage	System Power	Notes
Cree (Cree 2015)		2015	99.1%	1.2 kV SiC MOSFET modules	1 kV	50 kW	1.5 kW/kg; much smaller; prototype only
Fuji (Oshima, Maeda, and Muratsu 2015)	PVI1000 AJ-3	2015	98.8%	1.2 kV SiC Module	1 kV	1 MW	In converter only To be released "soon" 40% small footprint
GE (Kellner 2015)		2016	~99%	SiC	1.5 kV	1 MW	40% size reduction; roof; installed in German hybrid plant
Mitsubishi (Mitsubishi Electric n.d.)	PV-PN44kX	2014	98%	SiC	1 kV	4.4 kW	To be released "soon" Japan only
Yaskawa (Teschler 2015)	Enewell-SOL V1	2015	98%	600 V GaN module		4.5 kW	To be released "soon" Japan only; 40% smaller than conventional model

3.2.3 PV Market

Major suppliers of PV inverters include SMA, Huawei, SunGrow, ABB, Enphase and Solaredge; Advanced Energy recently sold their PV division leaving a large hole in market (Gifford 2015). As of 2014, the PV inverter market constitutes $7 billion out of the nearly $50 billion inverter market (Gueguen 2016). Semiconductors for PV inverters are $387.1 million (IHS Technology 2015) with WBG semiconductors comprising $31.4 million (Eden 2016) (Figure 3-4). PV is currently and is expected to be a major part of the future WBG market, with the majority of revenue from hybrid SiC modules followed by SiC discretes and full modules with GaN only a small segment in low voltage micro-inverters (Eden 2016).

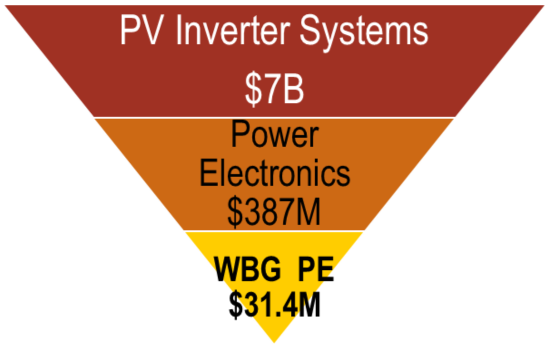


Figure 3-4. 2014 global PV inverter market (Gueguen 2016; IHS Technology 2015; Eden 2016)**.**

Of the PV manufacturers, only a few are known to be working with WBG power electronics and several have used WBG in the past or have prototyped new WBG inverters ("Personal Communication with Michael Mahon (SMA-America) 04/08/2016" 2016; Gueguen 2016) (Table 3-2). Overall, the renewable generation WBG PE supply chain is very similar to other WBG applications, with the addition of "field integration," the installation of renewable systems. Often these are smaller third parties but several (e.g., Toshiba, Hitachi, Mitsubishi, Fuji and GE) will perform installations themselves and GE not only has prototyped a large PV inverter, but have installed it in a hybrid power plant. Like other WBG applications, there are many companies involved through-out the WBG supply chain, but unlike other applications, PV already has several end-users who have used or will be using WBG in their power conversion equipment. PV inverter manufacturers are distributed throughout the world, but those from Europe seem to be moving away from SiC while those in Asia seem to be moving toward inclusion. The two American manufacturers are split, Enphase retiring the use of SiC and GE, heartily embracing SiC.

3.2.4 Additional Energy Generation Estimation

WBG can bring inverter system efficiency up from about 96% (weighted average of California SB1 compliant inverters (Go Solar California 2016)) to about 98.5% with full SiC module (Cree 2015; Oshima, Maeda, and Muratsu 2015; Kellner 2015; Mitsubishi Electric n.d.) or 98% with GaN (Teschler 2015). PV generation in 2015 was about 37.6 TWh (U.S. Energy Information Administration 2016a); via efficiency increases, WBG could add an additional 1.0 TWh, for a total of 38.6 TWh. Compared to total U.S. electricity generation (4100 TWh) (U.S. Energy Information Administration 2016a) this is quite small, however, it can still reduce the use of coal by 200,000 tonnes and CO_2 emissions by 400,000 tonnes (see Section 10.2.2 in Appendix B). Additionally, by 2025, solar-based electricity generation is expected to be higher, 58.7 - 170 TWh (U.S. Energy Information Administration 2016a, 2015), leading to a potential increase in generation of 1.5 - 4.4 TWh (Table 3-3). As stated above (in Section 3.1.1), the future of renewable generation is highly dependent on the policies at the time of installation. For example, a significant contributor to the difference between the 2015 and 2016 projections is the introduction of the Clean Energy Plan and its likelihood of continuing.

Table 3-3. Estimated solar-based electricity generation with Si and WBG power conversion equipment

	Expected Annual Generation (TWh/yr)		WBG Additional Annual Generation			
Year	As Is	WBG	TWh	1000s Homes	Coal avoided (M tonnes)	CO_2 avoided (M tonnes)
2015	37.6	38.6	1.0	90	0.2	0.4
2025	58.7 - 170.1	60.2 - 174.5	1.5 - 4.4	140 - 400	0.3 - 0.9	0.6 - 1.8

3.3. WIND

3.3.1 Wind Generation Systems

Wind energy is generated by wind pushing the blade system that is connected to a generator where current is produced. Wind turbines are large and often consolidated together as wind farms. A wind turbine consists of rotor blades connected to a generator, usually with a gearbox, and set in a nacelle on top of the tower. The tower is often one of the most expensive parts of wind turbine systems (24% of the turbine costs and 16% of *total installation* cost for the system), followed closely by the blades (23% of the turbine costs, 15% of total installation cost). As the wind pushes the blades, the connected generator (5% of the turbine costs, 3% of total cost), spins producing AC current, which is often then conditioned by PE (5% of the turbine costs, 3% of total installation cost) to match the frequency, voltage, and phase angle of the grid (IRENA 2012) (Figure 3-5).

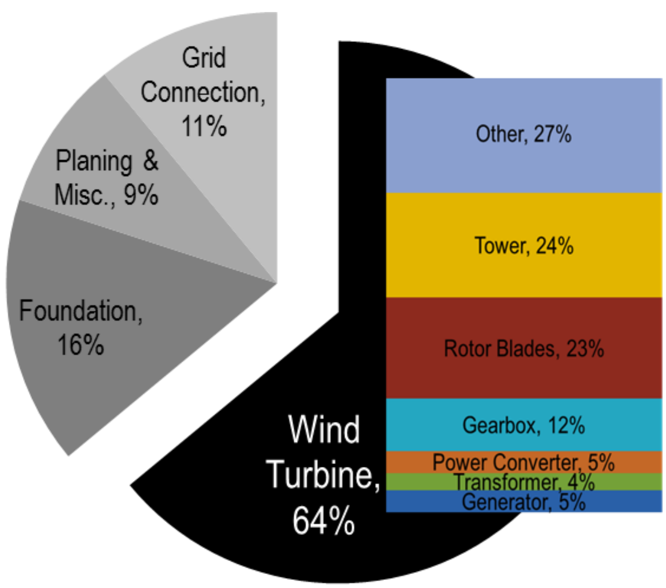


Figure 3-5. Breakdown of wind turbine installation cost. Colored bar illustrates fraction of turbine costs (IRENA 2012)**.**

Small turbines (less than 4 kW) have a generator (Squirrel Cage Induction Generator, SCIG, or wound rotor induction generators, WRIG, with variable resistance) that limits the rotation of the generator to match the frequency of the grid, eliminating the need for power converters. However, any wind power that would push the generator beyond the fixed speed is lost and the turbine is locked at low wind speeds that would not meet the generator speed. Larger turbines (400 kW – 2 MW) often have doubly fed induction generators (DFIG) (Serrano-Gonzalez and Lacal-Arantegui 2016). DFIGs have two output windings:

- the rotor winding is variable frequency, its frequency is adjusted, relative to the speed of the turbine, using AC stator power conditioned via PE,
- the other winding (the stator) is then able to produce a constant output of 3-phase AC at the frequency of the grid.

With two controllable windings, the generator is able to have a consistent output voltage and frequency, no matter the wind speed. This allows the turbine to capture more energy than a fixed generator and better respond to the grid, and still have smaller PE circuitry than would be necessary to condition all incoming power (only the power to or from the rotor, about 30%, must be processed by PE). This also requires a more expensive and high maintenance wounded rotor. As of 2014, the majority of the wind turbine generators are DFIG (Serrano-Gonzalez and Lacal-Arantegui 2016) (Figure 3-6).

The largest turbines usually feed all generated electricity though PE (Full Power converters, FPC). This size employs permanent magnet or electrically excited synchronous generators (PMSG or EESGs) or SCIG (Serrano-Gonzalez and Lacal-Arantegui 2016). Some of these configurations may eliminate the gearbox, a high maintenance (Spinato et al. 2009) and expensive (8% of installed cost) (IRENA 2012) part of the turbine system. These systems use full conversion to continuously adapt the rotational speed of the turbine to the wind speed, increasing the overall generation of the turbine (P. Smith 2014), but use medium voltage-high current and thus expensive PE. FPCs also support fault ride-through and more reliably match grid requirements (P. Smith 2014). As 2 MW and higher power turbines become more common, full power conversion with SCIG or PMSG is increasing in the share of wind capacity; however, the use of rare earth minerals in the construction of PMSG are a limiting factor to their uptake (P. Smith 2014; Serrano-Gonzalez and Lacal-Arantegui 2016).

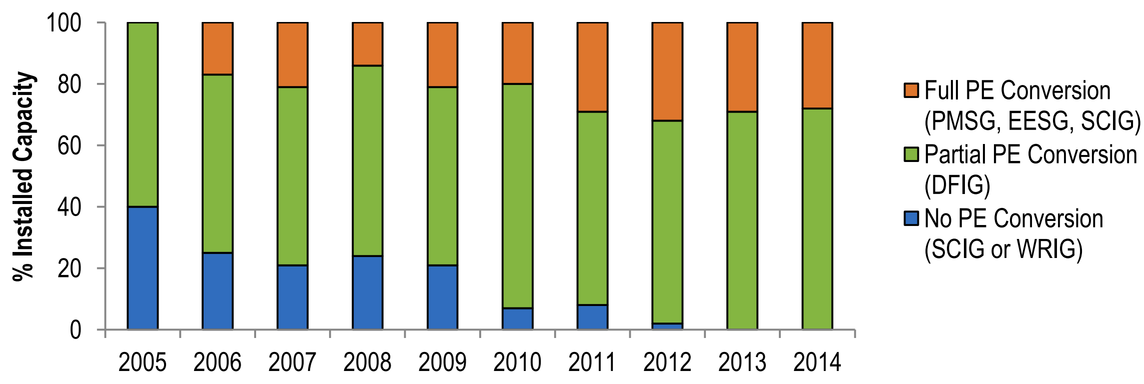


Figure 3-6. Fraction of installed wind capacity in North America using power electronics for power conversion (adapted from Serrano-Gonzalez and Lacal-Arantegui 2016)**.**

3.3.2 Wind Generation Power Electronics

With both partial and full conversion, the power throughput is high, requiring PE with high voltage and current ratings. For turbines between 400 kW and 2 MW, 1.2 to 1.7 kV IGBT modules are sufficient, but require current ratings between 800 and 3600 A. Larger turbines require 3.3, 4.5 or 6.5 kV modules depending on the chosen topology but with lower current ratings (200 – 1500 A) (Fuji Electric Co. Ltd 2013a). At this time, while the lower voltages are available with SiC, the current ratings are not likely to be sufficient without paralleling lower current modules (600 A for 1.2 kV and 225 A for 1.7 kV modules are the highest available from Wolfspeed/Cree (Wolfspeed n.d.)). The use of SiC could increase the efficiency of wind turbine power conversion from less than 95% to nearly 98% (H. Zhang and Tolbert 2008) and through increased switching frequency, reducing system size (H. Zhang and Tolbert 2011). PE are usually housed within the nacelle (AWEA 2011), making reduced size and weight a prized commodity (Yole Development 2013a). Overall, there is little push for WBG entry into wind, due to the lower drive for high inverter efficiency and reduced need for high frequency switching (as they do not require a DC-DC converter). When paired with the current handling limitations, there are no commercial wind turbine inverter systems using WBG devices at this time. IHS estimates that wind will begin using hybrid modules soon and full SiC modules shortly after (Eden 2016).

3.3.3 Wind Market

In 2014 there are three major suppliers of wind turbines in the U.S., GE, Siemens and Vestas (Wiser et al. 2015). These three manufacturers make their own power conversion systems or it is made by one of their subsidiaries (de Vries 2012). While not necessarily working on WBG wind power converters, GE and Siemens both have R&D devoted to WBG power conversion (Point the Gap 2016; Siemens 2013).

Despite having a higher installed capacity, as of 2014, the wind inverter market is only $2.7 billion out of the nearly $50 billion inverter market (Figure 3-7)(Gueguen 2016), compared to PV's $7 billion. This is likely due to wind inverters ability to handle much higher power, fewer are needed for the installed capacity. The market for semiconductors for wind inverters is $258 million, but there are no WBG semiconductors currently used in the wind market (Eden 2016; Fodale and Eden 2015). Given the comparative size of the wind inverter market and the lack of high current WBG devices, the wind generation industry is currently not and is expected not to be large part of the future WBG market. Wind is expected to begin using hybrid SiC modules in 2016 and full SiC modules when the prices come down, possibly as early as 2017. By 2017, WBG modules are expected to be used in 15% of the wind market, reaching 20% by 2025. WBG discretes and GaN modules are not expected to be used by wind turbine manufactures (Eden 2016).

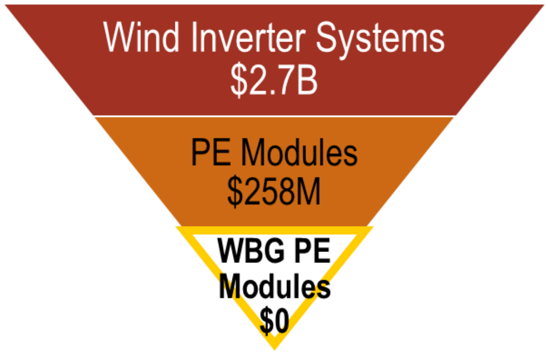


Figure 3-7. 2014 global wind inverter market (Gueguen 2016; Fodale and Eden 2015; Eden 2016)**.**

3.3.4 Additional Energy Generation Estimation

WBG can bring inverter system efficiency up from about 95% to about 98% with SiC (H. Zhang and Tolbert 2008). 2015 wind generation was about 190 TWh (U.S. Energy Information Administration 2016a); full integration of WBG-PE could add an additional 6.5 TWh, which would provide over 196 TWh (see Section 10.2.2 in Appendix B). Compared to total U.S. electricity generation (4100 TWh) (U.S. Energy Information Administration 2016a) this is quite small, however, assuming the new generation replaces the fossil fuel-based generation, it can still reduce the use of coal by 2.8 billion pounds and CO_2 emissions by 5.9 billion pounds. Additionally, by 2025, wind generation is expected to be much higher, 235 - 453 TWh (U.S. Energy Information Administration 2016a, 2015), leading to a potential increase in generation of 8.0 - 15 TWh (Table 3-4).

Table 3-4. Estimated wind-based electricity generation with Si and WBG power conversion equipment

	Expected Annual Electricity Generation (TWh/yr)		WBG Additional Annual Generation			
Year	Si	WBG	TWh	1000s Homes	Coal avoided (M tonnes)	CO_2 avoided (M tonnes)
2015	190	196	6.5	590	1.3	2.7
2025	235 - 453	243 - 468	8.0 - 15	730 - 1400	1.5 - 3.0	3.3 - 6.4

3.4. RENEWABLE GENERATION CONCLUSION

3.4.1 Strengths

There are many benefits to WBG integration into power electronics. Solar will benefit most from the increased efficiency, higher operating temperature, and smaller passives, achieving decreasing system costs. Wind will also benefit from all WBG strengths, but decreased size (via decreased cooling needs and decreased passives) is the major incentive, reducing size and weight of the power conversion systems in the nacelle (Yole Development 2013a).

Most of the WBG device manufacturers produce SiC and GaN devices within the required voltage ranges of PV inverters (600 V – 1.7 kV). Additionally, there are also several renewable energy inverter manufacturers in the U.S. (Enphase, GE, etc.), and GE has announced plans to begin transitioning all of their power electronics to SiC (Willis 2015).

3.4.2 Weaknesses

There are few renewable generation-specific weaknesses for the integration of WBG devices; the biggest deterrents for WBG integration are the same as other applications). Given the decreasing cost of PV modules, reducing PV inverter cost is being emphasized more than efficiency, potentially hurting WBG uptake. Additionally, there are no commercially available devices suitable for higher power PV (3.3 kV) or wind power (rated for more than 600 A or 3.3 kV). Both higher voltage and current handling WBG devices or more complicated topologies must be developed before WBG can penetrate these high power markets.

3.4.3 Opportunities

Global energy demand is on the rise, prompting efforts to increase the share of renewable energies to decrease the impact on the environment. Renewable energy generation is expected to increase significantly in the United States over the next 30 years, attempting to reduce the energy lost to inefficiencies in power conversion could increase the energy added to the grid without having to add significantly more installations. There are several government tax incentives and research initiatives in place to further promote new renewable energy installations (Sunshot & Wind Vision (U.S. Department of Energy n.d., n.d.)) by reducing installation costs and increasing energy generated.

While the WBG market for wind is not expected to grow significantly in the next ten years (less than 2% of the market by 2025), the WBG PV-inverter market is expected to be one of the major WBG markets, with nearly 17% of the total WBG market by 2025. Additionally, WBG devices have the potential to add additional generation of 15 and 6.5 TWh of electricity in 2025 if integrated into wind and PV inverters respectively.

Beyond the increase in renewable generation, many of the opportunities for WBG inclusion in PV and Wind generation are the same as other applications: established U.S. supply chains from wafer to end-product manufacturing and a strong governmental desire to increase U.S. strength in the field of WBG power electronics and decrease our fossil fuel use. Furthermore, the U.S. already has several PV and wind specific inverter manufacturers, which have used WBG either in the past or for other applications (e.g., Enphase and GE).

3.4.4 Threats

In addition to threats that could hinder all U.S. WBG manufacturing, there are a few renewable generation specific threats. As previously state, a major threat to WBG/PV generation integration is the price of the PV inverter, as other system prices decrease, any increase in inverter price is more pronounced. Reductions in tax credits and the currently low price of natural gas reduce the number of new installations, reducing any call for WBG inclusive inverters.

While the U.S. has manufactured WBG solar inverters, so have Europe and Japan. However, while many U.S. and European solar inverters have recently removed or are removing the WBG inclusive inverters, Japanese manufacturers has introduced several in recent years. Wind generation capacity is expected to increase for the next few years; it is likely to stagnate (expected to occur around 2022) before WBG devices with appropriate voltage and current ratings are on the market and have significantly penetrated wind inverter manufacturing (not expected before 2025).

Strengths

– WBG strengths lead to reduced electricity losses, size and system cost
  - Faster switching
  - Higher operating temperature
  - Smaller footprint & lighter weight

– Commercial SiC devices with required breakdown voltage for PV (and low V wind) available in US
  - PV: 600 – 1700 V
  - Wind: 1700 V, but not at required current capacity

Weaknesses

– Immature technology compared to Si
  - Higher cost
  - "Unproven reliability"
  - Low manufacturing level
  - "Design Inertia"
    - Redesign for thermal benefits
    - Redesign for high frequency switching

– Devices with appropriate current capacity or higher breakdown voltage (+1.7 kV) for wind are not available

Opportunities

– Increase in energy needs

– Increase in desire for reducing energy use & renewable energy generation

– Government incentives for renewable energy generation

– Growing U.S. supply chain
  - Wafer & Discrete
  - U.S. inverter manufactures have used WBG or are prototyping new WBG inverters
  - GE switching PE to SiC

Threats

– Alternative energy/cost savings techniques

– Alternative low impact generation technologies (e.g., Natural Gas)

– Non – U.S. WBG technology advances
  - European & Japanese have developed WBG inverters

– Global WBG Market
  - Competition from Europe, China & Japan
  - Asian vertical integration
  - U.S. company buyouts (IR → Infineon)

Figure 3-8. SWOT matrix for WBG power electronic in U.S. renewable generation.

Renewables are poised to generate a substantial fraction of the world's energy, and demand for them is rising. As generation systems become more efficient, WBG may provide that last increment of increased efficiency needed to make renewable generation an economically viable energy option, increasing generated electricity without additional costly installations. Several PV inverter manufacturers have noticed the benefits of WBG and integrated them into inverters in the past and are looking to it in the future, but only if WBG inverters remain cost competitive.

4. MOTOR DRIVES

Motors demand a lot of electricity: approximately 40% of all electricity in the U.S. is used by motors(U.S. Energy Information Administration 2016a). Industrial and commercial motors use 16% and 14%, respectively, of the U.S. electricity supply, and even residential motors use a large amount (8%) (Waide and Brunner 2011; U.S. Department of Energy 2014)(see Figure 4-1). Motors can power different devices for multiple applications. Most motors run pumps, fans, compressors or some type of mechanical movers (conveyor belt system). For example, 6.0% of all U.S. electricity use is devoted to commercial compressors, such as those for food refrigeration or HVAC systems. Pumps and fans require 6.8% and 8.0% of U.S. electricity, spread throughout the three sectors while movers are mostly used in the industrial sector (see Figure 4-2) (U.S. Department of Energy 2014; Waide and Brunner 2011).

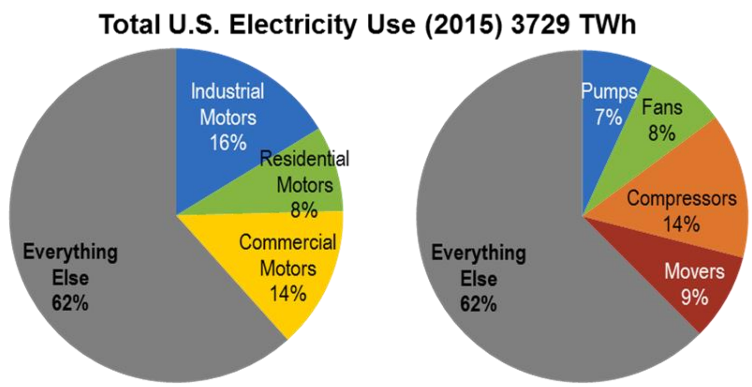


Figure 4-1. Motor electricity demand within total U.S. electricity use, by sector (left) and motor application (right) (U.S. Energy Information Administration 2016a; U.S. Department of Energy 2014; Waide and Brunner 2011)**.**

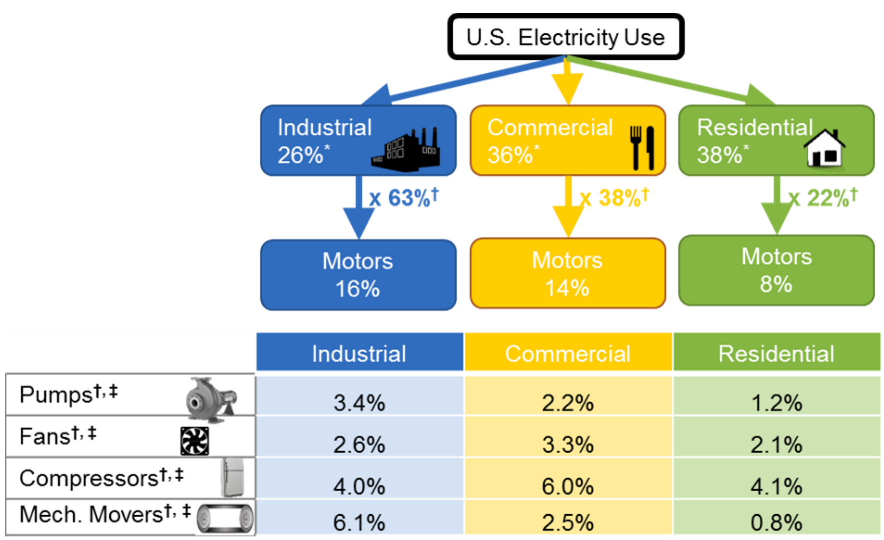


Figure 4-2. Motor application electricity demand within total U.S. electricity use*(U.S. Energy Information Administration 2016a) †(U.S. Department of Energy 2014) ‡(Waide and Brunner 2011)**.**

Within the residential sector, cooling, heating and refrigerators (fans and compressors) use the most energy (see Figure 4-3, left). The commercial sector is similar, with most of the energy being used for HVAC and refrigeration (see Figure 4-3, right) (Goetzler, Sutherland, and Reis 2013). In the industrial sector, a significant portion of the motor energy is used by mechanical movers, such as conveyor systems. Compressors followed by pumps and fans (U.S. Department of Energy 2014) make up a substantial portion of energy use supplied by motors. The industrial sector motor electricity use can be broken down by specific industry (as shown in Figure 4-4); the chemical industry uses the most motor energy (24%) followed closely by the paper industry (20%). The industries using the most motor electricity (chemical, paper, petroleum and metal) also are the ones that use a higher share of high-powered motors, an exception being the food industry (U. S. Department of Energy 2002).

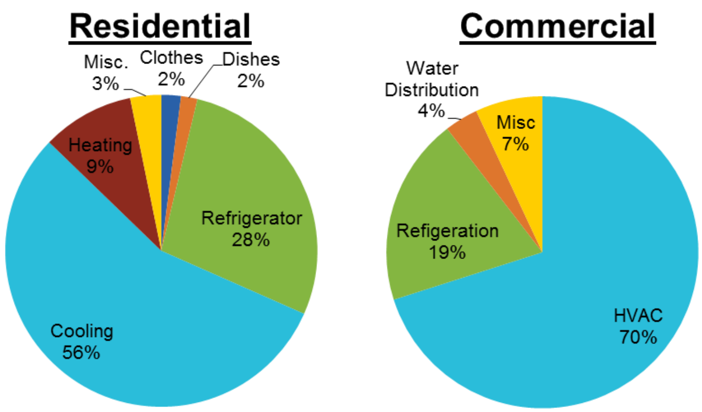


Figure 4-3. Breakdown of residential and commercial motor electricity use (Goetzler, Sutherland, and Reis 2013)**.**

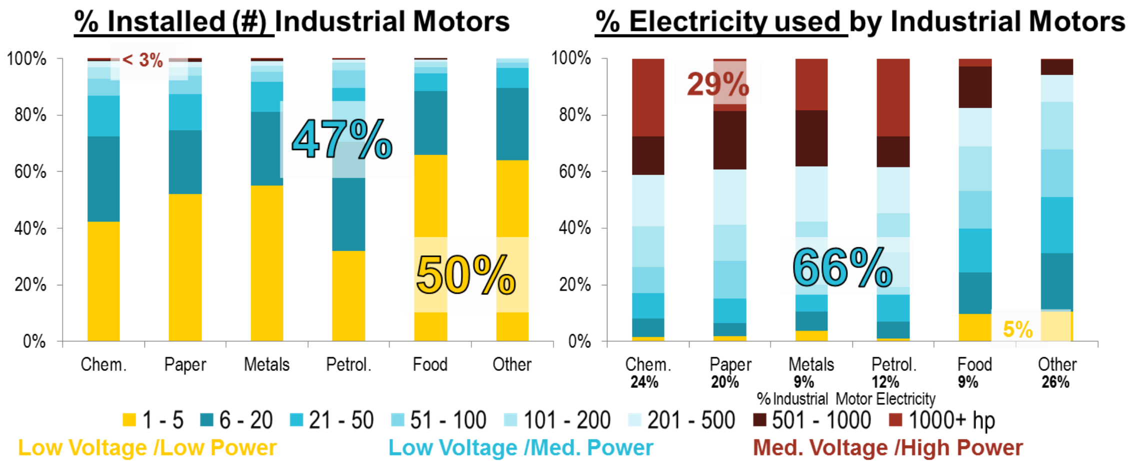


Figure 4-4. U.S. industrial motor use : Installations per industry and electricity use per industry, sorted by motor voltage/power rating (U. S. Department of Energy 2002)**.**

Large motors (high power) are those that provide more than 375 kW (500 hp). Small motors (low power) are less than 4 kW (5 hp), and medium motors are between (Waide and Brunner 2011). In general, low power motors use lower grid voltages (110 – 460V), and thus, are considered "low voltage." High power motors use higher input voltages (usually greater than 2kV, up to 13.8kV), and are considered "medium voltage." Medium power motors, again, range between the two other sizes (230 - 460V), and are usually considered low voltage, but may extend into medium voltages (Waide and Brunner 2011; VFDs.com n.d.) (see Table 4-1). The residential sector only uses low power motors while the commercial sector is split between low and medium power (Goetzler, Sutherland, and Reis 2013). Within the industrial sector, all three motor sizes are used, and by the numbers, most installed motors are low voltage and low power. However, electricity use is more spread out, with low voltage, medium power motors using 66% of the power and medium voltage, high power using 29% and the remaining 5% is used by low power (see Figure 4-4). Over all, high power motors use about 12% of motor electricity, or 5% of total U.S. electricity, medium power motors use 48% (18% of total U.S. electricity) and low power motors use 40% (15% of total U.S. electricity) (U. S. Department of Energy 2002). It should be noted however, despite the large motor stock in the U.S. (estimated to be between 24 and 35 million (U.S. Department of Energy 2014), no in-depth survey of the U.S. industrial motor population (including motor size) has been conducted since the U.S. Industrial Electric Motor Systems Market Opportunities Assessment in the late 1990s (Rao et al. 2016). The manufacturing energy consumption survey (last conducted in 2010) surveyed manufacturing energy use, including that by motors, but does not include any data on motor size or population (U.S. Energy Information Administration n.d.).

Table 4-1. Summary of motor size classifications (U.S. Department of Energy 2014; Goetzler, Sutherland, and Reis 2013; Waide and Brunner 2011)

Motor Size Categories		Power	Incoming Voltage	Total Installed (Industrial) (M Units)	Fraction of Total U.S. Electricity	Fraction of U.S. Industrial Electricity	Major Sector
Low Power	**Low Voltage**	0.75 – 4 kW (1-5 hp)	115 – 460V	16 (7.3)	15%	5%	Residential/ Commercial
Med. Power	**Low Voltage**	4 kW – 375 kW (5-500 hp)	200 - 1000V	12 (5)	18%	18%	Commercial/ Industrial
High Power	**Med. Voltage**	> 375kW (> 500 hp)	2.3 – 13.8kV	0.1 (0.1)	5%	29%	Industrial

4.1. MOTOR DRIVE OVERVIEW

Motors often have higher power ratings than what is required for their day-to-day operations, in order to compensate for periodic increased power demand, depending on downstream system needs as their output requirements vary. The output is reduced to desired levels by valves, throttles or cycling the motor on and off (ABB 2014a, 2014b; Anibal T. de Almeida et al. 2001). Operating the motor at reduced speed will reduce the power required and by tailoring motor speed, torque or power to the process demand, process scrap and rejected-product waste can also be reduced (e.g., by increasing product uniformity and reducing product rejects, optimizing material movement speed), potentially saving significant amounts of money (Progress Energy n.d.; Zinski 2015; Hartman 2014; ABB 2014b; Anibal T. de Almeida et al. 2001). However, motors are usually designed to provide steady output based on the incoming grid electricity. Motor drives can be installed between the grid and the motor; they control the frequency and voltage of the electricity into the motor to match motor speed to process demands (see Figure 4-5). For AC motors, the most common drive is a variable frequency or speed drive (VFD or VSD). VFDs consist of a rectifier and inverter to transform the frequency and voltage of the incoming current to meet the power demands of the motor driven application, as well as sensing and computational equipment to determine the required motor input. Running at a lower speed also reduces mechanical wear on the motor. Additionally, VFDs can start and stop the motor more gradually (soft start/stop), especially for high starting torque motors, reducing mechanical wear on the motor (Waide and Brunner 2011; ABB 2014b, 2014a; Anibal T. de Almeida et al. 2001).

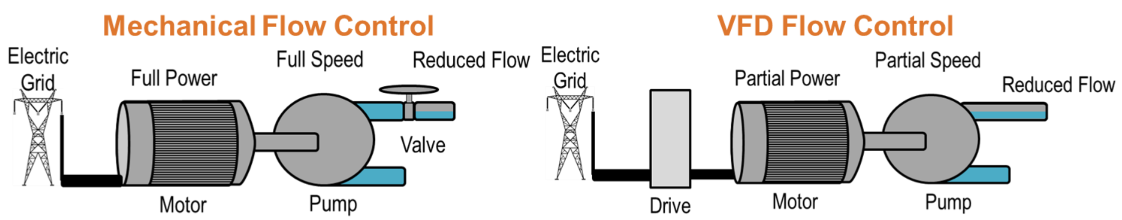


Figure 4-5. Mechanical and VFD flow control example.

4.1.1 Power Electronics for VFDs

Like an uninterrupted power supply (UPS), the rectifier takes incoming grid 60Hz AC and converts it to DC (using capacitors to smooth the voltage waveform). The inverter then switches the current back to AC, but at a different voltage or frequency, which will change the motor output (see Figure 4-6). The size of the power electronics within the conversion equipment depends on the drive’s incoming and output voltages, with low voltage drives using low voltage discretes (around 600V) and medium voltage drives using medium voltage modules (greater than 1.7kV) (see Table 4-1 and Figure 8-1) (Fodale and Eden 2015).

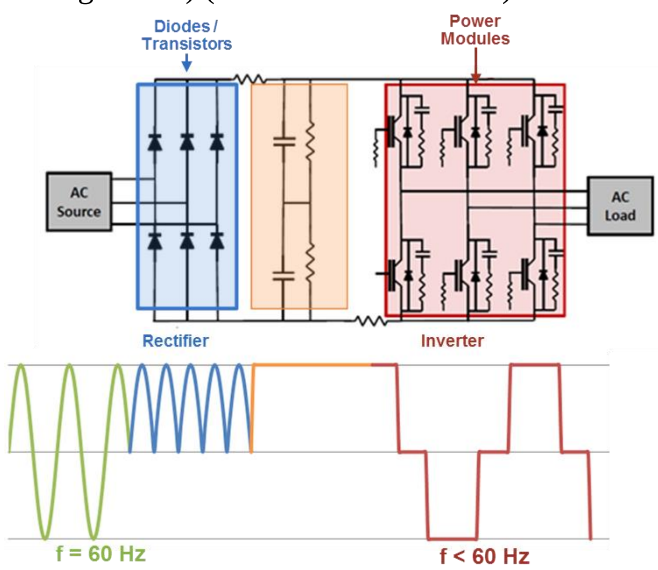


Figure 4-6. Example VFD circuit diagram with approximate electricity wave for each device.

4.1.2 Energy Savings Potential from Motor Drives

Motor drives (like VFDs) allow for more control over a manufacturing process, reducing costly electrical and material waste. They also benefit the motor by allowing soft start/stops, reducing mechanical and thermal wear, saving more money on maintenance. Centrifugal processes, e.g., fans and pumps, can save energy based on a cubic relationship between motor speed and motor power, where constant torque equipment, like conveyors, will only save energy via a linear relationship. This means that running at 75% speed will result in conveyors using 25% less energy and pumps or fans over 55% less energy (see Figure 4-7) (Anibal T. de Almeida et al. 2001; ABB 2014a). This energy savings translates to significant cost savings.

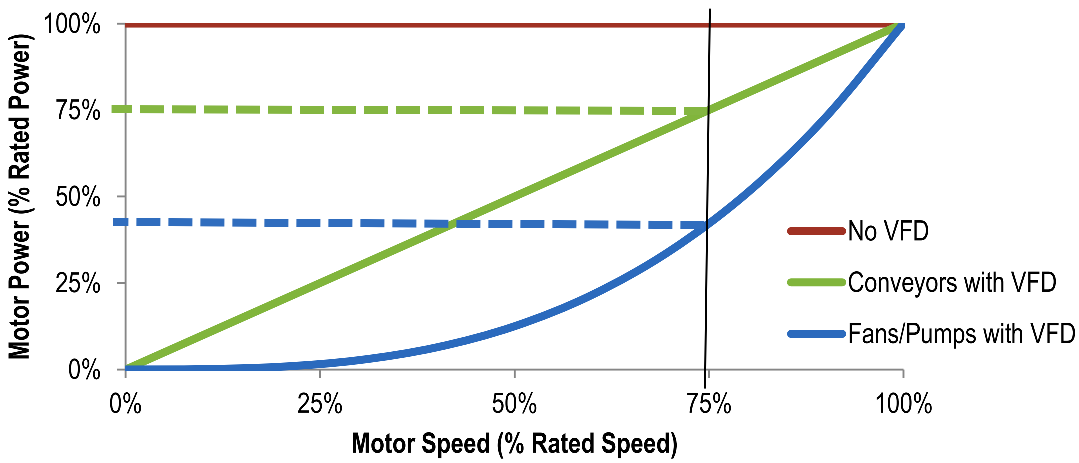


Figure 4-7. Relationship between motor speed and power demand for different motor applications and potential power reduction when reducing motor speed to 75% of rated.

Approximately 40% of motor systems will not benefit from the addition of VFDs (Anibal T. de Almeida et al. 2001), such as non-variable speed motors and very high power motors (due to the losses added from the VFD PE). Within the fraction of applicable systems, only a small fraction has VFDs installed. The most recent estimates for U.S. industrial motors are from a 1997 survey (U. S. Department of Energy 2002) and likely no longer accurate given the aggressive marketing from VFD manufacturers (e.g., ABB, Eaton, etc.). The report, published in late 2002, estimated that only 3.2% of pumps, 7.3% of fans, and 1.7% of compressed air systems had adjustable speed drives (which include, but is not limited to VFD). Estimates from the Swiss Agency for Efficient Energy Use (S.A.F.E) Efficiency for Electric Motor Systems (Easy) Program (Werle, Brunner, and Tieben 2014) in 2013 showed 34% and 38% of pumps and fans assessed in Switzerland have VFDs, with compressors and conveyors only at 3% and 8%, respectively. Section 10.2: Appendix B provides more information on VFD installation potential and energy savings.

It should be reiterated that, while decreasing overall energy use, introducing a VFD would add losses to the motor system by introducing non-perfect power electronics. However, even with these losses, the energy savings, and thereby cost savings, is still quite significant compared to running the motor at full speed and using a throttling valve to control flow (ABB 2012a).

