U.S. DEPARTMENT OF ENERGY

Semiconductor

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

February 24, 2022

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About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- commercialization and competitiveness, and
- cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

Acknowledgments

The U.S. Department of Energy (DOE) acknowledges all stakeholders that contributed input used in the development of this report – including but not limited to federal agencies, state and local governments, U.S. industry, national labs, researchers, academia, non-governmental organizations, and other experts and individuals. DOE also issued a request for information (RFI) to the public on energy sector supply chains and received comments that were used to inform this report. The authors acknowledge input and guidance from Tsisilile Igogo of the DOE Office of Policy and National Renewable Energy Laboratory, the lead organizer of the overall effort.

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List of Acronyms

AMO	U.S. Department of Energy's Advanced Manufacturing Office
ASIC	application specific integrated circuits
ATP	assembly, testing, and packaging
CAGR	compound annual growth rate
CHIPS	Creating Helpful Incentives to Produce Semiconductors
DBC	direct bonded copper
DOE	Department of Energy
EO	Executive Order
EPA	Environmental Protection Agency
GaN	gallium nitride
GDP	gross domestic product
ESIB	Energy Sector Industrial Base
EV	electric vehicle
HV	high voltage
HVDC	high-voltage direct current
IDM	integrated device manufacturer
IP	intellectual property
PE	power electronics
PFAS	per- and polyfluoroalkyl substances
PV	photovoltaic
R&D	research and development
RDD&CA	research, development, demonstration, and commercial application
SIA	Semiconductor Industry Association
SiC	silicon carbide
SME	semiconductor manufacturing equipment

SRC	Semiconductor Research Corporation
TRL	technology readiness level
TSMC	Taiwan Semiconductor Manufacturing Company
TSV	through-silicon-via
WBG	wide bandgap
ZIP	10^{21} (‘zetta’) compute instructions per second

Executive Summary

In February 2021, President Biden signed Executive Order (EO) 14017, "America's Supply Chains," directing seven executive agencies to evaluate the resilience and security of the nation's critical supply chains and to craft strategies for six industrial bases that underpin America's economic and national security. See Sec. 3(b) of E.O. 14017. As part of the one-year response to EO 14017, the U.S. Department of Energy (DOE), through the national laboratories, conducted evaluations of the supply chains that encompass the Energy Sector Industrial Base, with a particular focus on technologies required to decarbonize the U.S. by 2050.

This report focuses on one of these technologies, semiconductors, both conventional and wide bandgap (WBG) power electronics (PE). As noted in the 100-Day report, conventional semiconductors are a keystone technology that are essential for the operation of nearly every electronic device, including those that are critical to decarbonization, such as electric vehicles (EVs), industrial and building applications, and electricity generation and end use. In addition, power electronics have been applied to industrial equipment to improve energy efficiency and enhance controllability. Power electronics have also been used to improve the reliability of data centers and critical infrastructure, including the stabilization of the electric grid while subjected to disturbances. Increasingly, power electronics are being used to integrate renewable energy and battery storage systems, enabling new grid services and the development of microgrids. It is estimated that 30% of the electricity used in the U.S. passes through power electronic devices, and studies suggest that this number could reach 80% as power electronics are deployed in more markets. Nearly all forms of electrified transportation will depend on power electronics. Power electronic systems utilize high-capacity semiconductor devices at their core. The continued growth in power electronics depends on sustained innovation in the semiconductor industry.

The U.S. Energy Sector Industrial Base will require radical transformations to decarbonize by 2050, and the growth, energy efficiency, and security of the semiconductor supply chain also must transform.

The current semiconductor industry has a complex, competitive, and highly integrated international supply chain in which the United States has historically enjoyed a dominant position, but where this position has been eroding over time as described in the 100-Day report. This report conducted a risk assessment of the domestic semiconductor supply chain that is focused on energy-industrial-applications and identified several vulnerabilities. The three most critical vulnerabilities are listed below.

- **Impacts of Explosive Growth:** Decarbonization efforts will increase the demand for renewable energy and its supporting infrastructure, including both conventional semiconductor and WBG power electronic supply chains. The demand for products that will use both WBG semiconductors and conventional semiconductors in the future is projected to increase by more than an order of magnitude by 2050 (e.g., wind 23-fold; EV-68-fold increases) (Larson, et al., 2020). The current lack of domestic manufacturing capacity and access to raw materials will be exacerbated. In fact, current projected global silicon production cannot keep pace with this growth, and it is likely that other supply chains will be stretched as well. The EV sector could be especially impacted due to the rising semiconductor use in in the vehicles as well as the necessary charging infrastructure.

- **Significant and rapidly rising energy demand of semiconductors during use[1]:** the potential climate impacts of the use phase of semiconductors was identified in as a concern (Semiconductor Research Corporation, 2021) (U.S. Department of Energy Advanced Manufacturing Office, 2021-2). The global energy use of products featuring semiconductors has doubled every three years since 2010 primarily due to the accelerating use of semiconductors in all facets of our modern economy and the deceleration of energy efficiency increases due to miniaturization. This exponential growth in energy use is projected to accelerate even more due to: 1) increased electrification from decarbonization, noted above and 2) the exponential growth in energy-intensive computer applications (e.g., artificial intelligence).
    - With the explosion in use of semiconductor technologies in all sectors, especially the energy sector, the performance and efficiency of semiconductors has a direct effect on the performance and efficiency of technologies in those other sectors.
    - Artificial intelligence algorithms are doubling their power every two months, and semiconductor energy use just for Bitcoin mining uses more electricity than some European countries, with a 1-year doubling time (U.S. House of Representatives' Committee on Energy and Commerce, 2022).
- **Decreasing manufacturing base** – In 1995, 26% of global semiconductor manufacturing capacity was located in the United States, this has decreased to 10% by 2020 (European Semiconductor Industry Association (ESIA), 2021). Another segment of the supply chain that is becoming more important is packaging in the form of advanced packaging and the United States could fall behind in this area if current trends hold.

To address these vulnerabilities, DOE has identified the following opportunities:

- **Investment in the development and deployment of silicon carbide (SiC) WBG PE** focused on the higher voltage (>1700 V) applications that are critical to utility-scale renewable energy deployments. Although the United States invented SiC WBG PE technology and is a leader in this area, this advantage could be lost in the rapidly evolving and highly competitive WBG PE industry. One method to maintain and perhaps improve the competitiveness of the U.S. WBG PE industry is to enable production of significantly higher performance and higher efficiency domestically produced WBG PE devices to supplant imported silicon-based PE devices. Such efforts to increase U.S. manufacturing of WBG semiconductor power devices are a significant opportunity for the United States and could also provide a strategic advantage for U.S. electric equipment manufacturers through integration with a local U.S. supply chain for advanced WBG power semiconductors. This integration will provide product differentiation (e.g., smaller footprint, higher efficiency, and speed) in rapidly growing electric equipment markets such as electric vehicles (EV), EV charging stations, wind, and solar generators, as well as equipment for flexible AC and DC power delivery.
- **Investment in research, development, demonstration, and commercial application (RDD&CA) for conventional semiconductors with a biennial energy efficiency doubling goal**. Because of the unsustainable increase (i.e., a doubling every three years) in the energy use of key energy-related semiconductor applications a new "Moore's law" for energy efficiency is required to guide future

[1] The use phase of large electronic devices (e.g., servers) is by far the largest source of carbon emissions in the device's life cycle (Global Electronics Council, 2021).

generations of semiconductor investments. This goal for successive generations of semiconductors-- to double energy efficiency of semiconductor use every two years or faster for the next 20 years also could help reestablish U.S. leadership in semiconductor manufacturing and would support Biden-Harris Administration electrification and decarbonization goals. Several recent studies have documented that ten generational doubling or a 1000x improvement in energy efficiency is technically achievable (Semiconductor Research Corporation, 2021); (Shankar, 2021). If aggressive effort and significant investment in the RDD&CA for more energy efficient semiconductors is not undertaken soon, however, it could affect the United States' ability to reduce carbon emissions as rapidly, economically, and efficiently as possible.

- **Promote opportunities for training, education, and certification for U.S.-based workers** to ensure that they are prepared to be a part of the domestic semiconductor industry, including the burgeoning WBG PE industry.

Pursuing these opportunities would address the three key vulnerabilities listed above, complement the recommendations outlined to help the U.S. regain its dominant position in this critical area of the energy sector.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1 Introduction

This document builds on the work conducted in the "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" 100-Day report in response to EO 14017. Here, the U.S. Department of Energy (DOE), through the national laboratories, conducted evaluations of the supply chains that encompass the Energy Sector Industrial Base (ESIB)

The U.S. ESIB will require radical transformations to decarbonize by 2050, including renewable energy generation from carbon-neutral sources combined with zero-emission transportation. While efficient clean energy and zero-emission transportation technologies are available to help achieve these goals, they currently rely on raw materials sold in opaque and volatile global markets and often concentrated in geopolitically sensitive areas. Furthermore, midstream stages of supply chains, such as material processing and component manufacturing, may be concentrated in foreign countries with complicated geopolitical relationships with the United States. DOE's Advanced Manufacturing Office (AMO) has particular interest in evaluating the supply chain risk and resilience of semiconductors[2]. In 2021, the supply chain for semiconductors was evaluated as part of the 100-Day Reviews under EO 14017 (The White House, 2021). This report builds on this earlier work by focusing on semiconductor applications and needs in the energy sector.

Semiconductors are a keystone technology in the energy sector as they are essential for the operation of nearly every electric vehicle, recharging station, and wind turbine as well as the entire electrical grid. Semiconductors are also critical to the American economy, contributing over $246.4 billion to the gross domestic product (GDP) of the United States in 2020 (Semiconductor Industry Association (SIA), 2021). With an export value of $49 billion, they were the fourth largest U.S. export in 2020 behind aircraft, refined oil, and crude oil (Semiconductor Industry Association (SIA), 2021). Wide-bandgap (WBG) power electronics (PE) are a small component (i.e., 0.1%) of this important industry; however, they are set for explosive growth to help meet the demands of decarbonization through electrification. Continued development of this technology is required to move it to high voltage (>1700 V) applications to meet the demands of the energy sector.

