U.S. Department of ENERGY | Office of Energy Efficiency & Renewable Energy

DRAFT REPORT

Wide Bandgap Power Electronics Strategic Framework

January 2025

Disclaimer

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Acknowledgments

This document was developed under the guidance of Paul Syers, Nebiat Soloman, Tina Kaarsberg, and Diana Bauer of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, Advanced Materials and Manufacturing Technologies Office (AMMTO). The members of the working groups who made significant contributions through facilitated workshop sessions are identified below. ICF International and Nexight Group supported the road mapping process and report development.

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This report was prepared by ICF and the Lawrence Livermore, National Renewable Energy, and Sandia National Laboratories of or the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Materials and Manufacturing Technologies Office.

List of Acronyms

2DEG	Two-dimensional electron gas
AC	Alternating current
Ag	Silver
AI	Artificial intelligence
Al	Aluminum
Al_2O_3	Aluminum oxide
AlGaN	Aluminum gallium nitride
AlN	Aluminum nitride
ALD	Atomic layer deposited
AM	Additive Manufacturing
AMB	Active metal brazing
AMMTO	Advanced Materials and Manufacturing Technologies Office
ARPA-E	Advanced Research Projects Agency – Energy
$BaTiO_3$	Barium Titanate
BESS	Battery Energy Storage Systems
BEV	Battery electric vehicles
BiGaN	Bidirectional Gallium Nitride
$Bi(M)O_3$-$BaTiO_3$	Bismuth modified Barium Titenate, including an additional element, represented as “M”
BFOM	Baliga figure-of-merit
C	Celsius
cm	Centimeters
CMOS	Complementary metal-oxide-semiconductors
CO2	Carbon dioxide

CPU	Central Processing Unit
CTE	Coefficient of thermal expansion
Cu	Copper
CZ	Czochralski
DBA	Direct bond aluminum
DBC	Direct bond copper
DC	Direct current
DER	Distributed energy resources
DMOSFET	“Depletion Mode” MOSFET
DOE	U.S. Department of Energy
DSP	Digital signal processing
EFG	Edge-defined film-fed growth
EIM	Electromagnetic interference
EM	Electromagnetic
E-mode	Enhancement mode
EoL	End-of-life
EPA	U.S. Environmental Protection Agency
ESL	Equivalent series inductance
ESR	Equivalent series resistance
EV	Electric vehicle
EWD	Education and workforce development
FinFET	A type of field effect transistor with taller, “fin-like” structure
FOM	Figure of Merit
FQS	Four quadrant switches
Ga	Gallium

GaN	Gallium Nitride
Ga2O3	Gallium Oxide
GDP	Gross domestic product
GHG	Greenhouse gas
GPU	Graphics processing unit
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GW	Gigawatt
GW-hr	Gigawatt hours
HEMT	High electron mobility transistor
HFTO	Hydrogen and Fuel Cell Technology Office
HVAC	Heating ventilation and cooling
HVDC	High voltage direct current
HVPE	Hydride vapor-phase epitaxy
ICE	Internal combustion engine
IGBT	Insulated-gate bipolar transistor
IMOSFET	Trench-form MOSFET. The deep trench shape looks like an "I"
InAIN	Indum Aluminum Nitride
Ir	Iridium
JFET	Junction field-effect transistor
Kg	Kilogram
kHz	Kilohertz
km	Kilometers
kW	Kilowatt
kW-hr	Kilowatt-hour
LCA	Lifecycle assessments

LCOE	Levelized cost of electricity
m	Meters
MBE	Molecular beam epitaxy
MC-HEMT	Multi-channel HEMT
MC2-HEMT	Multi-channel monolithic-cascode HEMT
MECS	Manufacturing Energy Consumption Survey
MESFET	Metal-semiconductor field-effect transistors
MeV	Mega electron volts
MHz	Megahertz
ML	Machine learning
MME	Metal-modulated epitaxy
MMT	Million metric tons
MOCVD	Metal-organic chemical vapor deposition
MOSFET	Metal-oxide-semiconductor field-effect transistor
MTDC	Multi-terminal HVDC systems
MVDC	Medium voltage DC
MW	Megawatt
O&M	Operations and maintenance
P2H	Power-to-hydrogen
PCB	Printed circuit boards
PCR	Primary control reserve
PE	Power electronics
POLFETS	Polarization-doped field effect transitors
Pt	Platinum
PTFE	Polytetraflouroethylene