4.2. WBG POWER ELECTRONICS IN VFDS

Conventional VFDs usually cause 2% - 8% of the energy they convert to be lost when running at full speed; if run at 75% rated speed (shown in Figure 4-7), VFD efficiency drops to between 90% and 97% (Waide and Brunner 2011; Vogel and Rossa 2014; A T de Almeida, Ferreira, and Both 2004) (see Figure 4-8), and even lower at lower loads. In general, compared to larger motors, low power motors have lower efficiency and a larger spread of efficiencies between very low load and full load. As VFD load decreases, so does VFD efficiency. This efficiency decline is a problem when one considers that the major selling point of VFDs is to run at lower loads. In 2015, approximately 16 TWh of electricity were lost via VFDs' inefficiency, assuming a weighted average VFD efficiency of 93.6% (based on approximate motor efficiency at the median power within a motor size class and relative energy use for each size class, see Table 4-2). The addition of a VFD to every applicable motor (see Section 10.2: Appendix B) would add further power electronics losses, in the range of 21-70 TWh -- still less than the net amount of energy that could be saved with VFD (68 - 95 TWh).

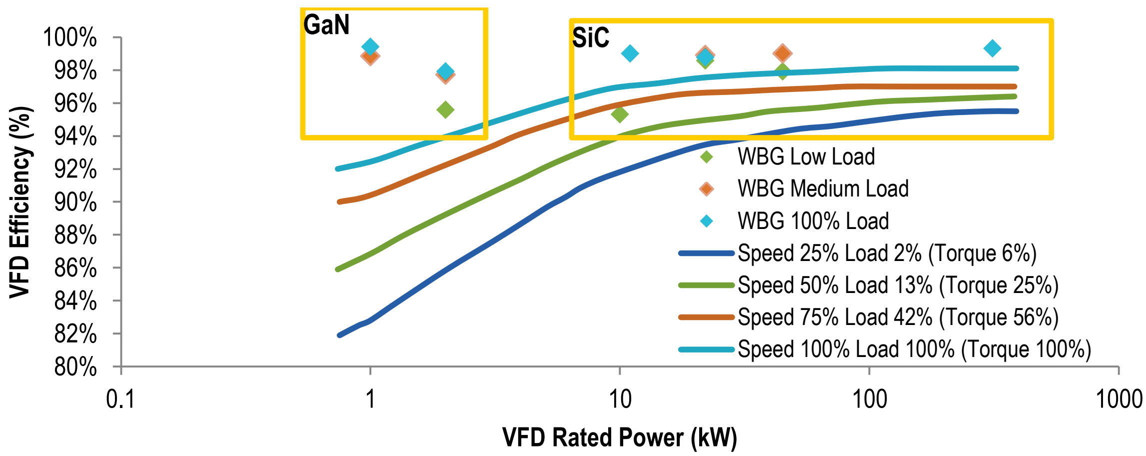


Figure 4-8. VFD efficiency by rated power and load fraction for Si-VFD (lines (Waide and Brunner 2011)**) and WBG-VFD (diamonds** (Han et al. 2014; Shirabe et al. 2012, 2013; Lai et al. 2009; Rice and Mookken 2014; Vogel and Rossa 2014; Colmenares et al. 2015)**.**

Table 4-2. VFD efficiency at 75% motor speed by motor size

Power	Median Power (Waide and Brunner 2011)	Fraction of U.S. Motor Electricity (U.S. Department of Energy 2014; Goetzler, Sutherland, and Reis 2013)	Si VFD Efficiency at 75% Speed (Waide and Brunner 2011)	WBG VFD Efficiency at 75% Speed
Low	0.19 kW	40%	90.0%	98.3% (Han et al. 2014; Shirabe et al. 2013)
Med.	9.5 kW	48%	95.8%	99.0% (Vogel and Rossa 2014; Rice and Mookken 2014)
High	750 kW	12%	97.0%	99.0% (Schelmetic 2016)
Weighted Average			93.6%	98.6%

4.2.1 Benefits of WBG PE in VFDs

Like most power conversion systems, WBG semiconductors can reduce PE losses by over 60% (Rabkowski, Peftitsis, and Nee 2013; Rice and Mookken 2014; Shirabe et al. 2013; Vogel and Rossa 2014), increasing power conversion efficiency to greater than 95%, even at lower loads (Lai et al. 2009). Figure 4-8, discussed earlier, shows WBG VFD efficiencies with different nominal power output from several different studies. Presently, there is not enough data to produce power/efficiency curves for WBG VFDs; however, the figure does show that WBG VFD efficiency does change with load fraction. The figure also shows that the difference in efficiency at different loads is less pronounced than conventional Si-VFD: for several of the data sets, the difference is nearly non-existent (e.g., Lai (Lai et al. 2009), Vogel (Vogel and Rossa 2014)). WBG peak efficiency ranges between 97% and 99.4% for SiC (power ranges between 1 kW and 1 MW) and is over 99% for GaN (though only for lower power drives).

Additionally, like most WBG applications, motor drives do benefit from the smaller size of WBG power conversion systems. Smaller size aids in positioning VFDs near the motor or even allows for co-packaged systems. However, for most motor drive applications, space is not a major constraint (e.g., most manufacturing applications); exceptions include the oil and gas industry and non-industrial applications (e.g., commercial or residential HVAC systems) (Schelmetic 2016). Beyond the reduction in passive size, the ability of WBG to run at higher frequency can also reduce the audible system noise and allow the drive to react to changes in motor demand more quickly (Shirabe et al. 2012). This is not without a downside, operating motor drives at higher frequencies can cause new problems (e.g., motor bearing damage, high levels of conducted EMI, breakdown of winding insulation), which must be addressed before WBG can be adopted into VFDs.

For conventional power electronics, increases in system temperature and voltage can have a strong impact on losses, increasing them to the point where they are unacceptable, limiting the use of VFDs. This impact is significantly less for SiC, and can be near negligible (Rohm Semiconductor 2013), making SiC potentially more suitable for medium voltage applications than Si, if appropriate packaging and higher voltage devices can be developed and commercialized. Another major advantage for WBG-inclusion in motor drives is the reduced market volume of medium voltage VFDs. The small demand for medium voltage VFDs matches the lower production volume of WBG PE and provides less "design inertia" for WBG devices to overcome (Hostetler et al. 2016). WBG-inclusive VFDs require design changes (from conventional Si-VFDs) to take full advantage of their temperature and switching capabilities. As there are fewer "standard designs" for medium voltage VFDs (Baccani et al. 2007; Martinez et al. 2005), it is easier to incorporate design changes in this application area than other WBG areas.

4.2.2 WBG PE Voltage Requirements

Table 4-1 and Section 4.1.1 discussed the power electronics requirements for the different motor size classifications, which are applicable for both conventional Si PE and WBG PE (see Figure 8-1). For low power (low voltage) drives, both GaN and SiC discretes (600 to 650V) can be used and are available commercially from most suppliers. Higher rated modules are available as 1.2 to 1.7 kV SiC MOSFET modules for medium power drives and high power drives can use 1.7kV if they operate at the lower end of medium voltage or use a high multi-level topology. Some devices are available at higher voltage; 3.3 kV SiC modules have been developed and tested MOSFET modules up to 15 kV have been developed, but are not yet commercially available (Casady and Palmour 2014). Beyond MOSFET modules, GeneSic offers PiN rectifiers and thyristors at 8 -15 kV (1 - 2A) and 6.5kV (40 – 80 A) respectively (GeneSiC Semiconductor n.d.).

Presently, if high system voltage is required, power electronics equipment can be designed to be multi-level, increasing the system voltage while still using lower voltage devices (Ikonen, Laakkonen, and Kettunen 2006). The practicability of this must be assessed for the specific system; there are positives and negatives to this approach. The most important factor to most applications will be cost; increasing the levels of a system will drastically increase the number of system devices (semiconductors, passives, and gate drivers) and is likely to increase the cost. However, high voltage devices are more expensive and sold by fewer suppliers than low voltage devices, so more levels could lead to a lower system cost (Corzine 2001). Additionally, as the number of devices in the system increases (by moving to multi-level topologies), so does the chance that any one device will fail; but with smaller and cheaper devices, it is easier to add redundancies. Multilevel power conversion is generally more complex with increasing levels, but the output is a smoother waveform with reduced harmonics, switching and conduction losses (Rodríguez et al. 2007; Ikonen, Laakkonen, and Kettunen 2006). Lastly, with multiple devices the cumulative efficiency goes down (multiple devices with power losses), but individual device efficiency may increase (higher turn-on resistance with higher breakdown voltage, leading to more switching losses). There are additional challenges and benefits to multi-level topologies, making the final decision a complicated one (Ikonen, Laakkonen, and Kettunen 2006; Corzine 2001; Giesselmann et al. 2001; Rodríguez et al. 2007). Nevertheless, the limitation of currently available WBG voltages does not eliminate WBG devices from medium voltage applications, given the option to use new topologies.

4.3. MOTOR DRIVES MARKET

4.3.1 Motor and Motor Drive Market

While European companies have the strongest market share of industrial motors, industrial motor drives are split between the three major regions (Europe, America, and Asia). Three of the top five motor drive manufacturers are European based, as are several of the smaller manufacturers. Japan and the U.S. each have one manufacture in the top five and several smaller suppliers as well (Reine 2015). As with energy use, larger motor drives cost more per drive and shift the market shares toward medium power drives. In 2013, motor drives greater than 1kV were less than 0.07% of units sold, but more than 21% of revenues. Drives less than 600V were over 98% of the drives sold, but only comprised 74% of the revenues (see Figure 4-9) (Campos 2013a, 2013b).

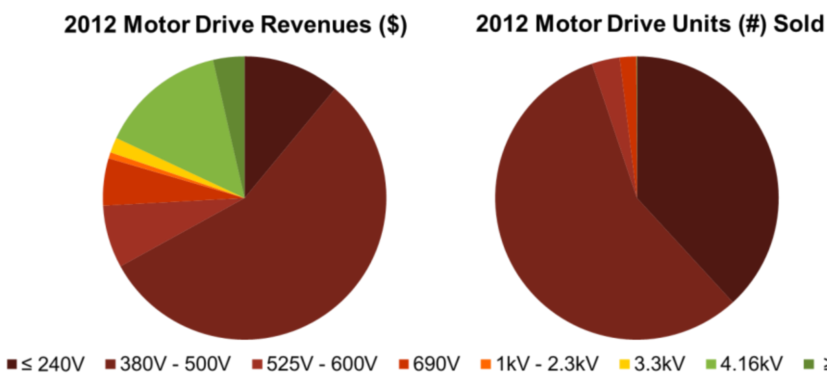


Figure 4-9. 2012 global market for motor drives by voltage (Campos 2013a, 2013b)**.**

The industrial motor drive market is the largest inverter system market ($19.4B out of $46B globally (Gueguen 2016)). For power electronics, IHS only specifically tracks modules for industrial motor drive, which itself is $1.6B. This may also include motor drives used for commercial applications (such as HVAC and refrigerators). Any discretes used for industrial motor drives might be found under “Industrial” ($2.5B) (Fodale and Eden 2015) which also includes discretes used for a variety of industrial and commercial applications: ATM machines, cash registers, factory automation equipment, environmental systems (e.g., HVAC), power transmission and 3D printers, to name a few. Residential motor drives are likely included under the “consumer” heading, with revenues around $1.0B for both discretes and modules (Fodale and Eden 2015).

4.3.2 WBG-Inclusive Motor Drive Market

Motor drives are the largest inverter market ($19.4B out of $46B (Gueguen 2016), globally in 2014) with semiconductors comprising a significant portion of this revenue ($1.6B) (Fodale and Eden 2015), making this the largest potential market for WBG devices (see Figure 4-10). However, there are currently no revenues for WBG industrial motor drives (Eden 2016), though several SiC module manufacturers offer modules “designed for” industrial equipment. Motor drives for non-industrial purposes are not explicitly tracked by market analysts; however, two WBG-inclusive motor drives systems have been released. Fuji has released a “general purpose motor inverter” with SiC devices; they claim it reduces power consumption by 20% (200 V and 400 V, 5.5 – 11 kW) (Yasushi, Yasushi, and Hiroshi, n.d.). Additionally, in 2010, Mitsubishi released a SiC-inclusive residential air conditioner in Japan that also reduced power consumption by 20% (Nozawa 2010). These and future commercial and residential motor drives might be tracked under the “other” ($7.1M) or “power supplies” ($87.1M) (Eden 2016) categories. Additionally, for WBG, IHS only provides forecast data for low voltage WBG-motor drives. Medium voltage motor drives are expected to begin integrating WBG within the next few years, but currently there is no forecast available. IHS expects the majority of the devices for low voltage motor drives to be SiC and GaN discretes. However, most of the revenues are expected to be from SiC hybrid and full modules, due to the higher cost of modules compared to discretes (Eden 2016).

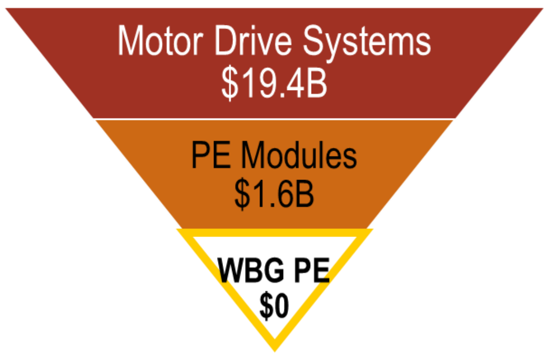


Figure 4-10. 2014 global motor drive market (Gueguen 2016; Fodale and Eden 2015; Eden 2016)**.**

It should be noted given the immaturity of the WBG market, all forecasts are extremely dependent on the current market situation, leading to drastically different forecasts depending on the assumptions. Initial projections from IHS are very optimistic, projecting a low voltage industrial motor drive market over $500M by 2022. In the following years, IHS has reduced the projected market revenue to not exceed $200M until 2023. This is due to changes in IHS’s understanding of the motor drive market (e.g., design cycles, cost-sensitivity, and reliability constraints) and time frame of the expected price drop of WBG devices (Eden 2016, 2014).

There are several motor drive OEMs that are working with WBG products but do not yet have a commercially available WBG motor drive, but do produce Si-motor drives (e.g., Toshiba). There are also several OEMs active in the WBG research community. With government sponsored research programs like the Next Generation Electric Machines program (NGEM) and PowerAmerica, there are several manufacturers developing WBG motor drives suitable for applications they target. For example, Eaton is developing 1 MW integrated motor-motor drive for oil and gas, mining, utility, and wastewater applications (Schelmetic 2016).

4.4. ENERGY SAVINGS ESTIMATION

Incorporating motor drives (like VFDs) can reduce electricity usage 10 to 35% for applicable systems, depending on the type of load (accounting for power electronics losses) (see Section 4.1.2 and in Section 10.2.3 in Appendix B). Table 4-3 shows the potential savings if WBG VFDs replaced all currently installed VFDs in 2015. In the absence of any increase in the existing number of installed VFDs, the potential savings would be approximately 12 TWh, which is comparable to potential WBG energy savings in data center and renewable energy generation applications as discussed earlier. If installed with all applicable motors, 33 TWh could be saved with WBG VFDs (in addition to the 68 to 95 TWh of electricity to be saved by VFD inclusion alone), reducing 2015 motor electricity demand from 1427 TWh to as low as 1300 TWh. By 2025, motor electricity demand is expected to grow to 1611 TWh (U.S. Energy Information Administration 2016a), which could be reduced by 77 to 107 TWh with VFDs (see Table 10-7) and an additional 38 TWh could be saved with WBG VFDs, based on the maximum VFD penetration.

Table 4-3. Estimated electricity use of Si and WBG power conversion equipment within motors & drives

Installed VFD Level	Year	Expected Annual Electricity Use (TWh/yr)		Estimated Annual WBG savings (Does not include savings from addition of new VFD)			
		Si	WBG	TWh	Millions Homes	Coal avoided (M tonnes)	CO_2 avoided (M tonnes)
As Is (3%-38%)	2015	1427	1415	12	1.1	2.3	6.0
All Applicable (30%-60%)	2015	1333 - 1360	1300 - 1327	33	3.0	6.1	17
	2025	1500 - 1529	1462 - 1491	38	3.5	7.0	20

4.5. CONCLUSION

4.5.1 Strengths

There are many benefits to WBG use in power electronics. Motor drives will benefit most from the reduction in power losses; additionally, the size and cost benefits of higher operating temperature and increased switching frequency are of interest (Eden 2016). WBG may increase the energy savings enough to increase the applicability of motor drives, allowing for more energy savings.

Discretes and modules with breakdown voltages for low voltage motors (900V, 1.2kV, and 1.7kV) are available in the current market. Modules with breakdown voltages on the low end of applicable (1.7kV) for medium voltage applications are also available. Modules with a breakdown voltage of 3.3kV have been developed and tested for rail applications (see Section 1.2.2: Challenges for WBG Integration), but are yet to be available commercially. Other medium voltage devices have been developed (Casady and Palmour 2014): PiN rectifiers and thyristors are available from GeneSiC (GeneSiC Semiconductor n.d.), and other SiC manufacturers have devices available for research.

4.5.2 Weaknesses

While motor drives hold significant potential for WBG devices, there are several weaknesses of WBG power electronics that hinder integration. As with other WBG applications, the major weaknesses stem from the relative immaturity of WBG power semiconductors; the high cost and low manufacturing level limit current WBG integration. As stated above, there are no commercially available devices suitable for higher power motor drives (3.3 kV and higher with sufficient current capabilities). Both higher voltage and current-handling WBG devices or more complicated topologies must be developed before WBG can penetrate these high power markets.

4.5.3 Opportunities

In the U.S., the Minimum Energy Performance Standard (MEPS) were established in the Energy Independence Security Act (EISA, 2007). In 2010, the National Electrical Manufacturer's Association (NEMA) established standardized efficiency levels, with Premium Efficiency (approximately equivalent to the International Technical Commission's IE3) being the standard for new motors between 1 and 200 hp (0.75 – 150 kW) beginning in 2010 (EISA, AMO Premium Eff). Beginning 2016, all *newly manufactured* motors between 1 and *500 hp* (0.75 – 375 kW, low and medium power) must meet NEMA Premium efficiency standards (U.S. Motors n.d.). The European MEPS first went into effect in 2011, regulating the efficiency of new motors placed on the market. Motor efficiency ranks were established based on motor type and size, and IE2 was mandated to be the minimum level for new motors. As of 2015, IE3 (equivalent to NEMA Premium) has become the minimum new motor efficiency level for motors between 7.5 and 375 kW. However, unlike the U.S., if equipped with a VFD, IE2 motors are also allowed on the European market. In 2017, the regulation will change to include all motors between 0.75 and 375 kW (ABB 2016b). This is expected to increase the demand for VFDs beyond the general marketing of VFD manufacturers.

For very high power applications, such as natural gas compression, motors may not be able to be driven by conventional Si power electronics without use of complex topologies due to the very high voltages (greater than 15 kV) that would be required. At these power ratings, Si-based power electronics require very complex topologies to compensate for the lower breakdown voltages that would have to be used, making electric motors with solid-state motor drives expensive, less reliable, less efficient, and thereby less common than other compressor drivers (e.g., gas turbines) (Baccani et al. 2007; Martinez et al. 2005). As SiC can withstand higher voltages than Si, WBG devices may soon be commercially available at these voltages. Using SiC will enable the development of solid-state motor drives with significantly reduced losses, allowing their use in very high power applications (Schelmetic 2016). The reduced presence of Si power electronics in this application space also means that there is less design inertia for WBG drive to overcome (Hostetler et al. 2016). Each of these potential benefits of WBG could increase VFD applicability, specifically in compressor applications, many of which are high speed, where VFDs are only installed in very few motors and applicability is currently estimated to be 30% (Anibal T. de Almeida et al. 2001; Werle, Brunner, and Tieben 2014).

While there is currently no market share for WBG within industrial motors drives, it is expected to reach over $250M by 2025 (Eden 2016). While this is still only a small portion of motor drive semiconductors, the potential market for medium voltage motor drives has not yet been quantified, nor that for non-industrial motor drives. WBG power electronics have the potential to reduce U.S. motor energy by nearly 1% if the use of VFDs remains constant. If every applicable motor system were to incorporate VFDs, an energy savings of approximately 2.5% could be realized, in addition to the 4.8% – 6.7% saved by adding VFDs.

As with data centers and renewable energy generation, WBG motor drives also can exploit the opportunities presented by the established U.S. WBG supply chains (from wafer to end-product manufacturing), as well as the strong governmental desire to increase U.S. strength in the field of WBG power electronics and decrease our fossil fuel use. Furthermore, the U.S. already has several motor drive manufacturers that are exploring WBG integration into motor drives or other applications (e.g., Eaton and GE).

4.5.4 Threats

Beyond the threats that could hinder all U.S. WBG manufacturing, there are few motor drive specific threats to WBG integration. Competition from Europe and Japan along the WBG supply chain may reduce U.S. global competitiveness.

Strengths	Weaknesses
– WBG material properties lead to reduced energy use and system cost • Faster switching • Reduced losses • Smaller footprint • Handle temp. at higher voltages better than Si – Commercial SiC devices with required breakdown voltage for LV available in US • SiC- 1.2 & 1.7 kV; GaN– 900 V	– Immature technology compared to Si • Higher cost • "Unproven reliability" • Low manufacturing level • "Design Inertia" • Design for thermal benefits • Design for high frequency switching • OEM aversion to risk – No MV (>2 kV) devices commercially available – Need higher current capabilities
Opportunities	**Threats**
– Increasing government efficiency standards (U.S. & Europe) • U.S.: EISA & NEMA • EU: new motors = IE3 or IE2 with motor drive – WBG enables use of new topologies prohibited by Si losses – Less design inertia to overcome at MV (2 – 6.5 kV) – Growing U.S. supply chain • Wafer & Discrete Manufacturing • GE switching PE to SiC	– Non – U.S. WBG technology advances • Japanese WBG inclusive motor drives – Global WBG Market • Competition from Europe, China & Japan • Asian vertical integration • U.S. company buyouts (IR → Infineon)

Figure 4-11. SWOT matrix for WBG power electronic in U.S. motor drives.

Motors require a significant portion of the U.S. electricity resources. While increasing motor efficiency will help reduce this, adding VFD, specifically WBG-VFD, will reduce electricity use even further, increasing VFD integration's cost effectiveness. WBG's inclusion into VFD may also allow for an increased applicability of VFD to very high power systems or those where energy savings from Si-VFD were not deemed sufficient for the incorporation of VFD.

5. RAIL TRACTION

The U.S. was once the leader in rail innovation, infrastructure, and manufacturing. However, by the 1950s, the federal government shifted federal support from rail to highways and airports, and thereby altering the U.S. transportation landscape from public to private. During the same time, other countries such as Germany, France, and Japan picked up the reins of rail transportation manufacturing and innovation, developing faster electric trains, and U.S.-based rail manufacturing became dominated by companies with foreign headquarters (Renner and Gardner 2010).

In the U.S., rail energy demand is only 2.3% of the U.S. transportation energy (0.6% of total U.S. on-site energy use) (U.S. Energy Information Administration 2016a). Within that 2.3%, only 4% is used for electric rail, making it a nearly insignificant electricity user (less than 0.2% of U.S. electricity demand) (U.S. Energy Information Administration 2016a). Comparatively, Italy, Korea, Japan, Russia, Germany and India are all over 50% electrified rail (by miles of track) and China is over 40% and rising (International Energy Agency 2015). Figure 5-1 shows how, in terms of 2013 rail-on-site energy use (energy used by the rail system), Russia (250 PJ), China (500 PJ) and India (160 PJ) (the nations closest to U.S. in terms of rail energy use, 525 PJ) each uses more electricity than the U.S. (180 PJ, 170 PJ, 55 PJ, and 25 PJ respectively). Despite this comparatively low electricity use, rail used 6.83 TWh of electricity in 2015, and approximately 6 to 7% was consumed by losses in the power electronics (Ciccarelli 2014; González-Gil et al. 2014; S. Su, Tang, and Wang 2016; Gunselmann 2005; Youssef et al. 2016; K. Smith 2015).

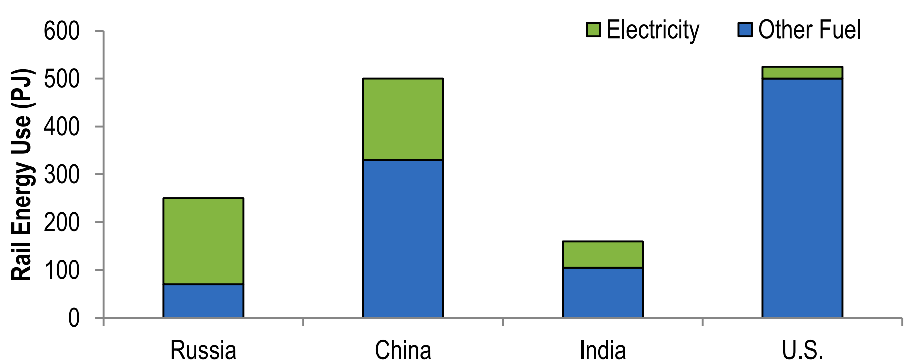


Figure 5-1. Rail electricity and other on-site energy use (International Energy Agency 2015)**.**

5.1. RAIL TRACTION OVERVIEW

Today, most of U.S. rail energy use is for freight transport (508 PJ out of 525 PJ) (U.S. Energy Information Administration 2016a). Rail freight in the U.S. uses solely diesel engines, unlike Russia and China, who also heavily employ electric rail for freight transport (International Energy Agency 2015). Passenger rail contributes to less than 10% of U.S. on-site rail energy use (17% primary energy, see Figure 5-2) and is not likely to experience any change in growth rate over the next 10 years (U.S. Energy Information Administration 2016a). There are three types of transport rail: high-speed or intercity, commuter, and transit. Table 5-1 describes each type and some of the key differences, and Figure 5-2 details rail primary energy use by type. Electric high-speed rail is used to move between cities on 25 kV AC lines (e.g., Northeast corridor Amtrak lines). Until recently, intercity rail was propelled by power cars, one or two cars devoted to housing motor systems capable of moving the entire train. Now, high-speed electric multiple units (EMU) are favored. With an EMU train, most of the train cars are self-powered, greatly reducing the overall size of the individual motor systems and increasing the train power density (Yole Development 2013a). In the U.S., intercity rail demanded 22 PJ of primary energy (18.4 PJ on-site) in 2014, 26% of which was from electricity (10% of on-site) (U.S. Energy Information Administration 2016a). Commuter rail provides shorter trips than intercity lines, moving from suburban to urban areas rather than between cities, and using 33 PJ of primary energy (19 PJ) in 2014, 62% from electricity (35% electricity on-site). For propulsion, commuter rail uses EMUs on 750V – 3kV DC lines (e.g., NJ Transit). Transit rail includes both heavy transit and light transit and both are fully electric in the U.S. Heavy transit is inner-city rail- elevated trains, subway, and other metro rail (50 PJ primary energy, 16.1 PJ on-site energy, in 2014) which runs on 600 V to 1500V DC lines. Light transit (i.e., streetcars and trams) runs on 600 to 750V DC and is a much smaller energy user (3.2 PJ).

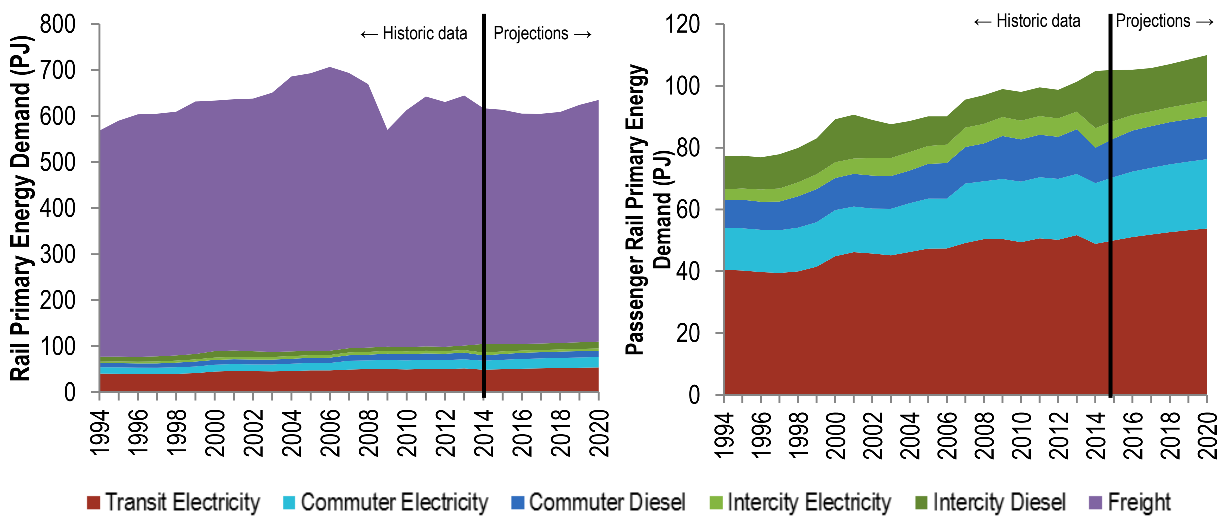


Figure 5-2. U.S. rail historic and projected primary energy use (S. C. Davis, Diegel, and Boundy 2015; U.S. Energy Information Administration 2016a)**.**

Table 5-1. Key attributes of U.S. passenger rail types (Yole Development 2013a; U.S. Energy Information Administration 2016a)

	Transit Light Rail	Transit Heavy Rail	Commuter	Intercity
Examples	Street cars, Trams	Elevated trains, Subway, Metro	NJ Transit	Amtrak (NEC) California (HSR)
Line Voltage	600 – 750 V	600 – 1500 V	750 V – 3 kV	25 kV
Current	DC	DC	DC	AC
PE Voltage	1.7 kV	1.7 – 2.5 kV	1.7 – 3.3 kV	3.3 kV+
2014 Energy Use (PJ)	3.2	16.1	19.0	18.4
% Electricity (on-site)	100%	100%	31%	16%
Global Rail Inverter Mkt Size (2012)	$39M	$51M	$2670M	$178M

5.2. POWER ELECTRONICS IN RAIL

Electric trains take electricity from the grid via a third rail or catenary line and convert it to a form that is usable by their motors and auxiliary systems. If the train is running on an AC line, there will be a transformer and rectifier to reduce and condition the voltage to DC. DC current (for both AC and DC trains) is split for the auxiliary and traction systems, depending on the demands of both, and sent though inverters to match the requirements of the systems. The auxiliary inverter feeds power for cooling systems, passenger comfort, and other loads not related to movement. The output of the traction inverter matches the demand of the train's motor, essentially like a VFD. The traction inverter also reconditions the electricity generated by regenerative breaking. The size of the power electronics within the traction inverter depends on the type of train: transit trains use 1.2 – 2.5 kV, depending on the incoming voltage; commuter trains use between 1.7 and 3.3kV; and intercity trains require 3.3kV devices or higher (see Table 5-1) (Yole Development 2013a). Overall, most trains use either 3.3kV (39%) or 1.7kV (31%), Figure 5-3 shows the percentage of units sold by different voltages for all types of trains.

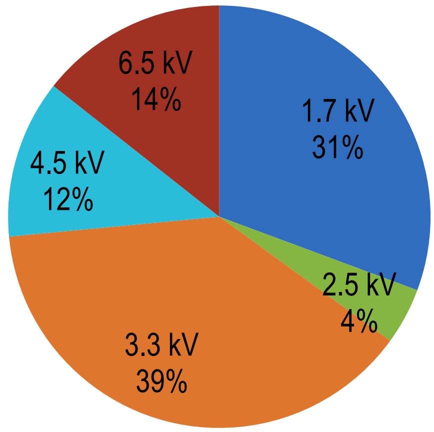


Figure 5-3. Breakdown of PE voltage by units sold globally for all types of trains in 2012 (Yole Development 2013a)**.**

The system becomes more complex than those in previously discussed applications due to regenerative braking, which send approximately one-third of the input electricity back through the traction system to be returned to the local grid or rail power distribution system or energy storage. Regenerated power must be stored or used immediately (e.g., by another train, to power the station, by a local residence), otherwise it is lost.

The overall system efficiencies for AC and DC trains are approximately equal, despite differences in traction system configuration (Ciccarelli 2014). AC trains' traction systems have additional losses due to the inclusion of a transformer and rectifier, which together are only about 90% efficient. Though they do not have an onboard transformer, DC trains stop more frequently and operate at a higher frequency and lower voltages (requiring additional power conversion from the grid at the power stations), causing the overall efficiency to be about equal to AC trains. Figure 5-4 shows the energy flow through a DC electrical power car, assuming that the car would use 100 units of energy. Within Figure 5-4, the yellow blocks represent systems with power electronics; green arrows are power flows to the wheels for movement; orange blocks and arrows are braking systems and power flows; light blue arrows are power flow though the auxiliary system; and purple arrows represent losses.

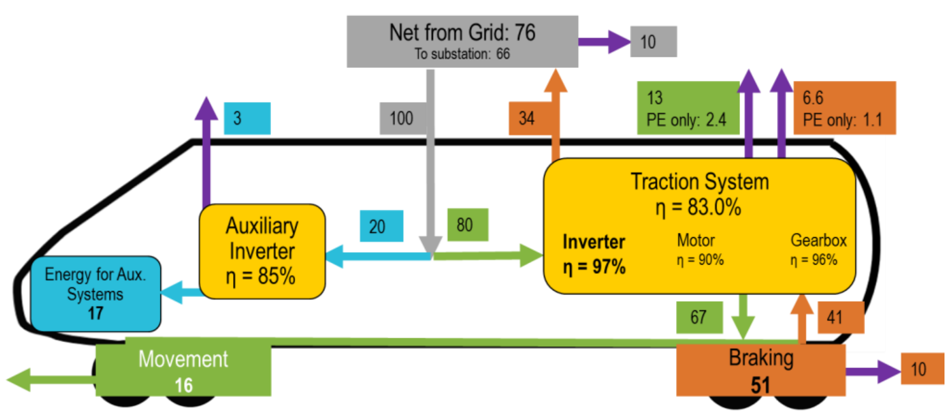


Figure 5-4. Rail energy flow for DC rail systems with Si - PE(Ciccarelli 2014; González-Gil et al. 2014; S. Su, Tang, and Wang 2016; Gunselmann 2005; Youssef et al. 2016; K. Smith 2015; Gao et al. 2014)**.**

Ten units are lost immediately in the power conversion and transmission from the substation to the catenaries or third rail. Much of the rail energy demand is lost to traction system inefficiencies (inverters, motors, gearboxes, and transformers), regenerative braking (same system as traction but backwards), and auxiliary systems (including PE losses), such that, only about 16% of the energy used is for train movement and 17% for auxiliary systems (Ciccarelli 2014; González-Gil et al. 2014; S. Su, Tang, and Wang 2016; Gunselmann 2005; Youssef et al. 2016; K. Smith 2015).

5.3. WBG IN RAIL

WBG power electronics can reduce the power lost in electric rail by about half (see Figure 5-5), from 5 – 6% to 2 – 3% of the total energy used by the train (Hamada et al. 2015; Brenna et al. 2014; Mitsubishi Electric Corporation 2015b, 2015a). This will reduce the energy required from the grid and increase the amount sent back via regenerative breaking. In addition to the efficiency gains, there are further advantages of WBG PE that greatly benefit rail transport. Reducing the weight of a train can have significant impacts on efficiency; reducing weight by 10% results in an energy savings of 3.2 – 8.6% (S. Su, Tang, and Wang 2016; Helms and Lambrecht 2007), depending on the type of train. The higher temperature capability of SiC allows for a smaller cooling system for the power electronics and the higher switching frequency allows for reduced passive size, both reducing the auxiliary and traction inverters' weight by 30 – 50% (Hamada et al. 2015; K. Smith 2015; ABB 2016a; Mitsubishi Electric Corporation 2015b). Additionally, the increased switching frequency allows the inverter and motor to react more quickly to changes in demand, further increasing efficiency. Finally, the higher frequency is less audible, and cooling fans may be eliminated, making train stations less noisy when trains are in the station (Yole Development 2012a; Mitsubishi Electric Corporation 2016b; Eden 2016).

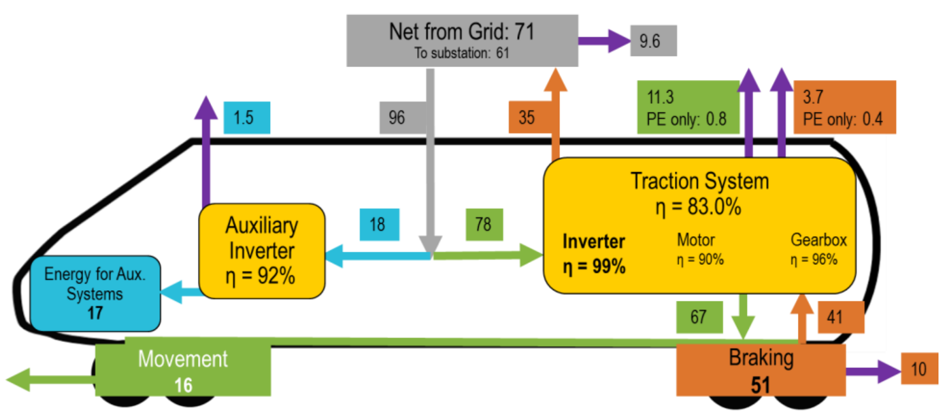


Figure 5-5. Rail energy flow for DC systems with SiC – PE (Hamada et al. 2015; Brenna et al. 2014; Ciccarelli 2014; González-Gil et al. 2014; S. Su, Tang, and Wang 2016; Gunselmann 2005; Youssef et al. 2016; K. Smith 2015; Gao et al. 2014; Mitsubishi Electric Corporation 2015b, 2015a)**.**

Not only are WBG PE advantageous for trains, but also the application of WBG in trains could be especially advantageous for WBG. One of the biggest challenges for WBG is the higher cost of WBG devices; however, the difference in cost for WBG-inclusion is very small compared to the cost of a train. Additionally, not many new trains are manufactured each year, making another challenge of WBG, the low production volume, less of a hindrance for WBG-integration with rail (Yole Development 2013a). Together, these would provide an entryway, allowing WBG to prove its advantages and reliability in the medium voltage (MV) market area, making entry into MV motor drives and H/EV easier. This is dependent on OEM's willingness to adopt new technologies; U.S. rail has high inertia and does not readily adopt new technologies whereas Japan and Europe have already begun work on WBG-integration.