This report provides an overview of the semiconductor supply chain, both conventional (i.e., silicon-based) and WBG semiconductors. It augments the previous semiconductor supply chain work in the 100-Day report (The White House, 2021) by focusing on the energy sector and it takes a deeper dive on WBG PE. Like the 100-Day report, it conducts a risk assessment followed by identifying the opportunities and challenges in addressing those risks.

1.1 Technology Description

Semiconductors are made from elements such as silicon, or from compounds such as silicon carbide (SiC). During the fabrication process, small amounts of other materials—called 'dopants' are added, which cause

[2] Although semiconductor materials are used in photovoltaics, these are covered in another supply chain report by the Solar Energy Technology Office and will not be covered here. For this report, "semiconductor" will refer to all semiconductors, except those in photovoltaics.

significant changes in the electronic properties of the material. This study will focus on semiconductors used in applications that are important for the decarbonization of the energy sector. These include:

- WBG semiconductors (e.g., SiC and gallium nitride (GaN)) that control, convert, and condition power flow for electric vehicles (EVs), electrified industrial technologies (such as industrial heat pumps), and other renewable energy applications such as wind and solar generators.
- Conventional semiconductors (e.g., silicon-based) that control data flow for energy efficiency and renewable energy applications, including EVs, integrated wireless sensor systems for energy-efficient manufacturing, energy efficiency in buildings, and other renewable energy technologies.

A high-level view of the types of semiconductors[3], their differing applications and those addressed in this study is shown in Figure 1.

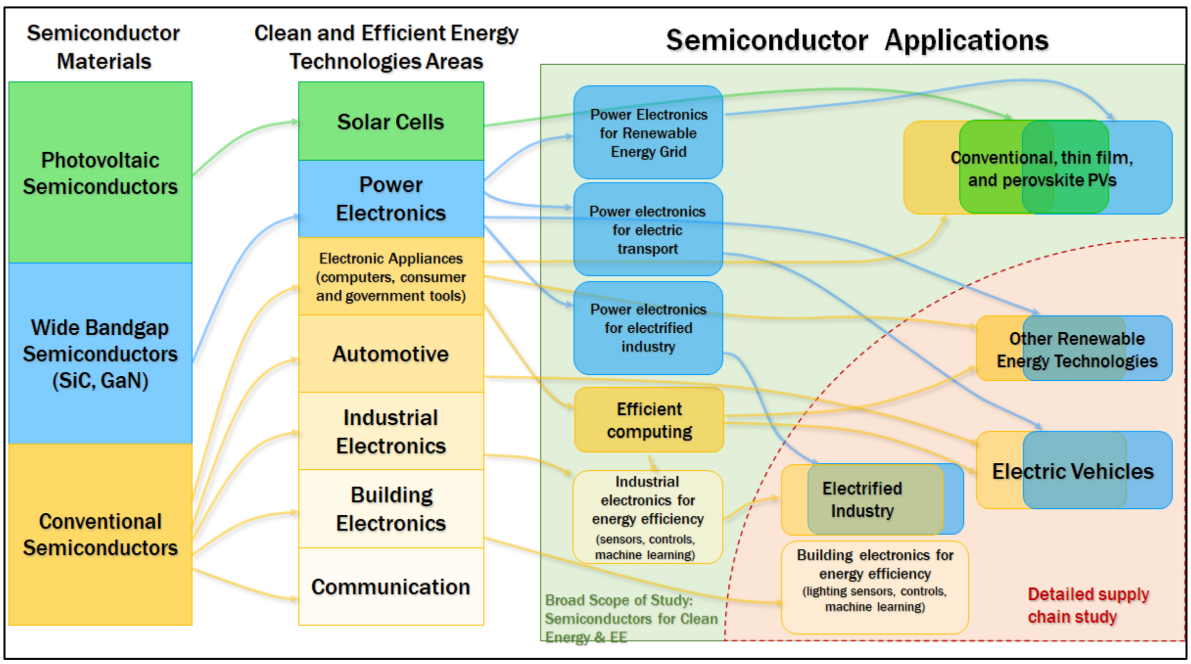

Figure 1. Semiconductor study scope.[4]

1.2 Global Market Assessment

1.2.1 Current Market

The overall global semiconductor market was valued at $553 billion in 2021, up from $440 billion in 2020, an increase of over 25% (World Semiconductor Trade Statistics (WSTS), 2021). The breakdown of conventional

[3] As noted earlier, PV semiconductors for solar energy production are excluded from this study because they will be addressed separately in the report from the Solar Energy Technologies Office.

[4] Note this is not to scale: Conventional (~$550 billion)>>PV (~$100 billion)>>WBG (~$1 billion) in market size (World Semiconductor Trade Statistics (WSTS), 2021); (Yole Développement, 2021);

semiconductors in 2020 by end-use sector is shown in Figure 2. Computing and communication are about equal in size and comprise the major end uses of semiconductors, representing over 60% of global market value. Industrial and automotive uses, covered in this report, comprise 12% and 11.4% of the global market value, respectively.

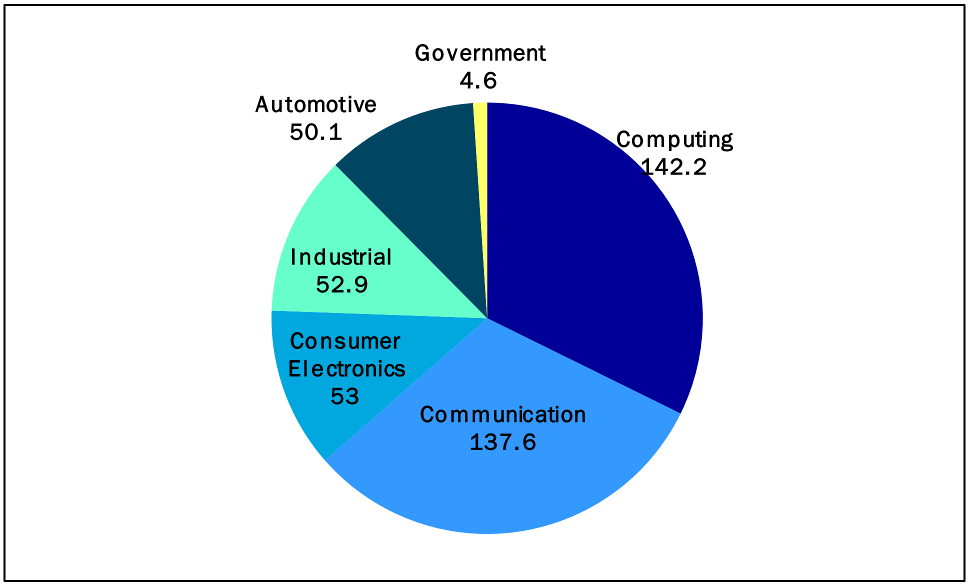

Figure 2. End-use market share ($million) for semiconductors.

Source: (Semiconductor Industry Association (SIA), 2021)

For a more detailed discussion of the semiconductor market, refer to the 100-Day report.

While global revenues of faster, more energy-efficient WBG semiconductors—SiC and GaN—has grown significantly from $0.2 billion in 2015 (PowerAmerica, 2020), together they still comprised less than 5% of the power device market in 2020 which is still is dominated by silicon-based power electronics (Yole Développement, 2021). The 2020 market value of WBG power devices was estimated at $0.6 billion or roughly 0.1% of the overall semiconductor market (Yole Développement, 2021). The market for WBG is expected to grow significantly by 2030 as key applications such as wind energy and EVs are expected to grow from a few percent to more than 50% of the market. Conversely, in 2019 semiconductors (WBG and conventional) comprised about 4% of the value of a new premium car. By 2030, they are expected to comprise >20% of the value (Intel, 2021).

The current market share of each of the major WBG technologies by market sector is shown below in Figure 3 and Figure 4 (Yole Développement, 2021). The market sectors for each type of WBG semiconductor are significantly different, with GaN obtaining most of its revenue from consumer electronics, while SiC has a strong presence in automotive, energy, and industrial applications.

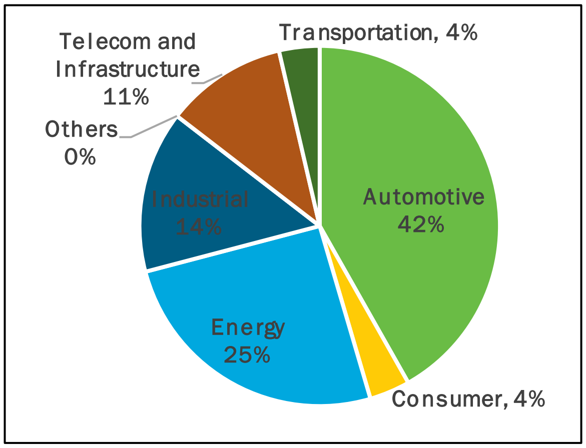

Figure 4. 2020 SiC power device by market.
Source: (Yole Développement, 2021)

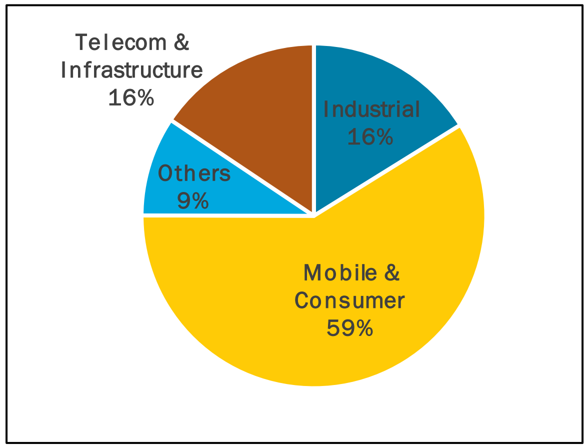

Figure 3. 2020 GaN power device by market.
Source: (Yole Développement, 2021)

The primary driving force behind the difference in applications is the semiconductors' operating range. As shown in Figure 5, both semiconductors perform well between 600 and 900 V, but SiC devices also operate at much higher voltages.