PV	Photovoltaic
R&D	Research and development
RCH	Channel resistance
RF	Radio frequency
Rh	Rhodium
RSUB	Substrate resistance
SCR	Secondary control reserve
Si	Silicon
SiC	Silicon carbide
SIPO	Series input, parallel, output
SMC	Soft magnetic composites
STEM	Science, technology, engineering, and mathematics
SWaP	Size, weight, and power
SWaP-C	Size, weight, power, cost
T&D	Transmission and distribution
TCO	Total cost of ownership
TECHTEST	Techno-economic, Energy, & Carbon Heuristic Tool for Early-State Technologies
TEA	Techno-economic analysis
TWh	Terawatt hours
UFOM	Unipolar figure-of-merit
USGS	U.S. Geological Survey
UWBG	Ultra-wide bandgap
V	Volt
VSD	Variable speed drives
WBG	Wide bandgap

WTG	Wind turbine generators

Executive Summary

This U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, Advanced Materials and Manufacturing Technologies Office (AMMTO) strategic framework identifies and elucidates the necessary technological innovations for wide bandgap (WBG) and ultra-wide bandgap (UWBG) power conversion technologies to advance America's energy independence and secure our power grid. WBG and UWBG materials offer performance and efficiency advantages over their silicon-based counterparts, and the opportunities for design and manufacturing improvements are significant that the future of the power electronics industry is mainly through leveraging WBG and UWBG materials. This framework is divided into specific areas of focus, considering the needs of 1) the various applications that use PE and the infrastructures they make up, 2) the common materials and devices shared across many PE technologies, 3) the packaging and passive elements that support PE devices and build full systems, and 4) nontechnical needs for the PE industry to grow and thrive. In order to meet these needs, it encourages those working to advance these areas to follow the recommendations and goals laid out in this framework, including sharing information and partnering with each other and the DOE on research, development, demonstration and integration activities where appropriate. AMMTO also encourages readers of this strategic framework to work with the DOE to build detailed roadmaps that industry can collectively follow to achieve the ambitious goals set forth in this framework.

Background

PE are essential to the conversion and control of electrical power in U.S. critical infrastructure. As this infrastructure—including grid-integrated power, industrial manufacturing, transportation, and digital networking and communications—brings more innovative technologies online to meet changing market demands and improve grid resiliency, it also places significantly higher performance demands on PE technologies. Silicon (Si) PE have been relied on for decades to meet infrastructure's power conversion and control needs, but these intensifying performance requirements have surpassed what traditional Si PE can offer.

Wide bandgap semiconductor (WBG) PE offer a replacement that has the potential to address U.S. infrastructure's changing needs, advancing America's energy independence and securing our power grid. To achieve this potential, technological innovation is needed across the entire PE system—at the material level, in the devices that allow these high-performance materials to function, and in the packaging that builds these devices into end-use applications.

In addition, the size, weight, power, cost (SWaP-C), and reliability requirements differ across PE applications as well as the infrastructure sector in which they are implemented. These "levers" need to be carefully considered and adjusted appropriately in the design phase to ensure that end products meet their sector-specific needs. The ability to source materials and manufacture advanced PE technologies at scale and at the differing volumes needed by each sector are also critical considerations in the innovation stage.

AMMTO supports the enhancement of economic competitiveness of U.S. manufacturing through increased energy efficiency and improved energy conversion technologies, and improving PE technologies is a crosscutting way to accomplish these goals. Improving PE technologies means not just increasing the efficiency and performance of PE in multiple application areas to meet future industry demands, such as supporting the reliability of the grid under expected future conditions, improving the efficiency and performance of the transportation infrastructure, enabling continued electrification of industrial processes to improve industrial flexibility and efficiency, and improving the efficiency of data centers and communication networks to handle ever increasing demand. It also means strengthening the PE innovation ecosystem through increased collaboration and information sharing, to shorten the time from idea to impact in the industry. To best focus the office's efforts to support the U.S. power electronics industry and to provide a vision for the future that can inspire coordinated action, AMMTO set out in creating a document that provides a strategic overview of the PE industry, its current trends, challenges, and pathways of opportunity to further growth and competitiveness.

The *AMMTO Wide Bandgap Power Electronics Strategic Framework* aims to address the challenges and considerations above by examining them in relation to different aspects of the PE landscape (e.g., application, materials and devices, passives and packaging, and nontechnical) and identifying the pathways and recommendations necessary for high-performance PE advance America's energy independence and secure our power grid.