As the system voltage requirements will not change with the inclusion of WBG devices, SiC – rail will require similarly rated PE as conventional rail, 1.7 kV or greater power modules (see Figure 8-1). Currently, only 1.7 kV modules are on the market, but 3.3 kV modules have been designed specifically for rail by Mitsubishi and other Japanese WBG and rail manufacturers (Sakai et al. 2015; Hamada et al. 2015; Fuji Electric Co. Ltd 2015b). Additionally Wolfspeed and other SiC device manufacturers are nearing commercialization of 3.3 kV and higher modules (John W. Palmour 2016). Still, the lack of commercially available MV modules is hampering the commercial use of SiC devices for rail traction applications.

5.4. RAIL MARKET

Rail is not one of the larger markets for power electronics, accounting for only $3.3B out of $46B sales in 2014 (Gueguen 2016) and the semiconductor modules market for rail is only $470M out of $16B (see Figure 5-6) (Fodale and Eden 2015). Rail is accounted for under the IHS category "Traction," which includes railway signaling equipment, and track controls, in addition to rail traction and auxiliary equipment. Unlike motor drives, there are currently some WBG market revenues from hybrid modules, used by several European and Japanese rail manufacturers (Yole Development 2012a; Toshiba International Corporation 2016; Mitsubishi Electric Corporation 2016a; Hitachi 2012).

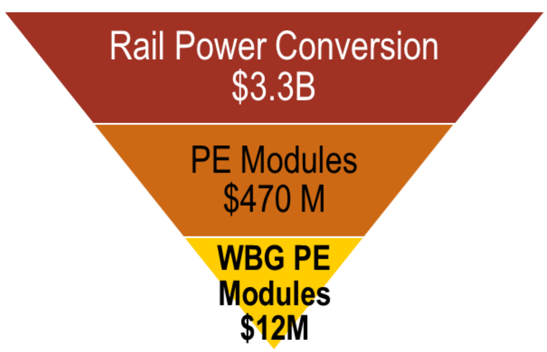


Figure 5-6. 2014 global rail inverter market (Gueguen 2016; Fodale and Eden 2015; Eden 2016)**.**

China Railway Rolling Stock Corp (CRRC), a Chinese rail manufacturer, had the largest rail market share in 2015. As a merger of the two major Chinese rail companies, Chinese Northern Railroad and Chinese Southern railroad, its main market is in China (Yole Development 2016b). After CRRC, the next top spots belong to Bombardier (Canada), Alstom (France) and Siemens (Germany) (Yole Development 2016b). Of those, only Alstom and Siemens are known to be working with SiC; however, there are other rail inverter manufacturers who have made significant strides in WBG-rail integration.

5.4.1 WBG Rail Market

WBG integration into rail power electronics has accelerated faster than early expectations. In 2014, WBG rail revenues were around $12M (Eden 2016), while the IHS market report released in early 2014 only expected $0.6M (Eden 2013). Currently, only hybrid modules are installed on traction power conversion systems, specifically, those produced by Toshiba and Mitsubishi in Japan and CSR in China, and train auxiliary inverters produced by Alstom in Europe (Toshiba International Corporation 2016; Hu, Liu, and Yang 2015; Mitsubishi Electric Corporation 2016a; Alstom 2016). ABB recently announced the inclusion of SiC in their new train battery charger, Bordline BC. The charger is one-tenth the size and 80% lighter than previous charger generations. High-speed trains running between Zurich and Milan will be equipped with the new charger (ABB 2016a). IHS expects full SiC modules to begin entering the market in 2016 and have about equal market share with hybrid-SiC by 2025 (Eden 2016), however, there have been few announcements to confirm this. ABB's battery charger is the only commercial product announced so far for 2016, and other than a showcase at InnoTrans 2016 (a large European transport industry fair) there have been no further announcements from Mitsubishi (Mitsubishi Electric Corporation 2016b). Overall, SiC is expected to comprise approximately 14% of the rail power electronics market by 2025 (Eden 2016; Fodale and Eden 2015). In addition to rail OEMs who are known to be working with SiC for rail (e.g., Alstom, Hitachi, Mitsubishi, Toshiba) (Yole Development 2012a; Fuji Electric Co. Ltd 2015b; Hitachi 2012; Mitsubishi Electric Corporation 2015b, 2015a), there are several rail OEMs who are known to be working with SiC in other areas such as motor drives or renewable converters (e.g., General Electric, Siemens, ABB and Eaton) (see Figure 1-18).

5.4.2 WBG-Rail Integration Research

Mitsubishi has completed testing of full SiC inverters on urban and N700 Shinkansen trains in Japan. Using 3.3kV modules, they have claimed significant savings in traction system weight (15%) and power consumption (40%) (Mitsubishi Electric Corporation 2015b, 2015a). Mitsubishi has also begun testing SiC in an auxiliary inverter, reducing size (15%) and power loss (30%) (Brenna et al. 2014). Fuji, in conjunction with Central Japan Railway Company, the Japanese National Institute of Advanced Industrial Science and Technology (NIAIST), Sumitomo Electric and ULVAC, Inc., has also produced a 3.3kV full SiC module and has begun testing on N700 Shinkansen in Japan (Fuji Electric Co. Ltd 2015b).

5.5. ENERGY SAVINGS ESTIMATION

Combining the energy saved from weight reductions and reduced power electronics losses (for more detail, see Section 10.2.4 in Appendix B), incorporating SiC into rail power electronics could save nearly 8% of the net energy of the system, i.e., the energy used from the grid (assuming a 6.6% reduction in energy use for every 10% reduction in train weight). In 2015, the electricity demand for rail was 6.83 TWh (U.S. Energy Information Administration 2016a); SiC-PE would have saved about 0.54 TWh. Rail transport energy is not expected to increase significantly over the next 10 years, with increases in efficiency compensating for any increase in use (U.S. Energy Information Administration 2016a). The expected energy use for rail in 2025 is 7.71TWh (U.S. Energy Information Administration 2016a), resulting in 0.61 TWh saved by SiC (see Table 5-3).

If all 2015 rail activity was electric, approximately 49.9 TWh (180 MJ) of electricity would have been required to move the 1.5 million miles and over 1.7 trillion ton-mi of passengers and freight (S. C. Davis, Diegel, and Boundy 2015), respectively (compared to 560 MJ of mixed diesel and electricity that was used (U.S. Energy Information Administration 2016a)), this does not increase significantly by 2025 (see Section 10.2: Appendix B).

Table 5-2. U.S. rail passenger and freight on-site energy use and estimated energy use for U.S. fully electrified rail system (As Is Data: U.S. Energy Information Administration 2016a)

	2015			2025		
	As Is Diesel	**As Is Electric**	**All Electric**	**As Is Diesel**	**As Is Electric**	**All Electric**
Passenger (MJ)	29	25	36	30	28	40
Freight (MJ)	508	0	144	534	0	150
Total (MJ)		562	180		592	190

Assuming the all-electric rail was used by WBG-inclusive trains, the energy demand could be reduced by about 3.0 TWh, between the reduction in power electronics losses and weight. The estimate for fully-electric rail use increases to 52.9 TWh/yr (190 MJ) by 2025, resulting in a 3.2 TWh SiC savings (see Table 5-3). Compared to other WBG applications, rail has the least potential U.S. energy savings, due to the overall low use of rail. Even assuming a fully electrified rail system, the SiC related energy savings is far less than other applications.

Table 5-3. Estimated electricity use of Si and WBG power conversion equipment within rail

Rail Electrification	Year	Annual Expected Electricity Use (TWh/yr)		PE Related Energy Savings	Weight Related Energy Savings	Total Annual WBG Savings			
		As Is	SiC	TWh/yr	TWh/yr	TWh	1000s Homes	M tonne Coal Avoided	M tonne CO_2 Avoided
As Is (U.S. Energy Information Administration 2016a)	2015	6.83	6.41	0.42	0.12	0.54	49	0.10	0.28
	2025	7.71	7.24	0.47	0.14	0.61	56	0.11	0.31
Fully Electric	2015	49.9	46.9	3.0	0.89	3.9	360	0.73	2.0
	2025	52.9	49.7	3.2	0.94	4.2	380	0.78	2.2

5.6. CONCLUSION

5.6.1 Strengths

There are many benefits to WBG integration into rail power electronics, such as the reduction in power electronics losses and the reduced size and weight benefits from higher operating temperature and increased switching frequency. While rail traction inverters already possess a high efficiency (greater than 97%), auxiliary inverters are less efficient (85%) and up to 20% of rail energy flows through them. WBG can increase both traction and auxiliary inverter efficiency and reduce the power conversion system weight by up to 50%. Considering there are between two and nine traction inverters and an equal number of auxiliary inverters per car, this could add up to significant savings.

SiC modules with appropriate breakdown voltages for the auxiliary inverter (1.2 kV – 1.7 kV) (Hu, Liu, and Yang 2015; Ocklenburg et al. 2014; Marz et al. 2015) are available in the current market. Modules with breakdown voltages on the low end of applicable (1.7kV) for rail traction are also available. Modules with a breakdown voltage of 3.3kV have been developed and tested for rail applications, but are yet to be available commercially. Other medium voltage devices have been developed (Casady and Palmour 2014), PiN rectifiers and thyristors are available from GeneSiC (GeneSiC Semiconductor n.d.) and other SiC manufacturers have devices becoming available.

5.6.2 Weaknesses

There are several weaknesses of WBG power electronics that hinder integration into rail systems. As with all WBG applications, the major weaknesses stem from the relative immaturity of WBG power semiconductors; the high cost and low manufacturing level limit current WBG integration, in addition to the less proven reliability. However, the largest hindrance to SiC rail integration is the unavailability of commercial SiC PE devices suitable for rail traction specifications, i.e., those 3.3 kV or higher with sufficient current capabilities. Additionally, there exists a strong aversion to risk for new rail technologies, as well as safety and reliability concerns.

5.6.3 Opportunities

While the aforementioned weaknesses substantially hinder the uptake of WBG devices for motor drives and H/EV, they are less of an obstruction for rail. Trains are expensive: the price difference between conventional PE and WBG PE is much less than the overall price of a train. Additionally, rail is a smaller market: not many new trains and inverters are required, making the low production volume of WBG PE less of a deterrent than for high volume applications such as H/EV. This may allow rail to be the starting ground for medium voltage WBG applications. Rail is not a major application for energy savings with WBG, due to the low use of electric rail in the U.S. If all electric rail systems were converted to WBG, rail electricity use would reduce by approximately 6%, which, even by 2025 is likely to be less than 0.5 TWh per year. Even if all rail in the U.S. were converted to electric, the resulting WBG savings would be less than 3.5 TWh in 2015, still lower than any other applications featured in this report.

As with all applications, WBG rail power electronics also can exploit the opportunities presented by the established U.S. WBG supply chains (from wafer to end-product manufacturing), as well as the strong governmental desire to increase U.S. strength in the field of WBG power electronics decreasing our fossil fuel use. Furthermore, the U.S. already has several rail inverter manufacturers, which are exploring WBG-integration into rail or other applications (e.g., Eaton and GE).

5.6.4 Threats

In addition to threats that could hinder U.S. WBG manufacturing, there are a few rail specific threats to SiC integration. In 2009, several expansions and upgrades to the U.S. rail system were proposed and funded by the American Recovery and Reinvestment Act. While some progress has been made in California, Chicago and other metro areas, many key states backed out of the plan for increased high-speed rail (e.g., Florida, Ohio, and Wisconsin) (Wilner 2014). This reduction in rail investments makes it less likely that the U.S. would replace working train power electronics systems with SiC. Additionally, U.S. rail improvements are often hampered by safety concerns and cost-driven inertia, also reducing the likelihood of U.S. SiC rail. However, as SiC rail is present in Europe and Japan, U.S. rail equipment manufacturers may begin including SiC in trains purchased for foreign use. Abroad, there are several countries increasing the electric rail lines (International Energy Agency 2015) and sponsoring new WBG rail initiatives (K. Smith 2015; Fuji Electric Co. Ltd 2015b; railway-technology.com 2015). Additionally, Japanese rail/PE manufactures have concluded testing of 3.3kV SiC-traction inverters in running trains, achieving significant energy savings (Mitsubishi Electric Corporation 2015b, 2015a; Fuji Electric Co. Ltd 2015b).

Strengths

- WBG material properties lead to reduced energy use and system cost
  - Faster switching
  - Reduced losses
  - Lighter weight
- **Train cost outweighs expense of SiC**
- **Commercial SiC devices with required breakdown voltage for LV available in US**
  - SiC- 1.7 kV; 3.3kV nearly commercial

Weaknesses

- Immature technology compared to Si
  - Higher cost
  - "Unproven reliability"
  - Low manufacturing level
  - "Design Inertia"
    - Design for thermal benefits
    - Design for high frequency switching
    - OEM aversion to risk
- No MV (>2 kV) devices commercially available

Opportunities

- Government rail incentives
  - U.S.: ARRA (for some projects)
  - EU & Japan: sponsoring research into rail efficiency improvements
  - Growing foreign rail electrification
- Small demand and high train cost would allow SiC to integrate despite low manufacturing level
- Growing U.S. supply chain
  - Wafer & Discrete Manufacturing

Threats

- Non – U.S. WBG technology advances
  - Japanese WBG inclusive motor drives
- Government
  - U.S. withdrawing funding for rail projects
  - **EU & Japan** sponsoring rail research
- Global WBG Market
  - Competition from Europe, China & Japan
  - Asian vertical integration
  - U.S. company buyouts (IR → Infineon)

Figure 5-7. SWOT matrix for WBG power electronic in U.S. rail systems.

Overall, while the expected U.S. energy savings from the adoption of SiC for rail power conversion is relatively low, SiC is expected to take over a large portion of the rail PE market. Adoption of SiC into rail could help overall WBG adoption, especially into the MV market by establishing the use and reliability of WBG in potentially high demand applications. As rail is less sensitive to costs and low production volumes, WBG's major challenges will be less of a hindrance for rail applications and could provide a steady customer for MV WBG until motor drives and H/EV are able to ramp up WBG integration.

6. HYBRID AND ELECTRIC VEHICLES

The U.S. transportation sector accounted for 29% of the 2015 U.S. energy consumption (U.S. Energy Information Administration 2016a) ; of that, 59% was light vehicles (S. C. Davis, Williams, and Boundy 2016) and 61% was fueled by gasoline (U.S. Energy Information Administration 2016a) (see Figure 6-1). Increasing CAFE standards are pushing more vehicle manufacturers to increase the number of electric powertrain vehicles in their fleets. However, the 2015 U.S. light-duty fleet (240 million vehicles) contained only around 1.7% electric powertrain vehicles (see Figure 6-2). Electricity use in transportation in 2015 was around 0.24% (U.S. Energy Information Administration 2016a) (see Figure 6-1) .

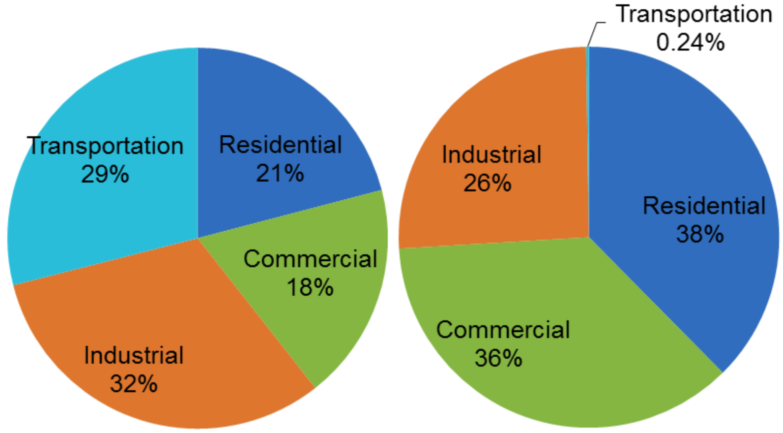


Figure 6-1. Total 2015 U.S. energy (left, 102 EJ) and electricity use (right, 13 EJ) by sector (U.S. Energy Information Administration 2016a)**.**

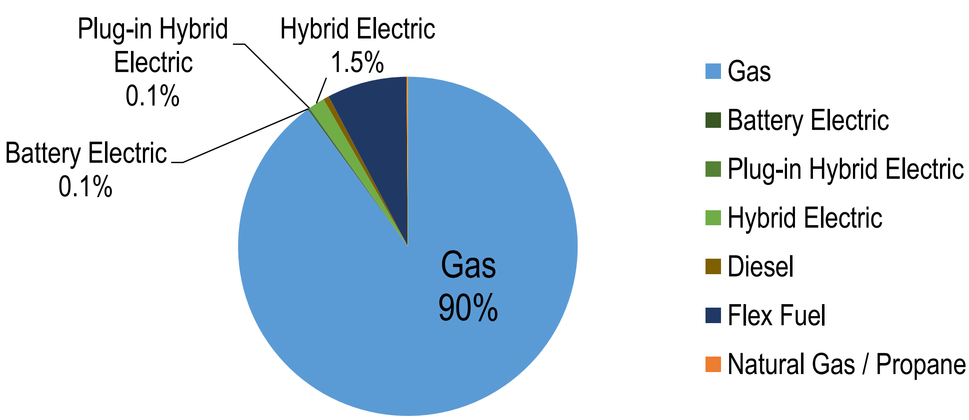


Figure 6-2. 2015 U.S. vehicle stock by fuel source (240 million vehicles) (U.S. Energy Information Administration 2016a)**.**

6.1. TYPES OF H/EV

There are three types of electric power train vehicles, collectively called H/EV in this report: battery electric vehicles (BEV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV).

6.1.1 BEV

In a BEV, the battery is charged through an on-board charger, either directly from a standard 120 or 240 V outlet or off-board/quick charger (to be considered in future work). Regenerative braking also contributes charge while driving. BEVs comprise 0.1% of the 2015 fleet (U.S. Energy Information Administration 2016a) and include vehicles such as the Nissan Leaf, BMW i3, and all models from Tesla.

6.1.2 HEV

An HEV uses an electric motor, a generator, and an internal combustion engine (ICE). HEVs use a small battery that can be charged by the engine and regenerative braking via the generator. HEVs are the most common H/EV today, with 1.5% of the 2015 fleet (U.S. Energy Information Administration 2016a) and are expected to increase significantly over the upcoming years (U.S. Department of Energy 2013) (see Figure 6-9). Many vehicle manufacturers offer hybrids, either versions of previous models (e.g., Toyota Camry hybrid and Ford Fusion hybrid) or new models (e.g., Toyota Prius). The Toyota Prius was the first mass-manufactured hybrid, introduced in Japan in 1997 and in the U.S. in 2000 (Union of Conserned Scientists n.d.). Since then, over 3.9 million Prius (including the Prius C, Prius V and the Prius Liftback) have been sold in the U.S., making it the top selling electric powertrain vehicle (U.S. Department of Energy n.d.).

6.1.3 PHEV

PHEVs are a cross between an HEV and a BEV: they can be charged via a grid connection, have a battery sized between a BEV and HEV, and comprise around 0.1% of the 2015 U.S. fleet (U.S. Energy Information Administration 2016a). PHEVs are classified by the distance they are able to travel on pure battery power; two common classifications are PHEV10 and PHEV40. A PHEV10 can only travel about 10 miles on pure battery power. In many ways, it is more like an HEV with a secondary means of charging (plugging-in). The National Household Travel Survey, conducted in 2009, showed that 72% of Americans trips are 9 miles or less, allowing the entire trip to be on grid-sourced battery power if initiated fully charged (U.S. Department of Transportaion Federal Highway Administration 2009). PHEV40 vehicles have a larger battery than PHEV10, allowing them to travel about 40 miles on a fully charged battery, which is sufficient for about 97% of trips.

6.2. PE IN H/EV

H/EVs work using several different power electronics systems to convert energy from the grid or engine to a form that can be used by the auxiliaries and motor. Most H/EVs also employ regenerative braking, where the wheels turn the generator, applying a charge to the battery instead of mechanically dissipating energy via brake pads. All H/EVs have a power control unit (PCU) which conditions power flowing between the battery pack and motor/generator or auxiliary systems. PHEVs and BEVs also have an on-board charger that converts grid electricity to be suitable for the battery. Figure 6-3 and Table 6-1 show the power systems in a H/EV.

Table 6-1. H/EV PE systems (‡ at 200 kHz – 1 MHz)

Type	On Board Charger	Inverters & HV Converter	LV DC-DC Converter
Power	~3.3 kW	12 – 400 kW	1 – 10 kW
Input V	120 – 240 V	200 – 400 V	200 – 400 V
Output V	200 – 400 V	100 – 650 V	12 – 48 V
Si Efficiency	85 – 93%	83 – 95%*	85 – 90%
SiC Efficiency	95 – 96%‡	96 – 97%*	96 – 99%
GaN Efficiency	94 – 98%‡	No data	95 – 99%‡
Power Electronics	600 – 900V Discrete	600V – 1.2kV Module or Discrete	600 – 900V Discrete
HEV	X	√	√
PHEV	√	√	√
BEV	√	√	√

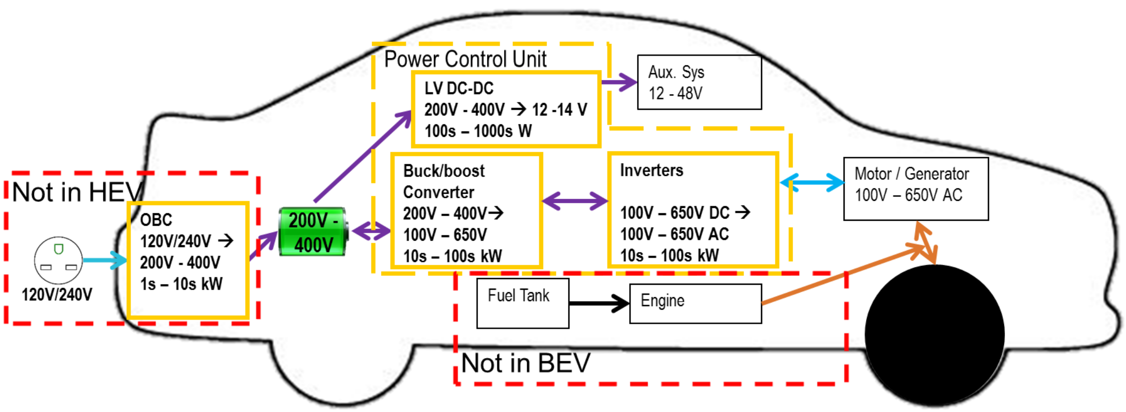


Figure 6-3. Voltage and power of PE systems in H/EV. PE systems are outlined in yellow; AC power flows are blue; DC bus is purple.

6.2.1 On-Board Charger (OBC)

BEVs and PHEVs connect the grid to the battery via the on-board charger (OBC) (see Figure 6-3). The OBC converts standard 120V or 240V from a wall outlet to 200 V – 400 V to charge the battery (J. M. Miller 2013). OBCs are usually between 3.3 kW – 10 kW (Shahan 2015) and use 600 V – 900V discrete devices, usually MOSFETs to take advantage of the higher operating frequency, resulting in systems between 85 - 93% efficient (Burak Ozpineci 2015; Karlsson and Kushnir 2013; Faria et al. 2012). The battery is connected to a DC line, which connects to the Power Control Unit (PCU).

6.2.2 Power Control Unit (PCU): Low Voltage DC-DC Converter

Part of the PCU is the low voltage (LV) DC-DC converter which converts the 200 – 400V battery power to a lower voltage (12V – 48V) for use by the auxiliary systems and storage in a low voltage battery (see Figure 6-3). The LV DC-DC converter is usually less than 1 kW. Like the OBC, it uses 600V – 900 V discretes (usually MOSFETs) and is between 85 – 90% efficient (STMicroelectronics n.d.).

6.2.3 Power Control Unit (PCU): High Voltage DC-DC Converter and Inverters

The traction drive system transforms the power from the DC bus into AC for the motor (see Figure 6-3). There is an inverter for the motor and an additional inverter in vehicles with separate generators. In many H/EV, the inverter system voltage is determined by the desire for low voltage (around 200V) battery system. Lower voltage battery systems are safer, cheaper and smaller than larger systems (Center for Advanced Automotive Technology n.d.); these concerns override any benefits of higher voltage in the inverter system. Some automotive inverter manufacturers (e.g., Toyota/Lexus, Nissan) also include a high voltage (HV), boost DC-DC converter to boost the voltage to the bus. Increasing the voltage of the DC bus via a boost converter reduces the system current, which allows the use of smaller cables and connectors, in addition to lower current losses, while still maintaining lower voltage battery systems. However, the boost converter does introduce new PE losses and a physical addition to the system (increasing system size and weight), leading many H/EV manufacturers not use a boost and keep the inverter system at lower voltages. Using SiC in the PE circuitry for the boost converter will reduce the PE losses, as well as the converter size and weight, allowing the inclusion of a higher voltage inverter system, without significant losses.

The output voltage of the inverter has to match the voltage required by the motor. Inverters handle tens to hundreds of kW, varying between small HEVs like the Prius, requiring 55kW peak, and high performance BEVs such as the Tesla Model S requiring more than 250 kW (Lambert n.d.). The power electronics for the inverter system are usually IGBT modules, though Tesla uses IGBT discretes (assembling the inverter system in-house to simplify assembly, reduce costs and allow Tesla to customize the PE cooling) (Avron 2015). Breakdown voltages range between 600 V or 650 V for mild or early non-boosted HEVs and 900 V (and 1.2 kV for future higher power motors) for boosted H/EV systems (see Figure 6-4) (Roberts 2014). With conventional Si PE, inverter systems' drive cycle efficiency ranges between 83 – 95% (using US06, Artemis urban, Empa C1, Hyzem urban drive cycles) (Ozdemir, Acar, and Selamogullari 2015; Chinthavali, Otaduy, and Ozpineci 2010).

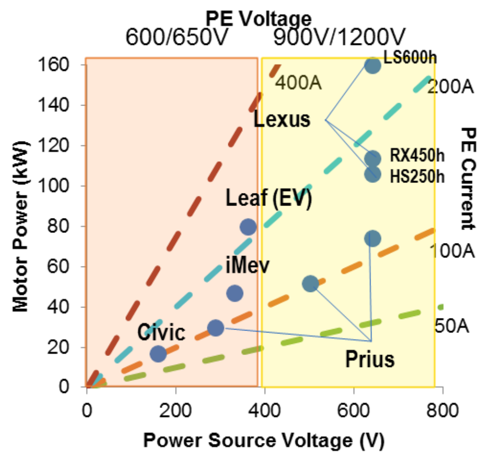


Figure 6-4. PE voltage and current requirements dependency of motor power and power source voltage with examples of past and current H/EVs (adapted from (Roberts 2014)**.**

6.3. WBG IN H/EV

In each of the power conversion steps, the power electronics are imperfect, causing significant losses that can be reduced with the introduction of WBG devices. In addition to efficiency, there are three major PE market drivers for H/EV: weight/size, reliability, and cost. Beyond the increased efficiency of WBG H/EV PE systems, WBG can also reduce system size by allowing higher switching frequency and operating temperatures. While both increased frequency and temperature will reduce the efficiency of the system, it is possible to optimize all three. Increasing the PE switching frequency, as in other applications, can reduce the passive components, reducing the size and weight of the system as well as component material costs. Additionally, it can allow the inverter to react to changes in motor demand more quickly, making the motor system more efficient at low load driving, such as city driving (Ding et al. 2016). The ability of SiC to operate at a higher temperature allows for a reduction in the PE cooling system and possibly even combining the PE cooling system with the much hotter engine cooling system in HEVs and PHEVs (Burak Ozpineci and Tolbert 2011; Rogers and Boyd 2014; Williamson and Li 2011). This, however, is still undeveloped, as other PE system components (e.g., passives and packaging) also need to be able to withstand the higher temperature of the engine cooling system (M. Su and Chen 2016). The other two market drivers (cost and reliability) are not yet to the level where H/EV manufacturers are willing to integrate WBG, but many expect that device prices will reduce within the next few years, and WBG-H/EV integration will begin (Eden 2016; Yole Development 2016e).

6.3.1 LV Converter and OBC

SiC diodes have been included in LV converters and OBC since 2014 (Eden 2016). The LV DC-DC converter and OBC are relatively low power systems, so for future H/EV systems, GaN is more favored than SiC due to the much higher switching frequency potential of GaN (Yole Development 2016e; Burak Ozpineci 2015). GaN devices are commercially available at 600V, but at low production volumes (compared to Si PE), so GaN converters and OBCs are not yet available. GaN systems can switch at 200 kHz – 1MHz, or higher, while maintaining a system efficiency greater than that of Si, thus enabling much smaller converter and OBC systems (Burak Ozpineci 2015; Nan, Yao, and Ayyanar 2015; Schulting et al. 2015; Xue et al. 2015). Additionally, for BEV and PHEV, the LV converter and OBC can be combined into a single system, sharing transformer and other components with two outputs (LV and HV) (Burak Ozpineci 2015). WBG converters and chargers can be greater than 99% efficient at lower frequencies but still greater than 94% at very high frequencies (Burak Ozpineci 2015; Nan, Yao, and Ayyanar 2015; Schulting et al. 2015; Xue et al. 2015).

6.3.2 Inverter and Boost

The use of WBG in the inverter system is expected to lead to an increase in drive efficiency. For this system, research and development has focused more on SiC, rather than GaN, due to the higher voltage capabilities of SiC (Yole Development 2016e; Burak Ozpineci 2015). Figure 6-5 compares Si and SiC H/EV inverter efficiency over a select torque and motor speed range. Comparing these to standard drive cycles, an approximation of the driving efficiencies of Si and SiC inverters can be established. The U.S. city cycle (UDDS) spends most of the time at low torque (50 Nm) and motor speeds (1000 – 2000 rpm) (Burwell, Goss, and Popescu 2013), where SiC is more efficient. For the highway cycle (HWFET), the cycle is still low torque but covers the medium motor speed range (2000 – 3000 rpm) (Burwell, Goss, and Popescu 2013), where both Si and SiC's efficiencies are approximately 97 – 98%. The aggressive cycle (US06), ranges over higher torques (a few spikes over 100 N-m) but still spends the majority of the cycle at the lower end (Burwell, Goss, and Popescu 2013). Motor speed is pushed even higher to 3000 – 4000 rpm where both Si and SiC are mostly 98% efficient, with SiC reaching 99% at higher torques and speeds. This cycle also spends more time braking, reaching large negative torques at lower rpms, where SiC is more efficient. This all implies that SiC will have a greater benefit to city and aggressive driving than to highway driving, as confirmed by other studies (M. Su and Chen 2016).

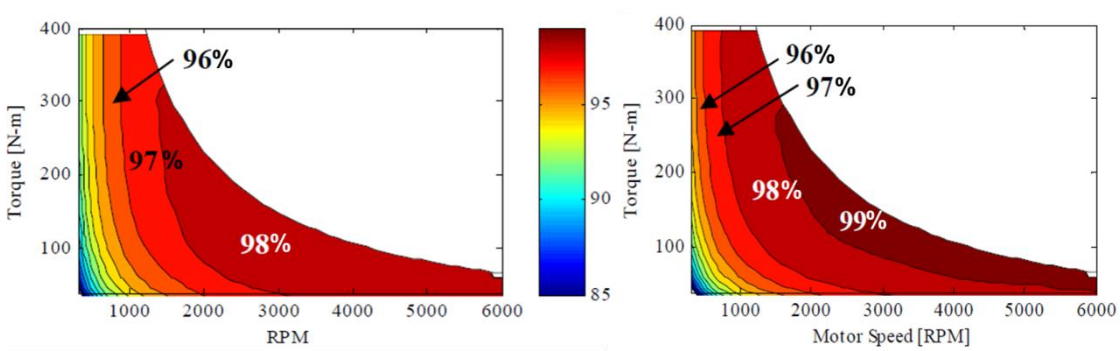


Figure 6-5. Predicted efficiency map over torque-speed range of HEV motor for Si (left) and SiC (right) based inverters (Reed et al. 2010)**.**

When tested over similar drive cycles (e.g., US06 (Chinthavali, Otaduy, and Ozpineci 2010), EPA City and Highway (M. Su and Chen 2016), and several European Urban cycles—Artemis urban, Empa C1, Hyzem urban (Ozdemir, Acar, and Selamogullari 2015)), WBG can increase inverter efficiency from baselines of 83 – 95% to over 97% (see Table 6-2). Additionally, PCUs with SiC devices have been developed and tested by several H/EV inverter manufacturers and have been shown to be more efficient, much smaller and up to half the weight of conventional inverter systems.

Table 6-2. Si and SiC H/EV inverter efficiency for representative drive cycles

Drive Cycle	Type	Citation	Si	SiC	Improvement	Reduction of losses
US06	Aggressive	(Chinthavali, Otaduy, and Ozpineci 2010)	95.1%	97.1%	2.1%	41%
EPA City	City	(M. Su and Chen 2016)	90.9%	97.9%	7.7%	77%
EPA Highway	Hwy	(M. Su and Chen 2016)	97.7%	99.7%	2.0%	85%
Artemis Urban	City	(Ozdemir, Acar, and Selamogullari 2015)	86.2%	96.6%	12%	76%
Empa C1	City	(Ozdemir, Acar, and Selamogullari 2015)	82.9%	96.0%	16%	77%
Hyzem Urban	City	(Ozdemir, Acar, and Selamogullari 2015)	87.2%	96.7%	11%	75%

6.3.3 WBG PE in H/EV

GaN or SiC devices suitable for H/EV PE are currently on the market (see Figure 8-1, located in Chapter 8). Several WBG suppliers have diode and transistor devices and modules at 600 V, 650 V, 900 V and 1.2 kV and up to 325A, many of which have at least begun AEC-101 (automotive) qualifications (STMicroelectronics 2016; John W. Palmour 2016; Wolfspeed n.d.).

6.4. H/EV MARKET

6.4.1 H/EV Suppliers

Currently H/EVs are only 1.7% of the vehicle fleet, and HEVs are 1.5%. In 2015, Toyota Prius H/EV models were by far the highest sold at 36%. This is followed by the Toyota Camry Hybrid (6%), Tesla Model S (5%), and Ford Fusion Hybrid (5%). Overall, in 2015, 54% of all H/EVs sold were Toyota or Lexus (both part of Toyota Motor Corporation), followed by Ford (12%) (see Figure 6-6). Additionally, 65% of all H/EVs sold were from manufacturers with HQs in Japan, 23% from the United States and the remainder from Korea, Germany, and Sweden.

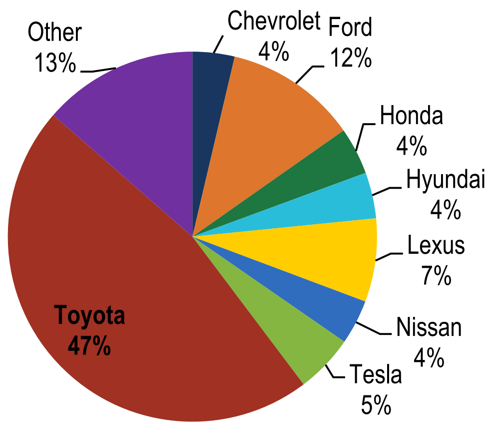


Figure 6-6. 2015 Top H/EVs sold by manufacturer. "Other" includes: BMW (3%), Kia (3%), Lincoln (2%), Fiat (1%), Infiniti (1%), Subaru (1%), Volkswagen (1%) and Acura, Audi, Buick, Cadillac, GMC, Mercedes, Mitsubishi, Porsche, Smart (< 1%) (Cobb n.d.)**.**

6.4.2 Future of H/EVs

There are several factors encouraging manufacturers to increase their H/EV offerings and increase the purchasing of H/EVs. U.S. CAFE standards are set to increase to up to 54.5 mpg (101 g/km) for 2025 vehicles (Center for Climate and Energy Solutions n.d.). The EU has set laws for a reduction in the CO_2 emissions of newly registered cars, placing CO_2 emission limits at 18% and 40% of the 2007 fleet average (158.7 g/km) by 2015 and 2021, respectively. The EU has added strict financial penalties to this: from 2019, there will be a €95 per gram over the limit penalty for each car registered (European Commission 2016). The increasingly tight global CO_2 emission policies and CAFE standards in the U.S. (see Figure 6-7, in terms of New European Driving Cycle (NEDC)) are pushing vehicle manufacturers to include H/EVs in their product fleet to meet the new standards.

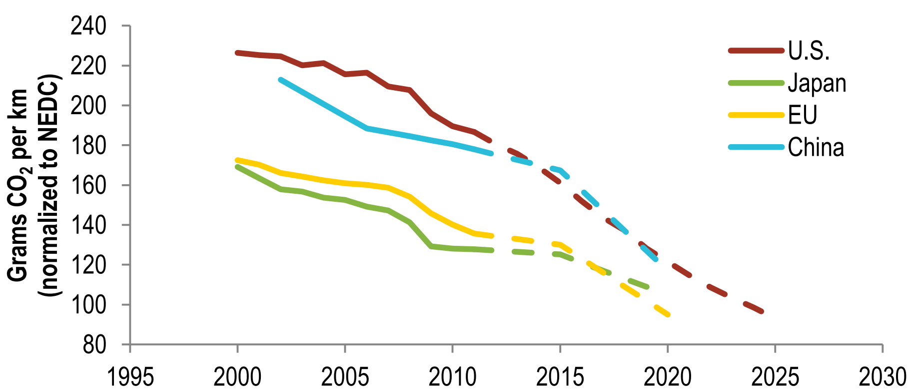


Figure 6-7. Decreasing global CO_2 standards. Adapted from (Yole Development 2015a)**.**

On the purchaser side, there has been a global increase in the ease of charging, with many countries encouraging employers to offer charging opportunities at work and increase other charging opportunities. There are also incentives and benefits associated with H/EV ownership including driving and parking privileges (e.g., use of the HOV lane), annual tax exemptions and credits, utility-based EV incentives and purchase rebates. It is generally accepted that the sales of fuel efficient vehicles such as H/EVs is directly related to the fuel prices. However, with the recent downward trend in fuel prices, there has not been a large decrease in H/EV sales. While overall H/EV sales were lower in 2015 and 2016 compared to 2014, BEV and PHEV sales have been increasing (Cobb n.d.).