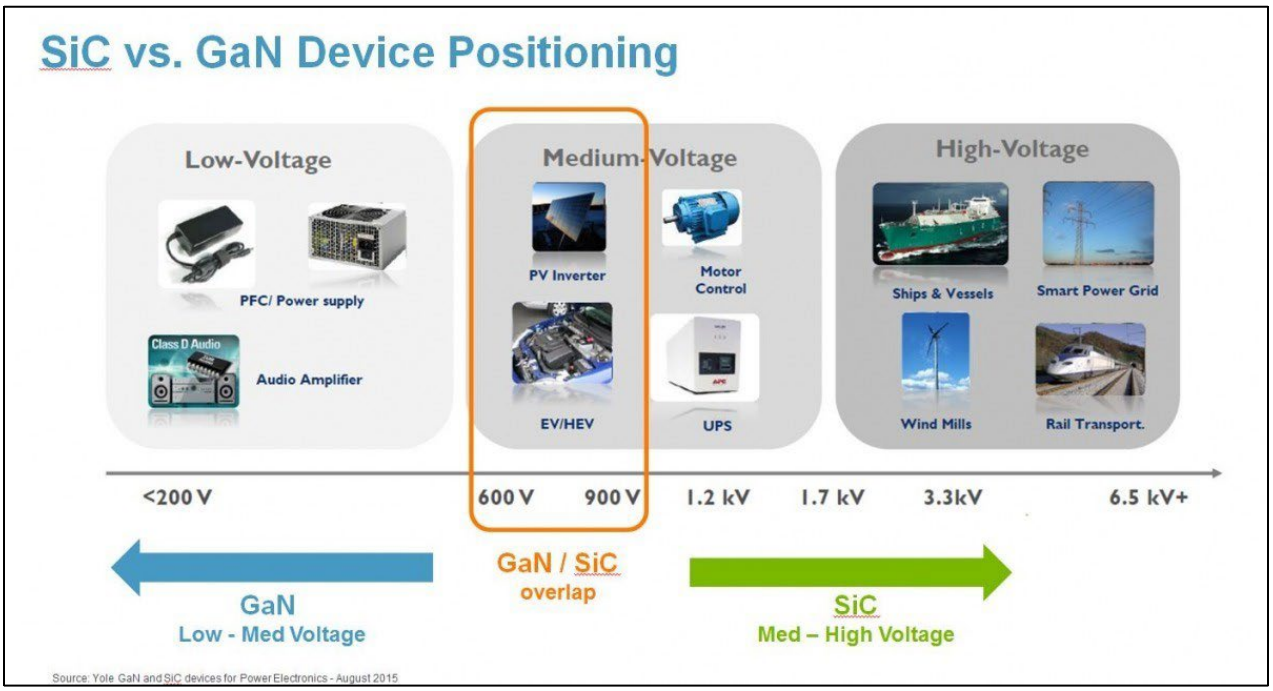

Figure 5. Today's WBG operating voltage and applications.
Source: (Yole Developpement, 2015)

One of the areas of current application overlap between GaN and SiC is in the EV sector. GaN devices are being used for non-traction (i.e., onboard charging) applications while SiC is focused on traction inverter applications within this sector. SiC devices are operating up to 1700 V onboard vehicles; and 1200- and 1700-V applications are being developed for EV propulsion inverters. SiC is also being developed for PV power applications and wind.

Significant effort is underway to develop thick epitaxy SiC wafer manufacturing technology that can be used to produce devices that operate at even higher voltages (much greater than the 1700 V technology widely available today). The ability to use a WBG semiconductor in higher-voltage applications would expand the use of WBG power semiconductors in rapidly growing renewable energy applications (e.g., wind power), and could penetrate other critical markets such as generic high-voltage direct current (HVDC) application.

Although the technology for thick SiC wafer epitaxy (i.e., suitable for up to 10 kV) has already been developed, a few issues preventing its widespread adoption. The biggest issue for this technology is its cost effectiveness due to immature manufacturing methods and the lack of high-capacity facilities. In addition, advanced packaging for the power modules is also needed, specifically direct bonded copper (DBC) insulator substrates are needed to provide thermal management for the high voltage (>10 kV) WBG power modules. Because of the limitations of silicon semiconductors at the high voltages, this market is currently limited. It has significant growth potential due to the increased need from energy applications that can be exploited by improving the performance of SiC power devices. Bulk GaN (single crystalline GaN substrate wafer) development is also underway for use in high-performance devices. Because bulk GaN work is still in the research stage at a very low technology readiness level (TRL), there is an opportunity to establish a strong and secure supply chain in this area.

1.2.2 Market Projections

In November 2021, The World Semiconductor Trade Statistics (WSTS) (2021) reported that it expected that the global semiconductor market growth would be 25.6% in 2021 to $553 billion compared to a 6.8% increase in 2020. It is projected to increase by another 8.8% in 2022 to reach $601 billion.

Although SiC and GaN power devices today are a small fraction of the total power sector, demands for both technologies are expected to increase significantly and are expected to comprise almost 20% of the power device market by 2026, with SiC reaching 14% and GaN at almost 5% (Yole Développement, 2021). Overall, the WBG power electronics market is expected to grow from $0.6 billion in 2020 to $2.2–$3.1 billion by 2026 (Markets and Markets, 2021); (Yole Développement, 2021), a CAGR of 20%–36%. Both markets are also expected to diversify, with GaN expanding into automotive and SiC growing its industrial and automotive markets. Figure 6 and Figure 7 show the projected growth of both technologies by end-use sector.

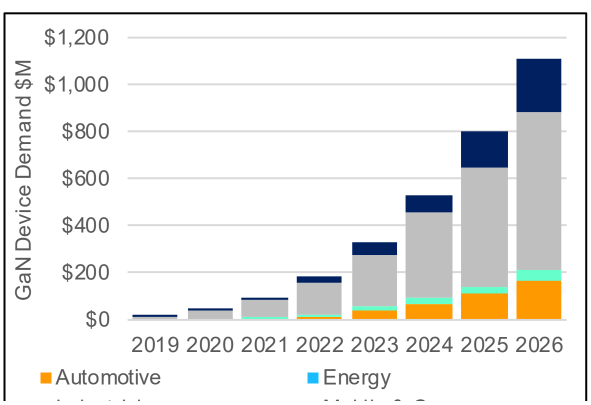

Figure 7. GaN device demand by sector.

Source: (Yole Développement, 2021)

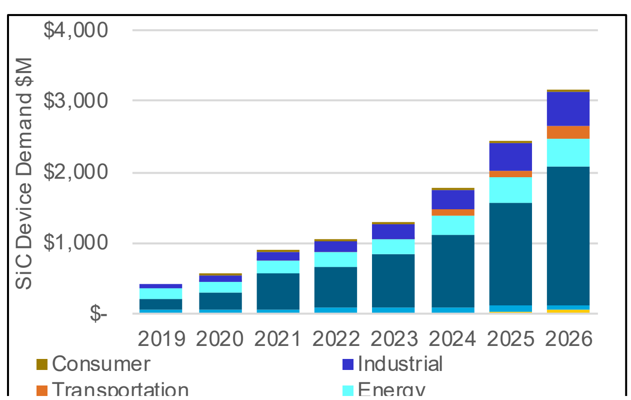

Figure 6. Projected SiC device demand by sector.

Source: (Yole Développement, 2021)

These significant growth rates (i.e., 8.8% annual increase for conventional semiconductors and >20% CAGR for WBG) are under current business-as-usual scenarios without considering deep decarbonization strategies.

While the total demand for conventional semiconductors and WBG power electronics under deep decarbonization scenarios has not yet been determined, rough estimates can be derived from key subsectors. In November 2021, the U.S. Department of State and U.S. White House released *The Long-Term Strategy of the United States* (LTS), which lays out how the United States can reach its goal of net-zero emissions no later than 2050 and was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) at the 26th Conference of the Parties. The LTS illustrates many plausible pathways through 2050 to achieve a net-zero emissions economy and offers insights into what the overall energy system for the United States could look like between now and 2050 under a range of assumptions about the evolution of technological costs, economic growth, and other drivers to 2050. (U.S. Department of State and the U.S. Executive Office of the President, 2021). Other groups have done similar analyses. For example, the *Net Zero America* report (Larson, et al., 2020) outlines five different cases to achieve net zero by 2050. In both studies, the demand for EVs, wind and other renewable power, and heat pumps (commercial and residential) increases significantly, and these increases are expected immediately. For example, in the Larson study, wind and solar generating capacity are expected to grow fourfold to 600 GW to supply half of U.S. electricity, up from 10% today. Increases in each of the technologies will in turn increase the demand for semiconductors. Table 1 summarizes the projected increase of some technologies that rely on semiconductors from both studies.

Table 1. Projected increase in end-use technologies due to decarbonization

Technology	U.S. Long Term Strategy	Net Zero Study
Wind Power[a]	4-7.5x increase in renewable generation	6x–28x increase in installed capacity
EVs	~100% of light-duty vehicles electrified and the associated charging infrastructure	40x–63x increase in the number of EVs and associated charging infrastructure
Commercial / Industrial	5x increase in industrial electrification	Increase heat pumps by 3x in commercial buildings by 2030

[a] The Wind Energy Technology Office is currently funding a study at the National Renewable Energy Laboratory to look at all the material requirements for wind energy, including semiconductors. When these results are available, they will be used to update the table.