Framework Overview and Summary of Recommendations

This framework begins by providing necessary context of the importance of PE to many major modern infrastructures as well as an overview of the ecosystem that drives PE innovation and manufacturing, and trends driving the growing shift to WBG PE, which also signal possible future demand for UWBG PE. Following this, the framework is divided into four main sections, each addressing a major focus area of the PE industry. Each focus area highlights some current challenges and innovation pathways to address them. Focus Area 1 takes a market needs perspective, looking at the variety of applications, grouped by major infrastructure type, for power electronics. Focus Area 2 looks at the core devices that make up PE and the growing and emerging materials systems upon which they are built. Focus Area 3 expands the technical scope from active devices to the supporting passive devices and the packaging materials & methods that work together with the active PE devices to build complete, fully functioning PE modules and systems. Finally, Focus Area 4 looks at non-technical aspects that the PE industry needs to thrive, such as a well-trained workforce and a robust understanding of full lifecycle and techno-economic drivers of the PE supply chain.

Each section also provides targeted recommendations, both technical and nontechnical in nature, to accelerate the innovations and impacts mentioned in that section. Here the recommendations from each section are listed.

1 WBG PE Applications to Infrastructures

Grid Infrastructure

1. Support pre-competitive R&D activities for advanced PE technologies
2. Focus on further development of the emerging WBG technologies such as solid-state transformers, multilevel modular converters for MVDC and HVDC systems, and PE Building Blocks
3. Support innovation in passive components & packaging to handle higher frequency PE operation
4. Identify and support opportunities for field-relevant demonstration projects for emerging PE technologies

Transportation Infrastructure

1. Focus on durability and reliability of WBG PE for transportation applications
2. Strengthen supply chain resilience for EV components
3. Encourage hybrid power management systems for heavy-duty vehicles
4. Develop WBG systems for electric rail infrastructure

Digital Infrastructure

1. Promote R&D for developing high-efficiency power converters for data centers
2. Work with industry partners to explore a transition to DC distribution systems in data centers
3. Support the development of grid-interactive data centers
4. Develop efficiency metrics and benchmarks
5. Increase partnerships & co-design opportunities with end-users

Industrial Infrastructure

1. Leverage demonstration projects for WBG PE in industrial applications
2. Establish standards and guidelines for PEs in industrial applications

2 Materials and Devices for WBG PE

Silicon Carbide

1. Develop novel gate dielectric approaches for SiC devices
2. Develop SiC IGBTs for high voltage applications
3. Develop SiC superjunction MOSFETs for high voltage applications
4. Reduce material costs for SiC technologies

Gallium Nitride

1. Increase domestic GaN supply chain presence in the United States
2. Increase operational voltage ranges for GaN devices

Ultrawide Bandgap Materials: Aluminum Gallium Nitride and Aluminum Nitride

1. Develop processes for reliably producing AlGaN on virtual substrates for PE applications
2. Innovate on device designs that leverage AlGaN characteristics for high-voltage applications
3. Identify optimal gate dielectrics for use with AlGaN

Ultrawide Bandgap Materials: Gallium Oxide

1. Improve and scale up Ga_2O_3 manufacturing processes for high voltage applications
2. Develop doping approaches and device architectures to overcome existing material system limitations
3. Innovate device design to overcome Ga_2O_3 thermal conductivity limitations

3 Passive Components and Packaging for WBG PE

Passive Components

1. Focus on increasing the operational temperatures of inductors and capacitors for PE applications
2. Integrate new materials into inductor and capacitor designs to improve performance and system energy densities
3. Increase scale of electro-thermal analysis and modeling

Packaging

1. Focus on process improvement & scale-up for double sided cooling designs
2. Innovate and integrate new materials to improve PE packaging across all measures of performance
3. Explore alternative and complementary manufacturing techniques

4 Non-Technical WBG Development Support Areas

1. Expand industry and academic partnerships
2. Support work visas for foreign students
3. Develop alternative educational pathways
4. Create partnerships with international institutions and the U.S. Department of Labor
5. Improve hands-on training and early exposure to PE
6. Reduce education costs and expand scholarships
7. Implement employer-based training programs and career pathways
8. Broaden outreach to underrepresented groups and veterans
9. Address barriers to employment and improve hiring practices
10. Increase early STEM exposure and PE awareness
11. Increase data collection and sharing for embodied carbon and energy of WBG PE technologies
12. Support supply chain transparency initiatives
13. Encourage case studies and real-world demonstrations
14. Promote collaboration between industry, academic, and government R&D resources

Strategic Goals for WBG PE

The collected recommendations summarized above were also analyzed together to identify common themes and connections among recommendations. In alignment with the different aspects of the PE landscape and AMMTO's vision for a competitive U.S. manufacturing sector supporting American energy independence, the Office has identified six specific strategic goals for advancing WBG PE, which are outlined below. Three of these strategic goals are technical in nature, and three are focused more broadly on supporting the growth of the U.S. power electronics manufacturing ecosystem. AMMTO and the authors of this framework hope that readers follow individual recommendations most relevant to their work in the PE ecosystem, described in the sections of this framework and summarized above, but we especially encourage the industry to work towards accomplishing the six goals described below. AMMTO welcomes input and engagement from industry to help develop a commonly supported roadmap to lay out timelines and estimated levels of coordination and effort to help achieve these goals.