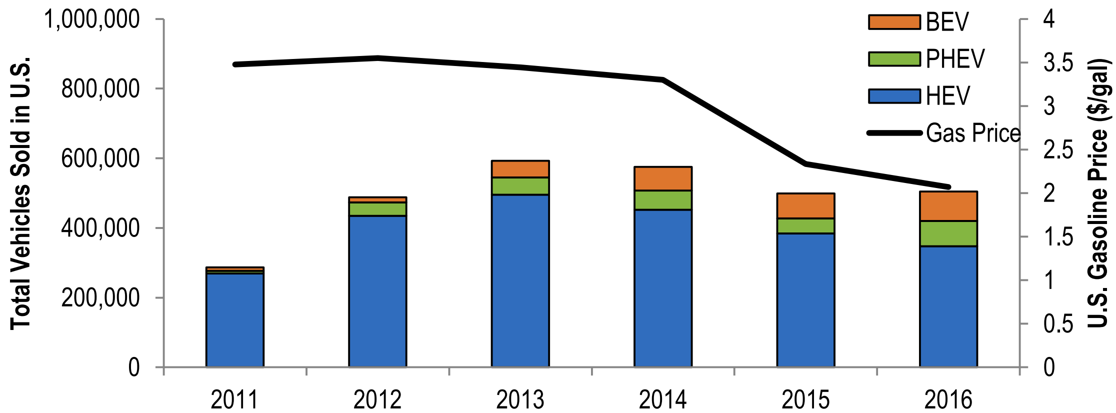


Figure 6-8. U.S. HEV, PHEV, and BEV sales with average U.S. gasoline prices (Cobb n.d.; U.S. Energy Information Administration 2017)**.**

The largest deterrent for H/EV sales is the cost; adding a full hybrid electric drive adds nearly $3000 to the cost of the vehicle (International Energy Agency 2012). One of the U.S. efforts to increase the number of plug-in electric vehicles on the road is the EV Everywhere program that combines R&D, outreach and education to reduce the costs of EV manufacturing and purchase; encourages workplaces and cities to offer EV charging; and encourages partnerships between R&D, electric utilities, the fuel industry and EV manufacturers (U.S. Department of Energy n.d.).

Given all of these factors influencing the offering and purchasing of H/EVs, the predictions of future H/EV sales and fleet makeup are varied (see Figure 6-9). With respect to the near future, the forecast of H/EV in the 2025 fleet ranges from a conservative 4.6% (EIA's Annual Energy Outlook, AEO) (U.S. Energy Information Administration 2016a) to 8.2% from IHS (Eden 2016), and a highly optimistic, 20% (Transportation Energy Futures (TEF) project) (U.S. Department of Energy 2013). Looking to 2040, the TEF predicts 67% of the fleet could be HEVs, PHEVs or BEVs, and 10% fuel cell vehicles, while the AEO predicts only 9.0% of the fleet to be H/EVs. The wide range of forecasts, even in the short-term, presents difficulties in developing projections for H/EV and H/EV components.

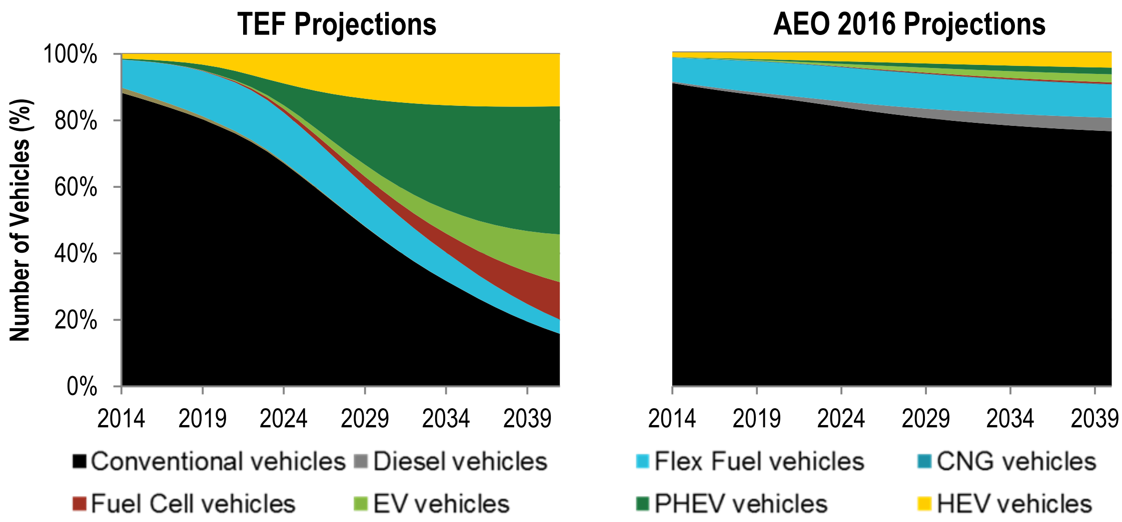


Figure 6-9. Optimistic and conservative H/EV adoption projections (U.S. Energy Information Administration 2016a; U.S. Department of Energy 2013)**.**

6.4.3 PE for Motor Drive Market

As of 2014, H/EV inverters were a very small sub-market of inverters ($2.5B out of $46B, see Figure 6-10) (Gueguen 2016). Consequently, semiconductor modules for H/EV are also a small market within PE ($415.8M out of $16B) (Fodale and Eden 2015). This is based on the "Cars & Light Vehicles Modules" and excludes "Automotive Discrete" categories from IHS for two reasons: most H/EV power conversion devices are modules and "Automotive Discretes" includes all discrete PE used in vehicles (e.g., lights, comfort, environment, safety, infotainment), many of which would not be replaced with WBG (very low voltage devices). Many forecasts (e.g., IHS, TEF) have H/EV sales greatly increasing over the next ten years, leading to a much higher automotive PE market; IHS expects automotive modules to almost reach $850M by 2019 (Fodale and Eden 2015).

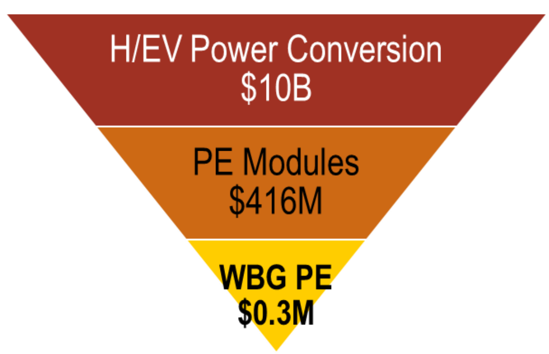


Figure 6-10. 2014 global H/EV power conversion market (Gueguen 2016; Fodale and Eden 2015; Eden 2016)**.**

6.4.4 WBG Motor Drive Market

Like the general automotive PE market, the WBG automotive market is currently very small ($0.3M out of $160M) but is expected to increase rapidly to $207M by 2019 and $1.4B by 2025, becoming by far the largest WBG PE market (see Figure 6-11) (Eden 2016). This rapid upswing is likely due to IHS' assumption that HEV shipments could overtake fossil fuel based vehicles within the next five years, with Si-PE, then transition to WBG-PE starting in 2020. Figure 6-11 also show how IHS has changed its forecast on how WBG devices will be used in H/EVs. The 2013 projection of units sold is higher than then 2016, however, the revenue is forecasted to be higher; this implies that fewer, but more expensive devices will be sold. The 2016 prediction for modules sold in 2022 is 4X higher than the 2013 prediction, implying a change in focus from the OBC and LV converter to the PSU (Eden 2013, 2016). Currently, WBG devices are used in chargers and the LV converter, according to IHS, but they do not specify who is using them. The only manufacturer advertising the use of WBG PE in their product is Shinry, a manufacturer of LV DC-DC converters for electric buses, who receives SiC devices from Wolfspeed (Cree 2013). Additionally, Delta provides the EV charger for the Chevrolet Volt, which utilizes SiC diodes (Delta Electronics 2016).

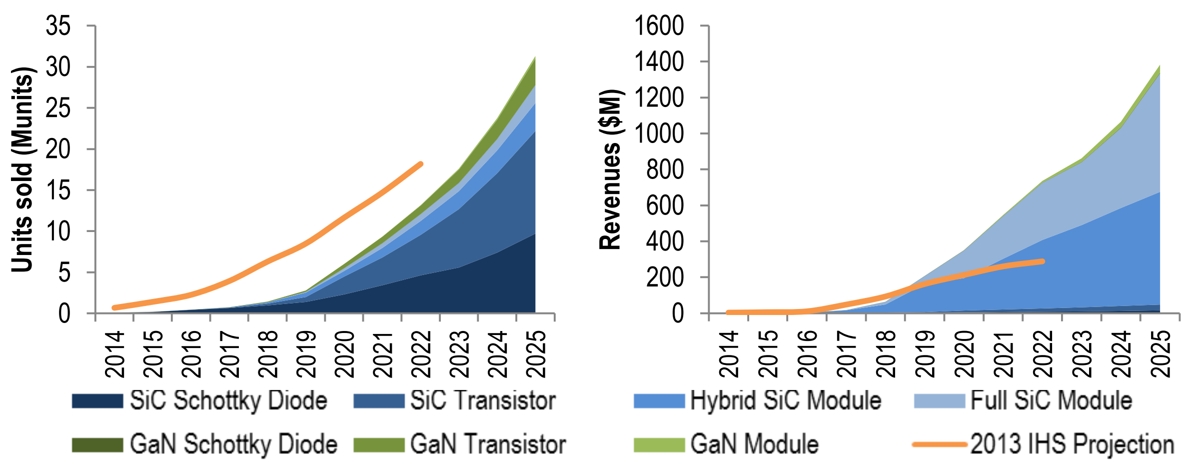


Figure 6-11. WBG H/EV PE market trends and projections (Eden 2016, 2013)**.**

Toyota is the leader in SiC for automotive applications, having built and tested an all-SiC inverter (with HV converter) in a hybrid Camry in 2015. The inverter is 80% smaller and half the weight of their standard PCU and, together with the increased PE efficiency, results in a fuel mileage increase of 5 – 10% (Toyota Motor Corporation 2016). Toyota does not plan on incorporating the inverter in their hybrids until 2020, giving SiC manufacturers time to increase the manufacturing levels, decrease the cost, and give sufficient proof of reliability. Additionally, Toyota has built a dedicated foundry for SiC device manufacturing and is a major owner of Denso, a SiC modules and inverters manufacturer that is also working on 150mm SiC wafers (Asian Technology Information Program 2013; Denso Global n.d.). In 2014 Mitsubishi announced it plans to commercialize a SiC automotive inverter by 2018 that is about half the size of a Si-inverter (Asian Technology Information Program 2013). Other manufacturers known to be working on WBG-inclusive automotive systems include Nissan, Honda, Hitachi, and Yaskawa, but no products have been announced yet.

There are only a few H/EV manufacturers working on WBG devices, however many of the other H/EV manufacturers have their power supplies manufactured by device manufacturers who provide WBG devices, suggesting that they could also begin WBG integration without disruption to the supply chain. For example, while BMW has not shown any direct interest in SiC or GaN, Infineon is one of their PE suppliers and has developed WBG devices that could be passed along to BMW.

6.5. ENERGY SAVINGS ESTIMATION

For each step of power conversion in an H/EV, there is an 8.5 – 9.5% improvement in efficiency from conventional Si-PE to WBG-PE. A substantial portion of H/EV power flows through their PE, all for BEVs, resulting in a significant energy savings potential for WBG PE. For details on the energy used by H/EV and the calculation of the WBG energy savings potential, see Section 10.2.5 in Appendix B.

Table 6-3. 2015 estimated electricity use of Si and WBG power conversion equipment within H/EV

	Vehicle Stock	Expected Annual Primary Energy Use (PJ/yr)		Estimated Annual WBG savings		
	(millions)	As Is	All WBG H/EV PE	On-site Electricity (TWh)	Gasoline (M gal)	CO_2 avoided (M tonnes)
HEV	3.7	160	149	- - -	91	1.7
PHEV	0.24	15.0	14	0.05	5.3	0.2
BEV	0.30	14.7	12.1	0.23	- - -	0.3
H/EV	**4.2**	**190**	**175**	**0.28**	**96**	**2.2**

Table 6-4. 2025 estimated electricity use of Si and WBG power conversion equipment within H/EV

	Vehicle Stock	Expected Annual Primary Energy Use (PJ/yr)		Estimated Annual WBG savings		
	(millions)	As Is	All WBG H/EV PE	On-site Electricity (TWh)	Gasoline (M gal)	CO_2 avoided (M tonnes)
HEV	7.2 – 26	260 – 950	240 – 880	- - -	150 – 540	2.8 – 10
PHEV	2.3 – 23	120 – 1200	110 – 1110	0.4 – 3.9	39 – 390	1.2 – 12
BEV	2.4 – 4.1	100 – 160	80 – 130	1.5 – 2.5	- - -	1.7 – 2.8
H/EV	**12 - 53**	**480 - 2300**	**430 – 2120**	**1.9 – 6.4**	**190 – 930**	**5.7 - 25**

Altogether, WBG integration into H/EV could have saved as much as 280 GWh and 96 million gallons of gas in 2015, and avoided 2.2 million tonnes of CO_2, as shown in Table 6-3. By 2025, the maximum savings potential could range between 50 PJ and 180 PJ of primary energy (1.9 – 6.4 TWh and 190 – 930 million gallons of gas) if all H/EV on the road were to include WBG devices. The true savings potential is much lower, as cars are replaced, on average, every 11.5 years (S. C. Davis, Williams, and Boundy 2016), and WBG PCUs are not expected to be on the market before 2017 (Asian Technology Information Program 2013; Yole Development 2016e). While they will have an initially high rate of penetration, it will be unlikely to reach 100% penetration for the forecasted year assumed here (2025).

On an individual vehicle basis, WBG could save an H/EV owner $62 - $99 per year in fuel/electricity costs (assuming $0.1265/kWh and $2.50/gal (U.S. Energy Information Administration 2016b, 2016g), see Table 6-5). BEVs can save nearly twice as much as HEVs due to the increased use of power electronics (OBC) adding more WBG savings. By 2020, the bill of materials cost of a SiC HEV 60kW inverter could only be about $60 more than a similar Si inverter (Yole Development 2015c). Even assuming significant additional costs, SiC could still pay the difference off well within the lifetime of the vehicle, but the payback period of the higher cost may not be as short as usually desired by an automotive consumer.

Table 6-5. H/EV energy savings per vehicle

	Estimated Annual Savings		
	Electricity (kWh / vehicle)	Gasoline (gal / vehicle)	Cost ($ /vehicle)
HEV	- -	25	$62
PHEV	200	22	$79
BEV	780	- -	$99

Compared to other WBG applications, the potential fuel savings for H/EVs is modest. The potential primary energy savings are the lowest of all applications other than rail. Considering the TEF projections, the potential energy savings are closer to the other applications. The biggest energy savings benefit to WBG-H/EV integration is the potential gasoline savings (about 0.2% of light-duty vehicle gasoline use in 2025 (U.S. Energy Information Administration 2016a)), which no other near-term major WBG applications can offer.

6.6. CONCLUSION

6.6.1 Strengths

There are many benefits to WBG integration into H/EV power electronics. H/EVs potentially have the most to benefit and most to risk from WBG inclusion. Each of the major WBG strengths and weaknesses are related to the major market drivers for H/EV: cost, reliability, size/weight, and efficiency. H/EV innovation is often driven by the goal of increasing fuel economy and vehicle range but tempered by cost and safety. The proven reduction in power electronics losses will contribute to this goal, especially on BEVs and PHEVs, which are more dependent on battery power and have an additional power conversion step (i.e., the OBC). WBG devices have the potential to reduce passives and cooling system size, especially with the possibility of combining systems (e.g., LV converter and OBC; PE and engine/motor cooling systems). This could reduce vehicle weight, thus, increasing fuel economy/range. Additionally, reducing the size of PE systems would allow designers more flexibility in the layout under the hood. Discretes and modules with breakdown voltages for H/EV power conversion (600 V, 650

V, 900 V, and 1.2kV) are available in the current market from several manufacturers. Additionally, several H/EV manufacturers, including Toyota (the leading H/EV manufacturer), have shown interest in WBG integration and are working on developing and manufacturing both SiC and GaN devices in-house (M. Su and Chen 2016; Toyota Motor Corporation 2016; Mitsubishi Electric Corporation 2014; Asian Technology Information Program 2013).

6.6.2 Weaknesses

Despite the proven benefits and the availability of applicable WBG devices, inclusion of WBG into H/EV has not yet begun on a large commercial scale. As stated above, cost and reliability are two major market drivers for H/EV, and WBG devices currently cost more, may not provide enough system-level cost reductions to cover the device cost increase, and have not been satisfactorily proven reliable. While some WBG devices have passed basic automotive semiconductor reliability tests, it is known by vehicle manufacturers that WBG-devices can fail differently than conventional Si devices. Therefore, Si-based qualification tests may not be applicable to WBG devices; JEDEC, the primary developer of microelectronics standards, is working on developing WBG-specific standards, but none are available yet (Keller 2016). Additionally, the low manufacturing level limits the availability of WBG devices for potential integration by any vehicle manufacturer not manufacturing their own devices.

6.6.3 Opportunities

With the number of perks, incentives and benefits from driving an H/EV increasing, the number of H/EVs on the road is also expected to increase (though at very different rates depending on the forecasting body). The United States and other world leaders are pushing for lower CO_2 emission limits, resulting in vehicle manufacturers contemplating increasing H/EV offerings to meet fleet emission standards, in addition to any pressure from potential future increase in fuel prices. As the number of H/EVs is potentially increasing, more thought is being given to H/EV power losses and ways to increase electric vehicle range. WBG devices can contribute to reducing vehicle weight (increasing fuel economy and range) while directly increasing vehicle efficiency. Using WBG devices also allows for smaller power conversion circuitry, giving more flexibility in vehicle design.

If the H/EV market increases as expected, it is likely that the WBG automotive market will also increase. Currently, both H/EV Si PE and WBG PE are small fractions of the PE market, but by 2019, Si automotive PE is expected to double and WBG based automotive PE is expected to increase by a factor of 70, then increase further to $1.4 billion by 2025.

While H/EVs do not offer the highest potential energy savings (motor drives, data centers and renewable generation all have higher potential savings), they can reduce total H/EV primary energy demand by 7.8 – 9.2% (depending on the mix of HEV, PHEV and BEV) and contribute to a reduction in gasoline demand.

As with all other WBG applications, WBG-inclusive H/EVs can exploit the opportunities presented by the established U.S. WBG supply chains (from wafer to end-product manufacturing), as well as the strong governmental desire to increase U.S. strength in the field of WBG power electronics and decrease our fossil fuel use.

6.6.4 Threats

The biggest threat to WBG use in H/EV power electronics is the cost and proof of reliability. Additionally, while WBG devices can make HEVs and PHEVs more efficient, the biggest gains are in urban, low load, stop-and-go, driving. Americans tend to spend more time on highway driving, compared to other countries, where WBG gains are less significant (M. Su and Chen 2016). Cost and driving style are apparently significant to Japanese H/EV manufacturers, many of whom are working on WBG-H/EV integration, possibly as early as 2018. Reliability and safety are major issues for vehicles, and failure of vehicle power electronics (especially in the inverter system) could have a significant impact on vehicle safety and performance. In general, competition from Europe and Japan along the WBG supply chain, such as Toyota's future use of SiC in their PCU, may reduce U.S. global competitiveness in the WBG market.

Strengths – WBG material properties lead to reduced energy use • Faster switching • Reduced losses • Much more efficient at light variable loads • Smaller footprint & lighter weight • Reduced cooling needs – Commercial SiC devices with required breakdown voltage for LV available in US • SiC- 600 V – 1.2kV; GaN– 600 V	**Weaknesses** – Immature technology compared to Si • Higher cost • "Unproven reliability" • Low manufacturing level • "Design Inertia" • Design for thermal benefits • Design for high frequency switching • OEM aversion to risk – High standards for automotive qualification
Opportunities – Increasing government CO_2 standards (Global) • U.S.: CAFE – Growing H/EV fleet – Potential to significantly reduce the size & weight of power control unit – Growing U.S. supply chain • Wafer & Discrete Manufacturing • Significant OEM WBG research (mostly Japan, but some in U.S.)	**Threats** – High cost of WBG PE devices – Non – U.S. WBG technology advances & H/EV manufacturing • Toyota – Global WBG Market • Competition from Europe, China & Japan • Asian vertical integration • U.S. company buyouts (IR → Infineon)

Figure 6-12. SWOT matrix for WBG power electronic in U.S. H/EV.

H/EV power conversion has a chance to be the largest WBG application market, possibly contributing to nearly one-quarter of the automotive PE market by 2019 and over one-third of the WBG market by 2025. While it does not have the highest energy savings potential, it does have the highest revenue potential, with automotive manufacturers only waiting for costs to go down and reliability to be fully established before beginning integration. WBG devices allow for smaller, lighter, and more efficient power conversion within H/EVs, allowing manufacturers flexibility when designing vehicle layout, battery size, maximum vehicle range, and other key aspects of H/EV design. At the end, it remains to be evaluated how the WBG-PE is cost-effective among the other options (e.g., vehicle lightweighting, powertrain improvements, electrification etc.) being considered to achieve the future vehicle emissions goal.

7. INDUSTRY PERCEPTIONS OF ISSUES AND OPPORTUNITIES FOR GROWTH OF THE WIDE BANDGAP SEMICONDUCTOR INDUSTRY

The perspectives of industry representatives from the United States and abroad were examined from a limited response rate of 12 SiC and GaN WBG semiconductor manufacturer representatives from a survey conducted in 2013 along with several responses to a survey project begun in 2012 (for more detailed responses see Sections 10.3 and 10.4). Costing information was generally not divulged as it is deemed highly proprietary. Industry participation ranged from companies who developed wafers and epitaxial layers to device and packaging manufacturers. Statements presented in this chapter express the perspectives of the participating industry representatives and have not been validated or updated by the authors.

7.1. 2012 SURVEY RESULTS

Comprehensive data from the WBG semiconductor industry survey is included in Section 10.3: Appendix C. Although the information is detailed, the industry's rapid changes make it somewhat dated. However, the data reveal an industry making rapid improvements in quality, yields, and cost. In the 2012 survey, industry representatives reported that micropipe defects had been significantly reduced and were no longer being considered an issue, and basal plane and threading dislocations were being reduced and not significantly affecting yield such that SiC yields were described as very close to Si yields. Costs remained at 3X that of Si, but were rapidly dropping and expected to drop over two years to twice Si cost. Most Si and SiC semiconductors were being made on 4" wafers, with limited production on 6", and even less on 8". Expectations were that the market would move toward more 6" production in a 5 – 8 year timeframe. No other significant bottlenecks in manufacturing were reported especially as defect issues were being or had been addressed. The remaining focus for improvements was on surface finish, high-temperature stability for DMOSFETs, and effective screening tests to assure quality and safety especially for sensitive applications, e.g., automotive standards. The current density of available SiC devices today is 200 A/cm^2, with intermediate and future goals of 400 A/cm^2 and 800 A/cm^2, respectively. Device cost was expected to decrease with a move toward 6" wafers, automated processing, and higher volumes. Packaging for discrete devices was identified as an area of interest, including achieving adequate creepage distance, thermal and resistance and parasitic inductance constraints.

7.2. GAN INDUSTRY PERSPECTIVES

From the little costing information given, it appears that quartz parts are the most expensive input to the production process. The majority of components and materials used in the production of the GaN devices came from within the United States. Cost and variability of pricing appeared to be a greater concern than availability of materials due to the already well-established LED industry. From the 2012 survey, approximate cost of 150mm GaN on Si was put at $200 for the epi, $500 for fabrication yielding a total of $730 (assuming a fully loaded fabrication run).

An average bulk GaN substrate selling price was given by a vendor as $570.00/wafer compared to $400 – $5,000, depending on deposition technology, for a 2" substrate (Evans et al. 2016). A web search reveals that the vendor sells wafers in 10 mm X10 mm, 18 mm X18 mm squares, and 30 mm round. They sell GaN templates (sapphire with a thin layer of GaN deposited epi) for $250/wafer. They also sell AlN templates. These products appear to be sold globally, though one vendor stated most were being sold in Asia. The substrates and templates are produced at less than 2X the material costs. The devices made from these substrates appear to be used primarily for LEDs, RF applications, pulsed power, and emerging power devices.

A major production issue is cracking of the GaN boules (statement made by vendor growing GaN from a sapphire seed). It was stated good GaN seeds needed to grow a boule are difficult to come by. Inconsistent yields also appear to be a problem as high quality bulk GaN substrates are costly and not readily available. Other issues of concern include a lack of qualified PhDs graduating with expertise in bulk crystal growth, and achieving high levels of reliability with devices.

Most respondents felt that the U.S. needs to be putting a significant amount of funding (>$1B annually) into material and processing technologies for it to dominate this industry. They feel R&D investment is piecemeal and a long term plan for GaN device development needs to be initiated, similar to what has been done in Asia. Japan is felt to be the leader in GaN material development with China moving ahead in the production of processing equipment. Company locations seem to be largely tied to proximity to universities, as most companies that responded to the survey have spun off from academia.

7.3. SIC INDUSTRY PERSPECTIVES

No specific costing information was given by this survey's respondents for SiC materials, though it was stated that TaC coated graphite, obtained from Europe, was the largest cost contributor to SiC epiwafer prices in SiC and was 5X the cost of SiC coated graphite parts. These are needed for multiple SiC processing parts. In the 2012 survey costing data for a SiC 150mm wafer was given as $1000, the epi as $300/wafer, fabrication another $550 for a total costing of $1850/wafer (assuming a fully loaded fabrication run).

The respondents stated that the products of their companies, SiC wafers and devices, were sold primarily to Asia and Europe and are being used in server power supplies, solar inverters, and industrial power supplies. Revenue appeared to be up substantially in 2013 for devices and wafers.

Inefficiency in the production of SiC appears to be primarily due to the lack of availability of power modules and the single source supply of the TaC coated graphite parts. Also mentioned was the shortage of engineers with expertise in SiC processing and basic SiC materials training. It was stated that only a few universities work in these areas, so it is hard to find talent with the needed background. To address issues with growing this industry in the United States, suggestions were made by the respondents that included building module manufacturing capability at the SiC die manufacturer level through private-public partnerships, providing tax incentives or credits for R&D and expansion of manufacturing capabilities, improving U.S.

energy policy to promote the adoption of more energy efficient technologies, as well as policies to encourage renewable energy and vehicle electrification. It was stated that not enough U.S. companies are working in this space, and design centers are being pushed to Asia.

The United States has high market share in SiC materials and diodes but is lagging Asia in other device markets. China is not currently a significant player. Emerging markets were stated as being primarily power supplies and low current inverters that traditionally use silicon power semiconductors. The use of SiC diodes is becoming fairly common in power applications to increase efficiency. One respondent also stated that SiC MOSFETs appear to be gradually replacing Si IGBTs in the 1200-1700 V range.

Manufacturing locations seem to be determined primarily by matching SiC expertise (located in the United States, Japan, and Germany primarily) with semiconductor manufacturing expertise (predominantly located in Taiwan, China, Korea, Japan, and to a lesser degree in Germany). One respondent stated that more investment was needed in “manufacturing technology” or prototyping efforts for companies with manufacturing facilities in the United States, and that funding early applications work would grow volume and lower costs. Significant growth was predicted in the next 20 years, particularly in inverters and motor drives.

7.4. LATEST WIDE BANDGAP INDUSTRY PERSPECTIVES

Several changes in the industry perspectives have occurred with the recent developments in this dynamic, immature industry since the last comprehensive industry survey was undertaken in 2013. In regards to SiC, capacity remains an issue. Although sales are rising, there is still insufficient capacity to fill 4” foundry manufacturing lines. Cost reduction of devices is intimately tied to volume and until it is economically advantageous to move to 6” foundry lines costs will remain high.

The success of PowerAmerica and its collaborative work with XFAB in Texas to establish a pure play SiC line alongside their 6” Si line will likely have a significant impact on pricing. Products from this venture with Monolith Semiconductor, USCi, GeneSic, and ABB along with several other SiC manufacturers have been announced, are being qualified, and will go on sale in 2017. The incorporation of the SiC line in their fab is a strategic move for XFAB as the trend of 6” Si fabs closing in the United States continues as semiconductor processing continues to move overseas to 12 and 18” lines.

The blocking of Wolfspeed’s acquisition by Infineon has resulted in some ripples within the industry. Cree remains the premier supplier of SiC MOSFETS. Their recent announcement of 900V, 160A dies will likely have a big impact in the automotive market, as prices drop and OEMs move to these technologies for efficiency, size, and weight improvements. SiC is already being utilized in vehicular chargers, and Toyota has announced the expansion of its use into the traction drive electronics. The automotive sector and data centers are seen as a large future market for SiC.

Significant progress has been made in terms of SiC and its oxide reliability issues, and the use of the body diode with MOSFET SiC appears more acceptable, eliminating the need for using discrete Schottky diodes with the switches.

Packaging remains an issue, with basically all packaging activities remaining offshore. The acquisition of APEI by Cree has made this issue even more problematic as they may soon become a captive packaging house.

The acceptance of GaN devices today is somewhat limited, depending on the application, when compared to SiC. Navitas's new technology of integrating the gate drive into the substrate of the GaN on silicon will result in a substantially smaller, lower inductance package that industries may find appealing. The fast switching ability of GaN will have substantial impact in the move to 5G communications technologies, in the low voltage markets.

Overall, the sales of WBG devices has been somewhat slower than was predicted at the time of the original survey and a lot of the issues still remain with the supply chain.

8. CONCLUSION

The United States used approximately 3870 TWh of electricity in 2015 and is expected to use over 4200 TWh by 2025 (U.S. Energy Information Administration 2016a). Silicon-based PE generally have an efficiency between 85% and 97%, this combined with the growing utilization (Tolbert et al. 2005) of PE, results in significant energy losses. Commercially available WBG PE, such as those using SiC and GaN, have been demonstrated to reduce PE losses by half or more, resulting in products with efficiencies that are usually greater than 95% and up to 99%. Initial examination of the application areas explored in this report led to a focus on SiC, although GaN is accounted for in application areas where integration is likely in the near future (e.g., power supplies, low power PV generation and H/EV OBC and converters). The material properties of SiC WBG semiconductors allow for a higher switching frequency and operating temperature than Si with reduced cooling requirements, leading to a smaller, lighter and potentially less expensive power conversion circuits(Burak Ozpineci and Tolbert 2011; Agarwal 2014).

8.1. POWER SEMICONDUCTOR MARKET

WBG device and module manufacturers are a varied group with a relatively young market today. There are many conventional power semiconductor manufacturers, LED or radio frequency discrete manufacturers, and new companies all trying to gain access into this field. Several manufacturers are involved in only one segment of the supply chain, such as device manufacturing, and others are integrated throughout several supply chain segments, from substrate to end-product manufacturing. Japanese companies tend toward full vertical integration, whereas European and American companies are more mixed, with some partially vertically integrated (e.g., Cree/Wolfspeed) and some specialized (e.g., Microsemi). The United States currently has a strong hold on SiC substrate production (e.g., Cree, Dow Chemical, II-VI), accounting for about 65% of substrate revenues (Yole Development 2016d).

Most initial SiC manufacturing was U.S.-based, at first from Cree, then Microsemi, GeneSiC, and United SiC. While the Unites States has a strong presence in the WBG device supply chain, there is significant competition from Europe, China and Japan (Hurst 2016). Europe has been ramping up SiC production for several years and Infineon, a major European semiconductor manufacturer, has purchased International Rectifier (IR) and attempted to purchase Wolfspeed (Cree's power electronics division), both formerly U.S.-based, though some of IR's SiC and GaN manufacturing capabilities have remained in the United States. Much of Japan's WBG electronic supply chain is vertically integrated (e.g., Panasonic, Toshiba, and Mitsubishi), reducing extraneous cost and increasing their ability to provide WBG devices and power conversion electronics at a lower price.

Further along the supply chain, there are U.S. manufacturers with WBG products (i.e., Enphase and Avogy) as well as many more in the R&D stage (e.g., Eaton, John Deere, Calnetix, and General Electric). Japanese manufacturers have more commercially available WBG-inclusive products (e.g., Toshiba, Mitsubishi, and Fuji) as well as significant R&D into WBG-integration (e.g., Nissan, Toyota, Honda, and Yaskawa). Additionally, while some WBG-device packaging occurs in the United States, most passives are produced in Asia, and it is expected that as production increases, more WBG-devices will be shipped there for packaging, if not device manufacturing as well, as has happened with Si devices.

8.2. CHALLENGES AND OPPORTUNITIES FOR WBG INTEGRATION

WBG power electronics have reduced switching and conduction losses, reduce energy losses, and may provide system level cost savings. Additionally, the reduced losses and higher operating temperature of WBG devices lead to smaller cooling systems and weight and size savings. Finally, faster switching allows for smaller passive devices (transformers, inductors and capacitors), and saves size, weight and cost (US Department of Energy 2015). Although presently small, the WBG industry is growing and may reach 13% of the PE market within 10 years (Eden 2016; Fodale and Eden 2015). SiC diodes, transistors and modules are available in a range of voltages from 600 V to 1.7kV from several different suppliers, and 3.3kV and 10 kV devices are near manufacturing readiness (John W. Palmour 2016; Hamada et al. 2015). The range of currently available devices allows the integration of WBG devices to begin in several application areas: data centers (UPS and power supplies), H/EV, low and mid-power PV generation, low power wind generation, motor drives, and rail operations (see Table 8-1). Medium to high power applications (e.g., renewable generation, motor drives, and rail) could also use the currently available voltage and current devices (1.2 – 1.7kV) in multilevel topologies (i.e., more devices). There are complications with this approach including having to purchase more devices and gate drives. The effectiveness of this approach is dependent on the goals of the design. The addition of 3.3 kV and 10 kV allows for simpler WBG-integration into medium to higher power applications, without the need for multilevel topologies. However, for very high power applications (i.e., wind generation and motor drives), high voltage devices are not sufficient since they must also be able to handle the very high currents necessary for high power operations. Along with SiC diodes, GaN transistors and modules are also available but at lower voltages (less than 600 V), making GaN currently only applicable for low voltage/power applications, at this time.

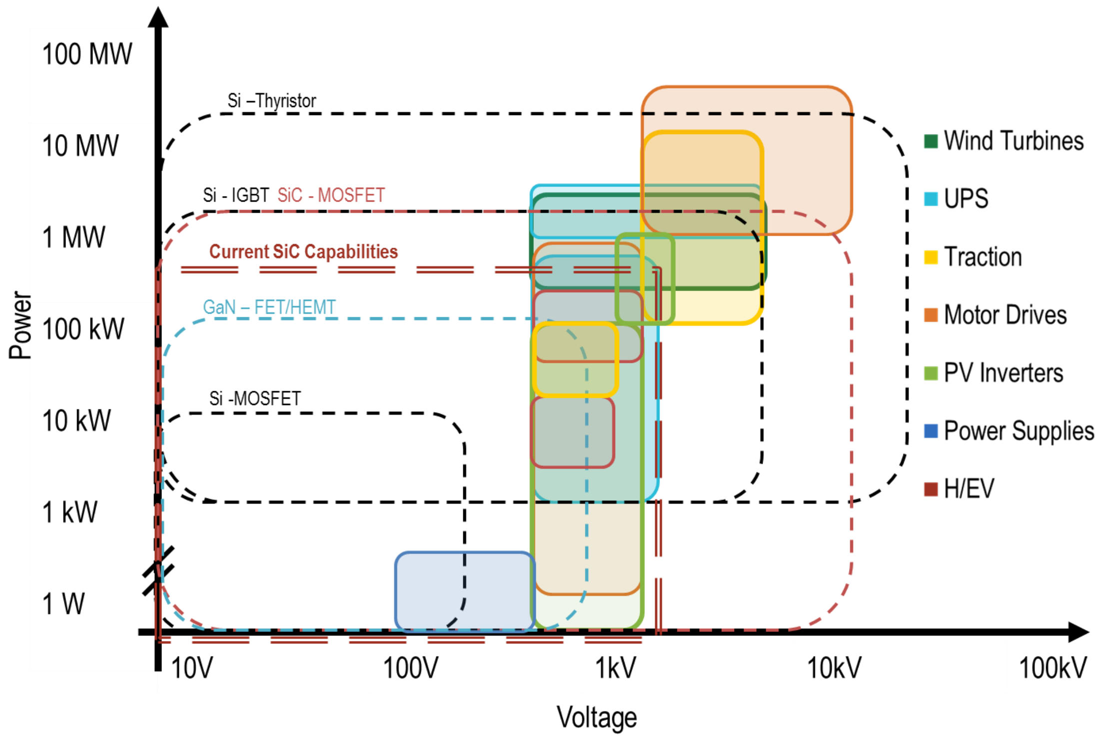


Figure 8-1. Power and voltage requirements for various applications.

Table 8-1. Power and voltage requirements for various applications

Application Area	Sub Application Area	Device Voltage (V)		System Power	
		Min	Max	Min	Max
Power Supplies	Data Centers	100	600		< 1 kW
UPS	Data Centers	600	2500	100 kW	750 kW
PV-Solar	Micro – String	600	1700	10 W	100 kW
	Central	1200	3300	100 kW	1 MW
Wind Turbine	On-shore	600	6500	400 kW	5 MW
Motor Drives	Low Voltage	600	1700	0.75 kW	375 kW
	Medium Voltage	1700	15000	375 kW	30 MW
Rail Traction	Traction	1700	6500	100kW	4MW
	Auxiliary	600	1200	20 kW	300 kW
HEV/EV	Traction	600	1200	55 kW	150 kW
	Converters/OBC	600	900	1 kW	20 kW

The relative immaturity of SiC technology is the root of most of its weaknesses: high device cost, low manufacturing levels, uncertain reliability, insufficiently high voltage, and current handling capabilities, and design issues (e.g., electromagnetic interference, passive and packaging thermal design) (M. Johnson 2015; Chow 2015). While WBG power devices still have these challenges to overcome, many governments and manufacturers have observed their potential and are working together to increase their capabilities, prove their reliability, and redesign systems to take advantage of all they can offer.