Sources: Larson et. al (2020); U.S. Department of State and Executive Office of the President

Although it is unlikely that the increase in conventional semiconductors due to decarbonization will accelerate to the same extent as these electric and electrification technologies, it is certain that the overall growth rate of both types of semiconductors will dwarf even what is predicted for clean energy technologies due to the explosion of memory needed for the data deluge and other exponentially increasing semiconductor applications (e.g., 5G+ communications). The Semiconductor Research Corporation (SRC) estimates that memory and storage demand will increase by a factor of greater than 100 by 2030.

In some cases, such as with EVs, the growth rate could be even higher than projected in Table 1 as EVs have more semiconductors, especially WBGs than conventional vehicles. CISION PR Newswire estimates that the value of semiconductors (conventional and WBGs) in EVs is 2.3 times the value in conventional vehicles (CISION PR Newswire, 2021). The United States International Trade Commission (Lawrence & VerWey, 2019) estimates that difference to be even greater, with conventional vehicles containing $300 worth of semiconductors and hybrid electric vehicles containing from $1,000 to $3,500 worth of semiconductors. Further illustrating demand beyond the EVs themselves, the effective integration of charging loads into the electric grid requires power semiconductors to convert and condition the power flow between grid and vehicle battery, and microelectronics within the charging equipment to communicate session data and to manage power flows (Harper, 2021).

2 Supply Chain Mapping

This section includes descriptions of the supply chains of both technologies. The 100-Day report (The White House, 2021) provided a detailed look at the supply chain of conventional semiconductors, including all segments, and will not be repeated here – only a high-level description is provided. More detail will be provided for the WBG supply chain where it differs from that of conventional semiconductors.

In the following discussion, unless noted otherwise, market share, sales, etc. of the segments are attributed by the headquarters of the company, even if the physical location of the facility is in another country. The market values are for 2019 unless otherwise specified.

2.1 Technology Overview

The market and supply chain for semiconductors is global and extremely complex. Numerous companies across the globe, specializing in one or more steps of the process, are involved. As noted in the 100-Day report (The White House, 2021), the designing, fabricating, and packaging of a semiconductor product takes up to 100 days, including 12 days of transit, and can cross international borders 70 times (i.e., travelling to the same countries more than once).

Most supply chains can be characterized by five main segments: raw materials, processed materials, subcomponents, product, and end-of-life recycling/reuse. The complexity of semiconductors, however, require several additional supply chain segments: design, semiconductor manufacturing equipment (SME), and assembly, testing, and packaging (ATP), including advanced packaging. Similarly, due to the continual rapid evolution of semiconductor technology, research and development (R&D) is also included in the supply chain. For simplicity, reuse/recycling will not be covered in this analysis; however, end-of-life issues are becoming more important as e-waste is the world's fastest growing waste stream.

Figure 8 shows the semiconductor supply chain, including examples of materials moving between segments. Raw material extraction, material processing, and subcomponent manufacturing for the semiconductor supply chain is similar to most other supply chains. The difference comes in the fabrication or production stages, as specialized equipment or SME is required along with specialized design tools and software.

As shown in the orange blocks in Figure 8, semiconductor production has three main steps: design, fabrication, and ATP. These steps can be conducted by a single company, known as an integrated device manufacturer (IDM), or by different companies. When production is conducted by different companies, a fabless firm (i.e., a design firm without a dedicated fabrication facility) conducts the design and contracts with a foundry to fabricate the chip with packaging at an outsourced semiconductor assembly and test (OSAT) firm.

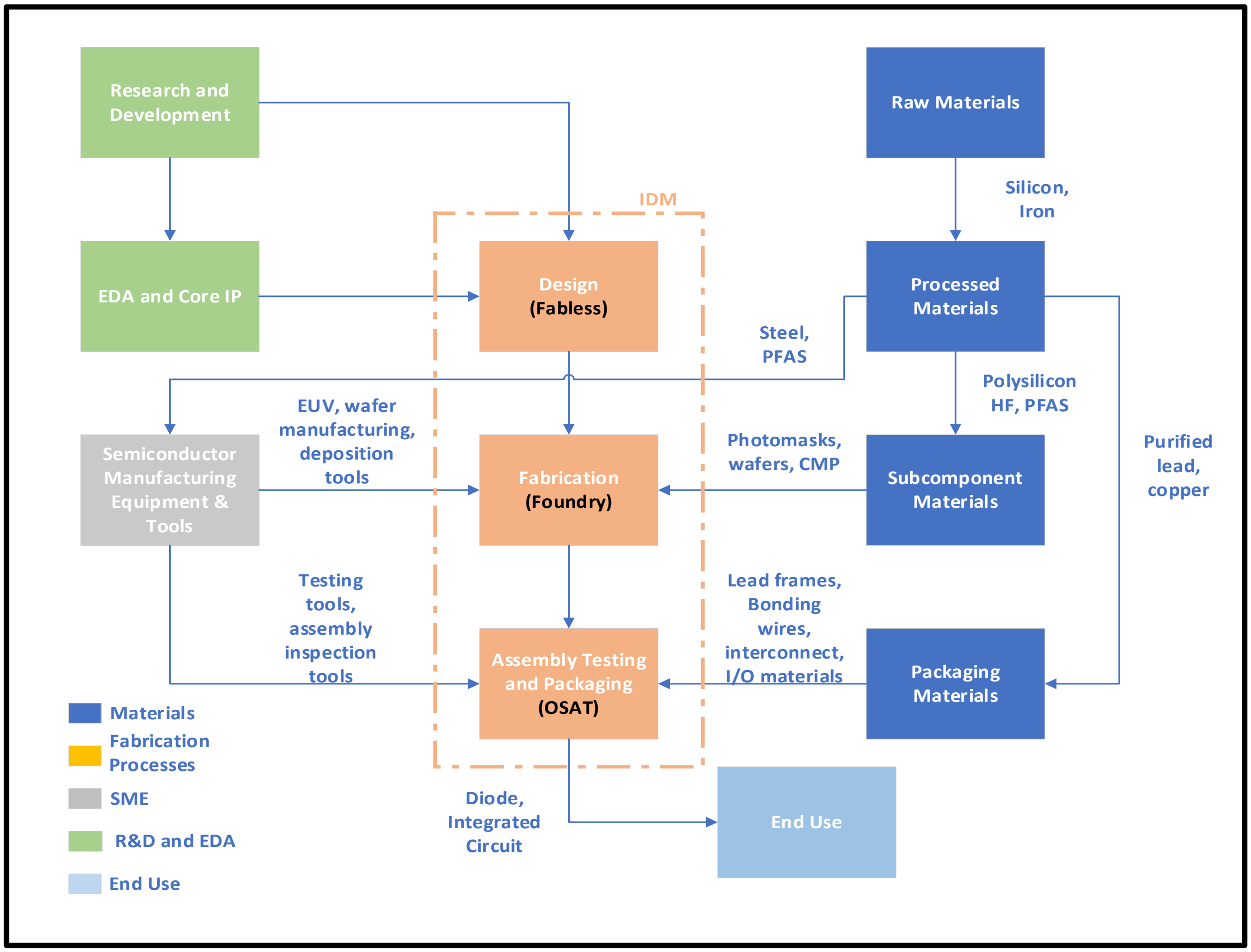

Figure 9. Semiconductor Supply Chain.

Advanced packaging includes technologies for heterogeneous integration (combined functionality of logic and memory within a single device) such as putting chiplets and/or more than one integrated circuit into a single package. It also includes vertical stacking for 3D architectures with through-silicon-vias (TSVs). These types of advanced packaging allow higher transistor density at the package level instead of the chip level and it enables a wider variety of chip functions in a single package – both of which can greatly increase energy efficiency. Of course, efficiency improvements also are needed for monolithic chips.

2.2 Conventional Semiconductor Supply Chain Segments

The 100-Day report mapped the conventional semiconductor supply chain in detail and will not be repeated here. However, the high-level summary of each domestic semiconductor supply chain segment is outlined below.

- **Design:** The United States has a robust and world-leading semiconductor industry but depends on limited sources of intellectual property (IP), labor and manufacturing.

- **Semiconductor Fabrication:** The United States lacks sufficient fabrication capacity and relies on sources in Asia for production.

- **Assembly, Test and Packaging and Advanced Packaging:** The United States relies on foreign ATP companies in Asia. Although the United States and its partners have advanced packaging capabilities, it lacks the ecosystem for developing advanced packaging technologies

- **Fabrication Materials:** The United States and its allies have strong capabilities in wet chemical and electronic gas production. Foreign suppliers dominate the markets for silicon wafers, photomasks and photoresists, but these products are manufactured in many places, including the United States.

- **Semiconductor Manufacturing Equipment:** The United States has a significant share of global production of most front-end SME with the exception of lithography equipment. While it has a significant share of back-end testing equipment, it has a small market share in packaging equipment.

2.3 Wide Band Gap Semiconductor Supply Chain

As noted earlier, the basic supply chain segments for WBG semiconductor-based power electronics are the same as those for conventional semiconductors. The differences lie in the products and processes within those segments. For example, much of the manufacturing equipment for (older node) conventional semiconductors can be used for WBG power electronics manufacturing. The most significant differences are in the raw materials, subcomponents, end products, and packaging.

Figure 9 shows the overall process steps, as well as some representative materials for each step, which are then described in more detail below.

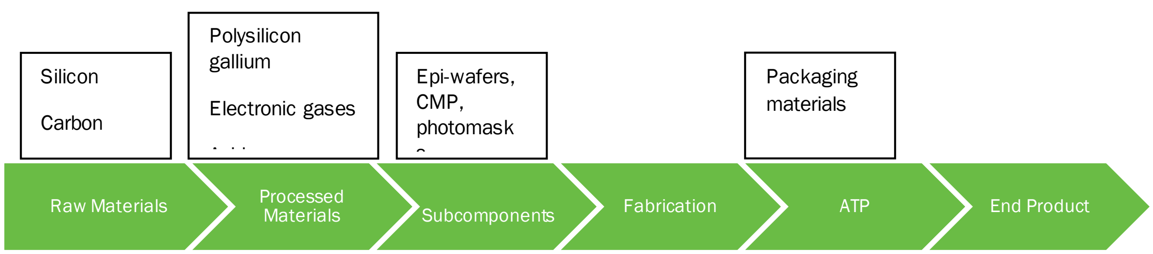

Figure 10. Simplified Supply Chain for WBG Semiconductors.