Table ES-1. PE Strategic Framework Goals and Areas of Focus

Technical Goals	Ecosystem Support Goals
T1. Increase system power density	**E1. Collaborate on pre-competitive R&D and innovation**
Increasing system power density is the most impactful single metric for most PE applications and will in most cases lead to cost reductions and other performance improvements. Nearly all major applications for PE will benefit from the impacts of improving system power density. Higher frequency operations are the most promising pathway to achieve this, as higher frequency operation results in more compact and efficient PE systems. Significant effort is needed to optimize materials, manufacturing processes, and system designs (including device, passives, and even packaging) to support high-frequency performance while maintaining system reliability and stability.	Achieving the full potential of WBG PE demands a unified effort across the entire innovation ecosystem. Unlocking the transformative benefits of WBG technologies requires collaboration on pre-competitive R&D that brings together industry leaders, academic researchers, government agencies, and research institutions. Leveraging the strengths and resources of all stakeholders will accelerate advancements in WBG PE technologies, drive down costs, overcome critical technical barriers, and encourage broader adoption.
T2. Enable higher voltage and power operation for grid applications	**E2. Quantify and validate the full lifecycle costs & benefits of WBG PE**
Achieving higher voltage and power operation will facilitate the integration of renewable energy sources, advanced grid management systems, and emerging high-power applications in areas like energy storage and transportation electrification. The need for PE systems that can operate at higher voltages and power delivery is acute.	Leverage techno-economic analysis (TEA) methodologies as tools for strategic planning and resource allocation in PE innovation. By systematically analyzing costs, benefits, and potential barriers, TEA can pinpoint specific areas where investment is needed to optimize performance, reduce costs, improve efficiency, overcome technical challenges, and expand market adoption for WBG-PE systems. Conduct comprehensive lifecycle assessments (LCAs) to demonstrate the performance, environmental, and economic benefits of WBG technologies over traditional Si-based PE. Utilize LCAs to baseline environmental impacts, promote sustainable practices, and target advancements that foster circularity and waste reduction.

Technical Goals	Ecosystem Support Goals
T3. Integrate and commercialize materials advancements to improve PE devices & systems	**E3. Increase educational and workforce training activities across the country to support PE industry growth**
Identification, development, and improvement of the fundamental materials in PE devices and packages are the most impactful pathway to improving the performance of the overall systems themselves. Complete integration and commercialization also require improvements in manufacturing processes and scale-up of the technologies that incorporate these materials, as well as supply chain optimization to ensure reliable access to them. Driving the largest impacts in WBG PE technologies will happen through materials innovation.	Expand educational programs and workforce training initiatives at all levels—ranging from technical training for manufacturing roles to advanced research programs for engineering and design positions. Establish partnerships with academic institutions, industry, and government to ensure a steady pipeline of skilled workers to meet the growing demands of the domestic PE industry.

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1 Introduction

Power electronics (PE) are essential to the conversion and control of electrical power in U.S. critical infrastructure. Innovations in PE will help the United States meet rising energy demands and improve grid resiliency goals through more efficient energy conversion, grid stability and reliability, and integration of renewable energy sources. Modern society has been rapidly changing over the past 50 years, which has also impacted how energy is produced, transmitted, and used. These changes have led to an overall increase in conversion, transmission, and use of energy in the form of electricity, as well as the complexity and volatility of demand on all levels of the nation's electric grid. Ever higher demand is placed on the PE that enable and control the conversion, transmission, and use of electricity throughout our nation. This section provides context of what PE are as a technology category, current trends driving the PE industry, and relevant details of how wide-bandgap (WBG) PE compare to the legacy Silicon (Si)-based PE in wide use today.