The WBG device market will have many opportunities to expand, as energy use is becoming more of a concern with the awareness of global climate change. There are several government tax incentives and research initiatives in place to promote renewable energy generation and increase the efficiency of electricity use. Additionally, the United States and state governments have formed collaborative efforts with industry and academia to promote the use and research into WBG device development, and the manufacture of WBG products ("Governor Cuomo Announces 100 Businesses Led by GE to Join $ 500 Million Partnership with State to Develop Next-Generation Power Electronics, Creating Thousands of Jobs in Capital Region and Upstate" 2014; Moniz 2014).

One of the major threats to WBG integration is the variety of alternate low cost methods of achieving energy savings by increasing efficiency (Masanet et al. 2011; Emerson 2009; Delforge and Whitney 2014; Sartor 2015). Additionally, reductions in renewable generation tax credits and the currently low price of natural gas is decreasing the number of new installations, damping any call for WBG inclusive inverters. While the future of WBG looks promising, the U.S. standing in the global WBG market is not certain. In addition to problems faced by all WBG manufacturers, the U.S. WBG competitiveness faces threats from Europe's and Japan's increasing device manufacturing capabilities and willingness to begin integrating WBG into power conversion products (e.g., UPS, rail, and HEVs). Additionally, both regions have strong government/industry research initiatives working to further their own manufacturing capabilities. However, if competition between WBG manufacturers becomes too strong, and cooperation is not embraced, it may hurt WBG's chance to displace Si (Wilson 2016). While U.S. manufacturers have produced WBG inverters, so too have European and Japanese manufacturers. Furthermore, while many U.S. and European solar inverter manufacturers have recently removed or are removing the WBG inclusive inverters (due to company restructuring and to reduce inverter costs), Japanese manufactures have introduced several in recent years.

The major challenges such as the cost, reliability, and a lack of production capacity of SiC devices were also highlighted in the industry surveys conducted in 2013. Cost reduction of devices is intimately tied to volume, and until it is economically advantageous to move to 6" (150 mm) foundry lines, costs will remain high. The success of PowerAmerica, and their collaborative work with X-Fab in Texas to establish a pure play SiC line alongside their 6" Si line, will have a significant impact on pricing. Automotive converters and data centers are seen as a large future market for SiC and the current industry focus is on expansion beyond 1.2 kV and 1.7 kV SiC devices for other potential high voltage market applications. The fast switching ability of GaN will have substantial impact in the move to 5G communications technologies, in the low voltage markets. Overall, the sales of WBG devices have been somewhat slower than was predicted, as a lot of supply chain issues remain to be resolved.

8.2.1 Data Centers

Data centers are presently responsible for over 2% of U.S. electricity use (U.S. Energy Information Administration 2016a; Yole Development 2016a). There is a push by both governments and private companies to decrease the electricity usage of data centers (Google

2016; Facebook 2016; Obama 2015), presenting an opportunity for WBG integration. There are two major power conversion steps using PE in data centers: UPS (which converts grid AC electricity into DC for storage and back to AC for transmission throughout the data center) and PSU (which converts AC electricity into the DC used by the servers). Both of these steps can have significant power losses, adding heat to the data center that must be cooled to protect the Si semiconductors in the servers. This cooling requirement is a major consumer of electricity within data centers power electronics (Emerson 2009). WBG devices can reduce PE losses, thereby decreasing the cooling demand. Although WBG power supplies (Eden 2016) and SiC UPS (Toshiba International Corporation 2015) are commercially available, their viability remains a concern as several simpler and less expensive actions to increase data center efficiency (e.g., increased server and UPS load factors, installation of VFDs for cooling fans) can be implemented.

Between the direct reduction in power conversion losses and the corresponding reduction in cooling load, medium- to large-sized data centers (those with UPS and dedicated cooling systems) could save around 220 PJ of primary energy from electricity in 2025, solely from the full inclusion of WBG power conversion. This could be increased to 270 PJ if the number of power conversion steps were reduced by switching to direct current (DC) architecture with WBG equipment. However, if other efficiency measures are put into effect, the data center energy demand, and thus, the savings potential will be reduced.

WBG-integration into data center power conversion architecture, whether AC or DC, could be an excellent application for WBG. The expected continuing growth of data centers implies that, not only is there more potential market, there will be need for *new* power conversion systems. Use of WBG-inclusive UPS and PSU could be more cost-effective in new data centers than replacing existing equipment.

8.2.2 Renewables

In an attempt to offset the environmental impact of increased energy demands, renewable energy generation such as PV-solar and wind turbines is increasing (U.S. Energy Information Administration 2016a). Unlike conventional energy technologies, where the generator output is designed to match the requirements of the grid, wind and solar generation output is dependent on the sources. Therefore, solar and wind generation, whether local or large-scale utility, requires an additional step where the generated electricity must be conditioned to match the voltage, phase, frequency and sine wave profile of the grid via inverters and other power conversion systems. If energy storage (e.g., batteries) is part of the system, then conversion systems must also match what the battery can accept, adding more power conversion systems.

Due to the significant efficiency improvements, solar inverters were an early adopter of WBG devices (Eden 2016; Advanced Energy, n.d.) but as the price of PV light modules decrease, the price of the inverter is becoming a major share of total cost, reducing use of WBG PE (Jones-Albertus et al. 2016; “Personal Communication with Martin Fornage (Enphase) 04/05/2016” 2016). While devices with suitable breakdown voltages and current handling are available for solar inverters (600 – 1700 V), the same cannot be said for wind generation. Wind generation inverters must be able to process very large quantities of power and require very high rated devices to do so. When suitable devices (1.2 – 1.7 kV and greater than 800 A for average-sized wind turbines, and greater than 3.3 kV and 200 A for large wind turbines) become available, wind inverters could not only benefit from the increased efficiency, the reduced size would allow for easier integration of equipment into the nacelle (H. Zhang and Tolbert 2008).

While WBG renewable energy inverters would have only added a modest amount of electricity in 2015, by 2025 solar and wind generation is expected to be between 6.9 – 14% of the electricity portfolio (compared to 2015's 5.5%) (U.S. Energy Information Administration 2015, 2016a), implying added generation capacity. Assuming that the new generation replaces what would otherwise be generated by the current grid mix, 110 – 220 PJ of primary energy for electricity generation would be available from 100% penetration of WBG into PV and wind. However, the future renewable generation capacity, and thus WBG potential, is very dependent on continued government support for renewable energy (U.S. Energy Information Administration 2016a), making the future of this application area very uncertain.

8.2.3 Motor Drives

Motor systems use approximately 40% of U.S. electricity (U.S. Department of Energy 2014). Motor drives, often variable frequency drives (VFD), change the electricity flow into the motors to match the speed variations and power requirements of the system, reducing power consumption but adding electrical losses. WBG devices can reduce these losses with a smaller motor drive that may be easier to retrofit into existing motor systems or co-package into newer motors. Most motor systems are low power systems (less than 4 kW) and most motor energy is used by medium power systems (between 4 and 375 kW) (Waide and Brunner 2011). GaN and SiC are both potentially beneficial for low power motors, such as those in home air conditioning units, but only SiC is currently expected to be utilized for larger, industrial motor drives (medium or high power) (Eden 2016).

Despite their cost savings benefits, motor drives are not installed on the majority of motors. They are most beneficial to pump and fan motors, where the cubic relationship between motor speed and power allows large energy savings for motor speed reductions (Waide and Brunner 2011). Correspondingly, they are more likely to be installed with those types of motors, but a recent survey found that less than 40% of pumps and fans had VFDs installed (Werle, Brunner, and Tieben 2014). Compressors and conveyors have a lower energy savings potential, which may contribute to the lower fraction of installed VFDs. The same survey found that less than 10% of conveyors and less than 5% of compressors have VFDs (Werle, Brunner, and Tieben 2014). Additionally, while not all motors have the variable loads that make VFDs most beneficial, they could benefit from the smoother starts of achieved with VFDs.

While SiC VFDs would provide energy benefits to all variable load motor systems, they have the potential to increase the system's power density such that installation becomes attractive where they are currently deemed not cost-effective. It is also possible, when suitable devices become available, SiC PE will increase the applicability of motor drives for very high power motor systems, such as those for natural gas compression, where Si drives are large and too inefficient to be used (Agarwal 2014; L. Xu 2016). Another opportunity for SiC motor drive integration is from the increasing global motor efficiency standards. These are changing to require higher efficiency motors or motor systems with drives and may eventually demand efficiencies higher than what can be obtained with Si.

Assuming full WBG integration and the addition of VFDs to all motor drives applicable (those having variable loads, such as data center cooling fans), 410 PJ of primary energy for electricity could be saved in 2025 via WBG power conversion. If no new VFDs are installed between 2015 and 2025, savings would only be 150 PJ of primary energy. This application area has the largest potential energy savings of all explored but also has some of the biggest challenges for WBG integration such as overcoming design inertia, high voltage and current handling requirements for medium and high power drives and demonstrating cost-effective, reliable drives.

8.2.4 Rail

A few WBG devices with sufficiently high voltage for rail devices are currently on the market; 3.3 kV devices have been developed and tested in urban- and high-speed trains in Europe and Japan (Hamada et al. 2015; Fuji Electric Co. Ltd 2015b; John W. Palmour 2016). Electric rail systems include many power conversion steps, and, at minimum include a variable frequency drive to meet train speed/motor demands. If the train uses regenerative breaking, the electricity is also conditioned to return to the grid. Additionally, auxiliary systems require another power conversion step to match those loads. SiC integration into rail PE systems will not only increase the efficiency of each power conversion but will lighten the train, further reducing electricity demand.

Rail traction inverters may be a breakout application for medium voltage SiC devices if OEMs and transit authorities' risk tolerance accommodates SiC technology. Two of SiC's major challenges (high cost and low production volume) are less challenging for rail applications. Trains are expensive, easily absorbing an additional cost from higher priced SiC electronics. Furthermore, there is a low demand for new trains, and, consequently, the low production volume of SiC will not hinder SiC train integration (Yole Development 2013a). While the introduction of SiC PE into rail could save up to 4.5% of rail electricity use, it will not provide significant energy savings in the U.S. (6 PJ of primary energy in 2025) due to the low level of rail electrification. Even if all rail in the U.S. was converted to electric rail, only 50 PJ of primary energy would be saved due to WBG PE.

8.2.5 H/EV

Hybrid/ electric vehicles (H/EV) are expected to be the largest revenue WBG application area by 2025 (Eden 2016). H/EV can greatly benefit from most of WBG's strengths, making it very attractive to vehicle manufacturers. Beyond the increased efficiency provided by WBG PE, the higher frequency switching allows for size and weight reductions, allowing vehicle manufactures more flexibility in vehicle layout and battery size. Also SiC system efficiency at low loads, such as city driving, can be much higher than Si, having a greater effect on fuel economy than at high loads (Ding et al. 2016). The higher temperature handling capability of SiC could allow for OEMs to include the inverter in the higher temperature cooling loop, further decreasing the traction system size and weight (Burak Ozpineci and Tolbert 2011; Rogers and Boyd 2014; Williamson and Li 2011). Finally, like rail traction, many H/EVs have regenerative braking, meaning electricity must be conditioned again when braking. SiC is presently being explored for traction inverters, diodes are used in low voltage DC-DC converter and on board chargers and all SiC and GaN could be utilized in the future.

In 2025, H/EVs could account for between 5.0 – 20% of the U.S. vehicle fleet (U.S. Energy Information Administration 2016a; U.S. Department of Energy 2013). If all of these had WBG based PE, they could save approximately 40 – 180 PJ of primary energy, or 1.9 – 6.4 TWh of electricity from BEV and PHEV and 190 – 930 million gallons of gasoline from HEVs and PHEVs. WBG devices are currently available in OBC and LV converters but is not likely to be included in the inverter systems before 2017 (Mitsubishi Electric Corporation 2014; Yole Development 2016e).Widespread integration is currently hampered by cost, industry standards and safety concerns.

8.3. WBG ENERGY SAVINGS OPPORTUNITIES

WBG-integration into each of the application areas will result in energy savings, though some are quite small. Table 8-2 includes the forecasted energy demand and estimated energy savings for each of the applications discussed in this report. Energy savings are presented as a range, which is specific to each area. The energy savings for each application also assumes 100% market penetration of WBG into the power electronics of the application. Over the five application areas, it was estimated that WBG devices could, at maximum, reduce the 2025 United States' electricity demand by 1.2 – 2.2% and gasoline demand by 0.3 – 1.1B gallons.

Table 8-2. WBG potential energy savings for various applications in 2025

Application Area	2025 Forecasted Demand	2025 WBG Savings			
	Primary Energy (PJ)	Primary Energy (PJ)	On-site Electricity (TWh)	Gas (B gal)	CO_2 (M tonnes)
Data Centers	1,300	300 - 350	27.1 – 31.8	- - -	14 - 16
Renewables*	1,100 – 2,200	110 – 220	9.47 - 19.8	- - -	4.0 – 8.2
Motor Drives	17,900	150 – 410	13.9 – 37.9	- - -	7.3 – 21
Rail Traction	90 – 600	6 – 50	0.47 – 3.23	- - -	0.3 – 2.1
H/EV	480 – 2,300	40 – 180	1.88 – 6.41	0.3 – 1.2	3.7 - 18
Total	**20,800 – 23,700**	**600 – 1,210**	**52.8 – 99.1**	**0.3 – 1.2**	**29.3 – 65.3**

8.3.1 Summary

WBG devices have been proven to increase the power density of power conversion systems in real world situations. In addition, WBG devices may open up the applicability and utilization of semiconductor power conversion devices, such as UPS, VFDs and wind inverters, where a Si-power converter may not have been used due to inefficiencies or size constraints. WBG is expected to continue or begin integration into the discussed applications within the next five years, leading to a possible market of $3.7 billion by 2025.

While the United States was once the leader in WBG wafer and device manufacturing, with the loss International Rectifier (Infineon 2015) and the growth of foreign WBG capabilities, itis losing its place on top. There is, however, still a strong WBG presence and growth in the Unites

States, with companies like X-Fab ramping up manufacturing in Texas (Manners 2016), and GE ramping up its SiC capabilities (Point the Gap 2016) and the research consortiums, PowerAmerica and NY-PEMC, promoting WBG education and two different approaches to WBG manufacturing.

All of the application areas discussed can benefit from reduced energy losses and will have a share in the WBG market in years to come. Due to the large amount of electricity used by motors, WBG integration into motor drives stands to have the largest energy impact. Data centers, renewable generation, and hybrid/ electric vehicles follow. However, the future of these applications is not certain. The energy use of data centers could remain steady over the next few years if other energy savings strategies (such as removing “zombie” servers and UPS) are implemented (Shehabi et al. 2016), reducing WBG energy savings. Renewable energy and H/EV market shares are very dependent on future gasoline prices, energy policies (such as CAFE standards in the U.S.) and continued government support, therefore, renewable generation and H/EV sales may not reach the forecasted levels. This would result in much lower energy use, and thus, WBG energy savings potential for the applications. Rail, due to the very low level of electrification in the U.S., has by far the lowest energy potential. In terms of market, WBG devices for hybrid/ electric vehicles have the highest expected market potential, but is, again, highly dependent on the market. PV inverters are expected to be the next highest WBG market, with industrial motor drives, rail, and UPS following. Wind is expected to be the lowest source of WBG revenue; devices necessary for wind PE still need to be developed and are likely to be expensive.

Low to medium power applications (i.e., data centers, PV-solar, and H/EVs) represent a large portion of the WBG market and energy savings potential, and several U.S based manufacturers (e.g., Dow Corning, Cree, Wolfspeed, Microsemi, GeneSiC and United SiC) can provide appropriate WBG wafers and PE devices (600 V – 1.7 kV) ready to be integrated into WBG power conversion circuitry. U.S. based manufacturers, such as Enphase, GE, and Ford are working with WBG devices. Research consortiums, such as PowerAmerica and NY-PEMC, are helping manufactures (e.g., John Deere, GE, and Toshiba) bridge the gap to higher power applications where higher voltages devices are not quite ready and new conversion designs must be considered. Continued success in WBG integration is dependent on the continuation of support for the clean energy application areas (i.e., renewable generation and H/EVs) and a continued focus on energy use reduction (e.g., data centers, motor drives).

While the future of WBG within the applications discussed here is not certain, it is becoming an established segment of power electronics. Additionally, there are still high power and high frequency applications to be explored; future work by authors will include process heating, medical applications, grid/smart grid infrastructure, wireless charging, and MHz radio frequency (5G) devices with a significant focus on GaN applications.

REFERENCES

ABB. 2012a. “ACS 1000 , ACS 1000i Medium Voltage AC Drive for Control of 315 to 5000 kW Motors.” https://library.e.abb.com/public/4964494671461df8c1257a5200465ba1/ACS 1000i_EN_V2.pdf.

———. 2012b. “World’s Most Powerful DC Data Center Online.” http://www.abb.com/cawp/seitp202/187b2f29acaea090c1257a0e0029fb1a.aspx.

———. 2014a. “What Is a Drive?” 2014. https://library.e.abb.com/public/790a1d33283b45bbbaebb8deb4de8124/ABB_what_is_a_drive.pdf.

———. 2014b. “What Is a Drive?” 2014. https://www.youtube.com/watch?v=JJbZSCSCIDg&feature=youtu.be.

———. 2016a. “ABB Launches Most Compact Silicon Carbide Battery Charger for All Rail Applications.” http://www.abb.com/cawp/seitp202/f50ed0ed8e5bec78c125802f0042cbb2.aspx.

———. 2016b. “EU MEPS Efficiency Requirements for Low Voltage Motors Updated for Stage 3 Requirements from January 1, 2017.” https://library.e.abb.com/public/556bb40e10b1b162c1257d8900443435/EU_MEPS_brochure_updated eff levels January 1, 2015.pdf.

Abbatelli, Luigi, Michele Macauda, Giuseppe Catalisano, Albert Boscarato, and Daniel Kohout. 2014. “Cost Benefits on High Frequency Converter System Based on SiC MOSFET Approach.” In *PCIM Europe Conference Proceedings*, 761–64. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6841303.

Advanced Energy. n.d. “Technical Datasheet REFU Sol 020K-SCI.” http://www.advanced-energy.com/upload/file/refusol/technisches_datenblatt_refusol_020k-sci_en.pdf.

Agarwal, Anant. 2014. “WBG Revolution in Power Electronics.” In *IEEE Workshop on Wide Bandgap Power Devices & Applications*. Knoxville, TN.

Agarwal, Anant, Laura Marlino, Robert Ivester, and Mark Johnson. 2016. “Wide Bandgap Power Semiconductor Devices and Their Applications.” In *46th European Solid-State Device Research Conference (ESSDERC),* 95.

Akerlind, Ingrid Bonde, Parisa Bastani, Irene Berry, Kandarp Bhatt, Alice Chao, Eric Chow, Valerie Karplus, et al. 2015. *On the Road toward 2050*. Edited by John Heywood and Don MacKenzie. https://energy.mit.edu/wp-content/uploads/2015/12/MITEI-RP-2015-001.pdf.

Almeida, A T de, F.J.T.E. Ferreira, and D Both. 2004. “Technical and Economical Considerations in the Application of Variable Speed Drives with Electric Motor Systems.” *IEEE Transactions on Industry Applications* 41 (1):136–44. https://doi.org/10.1109/ICPS.2004.1314992.

Almeida, Anibal T. de, Fernando J.T.E. Ferreira, Paula Fonseca, Bruno Chretien, Hugh Falkner, Juergen C.C. Reichert, Mogens West, Sandie B. Nielsen, and Dick Both. 2001. “VSDs for Electric Motor Systems.” http://www.watergymex.org/Watergy Toolkit/resources/54_VSDs_Save_Energy.pdf.

Alstom. 2016. “Traction Systems and Components.” http://www.alstom.com/Global/Transport/Resources/Documents/brochure2014/Traction Systems and Components - Brochure - English.pdf?epslanguage=en-GB.

Asian Technology Information Program. 2013. “Asian Auto Digest: Volume 44.” Vol. 44. http://atip.org/index.php/atip-publications-2/atip-digests/automotive/8462-asian-auto-digest-volume-44.

Avelar, Victor, Dan Azevedo, and Alan French. 2012. “PUE^{TM}: A Comprehensive Examination of the Metric.” http://www.thegreengrid.org/~/media/WhitePapers/WP49-PUE A Comprehensive Examination of the Metric_v6.pdf.

Avogy. n.d. “The Laptop Charger Reimagined.” Accessed June 8, 2016. http://avogy.com/products/zolt/.

Avron, Alex. 2015. “In a Tesla Model S, There Is No IGBT Packaging Trick.” Point the Power. 2015. http://www.pointthepower.com/on-tesla-electric-vehicles-semiconductor-packaging/.

AWEA. 2011. “Wind Energy Industry Manufacturing Supplier Handbook.” *Wind Energy Industry Manufacturing Supplier Handbook*. http://www.awea.org/Issues/Content.aspx?ItemNumber=4611.

Baccani, Roberto, Richard Zhang, Tommaso Toma, and Andrea Iuretig. 2007. “Electric Systems for High Power Compressor Trains in Oil and Gas Applications: System Design Validation Approach and Performance.” In *Proceedings of the Thrity-Sixth Turbomachinery Symposium*, 61–68.

Blaabjerg, Frede, Zhe Chen, and Soeren Baekhoej Kjaer. 2004. “Power Electronics as Efficient Interface in Dispersed Power Generation Systems.” *IEEE Transactions on Power Electronics* 19 (5):1184–94. https://doi.org/10.1109/TPEL.2004.833453.

Brenna, Morris, Federica Foiadelli, Dario Zaninelli, Davide Barlini, and Alstom Transport S A. 2014. “Application Prospective of Silicon Carbide (SiC) in Railway Vehicles.” In *AEIT Annual Conference - From Research to Industry: The Need for a More Effective Technology Transfer (AEIT)*, 3–8. http://ieeexplore.ieee.org/document/7002062/?arnumber=7002062&tag=1.

Brown, Richard, Eric Masanet, Bruce Nordman, Bill Tschudi, Arman Shehabi, John Stanley, Jonathan Koomey, et al. 2007. “Report to Congress on Server and Data Center Energy Efficiency: Public Law 109-431.” http://eprints.cdlib.org/uc/item/74g2r0vg.

Brunt, E. V. van, L. Cheng, M. J. O’Loughlin, J. Richmond, V. Pala, and J. Palmour. 2015. “27 kV, 20 A 4H-SiC N-IGBTs.” *Materials Science Forum*, 847–50. https://doi.org/10.4028/www.scientific.net/MSF.821-823.847.

Burger, B, D Kranzer, and O Stalter. 2008. “Cost Reduction of PV-Inverters with SiC-DMOSFETs.” *Integrated Power Systems (CIPS), 2008 5th International Conference on* 49 (0):1–5.

Burwell, Malcolm, James Goss, and Mircea Popescu. 2013. “Performance/cost Comparison of Induction-Motor & Permanent-Magnet-Motor in a Hybrid Electric Car.” In *Techno Frontier 2013*. Tokyo, Japan. http://www.slideshare.net/mcburwell/techno-frontier-2013-m-burwell-ica-ev-traction-motor-comparison-v18-eng.

Campos, Rolando. 2013a. “Motor Drives Report - Low Voltage.”

———. 2013b. “Motor Drives Report - Medium Voltage.”

Casady, Jeff, and John Palmour. 2014. “Power Products Commercial Roadmap for SiC from 2012-2020.” In *HMW Direct-Drive Motor Workshop*. http://www.nist.gov/pml/high_megawatt/upload/Approved-Cassady_Palmour-FINAL_short_release.pdf.

Center for Advanced Automotive Technology. n.d. “Converters, Inverters, and Controls.” Accessed December 8, 2016. http://autocaat.org/Technologies/Power_Electronics/Convertors_Invertors_Controls/.

Center for Climate and Energy Solutions. n.d. “Federal Vehicles Standards.” Accessed December 8, 2016. http://www.c2es.org/federal/executive/vehicle-standards.

Chinthavali, M., P. Otaduy, and B. Ozpineci. 2010. “Comparison of Si and SiC Inverters for IPM Traction Drive.” *2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings*, 3360–65. https://doi.org/10.1109/ECCE.2010.5618319.

Chow, T. Paul. 2015. “Wide Bandgap Semiconductor Power Devices for Energy Efficient Systems.” In *WiPDA 2015 - 3rd IEEE Workshop on Wide Bandgap Power Devices and Applications*, 402–5. Blacksberg, VA. https://doi.org/10.1109/WiPDA.2015.7369328.

Ciccarelli, Flavio. 2014. “Energy Management and Control Strategies for the Use of Supercapacitors Storage Technologies in Urban Railway Traction Systems.” University of Naples.

Clover, Ian. 2014. “No Longer the Introvert.” *PV Magazine*, August 2014. http://m.pv-magazine.com/archive-mob/article/beitrag/no-longer-the-introvert-_100016029/530/?tx_ttnews%5BbackCat%5D=247&cHash=df21d028b8f248ea7e9ef2ee516bc184.

Cobb, Jeff. n.d. “Monthly Sales December 2015 Dashboard.” Hybridcars. Accessed December 8, 2016. http://www.hybridcars.com/december-2015-dashboard/.

Colmenares, Juan, Dimosthenis Peftitsis, Jacek Rabkowski, Diane Perle Sadik, Georg Tolstoy, and Hans Peter Nee. 2015. “High-Efficiency 312-kVA Three-Phase Inverter Using Parallel Connection of Silicon Carbide MOSFET Power Modules.” *IEEE Transactions on Industry Applications* 51 (6):4664–76. https://doi.org/10.1109/TIA.2015.2456422.

Corzine, Keith. 2001. “Multilevel Converters.” In *The Power Electronics Handbook*, edited by Timothy L. Skvarenina. CRC Press LLC.

Cree. 2013. “Cree SiC MOSFETs Revolutionize Shinry Hybrid-Electric and Electric-Vehicle Power Converters , Achieving Industry-Leading 96-Percent Efficiency.” http://www.cree.com/News-and-Events/Cree-News/Press-Releases/2013/October/Shinry.

———. 2015. “Cree SiC Technology Enables the Quantum Reduction of Solar Power Inverter Size, Weight, and Cost.” 2015. http://www.cree.com/News-and-Events/Cree-News/Press-Releases/2015/March/SiC-MOSFETs-for-Solar-Inverters.

Crowell, Chris. 2016. “What You Need to Know about 1500-Volt Inverters.” *Solar Builder*, February 2016. http://solarbuildermag.com/news/what-you-need-to-know-about-1500-volt-inverters/.

Cui, Yutian, Fan Xu, Weimin Zhang, Ben Guo, Leon M Tolbert, Fred Wang, Benjamin J

Blalock, et al. 2014. “High Efficiency Data Center Power Supply Using Wide Band Gap Power Devices.” *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*, 3437–42. https://doi.org/10.1109/APEC.2014.6803802.

Davis, Brian. 2015. “The next Big Thing in Data Centers.” *ECN*, March 2015. http://www.ecnmag.com/article/2015/03/next-big-thing-data-centers.

Davis, Stacy C., Susan W. Diegel, and Robert G. Boundy. 2015. “Transportation Energy Data Book: Edition 34.” cta.ornl.gov/data.

Davis, Stacy C., Susan E. Williams, and Robert G. Boundy. 2016. *Transportation Energy Data Book*. 35thed. http://cta.ornl.gov/data/index.shtml.

Delforge, Pierre, and Josh Whitney. 2014. “Data Center Efficiency Assessment.” http://www.nrdc.org/energy/data-center-efficiency-assessment.asp.

Delta Electronics. 2016. “General Motors Honors Delta Electronics as Inaugural Winner of Coveted Supplier Innovation Award.” 2016. http://www.delta-americas.com/news/pressDetail.aspx?secID=3&pID=1&typeID=2;5&itemID=6277&tid=0&hl=en-US.

Denso Global. n.d. “SiC Power Device [Under Development].” Accessed December 9, 2016. http://www.globaldenso.com/en/tokyomotorshow/2015/images/sic-power-device.pdf.

Ding, Xiaofeng, Min Du, Tong Zhou, Hong Guo, and Chengming Zhang. 2016. “Comprehensive Comparison between Silicon Carbide MOSFETs and Silicon IGBTs Based Traction Systems for Electric Vehicles.” *Applied Energy*. Elsevier Ltd. https://doi.org/10.1016/j.apenergy.2016.05.059.

Doughty, Rani, and David Watts. 2015. “Lenovo Flex System Higher Voltage DC Solutions.” https://lenovopress.com/pdfs/431/redp5180.pdf.

Duoba, Michael, Richard Barney Carlson, and Daniel Bocci. 2009. “Calculating Results and Performance Parameters for PHEVs.” *SAE Technical Paper 2009-01-1328*. https://doi.org/10.4271/2009-01-1328.

EBay. 2013. “eBay Digital Service Efficiency.” 2013. http://tech.ebay.com/dashboard.

Eden, Richard. 2013. “IHS Report: The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors - 2013.”

———. 2014. “IHS Report: Silicon Carbide and Gallium Nitride Power Semiconductors - 2014.”

———. 2016. “IHS Report: The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors - 2016 Edition.”

Elgowainy, A., J. Han, J Ward, F. Joseck, D. Gohlke, A. Lindauer, T. Ramsden, et al. 2016. “Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A GReenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025-2030) Technologies.”

Ellabban, Omar, Haitham Abu-Rub, and Frede Blaabjerg. 2014. “Renewable Energy Resources: Current Status, Future Prospects and Their Enabling Technology.” *Renewable and Sustainable Energy Reviews* 39. Elsevier:748–64. https://doi.org/10.1016/j.rser.2014.07.113.

Emerson. 2009. “Energy Logic: Reducing Data Center Energy Consumption by Creating Savings That Cascade Across Systems.” *Emerson Network Power*. http://www.emersonnetworkpower.com/documentation/en-us/latest-thinking/edc/documents/white paper/energylogicreducingdatacenterenergyconsumption.pdf.

Energy Star. n.d. “Purchasing More Energy-Efficient Servers, UPSs, and PDUs.” Accessed June 8, 2016. https://www.energystar.gov/products/low_carbon_it_campaign/12_ways_save_energy_data_center/purchasing_more_energy_efficient_servers_upss_and_pdus.

———. 2012. “eBay Data Center Retrofits: The Costs and Benefits of Ultrasonic Humidification and Variable Speed Drives.” http://www.energystar.gov/ia/products/power_mgt/downloads/Energy_Star_fact_sheet.pdf.

———. 2013. “Source Energy.” https://portfoliomanager.energystar.gov/pdf/reference/Source Energy.pdf.

Environmental Protection Agency. 2016. “Clean Power Plan for Existing Power Plants.” 2016. https://www.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants.

Eubank, Huston, Joel Swisher, Cameron Burns, Jen Seal, and Ben Emerson. 2003. “Design Recommendations for High-Performance Data Centers.”

European Center for Power Electronics. 2016. “ECPE Starts Strategic Research Cooperation with Japan in the Area of Wide Bandgap Power Electronics and System Integration.” 2016. http://www.ecpe.org/news-projects/network-news/current/details/?tx_ttnews%5Btt_news%5D=366&cHash=891e64c7eccca583d01d27955d57c4ce.

European Commission. 2016. “Reducing CO2 Emissions from Passenger Cars.” 2016. http://ec.europa.eu/clima/policies/transport/vehicles/cars_en.

Evans, Keith, Dave Hurst, Kelly Jezierski, Roland Kibler, Swad Komanduri, Mark Loboda, and Dan Radomski. 2016. “Strengthening the Domestic Power Electronics Ecosystem.”

Facebook. 2016. “Prineville, OR Data Center Dashboard.” 2016. https://www.fbpuewue.com/prineville.

Faria, Ricardo, Pedro Moura, Joaquim Delgado, and Anibal T De Almeida. 2012. “A Sustainability Assessment of Electric Vehicles as a Personal Mobility System.” *Energy Conversion and Management* 61:19–30. https://doi.org/http://dx.doi.org/10.1016/j.enconman.2012.02.023.

Fodale, Victoria, and Richard Eden. 2015. “IHS Report: The World Market for Power Semiconductors - 2015 Edition.”

Fraunhofer Institute for Solar Energy Systems. 2016. “Photovoltaics Report.” https://doi.org/26.05.2014.

Fu, Ran, Ted L. James, Donald Chung, Douglas Gagne, Anthony Lopez, and Aron Dobos. 2015. “Economic Competitiveness of U.S. Utility-Scale Photovoltaics Systems in 2015: Regional Cost Modeling of Installed Cost ($/W) and LCOE ($/kWh).” *2015 IEEE 42nd Photovoltaic Specialist Conference, PVSC 2015*. https://doi.org/10.1109/PVSC.2015.7356261.

Fuji Electric Co. Ltd. 2013a. “Fuji IGBT Modules for Wind Power System.”

https://www.fujielectric.com/products/semiconductor/usage/box/doc/pdf/Wind_power_(ver4).pdf.

———. 2013b. “UPS.” 2013. https://www.fujielectric.com/products/semiconductor/usage/ups.html.

———. 2015a. “Fuji IGBT Modules for Solar Inverter.” https://www.fujielectric.com/products/semiconductor/usage/box/doc/pdf/Solar_inverter_(ver4).pdf.

———. 2015b. “Joint Development of Converter - Inverter for The Tokaido Shinkansen Cars Using SiC Power Semiconductor Modules.” https://www.fujielectric.com/company/news/2015/20150625120019879.html.

Gao, Zongyu, Zhongping Yang, Kun Zhao, Fei Lin, and Bin Wang. 2014. “Control Strategy Research of Urban Rail Transit for Equipped with Wayside-Based Supercapacitor Energy Saving and Reduction of Power Peak Demand.” *ICIC Express Letters* 8 (9). Elsevier Ltd:2477–84. https://doi.org/10.1016/j.ijepes.2014.11.019.

GeneSiC Semiconductor. n.d. “SiC Ultra High Voltage PiN Rectifiers and Thyristors.” Accessed October 31, 2016. http://www.genesicsemi.com/commercial-sic/sic-ultra-high-voltage-pin-thyristors/.

———. 2013. “1200 V SiC Schottky Rectifiers.” http://www.genesicsemi.com/images/references/reliability/00 Schottky Reliability Report.pdf.

———. 2014. “1200 V SiC Junction Transistor (SJT) Devices.” Vol. 1. http://www.genesicsemi.com/images/references/reliability/00 SJT Reliability Report.pdf.

Giesselmann, Michael, Attila Karpati, Istvan Nagy, Dariusz Czarkowski, Michael Ropp, Eric Walters, and Oleg Wasynczuk. 2001. “Inverters.” In *The Power Electronics Handbook*, edited by Timothy L. Skvarenina. CRC Press LLC.

Gifford, Jonathan. 2015. “GTM: Advanced Energy Exit Leaves 17% U.S. Inverter Market Share up for Grabs.” *PV Magazine*, July 2015. http://www.pv-magazine.com/news/details/beitrag/gtm--advanced-energy-exit-leaves-17-us-inverter-market-share-up-for-grabs_100020055/#axzz4F3nJB5jH.

Global CCS Institute. n.d. “Petroleum Diesel Life Cycle Energy Demand.” Accessed November 29, 2016. https://hub.globalccsinstitute.com/publications/biofuels-policies-standards-and-technologies/petroleum-diesel-life-cycle-energy-demand.

Global Wind Energy Council. 2016. “Global Wind Statistics 2015.” https://doi.org/10.1007/s13398-014-0173-7.2.

Go Solar California. 2016. “List of Eligible Inverters per SB1 Guidelines.” 2016. http://www.gosolarcalifornia.ca.gov/equipment/inverters.php.

Goetzler, William, Timothy Sutherland, and Callie Reis. 2013. “Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment,” no. December.

González-Gil, A., R. Palacin, P. Batty, and J. P. Powell. 2014. “A Systems Approach to Reduce Urban Rail Energy Consumption.” *Energy Conversion and Management* 80:509–24.

https://doi.org/10.1016/j.enconman.2014.01.060.

Goodrich, Alan, Ted James, and Michael Woodhouse. 2012. "Residential, Commercial, and Utility-Scale Photovoltaic (PV) System Prices in the United States: Current Drivers and Cost-Reduction Opportunities." *Technical Report NREL*. https://doi.org/10.2172/1036048.

Google. 2016. "Efficiency: How We Do It." 2016. https://www.google.com/about/datacenters/efficiency/internal/.

"Governor Cuomo Announces 100 Businesses Led by GE to Join $ 500 Million Partnership with State to Develop Next-Generation Power Electronics, Creating Thousands of Jobs in Capital Region and Upstate." 2014. 2014. https://www.governor.ny.gov/news/governor-cuomo-announces-100-businesses-led-ge-join-500-million-partnership-state-develop-next.

Greenberg, Steve. 2013. "Variable-Speed Fan Retrofits for Computer-Room Air Conditioners."

Greenberg, Steve, Dale Sartor, and William Tschudi. 2015. "Agency X: Data Center Energy Efficiency Assessment."

Gueguen, Pierric. 2016. "Si IGBT and SiC: Which Repartition for Power Devices?" In *Applied Power Electronics Conference (APEC)*.

Gunselmann, W. 2005. "Technologies for Increased Energy Efficiency in Railway Systems." *2005 European Conference on Power Electronics and Applications*, 1–10. https://doi.org/10.1109/EPE.2005.219712.

Hamada, Kenji, Shiro Hino, Naruhisa Miura, Hiroshi Watanabe, Shuhei Nakata, Eisuke Suekawa, Yuji Ebiike, Masayuki Imaizumi, Isao Umezaki, and Satoshi Yamakawa. 2015. "3 . 3 kV / 1500 A Power Modules for the World ' S First All-SiC Traction Inverter." *Japanese Journal of Applied Physics* 54:14–18. https://doi.org/10.7567/JJAP.54.04DP07.

Han, Di, Anuradha Ogale, Silong Li, Yingjie Li, and Bulent Sarlioglu. 2014. "Efficiency Characterization and Thermal Study of GaN Based 1 kW Inverter." In *IEEE Applied Power Electronics Conference and Exposition - APEC*, 2344–50. https://doi.org/10.1109/APEC.2014.6803631.

Harris, Shaun. 2015. "Microsoft Reinvents Datacenter Power Backup with New Open Compute Project Specification." *TechNet Blogs*, March 2015. https://blogs.technet.microsoft.com/msdatacenters/2015/03/10/microsoft-reinvents-datacenter-power-backup-with-new-open-compute-project-specification/.