Detailed analyses were not conducted for each supply chain sector of the WBG PE supply chain because for many of the sectors (e.g., SME), the components are similar, if not the same as those for conventional semiconductors that were analyzed in the 100-Day report. In addition, because the size of the market for WBG PE is so small compared to that for conventional semiconductors, it is likely that those sectors are similar to the larger market. Thus, only raw materials, processed materials, ATP and the final product form are discussed.

2.3.1 Raw Materials

One of the primary raw materials for SiC WBG semiconductors is quartzite or silicon, found in abundance across the globe as sand (U.S. Geological Survey, 2022). Demand for silicon for electronics applications such as PVs and displays (even though they don't require quite the same high purity) as well as for glass, and concrete (which have even lower silicon purity requirements), has grown so fast that the cheapest and most abundant silicon sources are being over-exploited. As the prices of the lowest cost sources of sand have increased, mining of river bottoms, beaches, and forest lands has become profitable, leading to environmental damage and, in some cases, labor exploitation (Beiser, 2019). Tracking of global sand mining, legal and illegal, is unreliable and likely missing significant operations (Bendixen, Best, Hackney, & Lars, 2019). Insofar as growing demands for high-purity silicas will impact semiconductor manufacturing, paying attention to environmental and social impacts, as well as calls to regulate sand mining (Gallagher & Peduzzi, 2019), will be essential for supply chain resiliency.

Graphite is another raw material for SiC WBG and is available in either natural or synthetic from. Natural graphite is obtained by mining and synthetic is made industrially from coal or petroleum coke. The United States produces no natural graphite and has limited reserves (U.S. Geological Survey, 2022)).

Gallium is not mined in the United States and globally is currently recovered as a secondary product from processing bauxite and zinc ores (U.S. Geological Survey, 2022). Gallium is also listed as a critical material in the 2021 proposed critical materials list from USGS (2021 Draft List of Critical Materials, 2021). Current production of GaN power semiconductors is limited to the low-voltage segment and only consumes a small amount of gallium as they are made in a thin ~1 µm layer of gallium grown on non-gallium substrates. If bulk GaN substrates were to emerge in the future and be used to produce high-voltage power devices, they would consume significantly more gallium. High voltage SiC power semiconductors have the advantage that they do not rely in critical materials such as gallium. China dominates gallium production, producing over 90% of the world's gallium (U.S. Geological Survey, 2022).

In 2021, one domestic company recovered and refined high-purity gallium from imported primary low-purity gallium metal and scrap (U.S. Geological Survey, 2022). Other companies import gallium metal and gallium arsenide wafers.

2.3.2 Processed Materials

Processed materials for WBG semiconductors include bulk SiC boules, SiC wafer substrates, and epitaxial SiC layers (thin and thick) grown on SiC substrate wafers. WBG processed materials also include thin GaN epitaxial layers grown on silicon, sapphire, or SiC substrates, but thick GaN epitaxial layers would require a source of bulk GaN boules and wafer substrates that are not yet produced at a TRL and quality suitable for power semiconductor devices. The power semiconductor devices are fabricated in the high-quality epitaxial layer where the substrate serves as mechanical support. Several U.S. companies produce SiC and GaN epitaxial wafers and the United States has a very strong market position in SiC wafers. Most of the production of GaN wafers is in Taiwan.

The two companies with the highest capacity for SiC wafers/boules are domestic companies—Wolfspeed and II-VI. Wolfspeed has an estimated capacity of 75,000–100,000 units per year while II-VI is estimated to have a capacity of about 70,000 units per year. Both companies have recently announced investment in the rapid expansion of production capacity in SiC substrates through devices. SiCrystal, which is a joint Japanese/European Union company, has a 60,000 unit per-year capacity and the remaining companies have capacities of 35,000 units per year and below.

The next level processed material is the SiC epi-wafer. This wafer product has been processed so that it is ready to go to chip processing. The open SiC power epi-wafer market is dominated by Wolfspeed (United States) and Showa Denko (Japan), each with similar market shares. Although the quality and performance of SiC with thick epitaxy (up to 100 µm) are well established, these materials are not produced at the scale needed to meet the demand of rapidly emerging clean energy applications.

2.3.3 Final Product

WBGs go into numerous products, primarily in the power sector. For this analysis, the product is assumed to be a WBG power device or module. As noted earlier, the WBG power device market is about $0.6 billion, and it currently is dominated by STMicroelectronics, a French-Italian company. Recently, a number of large SiC power device fabrication facilities have been announced in the U.S. including the largest in world being built in Marcy, New York by Wolfspeed (Wolfspeed, 2022).

2.3.4 Assembly Testing and Packaging and Packaging Materials

Packaging of WBG power semiconductors highly leverages technology used for previous generation silicon power semiconductor devices. Low-power discrete (single die) power device packaging is almost exclusively produced off-shore and there is currently limited value added or economic benefit to packaging discrete die in the United States. On the other hand, high power and high voltage module packages are critical to the performance of WBG power semiconductor device products and U.S. companies including Wolfspeed (Fayetteville, AR), Powerex (Youngwood, PA), and GE Aviation (Pompano Beach, FL) are leading innovators. However, the production capacity of these facilities is currently much lower than similar companies abroad. Danfoss also recently built a large production capacity SiC power module package facility in Marcy, New York to serve the U.S. automotive industry.

2.3.5 U.S. Resilience and Risk

The United States is the leader in SiC substrates with the greatest production capacity and the two largest suppliers, Wolfspeed and II-VI. While SiC epi-wafer is available from several companies around the world, U.S. products have the highest quality. Both companies have significant domestic expansion plans.

The United States is also the leader in quality production of thick (~100µm) SiC epi-wafers, which can be used to produce devices with voltage ratings up to 10 kV that are critical for renewable generation, manufacturing scale electric power systems, and the electricity grid. While Wolfspeed's quality is the highest, their product is expensive, and their production capacity is low. Although II-VI is looking to develop this technology in Sweden with their acquisition of Ascatron, without a second production source and significant capacity expansion, lack of thick SiC epi-wafers could become a significant supply chain bottleneck for clean energy technology advancement.

GaN on Si, SiC, or sapphire is widely available and is used for optical radio frequency (RF) and <600 V power semiconductors. Taiwan has more than 50% of the GaN Power foundry capacity in the world. Taiwan Semiconductor Manufacturing Company (TSMC), EPISIL, and Unikorn are the major Taiwanese companies. The United States has a single epi and fab facility which is a joint venture by Fujitsu and Transphorm. Power Integrations is another player in this space, but it is an epi facility only.

2.3.6 U.S. Competitiveness

The United States is highly competitive in SiC substrates and SiC thick epitaxial wafers because as noted below, it has most of the global capacity in these areas. However, this could shift quickly with respect to the SiC thick epitaxial wafer subsector. This is a huge potential growth area, especially for high voltage (up to 10 kV) semiconductor devices for energy technologies, but this is not an area where the manufacturing technology is fully vetted, and it has a development horizon that is longer than two to three years. It requires investment to help accelerate advancement and ensure continued U.S. dominance for competitiveness and national security.

For power semiconductor devices, module packaging is a key differentiator at higher power levels involving several large dies in parallel to meet current requirements and is becoming increasingly important with the voltage levels of SiC power devices already exceeding the voltages previously possible with silicon. Furthermore, with WBG devices operating at switching speeds of 10 to 100 times faster than possible with silicon, the package is often the limiting factor in achieving the full potential of the WBG semiconductors. The lack of U.S. manufacturing capability for power semiconductors packaging was a key factor leading to offshoring of previous generations of power semiconductor devices. Going forward, U.S. investment in domestic power module packaging fabrication facilities is essential to avoid offshoring of the WBG power semiconductor supply chain.

Taiwan controls most of the GaN on silicon device fabrication market, whereas the U.S. is competitive in the device design and application integration.

3 Supply Chain Risk Assessment

DOE developed a high-level methodology to identify potential supply chain risks by sector and subsector. This methodology is described in this section and results are provided for WBG semiconductors. The 100-Day report already conducted a supply chain risk assessment for conventional semiconductors (The White House, 2021); a summary of the recommendations from this risk assessment are provided in the conventional semiconductor discussion.

The raw material, processed material, and product sectors of WBG semiconductors were evaluated according to the criteria outlined below. The SME, ATP, design and fab material sectors were not evaluated as they do not differ considerably from the conventional semiconductor segments, which was well covered in the 100-Day report.

The evaluation criteria are related to market (domestic and global) size and their projected growth, U.S. manufacturing capabilities and suppliers, as well as exogenous factors such as environmental/climate or human rights concerns that could impact the supply chain. DOE selected a measure for assessment for each criterion and assigned a scoring scale to each resulting in a Green, Yellow, or Red score.

- Green scores show strength and/or low risk or vulnerability and have specific, measurable values.
- Red scores indicate a potential risk and are given when the sector does not meet the Green score.
- Yellow scores are given if there is not enough information to determine a score.

The evaluation criteria and method of scoring are described below.

- **Significant domestic supply:** Domestic supply is evaluated as significant (Green) if the domestic market supply can meet at least 50% of the estimated domestic demand.
- **Projected significant domestic demand:** The projected domestic demand is significant (Green) if the CAGR is projected to be greater than 2% for at least five years. If the specific projected demand for a sector or subsector cannot be determined, then the demand for the end product is used as a proxy.
- **Significant global market:** If the market for the sector or subsector is greater than $5 billion, then the market is significant and received a Green score.
- **Projected significant global market:** If the CAGR for that sector is projected to be greater than 2% for at least five years, it is considered significant, or Green. If the specific projected demand for a sector or subsector cannot be determined, then the demand for the end product is used as a proxy.