1.1 What are PE?

PE enable the manipulation of electricity, allowing it to be delivered and used when and how it is wanted and needed. They control power flow at both the point of generation and usage, convert electrical energy from one form to another (e.g., from alternating current [AC] to direct current [DC]), and change voltage levels as needed. Roughly 70% of all electrical energy today is handled by PE devices at some point between generation, transmission, and usage, with that percentage expected to reach 100% in the future.[1]

Compared with microelectronics, which process and control electricity for the purpose of storing, transforming, and transmitting data and therefore only need to operate at a narrow range of power and frequency, PE operate at the milliwatt (mW) or megawatt (MW) level[2] with up to a few megahertz (MHz) switching frequency.[3] This makes PE essential to the larger scale conversion and control of electrical power across a range of U.S. critical infrastructures:

- **Grid infrastructure** – Enables electric grids to process and deliver power with efficiency and reliability. *Example:* Advanced PE—including solid-state transformers, fault current limiters, high-voltage direct current systems, and power flow controllers—can reduce transmission and distribution (T&D) losses, optimize power delivery, protect critical assets, and enhance resilience.[4]
- **Industrial infrastructure** – Helps power large-scale manufacturing, including use within equipment for enhanced control. *Example:* Variable speed drives (VSDs) improve productivity and energy efficiency by allowing operators to optimize motor speed based on loading conditions for industrial equipment including pumps, fans, and compressors.[5]
- **Transportation infrastructure** – Allows for faster and more reliable charging of electric vehicles (EVs)[6] and use of power within vehicles. *Example:* PE circuits

including battery packs, power actuators, and traction motors help to facilitate the efficient conversion, transformation, and transfer of electrical power through the powertrain.[7]

- **Digital infrastructure** – Facilitates seamless, modern communication networks including enabling signal processing and transmission through circuits to enhance signals, improving system performance through digital signal processing (DSP) and power-efficient amplifiers, and enabling wireless power transfer technologies.

While both microelectronics and PE are essential to critical infrastructure, microelectronics are essential in the same way to all infrastructures (i.e., electricity for data) while PE are essential in different ways to different infrastructures. This means that microelectronics have traditionally relied on fewer fundamental system components (e.g., CPU, GPU, memory, and storage, all built on Si complementary metal-oxide-semiconductors [CMOS]), while PE require different core technologies for different application areas (e.g., high voltage direct current [HVDC] vs micro-inverters vs electric motors, etc.).

1.2 Hierarchical Nature of PE

In addition to requiring different core technologies for different applications, PE innovation must also occur at many levels—including at the material, device, and circuit (packaging and thermal management) level—to have the desired effect at the application level. Similarly, the needs at the application level determine the necessary parameters at lower hierarchical levels. This tight coupling between the needs of the application area and the capabilities of subsequent technologies is known as the "atoms to applications" concept, which is demonstrated in the DOE/AMMTO-developed figure, shown below (see **Error! Reference source not found.**).