Hartman, Craig. 2014. "What Is a Variable Frequency Drive?" March 20, 2014. http://www.vfds.com/blog/what-is-a-vfd.

Helms, H, and U Lambrecht. 2007. "The Potential Contribution of Light-Weighting to Reduce Transport Energy Consumption." *The International Journal of Life Cycle Assessment* 12:58–64. https://doi.org/DOI 10.1065/lca2006.07.258.

Henshall, David. 2015. "A Pathway to Commercialization of Wide Bandgap Semiconductors in Power Electronics." In *Applied Power Electronics Conference (APEC)*. Charlotte, NC. http://www.apec-conf.org/wp-content/uploads/IS-14.1.pdf.

Hitachi. 2012. "Hitachi Develops Smaller , Lighter Rail Car Inverter for 1 , 500V DC Overhead Power Supply Using SiC." http://www.hitachi.com/New/cnews/120419b.pdf.

Hostetler, John, William Simon, Xing Huang, and Anup Bhalla. 2016. "High Current SiC

Devices - United Silicon Carbide, Inc.” In *DOE Joint Kickoff Meeting for the Next Generation Electric Machines (NGEM)*. Knoxville, TN. http://curent.utk.edu/files/3814/6098/8506/John_Hostetler_DOE_April_1.pdf.

Hu, Jiaxi, Wenye Liu, and Jinfeng Yang. 2015. “Application of Power Electronic Devices in Rail Transportation Traction System.” *Proceedings of the International Symposium on Power Semiconductor Devices and ICs* 2015–June:7–12. https://doi.org/10.1109/ISPSD.2015.7123376.

Huber, Peter, and Mark P. Mills. 1999. “Dig More Coal -- the PCs Are Coming.” *Forbes*, May 1999. http://www.forbes.com/forbes/1999/0531/6311070a.html.

Hurst, Dave. 2016. “Driving Collaboration for Power Electronics Power Electronics Supply Chain Gap Analysis.” In *2016 PEIC Industry Summit*, 1–16.

Iannuzzo, Francesco, and Mauro Ciappa. 2016. “Reliability Issues in Power Electronics.” *Microelectronics Reliability* 58. Elsevier B.V.:1–2. https://doi.org/10.1016/j.microrel.2016.01.012.

IHS Technology. 2015. “IHS Forecasts Double - Digit Sales Growth for PV Inverter Chips , Over the Next Three Years.” 2015. http://press.ihs.com/press-release/technology/ihs-forecasts-double-digit-sales-growth-pv-inverter-chips-over-next-three-y.

———. 2016. “Semiconductor Competitive Landscape CLT Intelligence Service.”

Ikonen, Mika, Ossi Laakkonen, and Marko Kettunen. 2006. “Two-Level and Three-Level Converter Comparison in Wind Power Application.” In *IEEE Proc. Nordic Workshop on Power and Industrial Electronics, NORPIE 2006*.

Industrial Assessment Centers. n.d. “IAC Database.” Accessed August 29, 2016. https://iac.university/.

Infineon. 2015. “Infineon Technologies AG Successfully Acquires International Rectifier.” 2015. http://www.infineon.com/cms/en/about-infineon/press/press-releases/2015/INFXX201501-020.html.

———. 2017. “Proposed Acquisition of Wolfspeed.” 2017. http://www.infineon.com/cms/en/about-infineon/press/press-releases/2017/INFXX201702-028.html.

International Energy Agency. 2012. “Technology Roadmap: Fuel Economy of Road Vehicles.” https://doi.org/10.1007/SpringerReference_7300.

———. 2015. “Railway Handbook 2015” 1:1689–99. http://www.uic.org/IMG/pdf/iea-uic_2015-2.pdf.

———. 2016. “2015 Snapshot of Global Photovoltaic Markets.” *IEA PVPS T1-29:2016*. http://www.iea-pvps.org/index.php?id=trends0.

IRENA. 2012. “Wind Power.” *Renewable Energy Technologes: Cost Analysis Series*. Vol. 1. https://doi.org/10.1016/B978-0-08-098330-1.00011-9.

Johnson, Mark. 2015. “Integration of Wide Band-Gap Semiconductors.” In *WiPDA 2015 - 3rd IEEE Workshop on Wide Bandgap Power Devices and Applications*. Blacksberg, VA.

Johnson, Valerie H. 2002. “Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach.” *Society of Automotive Engineers, Inc.* 1:1957–70.

https://doi.org/10.4271/2002-01-1957.

Jones-Albertus, Rebecca, David Feldman, Ran Fu, Kelsey Horowitz, and Michael Woodhouse. 2016. “Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity.” *Progress Photovoltaics: Research and Applications*. https://doi.org/10.1002/pip.2755.

Kambly, Kiran R., and Thomas H. Bradley. 2014. “Estimating the HVAC Energy Consumption of Plug-in Electric Vehicles.” *Journal of Power Sources* 259. Elsevier B.V:117–24. https://doi.org/10.1016/j.jpowsour.2014.02.033.

Karlsson, Sten, and Duncan Kushnir. 2013. “How Energy Efficient Is Electrified Transport.” In *Systems Perspectives on Electromobility*, edited by Björn Sandén and Pontus Wallgren, 184. Chalmers University of Technology. http://www.chalmers.se/en/areas-of-advance/energy/publications-media/systems-perspectives/Pages/default.aspx.

Keller, Perry. 2016. “JEDEC Strategic Roadmap.” 2016. https://www.jedec.org/sites/default/files/JEDEC All Committee Briefing 2016_0608.pdf.

Kellner, Tomas. 2015. “Rise and Shine : This Diamond - like Material Is Helping Solar Power Cast a Bigger Shadow - GE Reports.” *GE Reports*. http://www.gereports.com/post/125184208085/rise-and-shine-this-diamond-like-material-is/.

Kimoto, Tsunenobu, and James A. Cooper. 2014. “Bulk Growth of Silicon Carbide.” In *Fundmentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications*, 39–74. Singapore: John Wiley & Sons Singapore Pte. Ltd. https://doi.org/10.1002/9781118313534.ch3.

Koomey, Jonathan G. 2011. “Growth in Data Center Electricity Use 2005 to 2010.” *Analytics Press*. https://doi.org/10.1088/1748-9326/3/3/034008.

Koomey, Jonathan G., Christian Belady, Michael Patterson, Anthony Santos, and Klaus Dieter Lange. 2009. “Assessing Trends over Time in Performance, Costs, and Energy Use for Servers.” http://www3.intel.com/assets/pdf/general/servertrendsreleasecomplete-v25.pdf%5Cnhttp://www.koomey.com/research.html.

Kramer, W, S Chakraborty, B Kroposki, and H Thomas. 2008. “Advanced Power Electronic Interfaces for Distributed Energy Systems Part 1: Systems and Topologies.” http://www.nrel.gov/docs/fy08osti/42672.pdf.

Lai, Rixin Lai Rixin, F Wang, Puqi Ning Puqi Ning, Di Zhang Di Zhang, Dong Jiang, R Burgos, D Boroyevich, K J Karimi, and V D Immanuel. 2009. “Development of a 10 kW High Power Density Three-Phase Ac-Dc-Ac Converter Using SiC Devices.” *2009 13th European Conference on Power Electronics and Applications*, 4748–59.

Lambert, Fred. n.d. “Tesla Model 3 Exclusive Leaked Specs: 300kW+ Inverter Architecture Putting Its Power Capacity near Model S.” Electrek. Accessed December 8, 2016. https://electrek.co/2016/06/29/tesla-model-3-exclusive-leak-specs-300kw-inverter-architecture-power-capacity-model-s/.

Liu, Gang, Blair R. Tuttle, and Sarit Dhar. 2015. “Silicon Carbide: A Unique Platform for Metal-Oxide-Semiconductor Physics.” *Applied Physics Reviews* 2 (2). https://doi.org/10.1063/1.4922748.

Loeffler, Chris, and Ed Spears. 2011. “UPS Basics.” http://pqlit.eaton.com/ll_download_bylitcode.asp?doc_id=21590.

Lowe, M, R Golini, and G Gereffi. 2010. “U. S. Adoption of High-Efficiency Motors and Drives : Lessons Learned.” http://www.cggc.duke.edu/pdfs/CGGC-Motor_and_Drives_Report_Feb_25_2010.pdf.

Manners, David. 2016. “X-Fab Offers SiC from Texas Foundry.” *Electronics Weekly.com*, March 11, 2016. http://www.electronicsweekly.com/news/business/x-fab-offers-sic-from-texas-foundry-2016-03/.

Mansoor, Arshad, and Brian Griffith. 2004. “Enabling High Efficient Power Supplies for Servers.” In *Intel Technology Symposium*, 1–25. http://energy.lbl.gov/ea/mills/_archive/HT-3-13-08/documents/PS/Intel_Enabling.pdf.

Martinez, Bobby, CB Meher-Homji, J Paschal, and A Eaton. 2005. “All Electric Motor Drives for LNG Plants.” *GasTech 2005*, 1–16. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:All+Electric+Motor+Drives+for+LNG+Plants#1.

Marz, Andreas, Roman Horff, Martin Helsper, and Mark M. Bakran. 2015. “Requirements to Change from IGBT to Full SiC Modules in an on-Board Railway Power Supply.” In *2015 17th European Conference on Power Electronics and Applications, EPE-ECCE Europe 2015*. https://doi.org/10.1109/EPE.2015.7309088.

Masanet, Eric R., Richard E. Brown, A. Shehabi, Jonathan G. Koomey, and Bruce Nordman. 2011. “Estimating the Energy Use and Efficiency Potential of U.S. Data Centers.” *Proceedings of the IEEE* 99 (October):1440–53.

Meneghesso, Gaudenzio, Matteo Meneghini, Riccardo Silvestri, D Bisi, S Stoffels, M Van Hove, S Decoutere, and E Zanoni. 2016. “Reliability and Parasitic Issues in GaN-Based Power HEMTs : A Review.” *Semiconductor Science and Technology* 31. IOP Publishing. https://doi.org/doi:10.1088/0268-1242/31/9/093004.

Miller, John, Lori Bird, Jenny Heeter, and Bethany Gorham. 2015. “Renewable Electricity Use by the U.S. Information and Communication Technology (ICT) Industry.” Golden, CO. NREL/TP-6A20-64011.

Miller, John M. 2013. “Oak Ridge National Laboratory Annual Progress Report for the Power Electronics and Electric Motors Program.” http://info.ornl.gov/sites/publications/files/Pub46377.pdf.

Miller, Rich. 2008. “Google: Raise Your Data Center Temperature.” *Www.Datacenterknowledge.Com*, October 2008. http://www.datacenterknowledge.com/archives/2008/10/14/google-raise-your-data-center-temperature/.

Millstein, Dev, and Surabi Menon. 2011. “Regional Climate Consequences of Large-Scale Cool Roof and Photovoltaic Array Deployment.” *Environmental Research Letters* 6 (3):34001. https://doi.org/10.1088/1748-9326/6/3/034001.

Misra, Veena, Narayanan Ramanan, and Bongmook Lee. 2015. “Optimizing Performance and Reliability of GaN Power Devices.” In *Applied Power Electronics Conference (APEC)*. Charlotte, NC. http://www.apec-conf.org/wp-content/uploads/2015APEC_Plenary_VeenaMisra.pdf.

Mitsubishi Electric. n.d. “Highly Efficient Power Conditioners for Household Solar Power Generation Systems.” Accessed January 1, 2016. http://www.mitsubishielectric.com/company/environment/report/technology/index_print.html.

Mitsubishi Electric Corporation. 2014. “Mitsubishi Electric Develops EV Motor Drive System with Built-in Silicon Carbide Inverter.” http://www.mitsubishielectric.com/news/2014/0213-d.html.

———. 2015a. “Mitsubishi Electric’s Railcar Traction Inverter with All-SiC Power Modules Achieves 40 % Power Savings,” 3–4. http://www.mitsubishielectric.com/news/2015/pdf/0622-a.pdf.

———. 2015b. “Mitsubishi Electric Installs Railcar Traction System with All-SiC Power Modules on Shinkansen Bullet Trains.” http://www.mitsubishielectric.com/news/2015/0625.html.

———. 2016a. “HVIGBT Module Hybrid SiC.” 2016. http://www.mitsubishielectric.com/semiconductors/application/railway/index.html?seriesid=12.

———. 2016b. “Mitsubishi Electric Exhibits Latest Rail Technology at InnoTrans.” http://de.mitsubishielectric.com/en/news-events/releases/2016/0908-b/pdf/160908-b_local_en_de.pdf.

Moniz, Ernest. 2014. “Wide Bandgap Semiconductors: Essential to Our Technology Future.” 2014. http://energy.gov/articles/wide-bandgap-semiconductors-essential-our-technology-future.

Morrow, Linda. 2015. “Mitsubishi Electric Introduces New SUMMIT Series UPS.”

Mouser Electronics. n.d. “Product Search.” Accessed January 18, 2017. http://www.mouser.com/.

Nan, Chenhao, Tong Yao, and Raja Ayyanar. 2015. “A 1 MHz eGaN FET Based 4-Switch Buck-Boost Converter for Automotive Applications.” In *3rd IEEE Workshop on Wide Bandgap Power Devices and Applications*, 365–70. https://doi.org/10.1109/WiPDA.2015.7369311.

Nozawa, Tetsuo. 2010. “Mitsubishi’s Air Conditioners Come with Inverter Module Using SiC-Based SBD.” Nikkei Technology. August 25, 2010. http://techon.nikkeibp.co.jp/english/NEWS_EN/20100824/185171/.

Nunez, Javier Villegas. 2016. “Multilevel Topologies: Can New Inverters Improve Solar Farm Output?” *Solar Industry Magzaine*, January 2016. http://www.solarindustrymag.com/online/issues/SI1301/FEAT_05_Multilevel Topologies.html.

Obama, Barack. 2015. “Executive Order -- Planning for Federal Sustainability in the Next Decade.” White House. https://www.whitehouse.gov/the-press-office/2015/03/19/executive-order-planning-federal-sustainability-next-decade.

Ocklenburg, Marc-André, Martin Helrsper, Holger Siemer, and Andreas Gusek. 2014.

"Potentials and Requirements of Silicon Carbide Hybrid Power Modules for Railway Onboard Auxiliary Power Supplies Requirements for Power Semiconductors in Railway Applications Potentials and Limitations of SiC Hybrid Power Modules." In *PCIM Europe*, 20–22.

Oshima, Masafumi, Tetsuya Maeda, and Hiroki Muratsu. 2015. "Mega Solar PCS Incorporating All-SiC Module 'PVI1000AJ-3/1000.'" *Fuji Electric Review*. Vol. 61. https://doi.org/10.3103/S1068371208100015.

Ozdemir, Sadik, Fatih Acar, and Ugur S. Selamogullari. 2015. "Comparison of Silicon Carbide MOSFET and IGBT Based Electric Vehicle Traction Inverters." *2015 International Conference on Electrical Engineering and Informatics (ICEEI)*, no. 113:1–4. https://doi.org/10.1109/ICEEI.2015.7387215.

Ozpineci, B, and L M Tolbert. 2003. *Comparison of Wide-Bandgap Semiconductors for Power Electronics Applications*. *Ornl/Tm-2003/257*. https://doi.org/ORNL/TM-2003/257.

Ozpineci, Burak. 2015. "Oak Ridge National Laboratory Annual Progress Report for the Power Electronics and Electric Motors Program." http://info.ornl.gov/sites/publications/files/Pub59624.pdf.

Ozpineci, Burak, Madhu Sudhan Chinthavali, and Leon M Tolbert. 2006. "Enhancing Power Electronic Devices with Wide Bandgap Semiconductors." *International Journal of High Speed Electronics and Systems*, 16 (2):545–56. https://doi.org/10.1142/9789812773081_0033.

Ozpineci, Burak, and Leon Tolbert. 2011. "Smaller, Faster, Tougher." *IEEE Spectrum* 48 (10). https://doi.org/10.1109/MSPEC.2011.6027247.

Palmour, J. W., L. Cheng, V. Pala, E. V. Brunt, D. J. Lichtenwalner, G. Y. Wang, J. Richmond, et al. 2014. "Silicon Carbide Power MOSFETs: Breakthrough Performance from 900 V up to 15 kV." *Proceedings of the International Symposium on Power Semiconductor Devices and ICs*, 79–82. https://doi.org/10.1109/ISPSD.2014.6855980.

Palmour, John W. 2016. "SiC MOSFET and Power Module Status and Market Development." In *4th IEEE Workshop on Wide Bandgap Power Devices and Applications*. Fayetteville, AR. http://www.wipda2016.org/uploads/7/1/0/7/71077267/palmour-wolfspeed-wipda2016.pdf.

Park, Jay. 2011. "Designing a Very Efficient Data Center." 2011. https://www.facebook.com/notes/facebook-engineering/designing-a-very-efficient-data-center/10150148003778920/.

"Personal Communication to Pablo Cassorla from Andy Wilson (X-Fab) 09/02/2016." 2016.

"Personal Communication with Martin Fornage (Enphase) 04/05/2016." 2016.

"Personal Communication with Michael Mahon (SMA-America) 04/08/2016." 2016.

Point the Gap. 2016. "GE Introducing Its Silicon Carbide Plans." *Point the Power*, 2016. http://www.pointthepower.com/ge-introducing-its-silicon-carbide-plans/.

PowerStudies. n.d. "Power Factor - The Basics." Accessed August 1, 2016. http://www.powerstudies.com/sites/www.powerstudies.com/files/Power Factor Basics Article.pdf.

Prabhala, V A K, Bhanu Prashant Baddipadiga, and Mehdi Ferdowsi. 2014. "DC Distribution

Systems – An Overview.” In *3rd International Conference on Renewable Energy Research and Applications*, 307–12. Milwakuee, WI.

Pratt, Annabelle, Pavan Kumar, and Tomm V. Aldridge. 2007. “Evaluation of 400V DC Distribution in Telco and Data Centers to Improve Energy Efficiency.” In *INTELEC, International Telecommunications Energy Conference*, 32–39. https://doi.org/10.1109/INTLEC.2007.4448733.

Progress Energy. n.d. “Energy Savers: Variable Speed Drives (VSD).” Accessed October 31, 2016. https://www.progress-energy.com/assets/www/docs/business/variable-speed.pdf.

Pryor, S. C., and R. J. Barthelmie. 2010. “Climate Change Impacts on Wind Energy: A Review.” *Renewable and Sustainable Energy Reviews* 14 (1):430–37. https://doi.org/10.1016/j.rser.2009.07.028.

Pushpakaran, Bejoy N., Anitha Sarah Subburaj, Stephen B. Bayne, and John Mookken. 2016. “Impact of Silicon Carbide Semiconductor Technology in Photovoltaic Energy System.” *Renewable and Sustainable Energy Reviews* 55. Elsevier:971–89. https://doi.org/10.1016/j.rser.2015.10.161.

Rabkowski, Jacek, Dimosthenis Peftitsis, and Hans Peter Nee. 2013. “Design Steps toward a 40-kVA SiC Jfet Inverter with Natural-Convection Cooling and an Efficiency Exceeding 99.5%.” *IEEE Transactions on Industry Applications* 49 (4):1589–98. https://doi.org/10.1109/TIA.2013.2258132.

Radiant Insights. 2015. “Data Center UPS Market Size, Share, Industry Report, 2020.” 2015. Data Center UPS Market Size, Share, Industry Report, 2020.

railway-technology.com. 2015. “JR Central Begins Tests of Mitsubishi â€™ S SiC Power Modules on Shinkansen Train.” 2015. http://www.railway-technology.com/news/newsjr-central-begins-tests-of-mitsubishis-sic-power-modules-on-shinkansen-train-4611531.

Rao, Prakash, Paul Sheaffer, Aimee Mckane, Paul Scheihing, Prakash Rao, Paul Sheaffer, Aimee Mckane, and Paul Scheihing. 2016. “Assessing Energy Efficiency Opportunities in US Industrial and Commercial Building Motor Systems Efficiency in Motor Driven Systems 2015 , Please Cite as :,” no. March.

Reed, Justin K., James McFarland, Jagadeesh Tangudu, Emmanuel Vinot, Rochdi Trigui, Giri Venkataramanan, Shiv Gupta, and Thomas Jahns. 2010. “Modeling Power Semiconductor Losses in HEV Powertrains Using Si and SiC Devices.” *IEEE Vehicle Power and Propulsion Conference*. https://doi.org/10.1109/VPPC.2010.5729068.

Reine, Preston. 2015. “Industrial Motors and Drives : A Global Market Update.” In . Helsinki, Finland. http://www.eemods15.info/midcom-serveattachmentguid-1e55deb201132bc5deb11e5b177919c6f24f0e5f0e5/policy1_preston_reine.pdf.

Renner, Michael, and Gary Gardner. 2010. “Global Competitiveness in the Rail and Transit Industry.” *Development*, 34.

Reusch, David. 2015. “Improving DC-DC Converter Performance with GaN Transistors.” In *Wide Bandgap Power Devices and Applications*. Blacksberg, VA.

Rice, Julius, and John Mookken. 2014. “Economics of High Efficiency SiC MOSFET Based 3-Ph Motor Drive.” In *PCIM Europe Conference Proceedings*, 1003–10. Nuremberg, Germany.

Roberts, John. 2014. “Lateral GaN Transistors - A Replacement for IGBT Devices in Automotive Applications.” *PCIM Europe Conference Proceedings*, no. May:310–17. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6841254.

Rodríguez, José, Senior Member, Steffen Bernet, Bin Wu, Senior Member, Jorge O Pontt, Senior Member, Samir Kouro, and Student Member. 2007. “Multilevel Voltage-Source-Converter Topologies for Industrial Medium-Voltage Drives” 54 (6):2930–45. https://doi.org/10.1109/TIE.2007.907044.

Rogalla, Sonke. 2013. “Basics of Inverter Technology and Grid Integration.” http://esc.u-strasbg.fr/docs/2013/lectures/ise/20130902 Rogalla Summerschool Uni Strasbourg.pdf.

Rogers, Susan, and Steven Boyd. 2014. “Overview of the DOE Advanced Power Electronics and Electric Motor R & D Program.” *2014 DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting*. http://energy.gov/sites/prod/files/2014/09/f18/fy_2014_vto_amr_apeem_overview-final_version.pdf.

Roggensack, Paul, Bill Tschudi, and Brian Fortenbery. 2008. “Uninterruptible Power Supplies : A Data Center Efficiency Opportunity.” http://www.energy.ca.gov/2008publications/CEC-500-2008-065/CEC-500-2008-065-FS.PDF.

Rohm Semiconductor. 2013. “SiC Power Devices and Modules: Application Note.” http://rohmfs.rohm.com/en/products/databook/applinote/discrete/sic/common/sic_appli-e.pdf.

Sakai, Mitsuhiko, Shigenori Toyoshima, Keiji Wada, and Masaki Furumai. 2015. “3.3 KV SiC Power Module with Low Switching Loss.” *SEI Technical Review* 81:51–55.

Sartor, Dale. 2015. “Learning Outcomes By Attending This Session , Attendees Will :” In *Data Center & Computing Conference*, June 15:1–52.

Scheihing, Paul. 2009. “Energy Efficiency Program DOE Industrial Technologies Program.” In , February:1–23.

Schelmetic, Tracy. 2016. “Design News - Blog - Eaton Is Working on a Variable Speed Drive with Near - Perfect Efficiency.” DesignNews. November 5, 2016. http://www.designnews.com/author.asp?section_id=1386&doc_id=279006.

Schulting, Philipp, Martin Rosekeit, Sarriegui Garikoitz, Matthias Biskoping, and Rik De Doncker. 2015. “Potential of Using GaN Devices within Air Cooled Bidirectional Battery Chargers for Electric Vehicles.” *IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2015*, 1–6. https://doi.org/10.1109/PEDG.2015.7223071.

Schupbach, Marcelo. 2015. “The Impact of SiC on PV Power Economics.” Electronic Products. 2015. http://www.electronicproducts.com/Power_Products/Invertors/The_impact_of_SiC_on_PV_power_economics.aspx.

Schwarzer, Ulrich, Stefan Buschhorn, and Klaus Vogel. 2014. “System Benefits for Solar Inverters Using SiC Semiconductor Modules.” In *PCIM Europe Conference Proceedings*, 787–94. http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6841307.

Scott, Mark J, Lixing Fu, Xuan Zhang, Jinzhu Li, Chengcheng Yao, Markus Sievers, and Jin

Wang. 2013. “Merits of Gallium Nitride Based Power Conversion.” *Semiconductor Science and Technology* 28 (7):74013. https://doi.org/10.1088/0268-1242/28/7/074013.

Semiconductor Industry Association (SIA). 2016. “The U.S. Semiconductor Industry: 2016 Factbook.”

Serrano-Gonzalez, Javier, and Roberto Lacal-Arantegui. 2016. “Technological Evolution of Onshore Wind Turbines - a Market Based Analsyis.” *Wind Energy*. https://doi.org/10.1002/we.1974.

Shahan, Zach. 2015. “Electric Car Charging 101 — Types of Charging, Charging Networks, Apps, & More!” 2015. http://evobsession.com/electric-car-charging-101-types-of-charging-apps-more/.

Shehabi, Arman, Sarah Smith, Dale Sartor, Richard E Brown, Magnus Herrlin, Jonathan Koomey, Eric Masanet, Nathaniel Horner, Ines Azevedo, and William Lintner. 2016. “United States Data Center Energy Usage Report.” https://doi.org/LBNL-1005775.

Shirabe, Kohei, Mahesh Swamy, Jun Koo Kang, Masaki Hisatsune, Mrinal Das, Robert Callanan, and Henry Lin. 2013. “Design of 400V Class Inverter Drive Using SiC 6-in-1 Power Module.” *2013 IEEE Energy Conversion Congress and Exposition, ECCE 2013*, 2363–70. https://doi.org/10.1109/ECCE.2013.6647003.

Shirabe, Kohei, Mahesh Swamy, Jun Koo Kang, Masaki Hisatsune, Yifeng Wu, Don Kebort, and Jim Honea. 2012. “Advantages of High Frequency PWM in AC Motor Drive Applications.” *2012 IEEE Energy Conversion Congress and Exposition, ECCE 2012*, 2977–84. https://doi.org/10.1109/ECCE.2012.6342519.

Siemens. 2013. “Tiny Energy Suppliers - Silicon Carbide Transistors.” 2013. http://www.siemens.com/press/photo/PN201305-03e.

Sintamarean, C., E. Eni, F. Blaabjerg, R. Teodorescu, and H. Wang. 2014. “Wide-Band Gap Devices in PV Systems - Opportunities and Challenges.” *2014 International Power Electronics Conference, IPEC-Hiroshima - ECCE Asia 2014*, 1912–19. https://doi.org/10.1109/IPEC.2014.6869846.

Smith, Kevin. 2015. “Osiris Delivers Improved Auxiliary Converters.” *International Railway Journal*, July 15, 2015. http://www.railjournal.com/index.php/rolling-stock/osiris-delivers-improved-auxiliary-converters.html.

Smith, Patrick. 2014. “Question of the Week: Will Permanent Magnet Generators Replace DFIG?” Wind Power Monthly. 2014. http://www.windpowermonthly.com/article/1315794/question-week-will-permanent-magnet-generators-replace-dfig.

Spinato, F., P.J. Tavner, G.J.W. van Bussel, and E. Koutoulakos. 2009. “Reliability of Wind Turbine Subassemblies.” *IET Renewable Power Generation* 3 (4):387–401. https://doi.org/10.1049/iet-rpg:20080060.

Stark, James. 2015. “380V DC Power: Shaping the Future of Data Center Energy Efficiency.” *Data Center Knowledge*, June 2015.

STMicroelectronics. n.d. “DC-DC Converter for Hybrid Electric Vehicle and EV.” Accessed December 8, 2016. http://www.st.com/content/ccc/resource/sales_and_marketing/promotional_material/magazi ne/31/23/c9/8f/30/6d/40/ae/TP 1800 DC-DC converter for Hybrid Electric Vehicle and EV ArrowTimes.pdf/files/TP 1800 DC-DC converter for Hybrid Electric Vehicle and EV A.

———. 2016. “STMicroelectronics Reveals Advanced Silicon - Carbide Power Devices to Accelerate Automotive Electrification.” http://www.st.com/content/st_com/en/about/media-center/press-item.html/p3830.html.

Strenger, Christian. 2010. “SiC Growth and Device Processing.” 2010. http://www.leb.eei.uni-erlangen.de/winterakademie/2010/report/content/course03/0307.htm.

Su, Ming, and Chingchi Chen. 2016. “Prospects for the Application of SiC Power Devices in Hybrid Electric Vehicle Drive Systems.” In *IEEE Workshop on Wide Bandgap Power Devices & Applications*. Fayetteville, AR. https://doi.org/10.1088/0268-1242/28/7/074012.

Su, Shuai, Tao Tang, and Yihui Wang. 2016. “Evaluation of Strategies to Reducing Traction Energy Consumption of Metro Systems Using an Optimal Train Control Simulation Model.” *Energies* 9 (2):1–19. https://doi.org/10.3390/en9020105.

Sullivan, Alexandra. 2010. “ENERGY STAR for Data Centers.” https://www.energystar.gov/ia/partners/prod_development/downloads/DataCenters_GreenGrid02042010.pdf.

Teschler, Lee. 2015. “Solar Inverters Get Smaller, More Efficient Thanks to Exotic Semiconductors.” *Solar Power World Online*, 2015. http://www.solarpowerworldonline.com/2015/07/solar-inverters-get-smaller-more-efficient-thanks-to-exotic-semiconductors/.

The Green Grid. 2008. “Qualitative Analysis of Power Distribution Configurations For Data Centers.” http://www.thegreengrid.org/~/media/WhitePapers/White_Paper_16_-_Quantitative_Efficiency_Analysis_30DEC08.pdf?lang=en.

Ton, My, Brian Fortenbery, and William Tschudi. 2008. “DC Power for Improved Data Center Efficiency.”

Toshiba International Corporation. 2014. “Traction and Auxiliary Power Systems.” https://www.toshiba.co.jp/sis/railwaysystem/en/products/catalog/pdf/traction_and_auxiliary_power_systems.pdf.

———. 2015. “Toshiba Introduces SiC-Based Three-Phase Uninterruptible Power Systems Lineup.” Houston, TX. https://doi.org/10.1017/CBO9781107415324.004.

———. 2016. “Toshiba’s Advanced Propulsion System to Drive Nishitetsu Railroad’s New Trains.” https://doi.org/10.1001/jama.287.21.2856.

Toyota Motor Corporation. 2016. “Toyota Develops New Silicon Carbide Power Semiconductor with Higher Efficiency.” 2016. http://newsroom.toyota.co.jp/en/detail/2656842.

U. S. Department of Energy. 2002. “United States Industrial Electric Motor Systems Market Opportunities Assessment.”

U.S.-Canada Power System Outage Task Force. 2004. “Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations.” https://reports.energy.gov/BlackoutFinal-Web.pdf.

U.S. Congress. 2007. *Energy Independence and Security Act of 2007*. *Public Law*. Washington: U.S. Congress. http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf.

U.S. Department of Energy. n.d. "About EV Everywhere." Accessed December 8, 2016a. http://energy.gov/eere/eveverywhere/about-ev-everywhere.

———. n.d. "Alternative Fuels Data Center." Accessed December 8, 2016b. www.afdc.energy.gov/data/.

———. n.d. "EERE Mission." Accessed August 2, 2016c. http://energy.gov/eere/about-us/mission.

———. n.d. "Find and Compare Cars." Accessed December 8, 2016d. http://www.fueleconomy.gov/feg/findacar.shtml.

———. n.d. "Sunshot Initiative." Accessed January 1, 2016e. http://energy.gov/eere/sunshot/sunshot-initiative.

———. n.d. "Wind Vision." Accessed January 1, 2016f. http://energy.gov/eere/wind/wind-vision.

———. 2012. "Photovoltaics: Technologies, Cost, and Performance." *SunShot Vision Study*. https://doi.org/10.1038/ncomms4069.

———. 2013. "Transportation Energy Futures Project."

———. 2014. "Premium Efficiency Motor Selection and Application Guide - A Handbook for Industry." http://energy.gov/eere/amo/downloads/premium-efficiency-motor-selection-and-application-guide-handbook-industry.

U.S. Department of Transportaion Federal Highway Administration. 2009. "National Household Travel Survey."

U.S. Energy Information Administration. n.d. "Manufacturing Energy Consumption Survey (MECS)." Accessed October 31, 2016. http://www.eia.gov/consumption/manufacturing/.

———. 2015. "Annual Energy Outlook 2015." Vol. 1. https://doi.org/DOE/EIA-0383(2013).

———. 2016a. "Annual Energy Outlook 2016." https://www.eia.gov/forecasts/aeo/index.cfm.

———. 2016b. "Electric Power Annual." 2016. https://www.eia.gov/electricity/annual/.

———. 2016c. "Electric Power Monthly: With Data for April 2016." http://www.eia.gov/electricity/monthly/pdf/epm.pdf.

———. 2016d. "Higher Renewable Capacity Additions in AEO2016 Reflect Policy Changes and Cost Reduction." 2016. http://www.eia.gov/todayinenergy/detail.cfm?id=26492.

———. 2016e. "How Much Carbon Dioxide Is Produced per Kilowatthour When Generating Electricity with Fossil Fuels?" Frequently Asked Questions. 2016. https://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11.

———. 2016f. "How Much Coal, Natural Gas, or Petroleum Is Used to Generate a Kilowatthour of Electricity?" Frequently Asked Questions. 2016. https://www.eia.gov/tools/faqs/faq.cfm?id=667&t=2.

———. 2016g. "Weekly Retail Gasoline and Diesel Prices." 2016. https://www.eia.gov/dnav/pet/pet_pri_gnd_a_epm0_pte_dpgal_a.htm.

———. 2016h. "Wind and Solar Data and Projections from the U.S. Energy Information Administration: Past Performance and Ongoing Enhancements." https://www.eia.gov/forecasts/aeo/supplement/renewable/pdf/projections.pdf.

———. 2017. “Petroleum & Other Liquids - Data.” 2017. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emm_epmru_pte_nus_dpg&f=a.

U.S. Motors. n.d. “Understanding the New DOE NEMA Premium Efficiency Rules.” Accessed October 31, 2016. http://www.usmotors.com/Energy-Efficiency/2016-DOE-NEMA-Premium-Efficiency-Rule.

U.S. Patent and Trademark Office. n.d. “USPTO Patent Full-Text and Image Database.” Accessed January 1, 2016. http://patft.uspto.gov/netahtml/PTO/search-adv.htm.

Union of Conserned Scientists. n.d. “The Hybrid Timeline.” Accessed December 8, 2016. http://www.ucsusa.org/clean-vehicles/electric-vehicles/hybrid-timeline.

US Department of Energy. 2015. “IHS Report: Wide Bandgap Semiconductors for Power Electronics: Technology Assessment 6N.” *Quadrennial Technology Review 2015*. http://energy.gov/downloads/chapter-6-innovating-clean-energy-technologies-advanced-manufacturing.

USAID. n.d. “Powering Health: Uninterruptible Power Supplies.” Accessed January 13, 2017. http://www.poweringhealth.org/index.php/topics/technology/uninterruptible-power-supplies.

VFDs.com. n.d. “Variable Frequency Drives Product Search.” Accessed October 31, 2016. http://www.vfds.com/variable-frequency-drives.

Vogel, Klaus, and Adalberto Jose Rossa. 2014. “Improving Efficiency in AC Drives: Comparison of Topologies and Device Technologies.” In *PCIM Europe Conference Proceedings*, 509–16. Nuremberg, Germany.

Vries, Eize de. 2012. “Who Makes Your Components? Vertical versus Horizontal Production Integration.” *Wind Power Monthly*, 2012. http://www.windpowermonthly.com/article/1156683/makes-components-vertical-versus-horizontal-production-integration.

Waide, Paul, and Conrad U. Brunner. 2011. *Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems*. International Energy Agency, Energy Efficiency Series. https://doi.org/10.1787/5kgg52gb9gjd-en.

Weimer, Joseph A. 2015. “Wide Band Gap (WBG) Power Electronics for the More Electric Aircraft (MEA).” In *WiPDA 2015 - 3rd IEEE Workshop on Wide Bandgap Power Devices and Applications*, 1–23. Blacksberg, VA.

Werle, Rita, Conrad U Brunner, and Rolf Tieben. 2014. “‘ Easy ’ Program for Electric Motor Systems Efficiency in Switzerland.”

White House. 2014. “Press Release: President Obama Announces New Public-Private Manufacturing Innovation Institute.” https://www.whitehouse.gov/the-press-office/2014/01/15/president-obama-announces-new-public-private-manufacturing-innovation-in.

Williamson, Sheldon S., and Xin Li. 2011. “Plug-In Hybrid Electric Vehicles.” In *The Industrial Electronics Handbook: Power Electronics and Motor Drives*, edited by Bogdan M. Wilamowski and J. David Irwin, 2nd ed., 1–8. CRC Press LLC.

Willis, Ben. 2015. "GE Eyes 20-30MW Solar Inverters as It Outlines next-Gen Technology Plans." *PVTech*, November 2015. http://www.pv-tech.org/news/ge-eyes-20-30mw-solar-inverters-as-it-outlines-next-gen-technology-plans.

Wilner, Frank N. 2014. "Blame Aplenty for High Speed Rail Woes." *RailwayAge*, January 2014. http://www.railwayage.com/index.php/blogs/frank-n-wilner/blame-aplenty-for-high-speed-rail-woes.html.

Wilson, Andy. 2016. "X-Fab: The More than Moore Foundry." In *DOE Joint Kickoff Meeting for the Next Generation Electric Machines (NGEM)*. Knoxville, TN. http://curent.utk.edu/files/2014/6098/8114/Andy_Wilson_DOE_April_1.pdf.

Wiser, Ryan, Mark Bolinger, Galen Barbose, Naïm Darghouth, Ben Hoen, Andrew Mills, Kristina Hamachi LaCommare, et al. 2015. "2014 Wind Technologies Market Report." https://doi.org/10.2172/1155074.

Wolfspeed. n.d. "Power Products." Accessed January 1, 2016. http://www.wolfspeed.com/power/products.