- **Competitiveness of the U.S. market:** Domestic competitiveness is measured by the number of domestic companies in the specific sector or subsector. Having more than three domestic companies in the sector shows a competitive market and receives a Green score.
- **Competitiveness of U.S. suppliers in the global market:** U.S. suppliers are competitive if they capture at least 30% of the global market.
- **Security of supply chain:** This criterion has two measures: identification as a critical mineral (U.S. Geological Survey, 2021) or the amount imported. If the material is identified or proposed as a critical mineral or is composed of a significant amount (>10%) of a critical mineral, then the supply is insecure. For other materials, if the amount imported is greater than 50%, it is significant and receives a Red score.
- **Environmental, climate, or human rights concerns:** Here DOE addresses important external factors that can affect the development of the supply chain. For example, if the current supply chain relies on slave or forced labor, not only is it against international law but it makes the supply chain less resilient and makes it more important to develop an alternative source. This criterion is more subjective than the others in that DOE did not develop a numerical scale. However, DOE wanted to ensure that these concerns were addressed. In general, if a sector has been identified in the literature as having significant energy demands or hazardous waste issues, etc., then it would be given a Red score. Similarly, if literature has identified human rights (e.g., use of slave labor) in a sector, this will be given a Red score. If there are no identified issues, a Green score will be given. If the sector is not known well or there are questions, then DOE gave it a Yellow score.

DOE used the risk assessment to identify vulnerabilities and to highlight subsectors that should be developed domestically.

3.1 Conventional Semiconductor Risk Assessment

As noted earlier, the 100-Day report conducted a comprehensive risk assessment of the conventional semiconductor supply chain. Based on this assessment, the following seven recommendations were made to expand and secure the U.S. semiconductor supply chain:

1. Promote investment, transparency, and collaboration, in partnership with industry, to address the current shortage
2. Fully fund the Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America provisions to promote long-term U.S. leadership
3. Strengthen the domestic semiconductor manufacturing ecosystem
4. Support small and medium enterprises and disadvantaged firms along the supply chain to enhance innovation
5. Build a talent pipeline
6. Work with allies and partners to build resilience
7. Protect the U.S. technological advantage

3.2 Wide Bandgap Power Electronics Risk Assessment

Much of the upstream supply chain for WBG power electronics is similar to that for conventional semiconductors (e.g., much of the equipment can be used for both products) and is not evaluated here. The following risk assessment matrix addresses WBG power electronics for raw materials, processed materials and end products.

Table 2. Risk assessment matrix for WBG power electronics.

Supply chain segments to meet the demand of the final product	Product/ Components	Significant domestic market	Projected significant domestic demand	Significant global market	Projected significant global demand	Competitive US Market	Cost competitive between US suppliers vs. global suppliers	Is the supply chain secure because the material is NOT on the proposed or current Critical Materials List? OR because the U.S. does NOT import > 50%	Is there sufficient effort to address environmental and human rights concerns?
Raw materials	Silicon	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	Graphite	No	No	No	Yes	No	No	No	No
	Gallium	No	Yes	No	Yes	Yes	No	No	Maybe
Processed material	Thick SiC epi-wafers (~100um)	No	Yes	No	Yes	No	Yes	Yes	Maybe
	GaN on Si Wafers	No	Yes	No	Yes	Maybe	No	No	Maybe
	Bulk GaN substrates	No	Maybe	No	Maybe	Maybe	Maybe	No	Maybe
	DBC insulator substrates (>1mm) – needed for high voltage WBG modules	No	Yes	No	Yes	No	Maybe	Yes	Maybe
End products	WBG GaN Power devices	No	Yes	No	Yes	Yes	No	No	Maybe
	WBG SiC Power devices	No	Yes	No	Yes	Yes	Yes	Maybe	Maybe

3.2.1 Raw Materials

WBG power electronics are primarily manufactured from silicon, carbon, nitrogen, and gallium. Nitrogen is not evaluated due to its ubiquitous nature. Both gallium and graphite are on the current (2018) as well as proposed (2021) U.S. Geological Survey's critical materials list (2021 Draft List of Critical Materials, 2021) and have specific supply concerns. In fact, gallium is identified as having the riskiest supply chain of all the critical materials (2021 Draft List of Critical Materials, 2021). Silicon is widely available.

Gallium is not produced in the United States except from imported gallium arsenide, gallium metal, or gallium scrap (U.S. Geological Survey, 2022). The United States does not export any gallium and so it is not competitive with other suppliers. All the gallium used in the United States is imported and China produces more than 90% of the world's gallium.

China is also the biggest producer of natural graphite. The U.S. has no domestic graphite producers and the overall global and domestic markets do not reach the $5 billion threshold. The global demand for natural graphite is expected to increase significantly due to demand for lithium-ion batteries.

The primary raw material for SiC WBG is quartzite or silicon, found in abundance across the globe as sand (U.S. Geological Survey, 2022). The U.S. has 6 companies that produce silicon materials in 2020 and the U.S. meets greater than 50% of its apparent consumption (U.S. Geological Survey, 2022). It has a robust domestic and global markets. Some concerns regarding human rights and environmental impacts of silicon mining have been identified (Beiser, 2019); (Gallagher & Peduzzi, 2019).

3.2.2 Processed Materials

Three processed materials were included in the risk assessment: thick SiC epi-wafers, GaN on silicon wafers, bulk GaN substrates and DBC insulator substrates. As with all processed materials and final WBG products, the domestic and global markets are insignificant. However, the demand for all these processed materials except bulk GaN substrates is expected to increase rapidly. As noted earlier, bulk GaN substrates are at an early TRL and it is unclear if they will be commercialized. Both GaN on Si wafers and DBC insulator substrates both have limited domestic suppliers. Wolfspeed is the only supplier of GaN on Si wafers and there are only three domestic suppliers of DBC insulators. Finally, U.S. suppliers are non-competitive for GaN on Si wafers; TSMC has the majority of this market.

3.2.3 End Products

None of the end products reach the market threshold for significance. The supply chain for WBG GaN power devices is insecure due to the gallium content. Taiwanese and European companies control this market. The domestic SiC WBG supply chain is stronger as there are more domestic suppliers.

Each of the products received a Yellow or Red score on the environmental and human rights concerns. The Red scores are due to concerns raised from foreign mining sources. The Yellow scores for all others are due to the high energy and water use for semiconductor manufacturing as well as the use of PFAS compounds. High water use and hazardous waste generation in semiconductor manufacturing facilities are a significant concern (Belton, 2021); (Crawford, King, & Wu, 2021). In 2019, Intel used three times as much water as Ford Motor Company plants and created more than twice the hazardous waste (Crawford, King, & Wu, 2021).

Semiconductor facilities use tremendous amounts of electricity and have a large carbon footprint (Belton, 2021); (Crawford, King, & Wu, 2021). TSMC uses 5% of Taiwan's electricity and a single facility in the United States used 561 million kWh of electricity in the first three months of 2021 (Belton, 2021).

PFAS are used to clean, manufacture, and lubricate many types of semiconductor manufacturing equipment (Demircan, 2020) and these are known to persist in the environment and are linked to adverse environmental and health impacts (U.S. EPA, 2021). It is unknown whether lithography equipment uses PFAS. PFAS include perfluorocarbons which have 100-year global warming potentials greater than 1000 and as of January 2021 a new law regulates perfluorocarbons providing limited quotas for manufacturers (U.S. EPA, 2021).

3.3 Key Vulnerabilities (Near Term)

Although the risk assessment matrix above identified numerous vulnerabilities, there are many other areas of risk not addressed in the matrix. These vulnerabilities cover issues such as energy efficiency, climate change, and workforce development, among others. This section covers those vulnerabilities.

3.3.1 Vulnerabilities Across Conventional and WBG Power Electronics Semiconductors

One of the most significant vulnerabilities is the increased energy use and associated carbon emissions due to the slowdown in energy efficiency improvements coupled with an explosion of semiconductor use (Semiconductor Research Corporation, 2021). For example, leading algorithms in artificial intelligence, are doubling their power use every two months (U.S. Department of Energy Advanced Manufacturing Office, 2021-2). Another application of conventional semiconductors, Bitcoin mining, saw a tenfold increase in semiconductor energy use in 10 years and as of August 2021, its estimated annual electricity used (91 TWh/yr) is more than the annual energy use of Finland (Huang, O, Neill, & Tabuchi, 2021).

Without a strong energy efficiency focus, conventional semiconductors' energy use may continue to double every three years or faster and energy production only increases at 2-3% per year. If this energy demand is unchecked, market dynamics (e.g., lower GDP) will limit the growth of new computational capacity (Semiconductor Research Corporation, 2021). Computational energy demand is rising exponentially while the world's energy production is increasing linearly (respectively shown as a diagonal or flat lines in the log plot in Figure 10[5] Also shown on the plot are the approximate number of computations conducted, measured in ZIPs or 10^{21} compute instructions per second. Currently, the world is at a level of less than 1 ZIP.

Because the increase in energy use (i.e., a doubling every three years) is unsustainable, a new "Moore's law" for energy efficiency is required. If the energy efficiency were doubled every two years for the next 20 years, semiconductor energy use could again be sustainable—that is, it would return to being a small percentage of electricity consumption. Roughly ten doublings (i.e., a 1000x improvement) in energy efficiency may be technically achievable with the use of neuromorphic architectures (Shankar, 2021) or resolving, even partially, the disconnect between instructions per second and bits per second (Semiconductor Research Corporation, 2021). Both these strategies, as well as many other advanced strategies, incorporate co-design or the concurrent design of hardware and software to optimize their interface and thus improve energy efficiency (Shankar, 2021); (Aiken, et al., 2021).