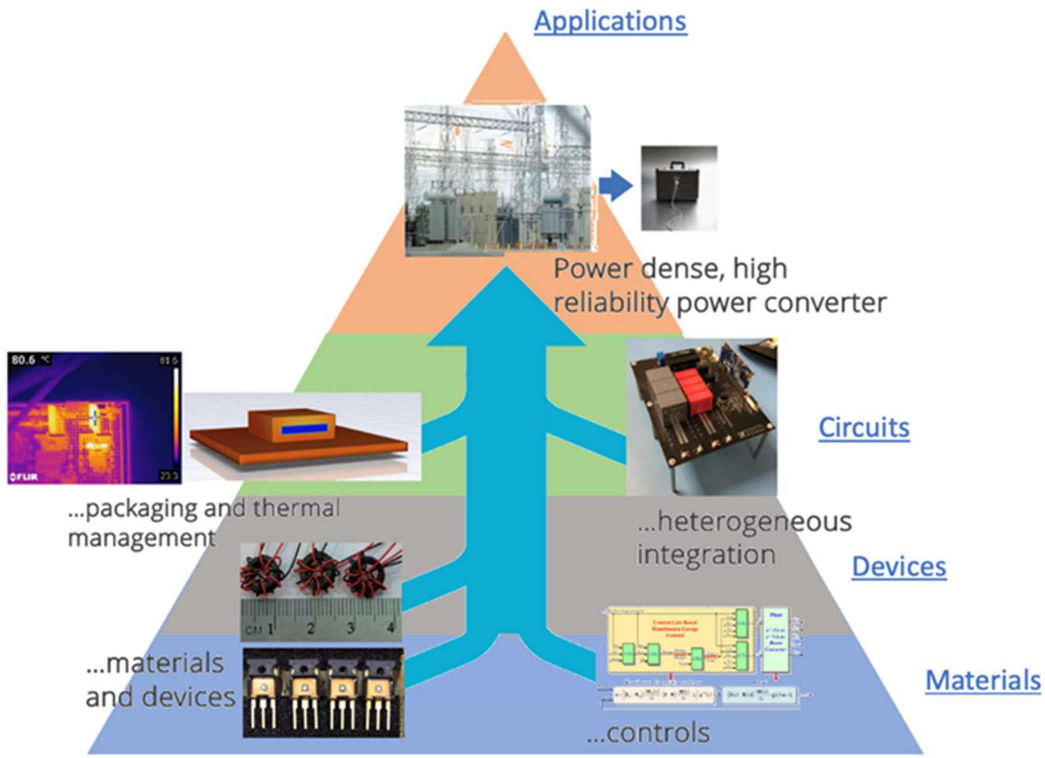

Figure 1. The "atoms to applications" hierarchical nature of PE, in which the capabilities of lower levels of the pyramid determine the capabilities at the apex, or application-level

While each application has its own hierarchical structure, there is significant overlap at lower levels of the hierarchy with differentiation occurring mainly at the end-use application level. As a result, fundamental research in materials, devices, circuits, and subsystems can impact multiple end-use applications levels. For example, power converters that interface solar energy resources to the grid and power converters that interface wind turbines to the grid have significantly different application areas, while the underlying technologies (e.g., the power conversion circuits, switching and passive elements, and materials systems) may be identical. Fundamental innovations in, for example, silicon carbide (SiC) switching elements, may impact multiple application levels simultaneously.

Because the innovations and usages at lower hierarchical levels are closely linked, there can be significant commonality between circuit architectures, devices, and materials systems supporting similar applications. As a result, the isolated hierarchy shown in Figure 1 actually becomes nested pyramidal hierarchies with significant areas of overlap at the lower levels, so that some innovations at lower hierarchies can impact multiple application areas, as shown in the DOE/AMMTO-developed figure, shown below (see Figure 2). For example, both photovoltaics and energy storage require medium voltage interconnects moderated through PE converters. Doing this efficiently and economically requires the advent of modular, medium voltage PE in certain cases that can be sized for specific system voltages and power levels arbitrarily.

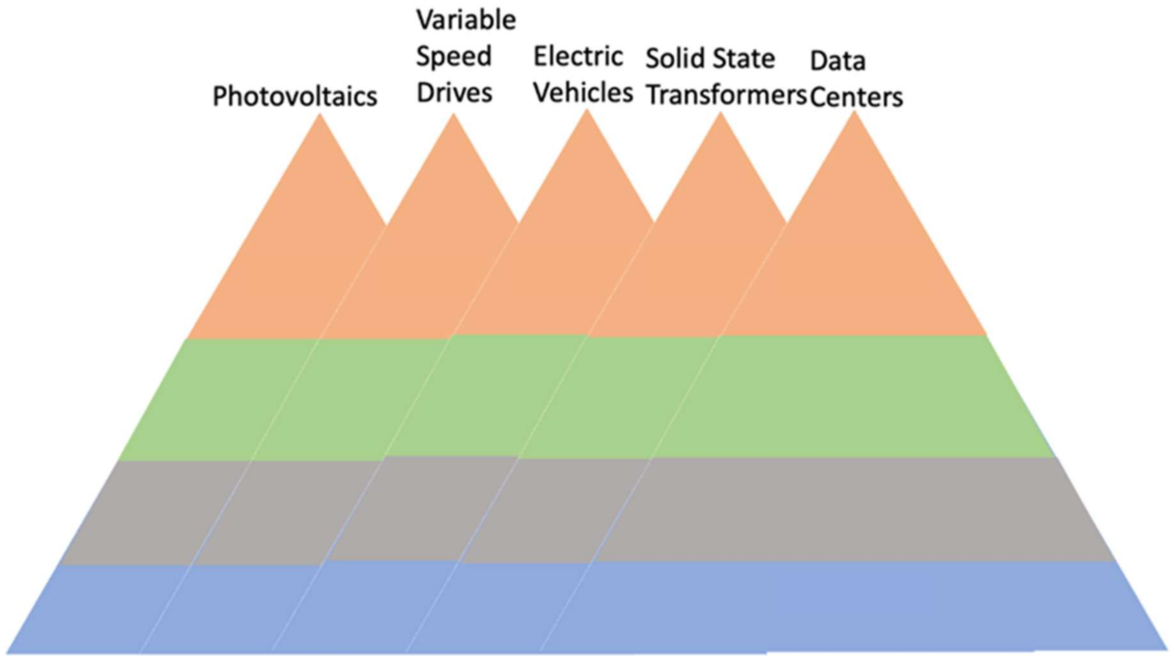

Figure 2. The "atoms to applications" hierarchical pyramid only differentiates at an end-use application