Wu, Tao, Jifeng Chen, Saijun Mao, and Michael J. Schutten. 2012. "1200V SiC MOSFETS for High Voltage Power Conversion." *2012 IEEE Energy Conversion Congress and Exposition, ECCE 2012*, 2921–26. https://doi.org/10.1109/ECCE.2012.6342523.

Xu, Fan, B Guo, L M Tolbert, Fei Wang, and B J Blalock. 2013. "An All-SiC Three-Phase Buck Rectifier for High-Efficiency Data Center Power Supplies." *IEEE Transactions on Industry Applications* 49 (6):2662–73. https://doi.org/10.1109/TIA.2013.2264923.

Xu, Longya. 2016. "High / Medium Voltage Modular Multilevel Converter for Variable Speed MW Drives." In *DOE Joint Kickoff Meeting for the Next Generation Electric Machines (NGEM)*. Knoxville, TN.

Xue, Lingxiao, Mingkai Mu, Dushan Boroyevich, and Paolo Mattavelli. 2015. "The Optimal Design of GaN-Based Dual Active Bridge for Bi-Directional Plug-in Hybrid Electric Vehicle (PHEV) Charger." *IEEE Applied Power Electronics Conference and Exposition (APEC)*, 602–8. https://doi.org/10.1109/APEC.2015.7104411.

Yasushi, Matsumoto, Kondo Yasushi, and Kimura Hiroshi. n.d. "Power Electronics Equipment Applying SiC Devices," 212–17.

Yole Development. 2012a. "Alstom Introduces Silicon Carbide to Improve Traction of Its Trains." I-Micronews. 2012. http://www.i-micronews.com/compound-semi-expertise/3201-alstom-introduces-silicon-carbide-to-improve-traction-of-its-trains.html.

———. 2012b. "Status of the Power Electronics Industry."

———. 2013a. "Inverter Technology Trends & Market Expectations."

———. 2013b. "SiC Market 2013 - Sample." http://www.slideshare.net/Yole_Developpement/yole-sic-market-report.

———. 2014. "Power GaN - Sample." http://www.yole.fr/iso_upload/Samples/Yole_GaN_for_Power_Electronics_June_2014_Sample.pdf.

———. 2015a. "EV-HEV Market and Technology Trends EV / HEV Market." In *Applied Power Electronics Conference (APEC)*. Long Beach, CA.

http://www.psma.com/sites/default/files/uploads/is24-ev-hev-market-and-technology-trends.pdf.

———. 2015b. “GaN and SiC Devices for Power Electronics Applications - Sample.” http://www.i-micronews.com/component/hikashop/product/gan-and-sic-for-power-electronics-applications.html.

———. 2015c. “Market & Technology Trends in Wide BandGap Power Packaging.” In *Applied Power Electronics Conference and Exposition (APEC)*. http://www.psma.com/sites/default/files/uploads/tech-forums-semiconductor/presentations/11-market-and-technology-trends-wbg-power-module-packaging.pdf.

———. 2015d. “Status of Power Electronics Industry 2015 - Sample.” http://www.i-micronews.com/images/SAMPLES/POWER/Status_of_Power_Electronics_Industry_2015_Sample.pdf.

———. 2016a. “From Technologies to Market Data Center Market and Technology Trends in Power Electronics.” In *Applied Power Electronics Conference (APEC)*. Long Beach, CA.

———. 2016b. “From Technologies to Market Inverter Technology Trends & Market Expectations - Sample.” http://www.yole.fr/iso_upload/Samples/2016/Yole_Inverter_Technology_Trends_and_Market_Expectations_May_2016_Sample.pdf.

———. 2016c. “Power SiC: 2016 Materials, Devices and Applications - Sample.” http://www.slideshare.net/Yole_Developpement/power-sic-2016-materials-devices-modules-and-applications-2016-report-by-yole-developpement.

———. 2016d. “Power SiC 2016: Materials , Devices and Applications.”

———. 2016e. “What Does the Future of Automotive Market Hold?” In *CAR-ELE Japan*. Tokyo, Japan. http://www.slideshare.net/Yole_Developpement/what-does-the-future-of-automotive-market-hold-2016-presentation-yole-developpement-at-carele-japan-tokyo.

———. 2016f. “Infineon Acquired Wolfspeed: What Will Be the Impacts?” *I - Micronews*, July 22, 2016. http://i-micronews.com/compound-semi-expertise/7763-infineon-acquired-wolfspeed-what-will-be-the-impacts.html.

———. 2017. “SiC and GaN Devices for the Power Electronics Market - Webcast.”

Youssef, Mohamed Z., Konrad Woronowicz, Kunwar Aditya, Najath Abdul Azeez, and Sheldon S. Williamson. 2016. “Design and Development of an Efficient Multilevel DC/AC Traction Inverter for Railway Transportation Electrification.” *IEEE Transactions on Power Electronics* 31 (4):3036–42. https://doi.org/10.1109/TPEL.2015.2448353.

Zhang, Hui, and Leon M. Tolbert. 2008. “SiC’s Potential Impact on the Design of Wind Generation System.” *IEEE IECON - Industrial Electronics Conference* 0 (3):2231–35. https://doi.org/10.1109/IECON.2008.4758303.

———. 2011. “Efficiency Impact of Silicon Carbide Power Electronics for Modern Wind Turbine Full Scale Frequency Converter.” *IEEE Transactions on Industrial Electronics* 58 (1):21–28. https://doi.org/10.1109/TIE.2010.2048292.

Zhang, Weimin, Ben Guo, Fan Xu, Yutian Cui, Yu Long, Fred Wang, Leon M Tolbert, Benjamin J Blalock, and Daniel Costinett. 2014. “Wide Bandgap Power Devices Based High Efficiency Power Converters for Data Center Application.” In *Wide Bandgap Power Devices and Applications*. Knoxville, TN. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6964638&tag=1.

Zinski, Jim. 2015. “Put the Brakes on Resin Conveying Speed to Minimize System Maintence.” Plastics Technology. January 2015. http://www.ptonline.com/articles/put-the-brakes-on-resin-conveying-speed-to-minimize-system-maintenance.

APPENDIX A: WBG MANUFACTURERS

APPENDIX A: WBG MANUFACTURERS

Table A-1. WBG wafer and epitaxy manufacturers with product and assigned U.S. patents

Manufacturer	SiC		GaN Epitaxy Material				# U.S. WBG Patents*
	Substrate	Epitaxy	Bulk GaN	Si	SiC	Other	
Enkris				✓	✓	✓	2
Epiworld	✓						0
SiCC	✓						0
Tanke Blue	✓						0
TySiC		✓					0
Xiamen	✓						0
Dowa				✓			25
Fuji	✓	✓					129
Mitsubishi	✓	✓					542
Nippon Steel	✓	✓					32
NTT-AT				✓			3
Rohm		✓					210
Showa Denko		✓					204
Sumitomo	✓	✓	✓				736
LG Siltron				✓			16
EpiGaN				✓	✓		0
Imec				✓			69
Soitec			✓				99
Allos				✓			0
Infineon		✓		✓			678
SiCrystal	✓						3
X-Fab	✓	✓					1
Ammono			✓				23
Ascatron							0
Norstel	✓	✓					6
Anvil Semi.		✓					1
IQE				✓			2
Raytheon	✓	✓				✓	56

Cree	✓	✓			✓		1049
Dow Corning	✓	✓					135
GSC				✓	✓		2
II-VI	✓						13
Kyma			✓	✓		✓	11
Microsemi	✓	✓					21
Soraa			✓				125

Table A-2. WBG Device Manufacturers (H- for in house use only, D- in development)

Manufacturer	SiC	GaN	# U.S. WBG Patents *	Manufacturer	SiC	GaN	# U.S. WBG Patents *
Denso	H		180	Cissoid	✓		0
Fuji / Powerex	✓	D	129	Exagan		D	0
Hitachi	H		0	Danfoss	✓		3
Mitsubishi	✓		542	Infineon	✓	D	678
New Japan Radio	✓		8	Semikron	✓		0
Panasonic	✓	✓	431	Vincotech	✓		1
Renesas	✓		220	Ascatron	D		0
Rohm	✓		210	ST Micro.	✓	D	170
Sanken	✓	D	96	Anvil Semi.	D		1
Shindengen			10	Raytheon	✓		56
Sumitomo	✓		736	TT Electronics	✓		0
Toshiba	✓		1138				
GaN Systems		✓	5	Littlefuse	✓		3
Avogy		✓	62	Microsemi	✓		21
Central	✓		0	Monolith	D		4
EPC		✓	14	Qorvo/Triquint		✓	44
Fairchild	✓		152	Texas Instr.		✓	513
Gene SiC	✓		0	Transphorm		✓	64
GE	H		406	USCi	✓		13
GPTG	✓		2	Wolfspeed/Cree	✓		1049

Table A-3. WBG Device Manufacturing Companies with device type

Manufacturer	SiC				GaN		
	Diode	MOSFET	Other	Module	Diode	Transistor	Module
Denso				✓			
Fuji / Powerex	✓			✓	✓	✓	
Hitachi				✓			
Mitsubishi				✓			
NJR							
Panasonic	✓			✓		✓	
Renesas	✓			✓			
Rohm	✓	✓		✓			
Sanken	✓				✓	✓	
Shindengen							
Sumitomo	✓	✓					
Toshiba	✓			✓			
Cissoid	✓	✓		✓			
Exagan						✓	
Danfoss				✓			
Infineon	✓		✓	✓		✓	
Semikron				✓			
Vincotech				✓			
Ascatron							
ST Micro.	✓	✓					
Anvil Semi.							
Raytheon	✓	✓	✓	✓			
TT Electronics	✓	✓					

GaN Systems						✓	
Avogy						✓	
Central	✓						
EPC						✓	✓
Fairchild	✓						
Gene SiC	✓		✓				
GE							
GPTG	✓	✓		✓			
Littlefuse	✓						
Microsemi	✓	✓		✓			
Monolith							
Qorvo/Triquint						✓	
Texas Instr.							✓
Transphorm							✓
USCi	✓		✓				
Wolfspeed/Cree	✓	✓		✓			

Table A-4. WBG device end user with assigned U.S. patents and type of work with WBG devices

Manufacturer	SiC	GaN	# U.S. WBG Patents *	R&D / Product
Delta	✓	✓	24	R&D (PV Inverter)/ EV Charger
Fuji Electric	✓		123	Industrial, R&D (Various)
Hitachi	✓		0	R&D (Rail & EV)
Mitsubishi	✓		465	Rail, motor drives, R&D (Various)
Toshiba	✓		1138	Various
Yaskawa		✓	6	PV Inverter
Danfoss	✓		3	PV Inverter
Refu Elektronik	✓		0	PV Inverter
Seimens	✓		0	R&D (large motor drive)
SMA	✓		3	PV Inverter
Eaton	✓		7	R&D (large motor drive)
ABB	✓		42	R&D (Motor Drive)
Avogy		✓	62	Consumer Charger
Calnetix	✓		0	R&D (large motor drive)
Enphase	✓		1	PV Inverter
GE	✓		406	R&D (Various)
John Deere	✓		0	R&D (large motor drive)

APPENDIX B. EXPANDED ENERGY SAVINGS CALCULATIONS

APPENDIX B: EXPANDED ENERGY SAVINGS CALCULATIONS

This section provides details for the energy savings calculations presented in this report. All calculations are derived from the reported efficiencies of WBG PE compared to Si PE and the energy demand of each application. Reported WBG savings in terms tonnes of "coal avoided" and "CO2 avoided" are based on the reduction on U.S. electricity demand assuming a grid mix of 41% of the electricity generated was via coal and an additional 24% from natural gas (matching the average U.S. generation) (U.S. Energy Information Administration 2016a). For each kWh of generated electricity, 1.04 lbs of coal are required. Coal and natural gas generate 2.1 lbs and 1.2 lbs of CO2, respectively (U.S. Energy Information Administration 2016f, 2016e).

B.1 UPS & PSU ENERGY SAVINGS ESTIMATION

According to literature, the average installed UPS efficiency falls between 85 and 95% (Mansoor and Griffith 2004; Roggensack, Tschudi, and Fortenbery 2008); however, current UPS on the market range closer to 92 to 96% (Energy Star n.d.). This analysis will assume an efficiency of 92% for Si, while SiC-based UPS have efficiencies greater than 98% (Toshiba International Corporation 2015; Morrow 2015).

Large data centers account for 71% of data center electricity (Brown et al. 2007), approximately 69.4 TWh in 2015, and UPS losses comprise approximately 7% of that (see Figure 2-4) (Yole Development 2016a), (Emerson 2009; Brown et al. 2007; Greenberg, Sartor, and Tschudi 2015; Scheihing 2009; Masanet et al. 2011). Therefore, it was estimated that 4.9 TWh of electricity was lost in UPS conversion in data centers. Switching to SiC UPS would have saved 3.7 TWh of electricity in 2015. To get closer to understanding the full potential of WBG power electronics, one must also include the reduced cooling load via reduced losses, which increases the amount of 2015 electricity used for UPS (PE losses and cooling) to 7.2 and could potentially save 5.6 TWh (assuming it takes 1W to cool 2W load, (US Department of Energy 2015; Ton, Fortenbery, and Tschudi 2008)), as seen in Table B-1..

Table B-1. 2015 Large data center UPS energy savings potential (TWh)

System	Si-Baseline	WBG	
	Loss	Loss	Savings
UPS	4.9 (7%)	1.2	3.7 (5%)
UPS + cooling	7.2 (11%)	1.6	5.6 (8%)

Installed PSUs range from 76 to 93% efficient (Prabhala, Baddipadiga, and Ferdowsi 2014; W. Zhang et al. 2014), creating losses between 8 and 14% of the total energy use of data centers (11% was assumed for this analysis, see Figure 2-4) (Emerson 2009; Brown et al. 2007; Greenberg, Sartor, and Tschudi 2015; Scheihing 2009; Masanet et al. 2011). More efficient PSUs may already include SiC or GaN, especially within the converter, and a full WBG PSU would be over 95% efficient[6] (Cui et al. 2014; F. Xu et al. 2013; W. Zhang et al. 2014). Switching to a WBG PSU could result in nearly 6% savings within data centers, and close to 9% if the reduction in cooling demand is accounted for (Table B-2).

Table B-2. 2015 Large data center PSU energy savings potential (TWh)

System	Si-Baseline	WBG	
	Loss	Loss	Savings
PSU	7.6 (11%)	3.2	4.4 (6%)
PSU + cooling	11.4 (16%)	4.8	6.6 (9%)

B.2 RENEWABLE ENERGY ADDITIONAL GENERATION ESTIMATION

As stated above, the potential additional energy generated with the inclusion of WBG devices into PV solar and wind generation is highly dependent on the base solar and wind generation. The additional energy generated was calculated using both the 2015 and 2016 Annual Energy Outlook forecasts for 2025 (U.S. Energy Information Administration 2015, 2016a).

WBG can bring PV inverter efficiency up from about 96% (weighted average of California SB1 compliant inverters (Go Solar California 2016)) to about 98.5% with full SiC module (Cree 2015; Oshima, Maeda, and Muratsu 2015; Kellner 2015; Mitsubishi Electric n.d.) or 98% with GaN (Teschler 2015). Additionally, SiC can bring the efficiency of a wind inverter system up from about 95% to about 98% (H. Zhang and Tolbert 2008).

Coal and CO_2 savings were estimated assuming that energy generated by conventional sources (e.g., coal and natural gas) would be replaced by the WBG enabled solar and wind. It was assumed that 41% of the energy generation in 2015 would have been via coal and 24% would have been from natural gas (matching U.S. generation mix) (U.S. Energy Information Administration 2016a). For each kWh of electricity generated by coal, 0.5 kg of coal is required. Coal and natural gas generate 1.0 kg and 0.5 kg of CO_2, respectively (U.S. Energy Information Administration 2016f, 2016e).

B.3 MOTOR DRIVE ENERGY SAVINGS ESTIMATION

Previous studies of VFD savings potential estimate that between 20% and 35% of energy used by pumps and fans can be saved by incorporating VFDs (Anibal T. de Almeida et al. 2001; Lowe, Golini, and Gereffi 2010). For compressors and conveyors, savings estimates are (10% - 15% and 15%, respectively). These numbers include estimates of load variations and energy lost by VFD power electronics (see Section 4.2).

While VFDs can save a large amount of electricity and money for many motor systems, there are several types of systems where they will not produce savings. If the motor system's output is not variable and the motor is not frequently shutdown, a VFD will not save much, if any, energy. De

[6] Combined efficiency of the SiC & GaN system described above (98.8% & 96.3%)

Almeida et al. (Anibal T. de Almeida et al. 2001) estimates that VFDs are only applicable to about 60% of most motor systems applications (only 30% of compressors) (see Table 10-7). Factors affecting applicability include fraction of time spent at lower than rated loads, variation in load demand, frequency of stop/start operations, and size of the motor. If a motor is too large, it may be unable to be controlled by VFDs efficiently due to the size and number of the power electronic devices required to convert the high voltage electricity required for very large motors. VFDs that are very small may be too inefficient to provide any energy savings (this will be discussed in depth below; see Figure 4-8). VFDs are most cost effective when installed in systems with high power variability or typically run at much lower than rated power and for larger motors with centrifugal processes (Anibal T. de Almeida et al. 2001; A T de Almeida, Ferreira, and Both 2004). Within this fraction of applicable systems, only a small fraction has VFDs installed. The most recent estimates for U.S. industrial motors are from a 1997 survey (U. S. Department of Energy 2002) and likely no longer accurate given the aggressive marketing from VFD manufacturers (e.g., ABB, Eaton, etc.). The report, published in late 2002, estimated that only 3.2% of pumps, 7.3% of fans, and 1.7% of compressed air systems had adjustable speed drives (which include, but is not limited to VFD). Estimates from the Swiss Agency for Efficient Energy Use (S.A.F.E) Efficiency for Electric Motor Systems (Easy) Program (Werle, Brunner, and Tieben 2014) in 2013 showed 34% and 38% of pumps and fans assessed in Switzerland have VFDs, with compressors and conveyors only at 3% and 8%, respectively. Using this more recent data as a proxy for U.S. motors, the "new install potential" fraction of motors that would benefit from VFD installation is between 22% and 52% of motors (see Table 10-7). However, it still may not be cost effective to install VFDs on these motors, as the energy savings may not pay for the VFD within the desired payback period. For example, the small share of compressors with VFDs is likely due to their large size (thus high cost) and lower savings potential, i.e., due to the linear speed/power relationship, compressors are estimated to only save 10 - 15% of overall energy use (Anibal T. de Almeida et al. 2001; Lowe, Golini, and Gereffi 2010). According to the Industrial Assessment Center database (Industrial Assessment Centers n.d.), almost 70% of all recommendations to incorporate motor drives (ARC codes 2.4141 – 2.4144) are not implemented, likely due to cost recuperation. Regardless, if all motors where VFD are applicable had a drive added, even if it is not economical to do so, the 2015 energy demand for motors would drop from 1427 TWh (U.S. Energy Information Administration 2016a) to between 1332 and 1359 TWh (depending on the assumed savings potential of VFDs), or a reduction of 4.8% to 6.7%.

Table B-3. Calculation for VFD savings potential in 2015 and 2025

	Pumps	Fans	Compressors	Mech. Movers	Total
Motor Energy Use (TWh in 2015) (U.S. Energy Information Administration 2016a; U.S. Department of Energy 2014; Waide and Brunner 2011)	255	298	528	352	1427
Average VFD Savings Potential (Anibal T. de Almeida et al. 2001; Lowe, Golini, and Gereffi 2010)	20 - 35%	20 - 35%	10 - 15%	15%	
VFD Applicability (Anibal T. de Almeida et al. 2001)	60%	60%	30%	60%	
Current level of installed VFD (Werle, Brunner, and Tieben 2014)	34%	38%	3%	8%	
New Install Potential	26%	22%	27%	52%	
Overall Savings Potential (Ave. Save. X New Install)	5.2 – 9.1%	2.2 – 7.7%	2.7 – 4.1%	7.8%	
Potential Saved Energy (TWh in 2015)	**13 – 23**	**13 – 23**	**14 - 21**	**28**	**68 – 95**
Motor Energy Use (TWh in 2025) (U.S. Energy Information Administration 2016a)	290	330	581	409	1611
Potential Saved Energy (TWh in 2025)	**15 - 26**	**15 - 25**	**16 - 24**	**32**	**77 - 107**

By 2025, motor electricity use is expected to reach 1611 TWh (U.S. Energy Information Administration 2016a) (assuming the fraction of energy demand from motors remains constant), due to increasing motor population and overall increase in electricity demand. With this increase in motor electricity use, there is a corresponding increase in potential energy savings from VFDs to 77 – 107 TWh.

B.3.1 WBG VFD Energy Savings Estimation

The presented ranges for expected energy demand of motors presented in Table 4-3 are due to the range of assumed VFD savings potential (10 – 35% depending on motor application (Anibal T. de Almeida et al. 2001; Lowe, Golini, and Gereffi 2010), see Table B-3). VFD efficiency used for energy calculations was a weighted average of VFD efficiency for the different motor size classes and the relative energy use of those classes (93.6% for Si-VFD and 98.6% for WBG-VFD) (see Table 4-2). It was also assumed that the VFDs would run at 75% speed or medium load (42 – 50%, as shown in Figure 4-8), as VFDs provide no energy savings when motors run at full speed/load.

B.4 RAIL ENERGY SAVINGS ESTIMATION

Rail systems are more complex than previously discussed applications due to regenerative braking, which sends approximately one-third of the input electricity back through the traction system (accruing additional PE losses) to be returned to the local grid or rail power distribution system or energy storage. Regenerated power must be stored or used immediately (e.g., by another train, to power the station, by a local residence), otherwise it is lost. For this analysis, it was assumed that the reported energy used by rail traction in the U.S. (U.S. Energy Information Administration 2016a) is the net electricity used by the rail system (energy used less the regenerated electricity plus what is lost between the train and the substation on the catenaries or third rail). This is approximately 76% of what is used by the train: 10% is lost by the substation and 34% is regenerated by the brakes (Ciccarelli 2014; González-Gil et al. 2014; S. Su, Tang, and Wang 2016) (see Figure 5-4).

It was assumed that the overall system efficiencies for AC and DC trains are approximately equal (Ciccarelli 2014). About half the input energy is required for braking; however, with regenerative breaking, approximately two-thirds of this can be returned to the rail/local grid or to an energy storage system. Auxiliary systems, such as air conditioning, battery charging, etc., utilization and energy demand vary greatly, with the total auxiliary power requirements usually between 14 and 28% of the total rail system's energy use (20% was assumed for the energy analysis (S. Su, Tang, and Wang 2016; González-Gil et al. 2014)), including auxiliary power electronics losses (~3%). The traction system is responsible for a large portion of lost energy in electric trains with the inverter, motor, gearbox, and, if an AC line, the transformer also contributes to losses. Altogether, losses in the traction system are responsible for approximately 14% of the energy demand of the system, with 2% lost by power electronics. An additional 6.6% is lost when reconditioning the energy from regenerative braking, with roughly 1% lost by power electronics.

B.4.1 Energy Savings from Weight Reduction

The introduction of WBG into electric rail would allow for energy savings from: reduced power electronics losses and weight savings. As stated above, a 10% reduction in weight can lead to a 6.6 – 8.6% reduction in energy use for transit or commuter trains. High speed trains stop less often than transit and commuter trains, leading to a lower potential for energy reduction (3.2%) (S. Su, Tang, and Wang 2016; Helms and Lambrecht 2007). Using Toshiba's catalog of rail traction and auxiliary power systems (Toshiba International Corporation 2014) as a guide to train weight distribution, on average, traction, and auxiliary inverters are 2.3% and 1.8% of the total train weight, respectively. If SiC can reduce inverter weight by 30 – 80% (ABB 2016a; K. Smith 2015; Brenna et al. 2014; Mitsubishi Electric Corporation 2015b), this could decrease the total train weight by approximately 2% (assuming 50% reduction for auxiliary and traction inverters). This results in a 0.9 – 2.5% reduction of energy pulled from the electrical source for train operation.

B.4.2 Energy Savings from PE Loss Reduction

Rail traction inverters are already highly efficient (97 – 98%) (Youssef et al. 2016; S. Su, Tang, and Wang 2016; Gunselmann 2005), but SiC could still reduce PE losses by about half, resulting in an inverter efficiency of approximately 99% (Hamada et al. 2015; Brenna et al. 2014). Unlike traction inverters, auxiliary inverters are only around 85% efficient, and SiC inverters could increase efficiency to around 92% (K. Smith 2015). As stated above, electric trains lose around 6.5% of the train input energy via power electronics (3% in the auxiliary system, 2.4% in traction, and 1.1% via regenerative braking) (Ciccarelli 2014; González-Gil et al. 2014; S. Su, Tang, and Wang 2016; Gunselmann 2005; Youssef et al. 2016; K. Smith 2015). The incorporation of SiC into the traction and auxiliary inverters reduces the energy required by the system, while SiC incorporation into regenerative breaking increases the amount of energy sent back to the source. SiC reduces PE losses by approximately 40% and reduces energy pulled from the grid by 6.1% (including the changes in energy flows in other systems, such as reduced losses between the grid and the rail power conversion station). While diesel rail may use power electronics, such as within its auxiliary systems, it is not accounted for in this study.

B.4.3 All Electric Rail

To estimate the maximum amount of energy that could be saved with WBG devices in U.S. rail, the energy demand for a future case where all rail lines were electrified was also determined. This was estimated using passenger and freight rail energy intensity data for electric and diesel rail from the 2015 Railway Handbook (International Energy Agency 2015) and the Transportation Energy Data Book (S. C. Davis, Diegel, and Boundy 2015), along with current energy demand from each fuel source (see Table B-4 and Table 5-2, the diesel based energy demand was multiplied by the ratio of the electric and diesel train efficiencies).

Table B-4. Rail passenger and freight on-site energy efficiencies

System Efficiency	Diesel	Electric
Passenger (MJ/km) (International Energy Agency 2015)	155	63
Freight (MJ/t*km) (S. C. Davis, Diegel, and Boundy 2015; International Energy Agency 2015)	0.213	0.06

If all 2015 rail activity was electric, approximately 49.9 TWh (180 MJ) of electricity would have been required to move the 1.5 million miles and over 1.7 trillion ton-mi of passengers and freight (S. C. Davis, Diegel, and Boundy 2015), respectively (compared to 560 MJ of mixed diesel and electricity that was used (U.S. Energy Information Administration 2016a)). If considering primary energy, the energy reduction is less substantial. Assuming that 1 MJ of electricity requires 3.1 MJ of primary energy (Energy Star 2013) and 1 MJ of diesel requires 1.2 MJ of primary energy (Global CCS Institute n.d.), the electric-diesel ratio for passenger rail is 1.1 (the on-site ratio is 0.4). This means all-electric passenger rail would use slightly more primary energy than diesel, given the current electricity portfolio (111 MJ, mixed; 113 MJ all electric).

However, even considering primary energy, electric freight is more efficient than diesel (with an electric-to-diesel ratio of 0.73), and, in the U.S., freight requires significantly more energy than passenger, such that all electric rail would require less primary energy than the current mix of diesel and electricity (200 MJ mixed, 155 MJ all electric).

B.5 H/EV ENERGY SAVINGS ESTIMATION

B.5.1 BEV

As a starting point, an energy flow diagram was constructed for a conventional BEV, assuming a battery charge of 100 units, akin to similar diagrams for conventional gasoline vehicles with 100 units of energy in the fuel tank (Akerlind et al. 2015). Then using the same value for units of energy used for the auxiliary systems and movement, another energy flow diagram was constructed for a WBG-BEV to determine potential changes to both battery size and energy drawn from the grid.

Figure B-1 shows the energy flow for a conventional BEV using the average of each system's efficiencies from literature (Burak Ozpineci 2015; Karlsson and Kushnir 2013; Faria et al. 2012; Ozdemir, Acar, and Selamogullari 2015; STMicroelectronics n.d.; Chinthavali, Otaduy, and Ozpineci 2010; Schulting et al. 2015; Xue et al. 2015; Nan, Yao, and Ayyanar 2015). Blue shows the traction energy flow; green, the regenerative braking energy flow; black, lower voltage (battery and LV converter) energy flow; and red is for energy losses. Electricity is received from the grid and converted by the OBC, then sent to the battery (due to regenerative braking, this is less than the full 100 units in the battery). From there, approximately 35% of the battery power is sent to the auxiliary systems via the LV converter and 65% is sent through the traction system (Karlsson and Kushnir 2013). The amount of energy used by BEV auxiliaries is higher than conventional ICE vehicles; auxiliaries that are typically powered indirectly by the engine (belt powered systems and heating) must be powered directly by the battery for BEVs (Kambly and Bradley 2014; V. H. Johnson 2002). In the driveline, energy is lost by the HV converter & inverter system, the motor, and the transmission. Approximately 25% of the energy sent to the wheels is used for braking (Akerlind et al. 2015), 77% of which is recovered by regenerative braking after the transmission line losses. Overall, energy is lost by the OBC, PCU, motor, and transmission along the driveline, resulting in 30% of the input energy used by auxiliary systems and 38% used for movement.

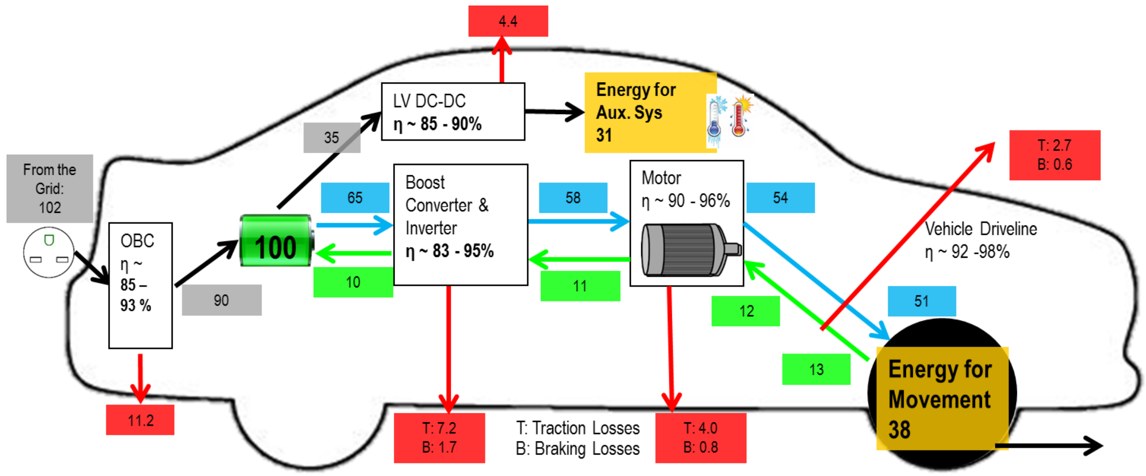


Figure B-1. Energy flow diagram for a conventional Si-PE BEV using average system efficiencies (Burak Ozpineci 2015; Karlsson and Kushnir 2013; Faria et al. 2012; Ozdemir, Acar, and Selamogullari 2015; STMicroelectronics n.d.; Chinthavali, Otaduy, and Ozpineci 2010)**.**

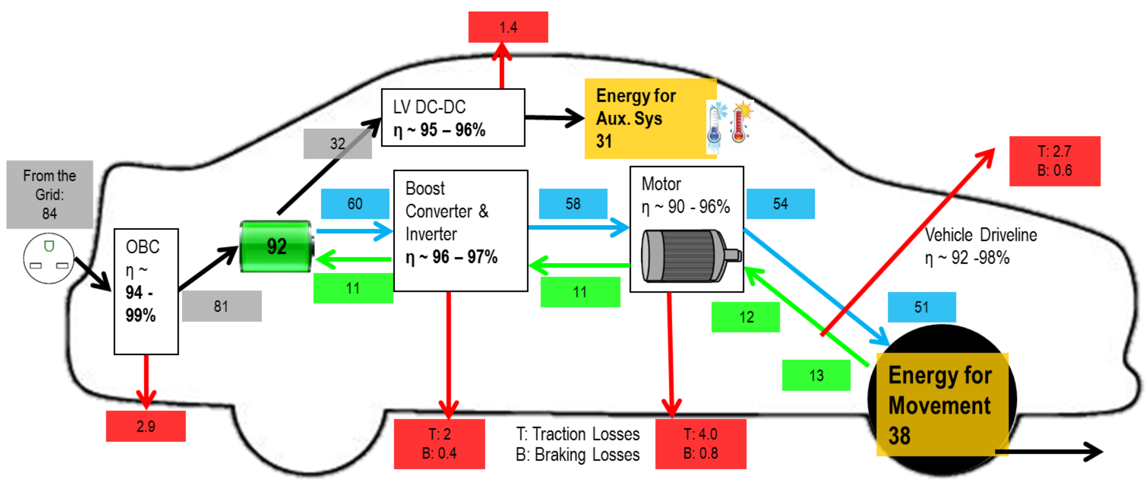


Figure B-2. Energy flow diagram for a WBG-PE BEV using average system efficiencies (Burak Ozpineci 2015; Schulting et al. 2015; Xue et al. 2015; Chinthavali, Otaduy, and Ozpineci 2010; Ozdemir, Acar, and Selamogullari 2015; Karlsson and Kushnir 2013; Nan, Yao, and Ayyanar 2015; Faria et al. 2012)**.**

For a WBG BEV, the PE system's efficiency rises (see Figure B-2), increasing the overall system energy efficiency (the fraction of energy for movement and auxiliary systems, combined, out of the input grid energy) to 82% (a 21% increase). Additionally, the fraction of the incoming energy is used for movement is increased to 46% (the fraction of just the energy for movement out of the input grid energy), providing a 17% increase in fuel economy, from 116 - 124 mpg_e[7] (U.S. Department of Energy n.d.) to 136 - 145 mpg_e. Furthermore, the demand on the grid reduces by 19% and the range is increased (or battery size decreased) by 8%.

[7] The fuel economy of BEVs are measured in terms of miles per gallon equivalent (mpg_e), by assuming 33.7 kWh of electricity per gallon.

The largest reduction in losses comes from the on board charger. All of the energy into the system flows through the charger, and conventional chargers are between 85 – 93% efficient (Burak Ozpineci 2015; Karlsson and Kushnir 2013; Faria et al. 2012) while WBG chargers are between 94 – 99% efficient (Burak Ozpineci 2015; Schulting et al. 2015; Xue et al. 2015). SiC integration into the inverter system could also result in a significant increase in efficiency (Burak Ozpineci 2015; Ozdemir, Acar, and Selamogullari 2015; Chinthavali, Otaduy, and Ozpineci 2010), leading to increased vehicle range. Conversely, approximately 35% of the system power is processed by the LV DC-DC converter, leading to minimal loss reductions, despite the increase in converter efficiency from WBG (STMicroelectronics n.d.; Nan, Yao, and Ayyanar 2015).

BEVs used 14.7 PJ of primary energy (1.3 TWh of on-site electricity) in 2015; if WBG PE were substituted into every BEV on the road this would save 2.5 PJ of primary energy (0.2 TWh on-site). The BEV forecasts for 2025 are relatively close: 2.4 million from the AEO and 4.1 million from the TEF project. This results in an estimated future energy use between 95 – 160 PJ. Again, if all BEVs in the future fleet had WBG PE, this would save 17 - 28 PJ (see Table 6-3).

B.5.2 HEV

Toyota has designed and tested an all SiC PCU by driving in Toyota City and has found an increase in fuel economy between 5 and 10%, increasing the Prius fuel economy to 53 – 55 mpg (compared to a 2015 Prius (U.S. Department of Energy n.d.)). HEVs used 160 PJ of electricity in 2015. If all of HEV had a WBG PCU with savings similar to the WBG Prius, 11 PJ of energy (91 M gal of gasoline) could have been saved. Unlike BEV, the two forecasts for the number of HEVs on the road in 2025 are not close, ranging between 7.2 – 26 million. By 2025, HEV energy use could rise to between 260 and 950 PJ, but could be reduced by 18 – 66 PJ if all the HEV fleet had WBG PCUs (see Table 6-3).

B.5.3 PHEV

PHEVs are inherently more complicated than BEVs or HEVs. They use energy from both the grid and gasoline, and it is difficult to parse the amount of energy used by each fuel. In order to do so, a utility factor was developed (Duoba, Carlson, and Bocci 2009) for the fraction of miles the vehicle is in charge sustaining (CS, engine running the generator to maintain battery state of charge) or charge depleting mode (CD, vehicle running mostly on electricity, depleting the battery). Using this fraction and data on PHEV energy use per mile (Elgowainy et al. 2016), the fraction of energy from each energy source was calculated (see Table B-5).

Table B-5. CD and CS mileage efficiency for PHEV10 and PHEV40 vehicles

		PHEV10	PHEV40
CD electric (Elgowainy et al. 2016)	kJ/mi	800	340
CD gas (Elgowainy et al. 2016)	kJ/mi	1190	0
CS gas (Elgowainy et al. 2016)	kJ/mi	3390	3490
Utility Factor (Duoba, Carlson, and Bocci 2009)		22%	58%

PHEV40s often use a series drive train (motor for movement and engine solely for battery charging), can drive 40 miles on battery power, and use no gasoline when in CD mode. The higher CD gives a utility factor of 58% of miles driven in CD mode, resulting in approximately 33% of the energy used being attributable to the grid, with the balance from gasoline. PHEV10s use a series/parallel drive train in which the motor or engine can be used simultaneously or individually for movement, while the engine also available for battery charging. PHEV10s can only travel 10 miles on battery, resulting in a utility factor of 22% of miles driven in CD mode. Additionally they do use gasoline when in CD mode, resulting in 94% of PHEV10 energy attributable to gasoline.

For both PHEV10 and PHEV40, the fraction of energy from each source was then assumed to have the same WBG energy savings as the analogous HEV and BEV case (5 - 10% fuel savings for gasoline consumption and 23% increase in efficiency for electricity use). If all of the PHEVs utilized WBG devices in 2015, this would reduce PHEV primary energy use to 13.9 PJ from 15.0 PJ. Like HEVs, the 2025 expectations for PHEV are widely different, from the 2.3 million (AEO projection) to 23 million (TEF projection). This leads to a forecasted primary energy demand ranging from 120 PJ to 1200 PJ, and thus a potential WBG savings ranging from between 9 PJ and 90 PJ (see Table 6-3).