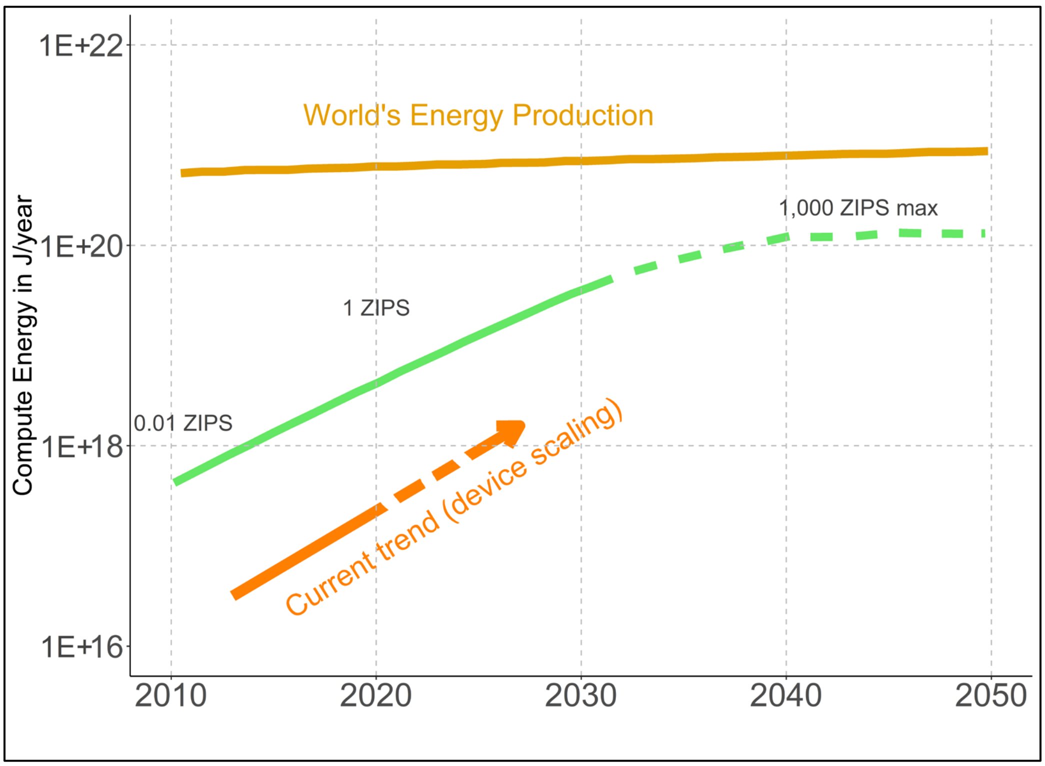

Figure 11. Total Energy of Computing.

Source: (Semiconductor Research Corporation, 2021)

[5] The scale of the plot is important: 1E+18 Joules is about 1 quad (i.e., 1 quadrillion Btus) and the total U.S. energy consumption is only 100 Quads.

DOE identified the following five major strategies for achieving the goal of doubling the energy efficiency of semiconductor use every two years for an 1000x increase as early as 2042 (Aiken, et al., 2021); (Black, et al., 2006) (Sabry Aly, et al., 2015); (Shankar, 2021).

- Reducing or eliminating losses in communicating data to memory (e.g., in-memory compute, low contact resistance interconnects)
- Atomically precise control for ultra-doping (starting with advanced packaging)
- Neuromorphic hardware
- Heterogeneous integration of ultra-energy efficient application-specific integrated circuits (ASIC) (e.g., analog, 3D imaging) and other combinations of architectures
- New methods of computing including nature-inspired computing, materials, devices, and algorithms/software

Another potential vulnerability is the projected gap between silicon wafer manufacturing capacity and silicon wafer demand. Due to the explosive growth in memory and data storage (Figure 11), reaching from $10^{24} – 10^{28}$ bits by 2040, the conventional semiconductor market's projected demand for silicon wafers (~10^{10} kg) is expected to outstrip projected global silicon wafer production 2040 by a factor of three, even without the additional growth in production required to support decarbonization (Semiconductor Research Corporation, 2021). Silicon wafer production is only growing linearly and cannot keep pace with the exponential growth of silicon-based semiconductors. Furthermore, this comparison is based on total silicon production and not all silicon currently produced is suitable for semiconductor production. (Semiconductor Research Corporation, 2021).

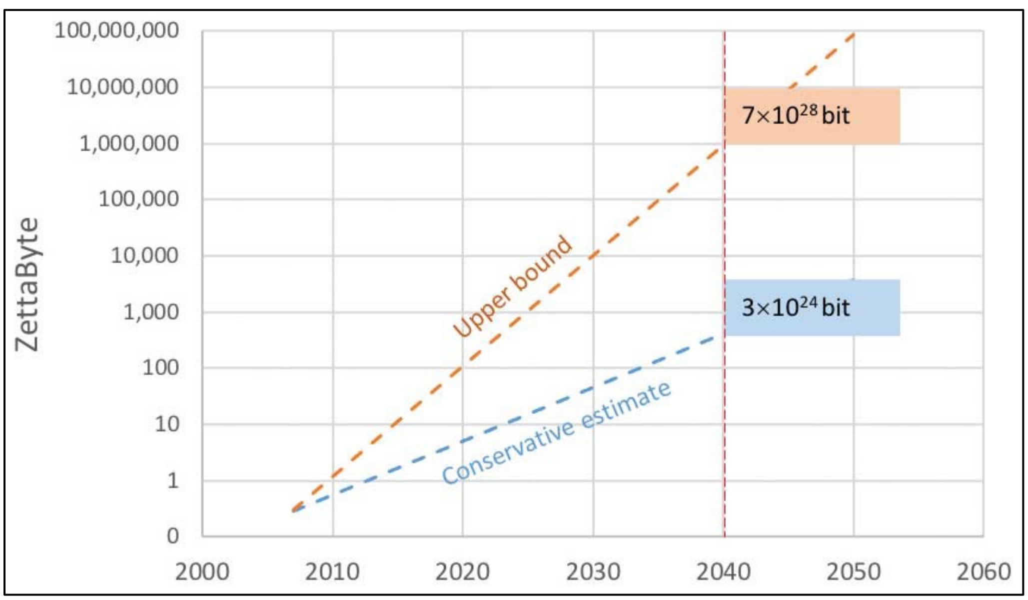

Figure 12 Global demand for memory and storage using silicon wafers.[6]

Source: (Semiconductor Research Corporation, 2021)

[6] One zettabyte = 10^{21} bytes or one trillion gigabytes.

As noted earlier, the manufacture of semiconductors also has significant energy and water demands and carbon footprint. In general, however, the energy use of large systems such as network switches or rack servers are responsible for over 90% of the life cycle carbon emissions (Global Electronics Council, 2021). In small, battery-operated devices such as smartphones, the carbon emissions from manufacturing are a much higher percentage (>75%) (Global Electronics Council, 2021). To combat the high-end use carbon emissions, many companies are powering their data centers with renewable energy. In fact, a recent article shows the impact that the companies such as Facebook, Apple, Google, and Intel are having on their end-use emissions using renewable energy for operations (Gupta, et al., 2020).

Another identified vulnerability of the domestic semiconductor industry is the need for a skilled workforce; (SEMI, 2021); (Semiconductor Industry Association [SIA], 2021a). The U.S. semiconductor industry is experiencing a severe to critical talent shortage. This shortage spans numerous specialties (e.g., engineering, quality control) and levels of education (skilled trades through advanced degrees). Training and educating workers require considerable time and effort. For example, training in the trades can take up to one year (SEMI, 2021).

While the workforce shortage was also identified in the 100-Day report, DOE wanted to emphasize this need in this report as decarbonization will exacerbate this issue and have significant impacts on development of the energy sector. The workforce shortage in WBG power electronics may become especially acute if the training and education programs don't account for the specialized needs of these fast-growing electronics sectors that are vital to energy applications. Furthermore, tackling the challenge in energy efficiency will result in additional workforce demands.

3.3.2 Vulnerabilities Specific to Wide Band Gap (Power Electronic) Semiconductors for Energy Applications

The WBG industry is based on newer technologies (e.g., SiC and GaN) and as noted earlier, is significantly smaller than the silicon-based semiconductor market. New technologies and a nascent industry have some unique vulnerabilities.

In the SiC industry, there is a concern regarding the higher incidence of defects in the material when compared to silicon (Emilio, 2020). While this generally impacts operating costs and thus the price of the finished chip or device, it can also impact chip reliability and hence industry trust. For example, recently, there were some EV battery failures (Hyundai, Polestar, GM) resulting in recalls, where SiC devices could be tied to or associated with the failures (Yole Développement, 2021). Furthermore, due to their low volumes, age of technology, and other factors, silicon carbide power devices are not commoditized and there are measurable differences among manufacturers in performance, reliability, and ruggedness (Emilio, 2020). To meet the predicted explosive demand, commoditization may be required.

Developing advanced packaging of WBG power electronics is especially important and can be a determinant of whether high voltage (HV) (up to 10 kV) WBG power semiconductors are commercially viable. Heterogeneous integration ability such as inclusion of different ICE die technologies is especially needed (SEMI, 2021). As mentioned earlier, DBC is a critical enabling technology for high-voltage silicon carbide power devices.

3.4 Key Vulnerabilities (Longer Term)

The most significant longer-term vulnerability is the environmental impact of semiconductor use and manufacturing due to explosive growth from electrification and artificial intelligence. For the United States to meet its climate goals, energy efficiency in conventional semiconductors must be addressed as deployment to major new sectors continues to grow.

It is also necessary to develop efficient and effective domestic technologies such as thick SiC that operate in the energy production space to enable the power sector transition. Furthermore, as advanced packaging becomes a more critical component of both conventional and WBG semiconductor products, the ability of the United States to compete in these areas will become more crucial to maintaining a robust domestic semiconductor industry. Heterogeneous integration—the new path to continuing performance and energy efficiency improvement—requires advanced packaging. U.S. semiconductor companies will need to significantly increase their advanced packaging capabilities to enable domestic manufacturing of the most advanced and energy efficient semiconductors.