1.3 Trends Driving WBG PE Adoption

To date, silicon (Si) has been the primary semiconductor used in PE devices across all industries—in 2022, Si-based PE accounted for 96% of the market share by value.[8] But the following trends have been driving a search for alternatives:

- **Increasing demand for higher performing PE to ease the adoption of distributed energy resources (DERs).** The future resilient and reliable grid of 2035 requires the addition of 100s of GW of solar, wind, and other renewable resources. Wind energy specifically requires higher voltage PE to enable the operation of larger wind turbines (e.g., 34.5 kV, AC is considered a medium voltage rating for 100+ MW wind plants). Wind energy also requires simpler, more efficient PE to connect to the electric grid, since wind energy inherently relies more on the transmission system to deliver power due to the best wind resource areas often being far from load centers. In addition, solar and energy storage need better performing PE to achieve better SWaP and longer lifetimes. The modernization of the electrical grid is projected to require 20-50% of all electricity generation to come from photovoltaic (PV) sources. To achieve this, DOE has set aggressive cost goals to lower the levelized cost of electricity (LCOE) of utility-scale solar energy (< 0.03 \$/kW-hr for utility-scale installations by 2030), which requires significant reductions in inverter costs and improvements in service lifetimes.
- **Increasing need for responsiveness of the electric grid due to faster changing and less predictable electric loads.** The electrification of daily life in

the United States—such as household electronics, electric buildings systems (e.g., HVAC, heat pumps), data centers, and the growth of EV charging and distributed solar—has resulted in a shift from more stable electric loads and sources to faster switching, less predictable loads and sources. Advanced PE technologies that can handle higher frequencies and have increased reliability are essential to enabling this transition.

- **Increasing priority of efficiency for power solutions in growing markets.** Demands for higher efficiency technology in data and transportation markets are increasing pressure to develop advanced PE technologies. The advent of cloud computing has resulted in an explosion of systems that store, process, and network data, all of which are inherently electrical processes—estimated global data center electricity consumption in 2022 was 240-340 TWh, or around 1-1.3% of global electricity demand. New methods of power routing and usage enabled by advanced PE are essential to ensuring that the grid can continue meet these rapidly expanding electricity usage needs. In the EV market, there is a push to make electric powertrains even more efficient to reduce component footprint and improve overall vehicle performance. Increasing PE switching frequency can help reduce the size and weight of PE components but also relies on greater improvements and reliability in PE technologies.

Demand for conventional and wide band semiconductors is projected to increase by more than an order of magnitude by 2050.[9] The $20.9B 2022 power electronic market (including discrete and modules) is expected to reach $33.3B by 2028, with the 1200V voltage range expected to have the largest increase.[10] Yole further projects that WBG materials such as SiC and GaN will go from an 8% market share in 2022 to 28% in 2028. Additional details concerning market dynamics are described in the application areas chapter of this document.

1.4 Advantages of WBG and UWBG Semiconductors

PE technologies rely on semiconductor-based devices, which directly influence the overall size, weight, cost, and efficiency of subsequent power systems. While Si has been the predominant semiconductor in PE systems for many decades, application requirements have exceeded the material limits of Si and demand a more suitable alternative. WBG and UWBG material systems have a significantly wider energy gap between the valence and conduction bands (Figure 3), which results in significantly higher breakdown strength and operating temperature for these materials. Thus, for a given breakdown voltage rating, these materials provide lower specific on-resistance (Figure 4).

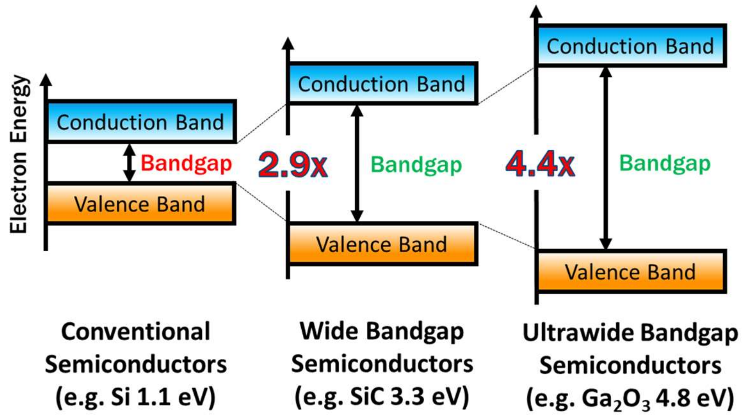

Figure 3. Energy bandgap comparison of conventional semiconductors (e.g., Si), WBG (e.g., SiC), and UWBG (e.g., gallium oxide)