For all vehicle types, CO_2 emissions were estimated assuming 8.6 kg CO_2/gal gas; 0.5 kg CO_2/kWh electricity.

APPENDIX C: DETAILED 2012 SURVEY RESULTS

APPENDIX C: DETAILED 2012 SURVEY RESULTS

The previous 2012 ORNL industrial survey contains more detailed information in regards to defects, yields, and costs. All respondents to the 2012 survey were involved with SiC technologies. Costs from one manufacturer based on a fully-loaded fabrication run are tabularized below, which may be somewhat outdated as the technology is maturing rapidly since the survey was undertaken.

Table C-1. Wafer Costs

Product Type	Wafer Cost (150mm)	
	GaN on Si	SiC
Substrate	$30	$1000
Epi	$200/wafer	$30/wafer
Fab	$500	$550
Total	$730	$1850

C.1 SIC 4" WAFERS COST, DEFECTS AND YIELDS

Defect densities were quoted from one source as '<1/cm^2 for micropipes and ~10^4 /cm^2 basal plane dislocations.

Epiwafer typically has a defect density of 2/cm^2 and a full quality area >85%

.

Schottky yields were 'extremely good, very close to Si yields. All SiC device yields are far better than GaN on Si devices.'

Schottkys are ~3X the cost of Si, closing in on 2X and anticipated in 2014.

Commercial grade 4H-SiC substrates cost ~$700

Wafer costs are dependent on volume purchases over a yearly time frame. Middle of the distribution is about $1500 for a 100mm diameter wafer with 10um of epi.

For a 4H, 4 inch diameter SiC substrate (n-type) with 1.2kV MOSFET epitaxy, the cost in volumes is about $1.2k per wafer. This varies somewhat from vendor to vendor, as does quality.

Composite (blocking, gate, $R_{ds\text{-}on}$ and threshold) finished yields are over 50% routinely, with upside for a 1.2kV vertical DMOSFETs, assuming 3x3 mm chips (nominally about 15A). With larger chip, yields are lower.

Screw dislocation defects in substrates impact the leakage currents which are currently estimated to ~ 1000-3000/cm^2 and likely to go to 100-300/cm^2 on a 4" wafer. However, micro pipes are no longer seen as an issue.

Most Si power semiconductors are still being made on 4" and 6" wafers as there are not yet the volumes to justify moving to larger wafer sizes. Only about 5% of Si power semiconductors (IGBTs) are on 8" wafers due to insufficient volume today. IGBT market is estimated to be a $4B market today.

Total worldwide WBG market is estimated to be $100M today, mostly SiC market with only $1M for GaN. Industry needs will justify move to 6" in projected 5-8 year timeframe. The 8" market would require to double market today.

There are various types of defects, but not all of them affect device yield. Micropipes are near zero for all vendors and hence are not of concern. Basal plane and threading dislocations may range from 10^2-10^4 on a vendor by vendor basis, but often those are not seen as 1.2kV DMOSFET yield limiters. The most important in DMOSFET fabrication seems to be surface finish.

76 mm and 100 mm diameter wafers are currently available. Micropipe density is relatively low, i.e., <1/cm^2 compared to other dislocation densities of less than 2000/cm^2.

C.2 MANUFACTURING PROCESS BOTTLENECKS FOR WAFER RELIABILITY OR COST

The length and diameter of the Boule is the biggest cost driver. The longer the length, the higher is the number of wafers per boule. With an increased loading on the existing equipment, the prices drop. Substrate costs are not a big issue, the focus is on the epi and defects in the fabrication process. SiC has additional high temp steps involved in the epi and fab processes than the GaN on Si, reflected in higher costs of the latter. SiC cutting and polishing are more expensive than for Si, resulting in a higher utility costs due to process electricity consumption besides more time to etch. GaN-materials are more expensive to grow.

There are no inherent bottlenecks that being observed. Potential for slow points in the wafer processing may relate to gaps in specific processing tools.

The substrate and the epi processes still dominate the SiC technology efforts today.

C.3 CURRENT DENSITY OF AVAILABLE DEVICES

1200V, 50A MOSFET -- 200A/cm^2 (Future goal: 400 A/cm^2, then 800A/cm^2)
1200V, 50A Schottky -- 270 A/cm^2
600V, 50A Schottky --.400A/cm^2
DMOSFET -- 225 A/cm^2 at room temperature

The latest generation diodes operate at >600A/cm² in discrete packages, since this parameter gain is strongly linked to assembly and cooling techniques. An adaptation of the chip development is linked to progress in this field.

Table C-2 shows the commercially available 1200 V SiC JFETs. Note that the current ratings are peak pulsed currents at a junction temperature of 25 C (done to remove the limitations of packaging).

Table C-2. Commercially available 1200 V SiC JFETs

Part	Description	Peak pulsed current	Current density
SJEP120R100	1200 V, 100 mΩ	30 A	1,138 A/cm^2
SJEP120R050	1200 V, 50 mΩ	60 A	871 A/cm^2
SJDP120R085	1200 V, 85 mΩ	75 A	2,845 A/cm^2
SJDP120R045	1200 V, 45 mΩ	140 A	2,031 A/cm^2

For all of our commercially available 1200 V SiC Schottky diodes, the current density is approximately 250 A/cm^2.

C.5 CURRENT DEVICE COST ($/A) WITHOUT PACKAGING

Current device cost is extremely dependent on packaging and the available pricing from Digikey would have a huge markup (approximately 30% in some cases). Company cost is way below in high volumes.

It is anticipated that a move to 6" wafers will allow more automated processes thereby reducing human involvement with a consequential reduction in defects.

The device cost maybe cheaper than Si with a move to 8" SiC.

In research quantities, the cost is nominally about $2/A (in a tested discrete package), but little effort has been put into practice to reduce this value. It is expected that with modest quantities (e.g. ~2-3 million amps/year), the price will fall below $1/A, and perhaps as low as $0.5/A with the successful introduction of 6 inch diameter substrates.

C.6 LIMITING TECHNOLOGICAL DEVICE DEFECTS

1C screw dislocations observed as device defects is the materials problem.

Improving oxide channel mobility is being actively pursued at the distinct processing levels of fab, epi defects, and devices.

Gate oxide-related extrinsic failures are a current focus, and perhaps the last major effort to ensure an effective screening test(s) are established for large-scale qualification of these parts (e.g. for automotive standards akin to AECQ101). The high temperature stability of SiC

DMOSFET's have been shown and are repeatable. Other areas, HTRB and HTOL show good promise and will be included in the final qualification testing to be done in 1H13.

C.7 KEY MANUFACTURING PROCESSES BOTTLENECKS FOR RELIABILITY/COST

The main bottleneck is manual handling of wafers. It results in process defects leading to a lower yield, increased cycle time, higher cost, and lower reliability. It is projected that with a moving to 6" will allow more automated manufacturing process as more automated tools will be available. However, in the long run moving to 8 inch will be ideal from this standpoint.

Very simply, costs are driven by volume, wafer diameter, and yield. The SiC market is only ~ $100 M at this time, and anticipated to be ~ $1B-$3B by 2021. A 10X-30X increase in market volume will drive prices down substantially over the next ten years. Additionally, the availability of 150 mm wafers estimated in 2013 will allow some diode product costs to be cut up to 50% or more.

C.8 COST AND REQUIREMENTS TO REALIZE DEVICE ADVANTAGES

Achieving an adequate creepage distance with existing packaging technology is often a limiting factor. In addition, parasitic inductance of discrete packages and module layouts/housings can also undermine the potential performance benefits of SiC. Finally, sintering contact formation in packages has the ability to reduce thermal and resistance constraints for SiC devices.

Table C-3. SiC temperature and costs

Maximum temperature	300 C	250 C	200 C	175 C/ 150 C
Cost	>$180	No known high-volume technology available today		< $0.25

The cost of a plastic TO247 is about $0.20 apiece in high volume.

Progress in extended power cycling capability, low inductances, and low R_{th} (thermal resistance) include:

For 200 degC, molded compounds that have been specially developed by GE in partnership with others have shown good promise. Its glass transition temperatures suggest this range is acceptable for implementation. Normal molding compound parts have been shown to work up to 175 degC as well.

There is a large variance to the type of modules contemplated. The best references for module prices might be Arkansas Power Electronic, Inc. or Powerex, who have both offered solutions in this area.

Regarding discrete devices, there is only one type of discrete package that would be rated up to 225 degC or potentially 250 degC. Initial discrete costs in low chip volume may be $1/A, however, with the introduction of 6 inch diameter wafers and manufacturing, will be lower than $0.70/W.

The above has strong dependence on the type of module and its size. It is projected to be low, likely less than 15% even in low device/discrete volumes.

The 400 W/cm^2 device manufacturing capability exists and theoretically as high as 1000 W/cm^2 with a double sided cooling requirement would offer 'huge' advantages.

A fundamental barrier to the growth of WBG, is seen as 'the packaging'.

No problems were envisioned in doing solderable top sides with a potential to offer it as a standard product. An interest in all packaging innovations, including sintering and diffusion bonding was expressed.'

Currently WBG device packaging is the same as used for 150C Si devices. Schottky dies that are 175C qualified are sold today besides 150C qualified MOSFETs. The 300C device packaging is not a big target and typically SiC runs is cooler than Si and dependent on die size. Discretes is running about 5% or less% for packaging.

C.8 COST DRIVERS OF PRODUCT COMMERCIALIZATION

Wafer size, fab loading, and automation are the major cost drivers of product commercialization. When system level benefits are considered, initially high chip costs may not be of primary concern. Higher volume applications will most likely drive taller expectations on overall costs. Fab/processing is perhaps the largest single cost component in low to modest volumes.
Raw materials, yield, development & engineering, qualification are the major cost drivers of product commercialization.'

APPENDIX D: DETAILED 2013 SURVEY RESULTS

APPENDIX D: DETAILED 2013 SURVEY RESULTS

The 2013 survey posed a series of questions to capture industry participants' perspectives on issues that hinder the growth and competitiveness of the U.S. wide bandgap semiconductor industry. Detailed responses were obtained from seven industry representatives. These representatives covered all major manufacturing supply chain points, starting with raw material production to final discrete packages and module development. The characteristics of seven industry representatives are presented in Table D-1. A summary of their relevant comments is presented in the following sections.

Table D-1. Companies represented in 2013 WBG industry survey

Company	Description
A	The most diversified; involved in manufacturing components, substrates, epitaxial layers, and semiconductor manufacturing equipment
B	Involved with high frequency transistors, and power amplifier development. They utilize external fab houses for their transistor designs and do end product development which may contain multiple transistors
C	Involved with the development of IP to reduce raw material content
D	Develops substrates, epilayers, and manufactures devices and modules
E	Involved in substrate and epilayer development
F	Does substrate and device as well as discrete packages and module development
G	Manufactures device, discrete packages and modules

D.1 Major Manufacturing Material Inputs

Company representatives share the information about manufacturing inputs for SiC and GaN semiconductors as presented in Table D-2 Table D-3.

Table D-2. GaN manufacturing input information, by company

	Major source materials	Amount (/yr)	Source country	Cost	Manufacturing technology	Primary advantage of this sourcing option	Primary disadvantage of this sourcing option
Company A							
1	Gallium Metal	60 kg/yr	USA	$380/kg	Hydrometallurgy from aluminum waste stream	Stable U.S. source	Price can vary greatly
2	Ammonia Gas	2500 lbs/yr	USA	$7.45/lb	Haber-Bosch process	High purity	Relatively high cost
3	Sapphire (2”, 4”, 6”)	1500 wafers/yr	Various	$27/wafer	Czochralski, EFG, Kyropoulos	Lots of vendors and great availability	None
4	Quartz Parts	120 parts/yr	USA	$400 /part	Fused Quartz	Highest quality and repeatability	Availability is sometimes an issue. Higher cost.
Company B							
1	Fully processed GaN wafers	---	USA	---	GaN/SiC HEMT fabrication	Performance, domestic supply	Cost

Table D-3. SiC manufacturing input information, by company

#	Major source materials	Amount (/yr)	Source country	Cost	Manufacturing technology	Primary advantage of this sourcing option	Primary disadvantage of this sourcing option
Company D							
1	SiC substrates		USA		Bulk growth	Internal	none
2	Graphite						
Company E							
1	Silicon		USA			Internal	
2	Graphite		USA, Europe		Traditional from pitch	Quality	
3	TaC coated graphite*		Europe	Very expensive			
4	TMGa/TMAI		USA		Chemical synthesis		
Company G							
1	SiC Epi wafers	3000/yr (2013)	USA				
	* many different TaC parts; very broad price range, on average 5X cost of SiC coated graphite						

D.2 MAJOR MANUFACTURING MATERIAL OUTPUTS

Company representatives shared information about manufacturing outputs for SiC and GaN semiconductors as presented in Table 10-4 and Table 10-5.

Table D-4. GaN manufacturing output information, by company

#	WBG-related material produced:	Amount (/yr)	Major destination country	Purchaser's price:	Manufacturing technology	Primary application(s) of material
Company A						
1	Bulk GaN Wafers	250 wafers/yr	1) USA 2) France 3) Switzerland 4) Japan	$570 avg	Hydride vapor phase epitaxy	LEDs, Lasers, Power Electronics, RF Electronics
2	GaN Templates	500 wafers/yr	1) USA 2) Saudi Arabia 3) Canada 4) Taiwan	$250 avg	Hydride vapor phase epitaxy	LEDs, Lasers, Power Electronics, RF Electronics
3	AlN Templates	2000 wafers/yr	1) USA 2) Taiwan 3) South Korea 4) Japan	$50 avg	Plasma Vapor Deposition	LEDs
Company B						
1	Packaged RF transistors	---	---	---	Standard package and assembly techniques	High power discretes for pulsed applications, DC-4GHz

Table D-5. SiC manufacturing output information, by company

#	WBG-related material produced:	Amount (/yr)	Major destination country	Purchaser's price:	Manufacturing technology	Primary application(s) of material
Company D						
1	SiC MOSFETs and diodes	---	Taiwan	---	SiC fab	Server power supplies, solar inverters, industrial power supplies
Company E						
1	4H-SiC wafers	>10k	Asia	---	PVT	Power semiconductors
Company G						
1	Semiconductor devices	---	Europe, USA	---	---	SiC switching devices

D.3 MANUFACTURING PRODUCT COST BREAKDOWN

D.3.1 GaN

Responses related to product cost breakdown were quite limited, one each for GaN and SiC. Company A, the most diversified manufacturer, indicated that it is clear that GaN substrates, AlN templates and related products can be fabricated with costs that are less than 2x the input materials costs, once high volumes are achieved along with good yields (based on a COGS calculation as a function of tool utilization and process yield). The reason is because the equipment depreciation cost is low (compared to MOCVD and MBE) as are labor costs due to a high degree of automation.

D.3.2 SiC

Company D indicated that its Power & RF unit, which manufactures SiC power MOSFETs, diodes and modules, as well as GaN HEMTs, had a total revenue of $89 M, up by 22% from FY12, with an overall gross margin of 54%, well above the overall semiconductor industry averages.

D.4 MAJOR PRODUCTION INEFFICIENCIES

D.4.1 GaN

Company A indicated that its bulk GaN manufacturing process is limited by the ability to produce bulk GaN boules with no cracks in them. Average cracking density has been reduced from >1,000 per wafer to 1 or 2 per wafer, but getting rid of those last couple of cracks is difficult. The cause is related to stress and strain which is related to using sapphire as the starting material and not a GaN seed. A good GaN seed is hard to come by, in sort of a "chicken and egg" way. Ammonothermally grown GaN would be the best seed, and its HVPE process would rapidly replicate its quality if that scenario could be enabled with sufficient funding.

Company B indicated that GaN HEMT yields are inconsistent and cause unpredictability in supply. Due to "good wafer" vs. "bad wafer" effect in a lot, the final output from a given fabrication lot carries significant uncertainty. An improvement in the understanding of issues surrounding manufacturing variability in GaN HEMT production is necessary. This yield variability can translate into reliability risk because manufacturing defects could lead to higher reliability risk.

D.4.2 SiC

Company D indicated that the major inefficiency point is lack of power modules within the company, which it is continuing to invest in and release products. For Company E, the supply of TaC coated graphite parts used in epitaxy was limited to a single source and was a major concern. These parts are the largest cost contributor to epiwafer prices in SiC.E. Company F indicated a mismatch in wafer diameter as the major concern for production efficiency.

D.5 Materials-Related Supply-Side Issues for the Domestic Industry Competitiveness

D.5.1 GaN

Company A indicated that high quality bulk GaN substrates are unavailable at the required price point, diameter and volume and thereby investments are needed in this area. There are a lot of 2"

GaN substrates on the market, but they cost too much and their quality is limited by mosaicity and dislocations typical of HVPE only processes. On the other hand, expensive SiC substrates drive up the cost of the fully processed wafer – indicated by Company B. In addition, 150mm GaN/SiC is not commonly available.

Company C noted that GaN was still in its infancy, and much work needs to be performed related to Dry/Wet etching of GaN doped films, as well as Ion implantation into various CS materials. In addition, ohmic contact schemes are just now being developed. Production related to MOCVD and HVPE need to be improved for through-put, cost and reduction in chemical use/waste. This company realizes the vast amount of experience related to Silicon wafer technologies and works to leverage this substrate material for CS device/process technologies.

D.5.2 SiC

As Company D is vertically integrated using its own bulk SiC wafers for all the products manufactured in its business unit, no major materials-related supply issues were identified. The company representative reported that the highly fragmented industry was causing a more a more expensive SiC project, compared to those manufactured in-house, and hindered SiC use. Secondly, customers often expect the design, application, and quality issues to be managed by a single source, a model that does not yet exist for SiC in volume. Mitsubishi (Japan), Infineon (Germany), and Fuji (Japan) represent about 58% of the power module market. They manufacture and sell these modules with die primarily manufactured internally.

Two other manufacturers, Company E & F did not highlight any materials-related supply-side issues. However, Company G indicated, a high cost of wafers is a widely known issue for widespread switching product uptake. A secondary issue is the “ease of use” by circuit designers of a SiC switch. The goal is to make the device as robust and stable as silicon MOSFETs or IGBTs.

D. 6 NON-MATERIALS-RELATED SUPPLY-SIDE ISSUES FOR THE DOMESTIC INDUSTRY COMPETITIVENESS

D.6.1 GaN

Company A indicated a lack of universities graduating students in this new area of research is a major concern. For example, UCSB seems like the only university graduating PhDs with experience in bulk GaN crystal growth; however, the graduates often go directly to a UCSB startup. The lack of universities participating in GaN research is due to dramatically less funding in bulk GaN in the United States compared to Japan. The company representative perceived change at DOE that would address this shortage.

A need for higher level of reliability in GaN-based products was indicated by Company B. The vendors must demonstrate low failure rates arising from manufacturing defects to enable adoption into high-volume applications. Neither capacity nor workforce constraints was anticipated as GaN processing can be done in currently GaAs PHEMT fabrication plants, with the possible exception of mass production of SiC substrates. GaN epi manufacturing has been scaled to high-volume for quite some time due to LED manufacturing. Epi reactors which can grow on wafers of 150mm diameters have been available for some time. High power die-attach of GaN die to commercially available packages is a production risk area since the thermals are a big performance driver for GaN. Sufficient knowledge and experience is not widely available.

Company C indicated that the WBG industry requires understanding of complex atomic film structures and their similar atomic level interactions. Failure modes and device physics tend to require a focused and skilled workforce which is difficult to develop and mentor, due to the limited size and mobility of the engineering/physicist workforce.

D.6.2 SiC

Responses related to non-materials related supply side issues for the SiC domestic industry competitiveness were rather limited. Company D commented on a shortage with the right background with only a few universities working in this new research area. This concern was similar to that raised relative to GaN. The lack of power module/packaging engineers, power fabrication process engineers, and basic materials engineers related to SiC was also highlighted.

Company E raised general issues associated with semiconductor device design, fabrication, and supply. Two other manufacturers, Company F & G did not highlight any non-materials-related supply-side issues.

D.7 POLICY-RELATED SUPPLY-SIDE ISSUES FOR THE DOMESTIC INDUSTRY COMPETITIVENESS

D.7.1 GaN

Company A raised concerns about our nation’s future being compromised by the lack of policy that requires technology paid for with U.S. tax dollars to stay in the US. For example, many DARPA and other previous funds to UCSB, Cree, Crystal IS, and others have ended up in Japan and China. Cree sold bulk GaN IP to Mitsubishi Chemical and plenty of that IP was generated at ATMI under DARPA funding. The policy issue related to the importance of materials was another area highlighted. The material issue is not being considered seriously by certain DOD, DOE, DHS, and other organizations which results in IP issues, particularly when locked by foreign companies.

Company C indicated that in some/most cases the availability of Rare Earth elements can impact the film stack design/selection.

D.7.2 SiC

Company E indicated that not much emphasis has been paid now to support growth of science and technology pertaining to materials manufacturing: raw materials variability, crystal growth, epitaxy, CVD equipment. Companies F & G did not raise any fundamental blocking points on this aspect.

D.8 ACTIONS TO MEET THE INDUSTRY ISSUES/CHALLENGES

D.8.1 GaN

Company A recommended support for a government-led $1B per year Innovative Materials Development Center – a joint collaborative organization among DOE, DOC, DHS, and DOD etc. with a mission to continuously evaluate new materials and generate IP to position the United States to become and stay the leader in all new materials enabled innovations of interest in the future. A major exploratory R&D component in such an organization would facilitate in locking up any new material IPs well before the market pull for an application it enables takes place. Major academic funding would also facilitate in building up the necessary talented workforce. In addition, policies need to be developed which motivates the U.S. to lead the research in this area.

Company B suggested the need for sustained investments into improving GaN manufacturing and reliability to enable broader adoption into higher volume applications. Investing in high-power DC-HTOL system which can handle up to a 100 samples at a time is critical for GaN to enter the next stage of development, as this will provide critical feedback on GaN quality and manufacturing variability. Investing and making 150 mm GaN/SiC broadly available is also essential to make GaN products cost competitive with incumbent technologies. However, the market demand can be met with existing 100mm GaN/SiC wafers.

Company C is currently engaged with several "small to large" semiconductor manufacturing companies to develop IP and proto-type samples. However, it suggested that performing any "meaningful" research and innovation in this industry is very capital intensive, requiring $US 100-500K, just to provide first samples in a given technology type, i.e., HEMTs, LEDs. The company continues to work to find ways to raise capital to fund research, and production intent technology development. The tool costs for MOCVD / HVPE can easily exceed $US 2-3 Million per reactor as an example.

D.8.2 SiC

Company D also highlighted the importance of the need for investments in building module and packaging manufacturing capability at SiC domestic die manufacturers through private-public partnerships to foster U.S. innovation that can unlock the potential of the WBG devices in terms of much higher operating speeds and higher power densities than conventional Si. Incentives (e.g., tax write-offs or credits) for R&D, installing new manufacturing equipment, and improved U.S. energy policy which would encourage an adoption of more energy efficient technologies like SiC are also necessary. Presently, no incentives exist for manufacturers to improve white goods motor drive efficiency standards to reduce the energy losses by 25% requiring only a few extra dollars to use SiC on a refrigerator compressor drive. Similar efficiency standards on power supplies and industrial motor drives with a 1/3 of total electricity use exist too. In addition, encouragement of EV through infrastructure improvements in charging stations, or tax credits for companies who install EV chargers or solar panels in their facilities, as well as wind and solar renewable energy development through a stable policy are necessary.

Company E suggested the MANTECH strategy focused on SiC and GaN/Si materials supply chain, but not sole sourced. Company F highlighted the immediate need on the customer side, and not component side, e.g., legislation forcing to move to more efficient systems. A more favorable tax treatment for R&D and equipment investment was thought to be a benefit by Company G.

D.9 DEMAND-SIDE IMPACTS ON THE GROWTH AND COMPETITIVENESS OF THE WBG INDUSTRY

D.9.1 GaN

Company A indicated a limited domestic demand for their products, other than for supporting R&D in federal laboratories. Most of its demand is from Asia today.

Company B has been touted for many GaN applications for many years but it has not been adopted by customers broadly. For example, commercial applications in wireless base stations have been touted as one of the largest potential GaN applications for many years, but there is virtually no adoption. This is because GaN does not offer a compelling value proposition relative to the added cost and risks associated with the new technology.

D.9.2 SiC

Company D indicated a weak in power electronics for U.S. relative to Germany, Japan, Korea, and China. U.S. automotive companies seem content to follow Japanese and others in EV. Many (but not all) UPS and server power supply designs are done off shore. Power electronics in industrial applications has long design-in, dedicated expertise and investment required for years. There are U.S. companies in this space, but not enough, and many of the larger U.S. companies push their design centers to Asia. With new technology, the ideal situation is that customers and vendors work very closely together. Power semiconductor companies are compelled to work off shore for many of their design-in opportunities.

Company E suggested a clear roadmap development by application to help define target areas for growth. In addition, standardization of wafer product (too may incrementally different specs) would help reduce substrate prices. Cost contribution of 99% is the major demand-side issue that adversely affect the industry market growth and competitiveness – was highlighted by Company G.

D.10 U.S. MARKET SHARE AND DIRECTION ALONG THE WBG SUPPLY CHAIN

D.10.1 GaN

Company A thought of Japan by far the leader in GaN materials and is coming on strong with SiC too. It is aggressively pursuing all new materials of interest too with Korea coming on strong as well. LG and Samsung are looking around for investments in small U.S. companies. The U.S. is in last place on GaN materials, but that is going to change if DOE invests as it appears they may. Interestingly, the United States often leads in equipment, but just last year over 20 new

MOCVD equipment companies were created in China! As far as advanced devices go, the Japanese are typically in the lead, with Cree and RFMD coming close behind.

Company B thought U.S. is likely a dominant GaN player but other nations have made strong GaN investments, particularly in GaN on Si that could pose a strong competitive threat, especially in GaN for power electronics.

Company C works to provide IP technology for all global markets. Presently, it is difficult to find U.S. partnerships willing to share in start-up costs due to the competitive nature of compound semiconductor markets, and patent rights. It believes compound semiconductors with use of large diameter (8”- 12”) silicon substrate material will trend to dominate the market share, and direction starting in the 2015-2018 timeframe as CS film stress control on silicon, and reduced defect density are realized. CS potential failure modes will need to be reduced to levels near 1-10 ppm, or similar to silicon based solutions as well, in order to dominate the marketplace. Semiconductor Innovation understands the FMEA/PFMEA process to target 0 ppm process/product technologies for automotive and space applications.

D.10.2 SiC

Company D felt U.S. to be in a strong position today, with approximately 40-50% of SiC diode market share according to Yole and others. However, most market reports projections indicate its market share will decline as Japan (Mitsubishi, Rohm, Fuji especially) is making a strong push into SiC power materials, devices, components, and modules, particularly in the traction drive market. A 1.7 - 10.0 kV SiC power transistors and diodes requirement in that market which is being currently dominated by Mitsubishi and Infineon has prevented new market entrants from being successful for decades. In addition, a lack of domestic strength in high-speed rail and traction drive market end customers could pose a big challenge for SiC to penetrate in which the world leaders Alstom Transport (France) and Bombardier (Europe) have already ~ 20% market share each besides other incumbent power semiconductor leaders such as Infineon and ST Micro in Europe.

Company E indicated having a comparable market share and direction in WBG materials, but it lags Asia in devices. On the other hand, U.S. is behind Japan but ahead of Europe was commented by Company G. The Japanese industry has a longer term vision and pay-back criteria while Europe is too encumbered with layers of government intervention in R&D. China is a worry, but at the moment not a significant player.

D.11 DRIVING FORCES FOR POTENTIAL WBG USE, EMERGING MARKETS, AND APPLICATIONS

D.11.1 GaN

Company A indicated several potential GaN market applications including LED lighting going everywhere, power electronics development, UV water purification and RF electronics for Department of Defense. Huge power demand over a wide bandwidth (multi-octave) in harsh high VSWR environments for RF applications such as an adoption of GaN for IED jammers was suggested by Company B. In addition, GaN potential applications for commercial base stations are driven by the need to drive large efficiency improvements over incumbent Si-LDMOS technology while minimizing cost-premium.

Company C similarly indicated solid-state lighting (SSL) applications or LEDs to replace incandescent lighting for reduced power consumption and hazardous materials such as mercury and/or lead. This company is also working on to provide 10-50% increased light per unit die area technologies for SSL applications based on its provisional patent rights. Additionally, it also has provisional patent rights for a Trench based HEMT (THEMT) using a vertical device technology for various inverter topologies applicable for electric vehicles/power converters. With the advent of the High Electron Mobility Transistor developed by use of GaN/AlGaN (2DEG) allows for more efficient and higher operating temperature power HEMTs.

Solar Cell and Photovoltaic applications make use of the WBG "spectrum" to capture more photon energy levels, thus increasing the overall cell efficiency. The 20-40% efficiency levels are now being developed and or deployed. Semiconductor Innovation is working similar technology as that used for LEDs.

D.11.2 SiC

Company D indicated an easy way for the customers to improve efficiency and lower costs by using SiC diodes in server power supplies in the power factor correction portion of the power supply. In addition, SiC MOSFETs are being adopted in solar inverters (public announcement from Delta Energy Systems and Cree in April 2013), industrial power supplies (public announcement from Delta Elektronika and Cree in July 2013), EV DC-DC converters (public announcement with Cree and Shinry in October 2013), and traction (public announcement by Mitsubishi in 2013). Primarily the SiC MOSFET is replacing Si IGBT in the 1200-1700 V range for now.

Emerging markets such as power supplies and low current inverters that traditionally used silicon power semiconductors were suggested by Company E. Efficiency targets, miniaturization, and power density were cited as the major driving forces for a potential WBG use in emerging market applications by Company F. Similarly, efficiency and end equipment footprint were also highlighted as major driving forces by Company G.

D.12 MAJOR FACTORS BEHIND THE EXISTING MANUFACTURING FACILITY INFRASTRUCTURE LOCATIONS

D.12.1 GaN

Company A is located near the university with which its founders were associated. The Tea Party state politics in North Carolina has them considering moving the company, as does power electronics interest by Michigan companies. The company recognized the fact for it to evolve into high volume template manufacturing, a joint venture or similar arrangement in Taiwan or China could be necessary. Instead it prefers to stay in the United States and offer equipment to the Taiwanese and Chinese.

Company B indicated that no new dedicated GaN manufacturing foundries are required as it can be fabricated in GaAs fabs with some additional tools.

Company C mentioned the requirements of compound semiconductors for HVPE and/or MOCVD process tools to produce fabricated wafer material as well as the need for cost effective substrates to provide for cost reductions. These tools are unique to CS industry, and few companies have these tools, resulting in limited pockets of expertise near key universities or companies such as Purdue University providing local engineering talents in Indiana. This has caused shrinkage in market share and technology advancement for the company. Other reasons contributing to decreasing market share are off-shore manpower/capital/tax-regulation competitive advantages, which cannot be realized locally at this time.

D.12.2 SiC

Company D indicated that the major factors towards location of existing manufacturing facility infrastructure has been matching SiC expertise (located in the United States, Japan and Germany primarily) with semiconductor manufacturing expertise (predominantly located in Taiwan, China, Korea, Japan, and to a lesser degree Germany and the United States). In the near future, SiC will be challenged as areas of the world strongly positioned in semiconductor manufacturing will be weak to move SiC technology to their manufacturing facilities. This is already happening with at least two smaller U.S. start-ups who utilize off-shore foundries, and represents a risk of SiC manufacturing IP "leak" to areas in Asia known for copying technology.

Company E was of the opinion that future will focus entirely on a reduction of manufacturing costs, whereas Company G recommends an adaptation of the existing facilities for WBG use as be the most cost effective option:

D.13 CRITICAL VALUE CHAIN SEGMENTS TO ACHIEVE SPECIFIC MARKET GOALS

D.13.1 GaN

Company A considered baseline materials to be critical for the entire value chain as they impact quality and yield throughout the entire process. With critical materials flaws (i.e. micropipes in SiC) that impact the yield, it is not possible to have high performance devices. Manufacturing cost reduction is also critical in order to allow volumes to grow. High prices would yield profits for manufacturers, but without competition and the resulting lower cost manufacturing, path to mass production and consumer adoption is unlikely to evolve.

For Company B, GaN epitaxy on non-native substrates is a critical step that determines the performance, reliability, and overall value of GaN products. Improving thermal performance of GaN products is another critical aspect that ultimately affects net benefits at the system level.

D.13.2 SiC

Company D indicated the difficulty to copy the SiC bulk wafer and SiC epitaxy infrastructure—a segment of the value chain critical to achieving technical performance, reliability, and cost of the end SiC power devices and modules. A need for a skilled workforce (e.g., "Nano-hub" / PhD level class offerings) and the need for special tooling/substrate materials for HVPE, MOCVd/Sapphire, SiC, GaN and Si was suggested by Company C.

Company E, F, and G indicated the importance of wafer cost/quality and device manufacturing.

D.14 POLICIES OF OTHER NATIONS TO ATTRACT MANUFACTURERS

D.14.1 GaN

Company A indicated that Japan has numerous coordinated and well-funded government/industry/university partnerships that are constantly doing millions of dollars of research with a consistent output of high quality R&D. Substantial and consistent R&D, not only in substrate development, but device work on those substrates, is critical to survival and growth in early materials markets. The United States has lots of programs in place, but they are piecemeal and staggered so there is no way to consistently fund development. There is a need for 5 and 10 year plans such as “Bell Labs for WBG”. Companies often survive by diversifying and too often by selling off chunks of IP and business assets to foreign entities. The amount of IP licensed/sold to Japan, via UCSB and companies that are either under stress or that have no incentive to keep IP in the USA is staggering.

Availability of tax breaks/infrastructure supportive of start-ups and government funding/co-development in other nations was mentioned by Company C.

D.14.2 SiC

Company D indicated that other nations offer fully utilized, large, domestic semiconductor foundries to manufacture SiC products. This allows only a small portion of the fixed costs to be absorbed by the SiC power device manufacturer until the volumes ramp up and warrant higher costs. The foundries are eager to have the SiC technology, so are very willing to make concessions in pricing to get SiC running on their manufacturing base. The smaller SiC start-up companies enjoy a much lower cost structure during the often very long design-in and qualification cycles that industrial customers often require. The only loser in this scenario is that the SiC IP is not fully protected, and it is impossible to keep trade secrets and IP from being stolen or modified.

For larger SiC manufacturers, the situation is quite different, as the cost of manufacturing is not dominated by labor as much as it is by lower volume, small diameter wafers, and low yield. Moving to Asia does not improve any of these cost drivers.

Company E indicated that Japanese programs link in applications companies with the materials and device suppliers while Company G did not think of any role of policies of other nations was important to attract manufacturers.

D.15 RESULTING INNOVATION FROM SUPPORTING U.S. MANUFACTURING

D.15.1 GaN

Company A indicated that innovation is critical to the U.S. manufacturing success because of its typical higher cost structure than in Asia. For the large step-function improvements instead of the every-day continuous improvement innovations, R&D and substantial experience in a given field are necessary.

Company B suggested that the wafer size increase will reduce manufacturing cost by driving more automation in fabrication combined with reduced fabrication cost. But the investment into larger wafers may not pay off for some time as the current wafer demand can be met with existing capacity for 100mm GaN.

Company C commented that with the U.S. support of the skilled workforce it is striving to develop new process, and device technologies to allow for break-through products for manufacturing in the U.S. and overseas. This trend needs to be continued as otherwise it could be lost as the technology tends to migrate away from US, and not return for several decades, if at all. There is a need for the semiconductor industry to migrate towards a photon based computing platform, and make use of CS films to exploit their unique properties. This appears to be areas that can be developed soon, but, require leading edge workforce.

D.15.2 SiC

Company D highlighted the need for more investment in “manufacturing technology” or prototyping efforts for companies with manufacturing facilities in the US. This will lead to continued innovation in improving yields and product design. Additionally, funding early applications work will also “jump start” the adoption of SiC power devices and shorten the time to mass market adoption, and enable the volume cost driver to be driven down more quickly. A loss of a manufacturing capability in the semiconductor industry often limits IP as most advanced designs require advancements in the manufacturing (e.g., 65 nm, 18 nm, lithography shrinkage in silicon). It is the advancement of the processing technology in a manufacturing environment which leads to advanced devices, components, and modules.

Company E stressed the innovation needs to in cost reduction. Programs partnering process equipment suppliers with materials and device suppliers can additionally help drive this area.

D.16 IMPORTANCE OF IP INTENSITY IN SUPPLY CHAIN'S LOCATION

D.16.1 GaN

Company A indicated the importance of IP which is usually put in place very early in the process (in universities and research labs). There are parts of Asia that tend to ignore IP initially, but it gets more important as the companies grow and seek out markets in the U.S. Similarly, Company C valued the importance of IP, and its effect on supply chain attributes. On the other hand, IP was considered by Company B less of a driving factor than ITAR regulations, which govern sale of many types of GaN products.

D.16.2 SiC

Unlike Company E and G, Company D valued the importance of IP-intensity in supply chain location. SiC material benefits have been known for over 100 years, but the technology is still largely focused on manufacturing processes and designs in bulk SiC crystal wafers, SiC epitaxy, and SiC process maturity for MOSFETs and IGBTs. Having the IP close to the manufacturing was considered to be a big help in the developmental phase of the technology.

D.17 DEMAND GROWTH PROJECTIONS IN EXISTING AND POTENTIAL WBG INDUSTRY MARKETS IN 5 AND 20 YEARS

D.17.1 GaN

Company C projected the LED market growth likely to be from present $15B to a $40B market by 2020, growth rates similar to solar films/cells. HEMT market is anticipated to explode once the various high voltage performance issues are resolved, and vertical device structures become the main.

D.17.2 SiC

Company D and G offered detailed projections of growth in the SiC market (Table D-6).

Table D-6. Industry projections of growth in the SiC market by application

Market/Application	In the next 5 years		In the next 20 years	
	U.S.	Worldwide	U.S.	Worldwide
Company D projections				
PV inverters	13%	13%	150%	150%
UPS inverters	3%	8%	300%	500%
Motor Drive	2%	10%	50%	500%
Industrial Power Supplies	2%	8%	40%	70%
Company G projections				
Motor Drives	12%	8%	100%	100%
Overall Switching Applications*	500%	700%	2000%	2000%
Automotive on Car Applications	300%	700%	2000%	4000%