3.5 Key Focus Areas

Based on the vulnerability assessment, six key focus areas were identified for further study and potential action. Each focus area is briefly described below.

- **Impacts of Explosive Growth:** Decarbonization efforts will increase the demand for renewable energy and its supporting infrastructure, including both conventional semiconductor and WBG power electronic supply chains. The demand for products that will use both WBG semiconductors and conventional semiconductors in the future is projected to increase by more than an order of magnitude by 2050 (e.g., wind 23-fold; EV-68-fold increases) (Larson, et al., 2020). The current lack of domestic manufacturing capacity and access to raw materials will be exacerbated. In fact, current projected global silicon production cannot keep pace with this growth, and it is likely that other supply chains will be stretched as well. The EV sector could be especially impacted due to the rising semiconductor use in the vehicles as well as the necessary charging infrastructure.

- **Significant and rapidly rising energy demand of semiconductors during use[7]:** multiple potential impacts (e.g., climate) of the use phase of semiconductors were identified in 2021 as concerns (Semiconductor Research Corporation, 2021) (U.S. Department of Energy Advanced Manufacturing Office, 2021-2); (Global Electronics Council, 2021). The global energy use of products featuring semiconductors has doubled every three years since 2010 primarily due to the accelerating use of semiconductors in all facets of our modern economy and the deceleration of energy efficiency increases due to miniaturization. This exponential growth in energy use is projected to accelerate even more due to: 1) increased electrification from decarbonization, noted above and 2) the exponential growth in energy- intensive computer applications (e.g., artificial intelligence).

[7] The use phase of large electronic devices (e.g., servers) is by far the largest source of carbon emissions in the device's life cycle (Global Electronics Council, 2021).

  - With the explosion in use of semiconductor technologies in all sectors, especially the energy sector, the performance and efficiency of semiconductors has a direct effect on the performance and efficiency of technologies in those other sectors.
  - Artificial intelligence algorithms are doubling their power every two months, and semiconductor energy use just for Bitcoin mining uses more electricity than some European countries, with a 1-year doubling time (U.S. House of Representatives' Committee on Energy and Commerce, 2022).

- **Decreasing manufacturing base** – In 1995, 26% of global semiconductor manufacturing capacity was located in the United States, this has decreased to 10% by 2020 (European Semiconductor Industry Association (ESIA), 2021). Another segment of the supply chain that is becoming more important is packaging in the form of advanced packaging and the United States could fall behind in this area if current trends hold.

  Developing technologies to address the needs of the HV (>1700 V) for energy sectors is especially critical. The United States already has significant strength in the SiC power electronics market and has a foothold in the HV market. However, this technology and supporting technologies (i.e., DBC substrates) require additional development to improve quality and bring down costs. Without investment now, this advantage could easily move offshore.

- **Partnering with toolmakers** to introduce new more energy efficient technologies is a key strategy of AMO's semiconductors for energy efficiency RDD&CA program. New devices (e.g., ultra-energy efficient devices) are nearly impossible to introduce directly into multibillion dollar fab facilities. Tools based on the ultra-precise control techniques used to make such energy efficient devices could instead be introduced through tool-makers—which, as already noted—are a key U.S. supply chain strength.

- **Growing importance of advanced packaging -** The United States must also improve its capabilities in advanced packaging. This technology is rapidly increasing in importance for performance and efficiency reasons and will only accelerate in importance with increased electrification. Advanced packaging is a growing, innovative area that depends heavily on design capabilities where the United States excels, but U.S. industry needs to build the manufacturing facilities here or it will risk being left behind in this critical field. The U.S. can partner with and learn from allies how to build automated and advanced packaging capabilities for today. By accelerating the translation of its own R&D capabilities (e.g., atomic precision manufacturing) to market, the United States can lead in advanced packaging tomorrow.

- **Environmental impacts from semiconductor manufacturing -** As noted earlier, the manufacture of semiconductors has a significant water demand and a high carbon footprint from substantial energy demands as well as the use of fluorinated compounds. So, it is critical to address the potential environmental impacts from increased manufacturing.

- **Workforce shortages** – Securing a resilient supply chain is underpinned by having a robust, well-trained workforce. This demand spans the trades to advanced degrees and will need to be met by both U.S. citizens and foreign workers. Ensuring that training programs, immigration policies, and all the supporting infrastructure work together to address this need, while also ensuring strong labor standards and competitive wages, is critical.

4 U.S. Opportunities and Challenges

4.1 Key Opportunities

Overall, the U.S. has a strong position in the semiconductor industry. To strengthen this position, however, the U.S. must focus on manufacturing the next generation of technology in both conventional and WBG semiconductors that will supplant existing technologies manufactured offshore.

To address the key vulnerabilities in the conventional semiconductor and WBG power electronic supply chains for energy applications, the United States should explore the following:

- **Investment in the development and deployment of SiC WBG PE** focused on the higher voltage (>1700 V) that are critical to utility-scale renewable energy deployments. Although the U.S. invented SiC WBG PE technology and is a leader in this area, this advantage has been declining. This decline can be reversed by enabling production of much higher performance and higher efficiency U.S.-produced WBG power semiconductor devices to supplant imported silicon-based PE devices. Such efforts to increase U.S. manufacturing of WBG semiconductor power devices are a significant opportunity for the United States and provide a strategic advantage for U.S. electric equipment manufacturers through integration with a local U.S. supply chain for advanced WBG power semiconductors. This integration will provide product differentiation (e.g., smaller footprint, higher efficiency, and speed) in rapidly growing electric equipment markets such as EVs, EV charging stations, wind, and solar generators, as well as equipment for flexible AC and DC power delivery.

- **Investment in RDD&CA for conventional semiconductors with a biennial energy efficiency doubling goal**. Because of the unsustainable increase (i.e., a doubling every three years) in the energy use of key energy-related semiconductor applications a new "Moore's law" for energy efficiency is required to guide future generations of semiconductor investments. This goal for successive generations of semiconductors—to double energy efficiency of semiconductor use every two years or faster for the next 20 years—also could help reestablish U.S. leadership in semiconductor manufacturing and would support Biden-Harris Administration electrification and decarbonization goals. Several recent studies have documented that ten generational doubling or a 1000x improvement in energy efficiency is technically achievable (Semiconductor Research Corporation, 2021); (Shankar, 2021). An aggressive effort and significant investment in the RDD&CA for more energy efficient semiconductors is needed to enable the United States to reduce carbon emissions as rapidly, economically, and efficiently as possible.

- **Promote opportunities for training, education, and certification for U.S.-based workers** to ensure that they are prepared to be a part of the domestic semiconductor industry, including the burgeoning WBG PE industry.

Addressing these opportunities will have significant benefits in terms of increasing well-paying skilled domestic jobs, improving the GDP, and ensuring minimal environmental impacts. It will also ensure that the United States maintains its lead in WBG power electronics, especially in the HV range, which will become even more important as electrification is implemented. Furthermore, it will address the potential climate and adverse environmental impacts of semiconductors, a cornerstone technology of the overall decarbonization strategy. All decarbonization strategies require explosive growth of conventional and WBG semiconductors; ensuring that they are developed and deployed with the lowest carbon footprint and minimal environmental impacts possible is critical in our domestic climate goals. Development of domestic design and manufacturing capabilities to produce more energy efficient semiconductors will also provide a new competitive advantage for U.S. semiconductor manufacturing, which can serve as a foothold for increasing U.S. global presence of cutting-edge chip fabrication and packaging.

4.2 Key Challenges

Key challenges to realizing these opportunities include potential siting challenges of new facilities as well as the significant capital requirements of supply chain investment.

Another challenge is the potential difficulties involved with adopting new processes for developing semiconductors. For example, the use of co-design or the concurrent design of hardware and software is critical for developing energy-efficient semiconductors—however it is possible to co-design without consideration of energy-efficiency. While co-design offers many advantages and can help lead to vastly more efficient semiconductors, its implementation and adoption must be coupled with a strong signal—such as the proposed biennial energy efficiency doubling goal--to yield energy efficiency improvements. Co-design is necessary, but not sufficient and co-design without energy efficiency goals could lead to lock-in of broad strategies that are suboptimal for efficiency.

5 Conclusions

The United States has a leading position in the semiconductor industry, but this position has been eroding, especially with respect to domestic manufacturing and advanced packaging. These issues must be addressed for the United States to maintain and expand its leadership in semiconductors.

In addition, the explosive growth in semiconductor use expected due to deep decarbonization and other uses such as artificial intelligence provides opportunities and risks. One significant opportunity is to increase the United States' advantage in HV power electronics through investment in SiC thick epi-wafer and DBC technology development and deployment. The use of co-design or the concurrent design of hardware and software is critical for developing energy-efficient semiconductors. To ensure energy efficiency is an integral part of co-design going forward, a strong signal—such as the proposed biennial energy efficiency doubling goal—will help optimize this critical parameter along with other performance measures.

In addition to existing policies that address many of the critical vulnerabilities and challenges within the U.S. semiconductor supply chain, five key energy sector concerns require new policy proposals that focus on the following areas:

- The competitiveness of the U.S. power electronics sector.
- The need for specific energy efficiency goals for semiconductor performance for RDD&CA programs.
- The importance of developing robust, energy-efficient domestic advanced packaging capabilities.
- The critical need for a domestic workforce in the semiconductor industry, especially in WBG power electronics technologies.
- The environmental impacts of semiconductor manufacturing.

Meeting the challenge of skyrocketing growth in the demand for conventional and wide bandgap power electronics will require increased manufacturing and use of both types of semiconductors. A pre-requisite to meeting this challenge is the development of a skilled domestic workforce for both conventional semiconductors and WBG power electronics. Furthermore, ensuring that the semiconductors are developed to operate as energy efficiently as possible is a critical component of any decarbonization strategy. Finally, known environmental impacts of semiconductor production should be addressed.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

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DOE/OP-0011 ▪ February 2022