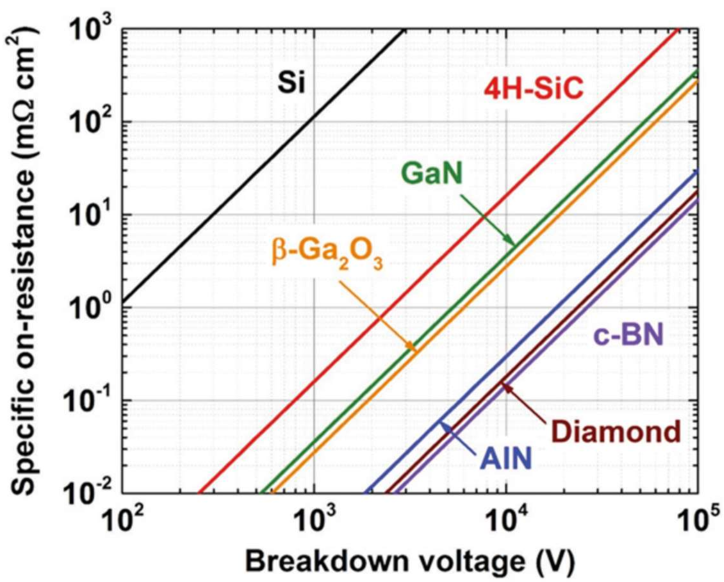

Figure 4. Contours of constant Baliga figure-of-merit (BFOM) showing relationship between on-resistance and breakdown voltage for various conventional, WBG, and UWBG semiconductors[11]

Achieving lower specific on-resistance for a given voltage rating ultimately enables reduced chip area (die size) and correspondingly lower device capacitance, which increases switching frequency and reduces losses. In total, WBG and UWBG materials offer significant improvements in power handling, switching speed, and temperature robustness in a smaller form factor. These benefits allow the use of smaller passive components and reduce the external cooling requirements, which are both major factors in the overall size, weight, and cost of the system. The increased frequency of operation and power density of WBG-based devices can advance efficiency and reduce chip-size requirements beyond what is possible with Si-based devices. Thus, overall system performance can be increased while costs can be reduced by transitioning to WBG-based devices. Furthermore, in some cases (U)WGB devices enable operation in environments that are not supported with legacy Si-based devices. For example, SiC devices have been demonstrated to operate up to 500°C,[12] and (U)WBG devices can offer significantly more resilience in radiation environments.[13] Additionally, from a systems perspective, some applications are simply not viable without the benefit derived from (U)WBG devices (e.g., pulsed-power and solid-state transformers). As the push toward modernization and the demand for reliable, efficient electricity continue to ramp up across U.S. critical infrastructure, **this strategic framework aims to identify recommended actions that will enable the replacement of Si in PE at scale.**

1.5 Strategic Framework Structure and Organization

The PE industry draws from a small number of core technologies to ultimately serve a large number of end-use markets with an extremely wide range of performance and cost requirements. Therefore, this framework aims to examine the technical landscape from both the "market pull" and "technology push" perspectives. Furthermore, this framework also considers a few nontechnical but nevertheless critical needs the industry will have over the next decade. The document is thus broken down into the focus areas that follow.

These four focus areas create a comprehensive framework for understanding both the technical and nontechnical needs required to drive the adoption and advancement of WBG PE in critical sectors. In cases where these impactful technologies overlap, this framework intends to:

- Introduce the research needs for areas with overlapping lower-level hierarchies only once where they first occur and then refer back to that section in specific application writeups.
- Identify targets and goals specific to the given application area

Focus Area 1: WBG PE Applications to Infrastructures

This section explores how WBG PE are transforming key sectors of infrastructure. WBG devices, which offer superior performance in terms of efficiency, power density, and high-temperature operation compared to traditional silicon-based technologies, are now being applied to a wide range of end-use markets:

- **Grid infrastructure:** As power grids evolve to accommodate renewable energy and electric vehicles, WBG PE play a critical role in enhancing grid efficiency, enabling HVDC interconnections, and integrating distributed generation and energy storage systems.
- **Transportation infrastructure:** Electrification of vehicles, from light-duty to heavy-duty, relies heavily on WBG PE for efficient power conversion, fast charging, and managing high-power drive systems. These technologies help overcome key challenges such as electricity demand management and energy efficiency in electric vehicles.
- **Digital infrastructure:** With the rising demand for data centers and digital communication systems, WBG devices are pivotal in reducing energy consumption and improving efficiency in powering data centers, telecommunication systems, and AI-driven infrastructure.

- **Industrial infrastructure:** WBG technologies improve energy efficiency and process control across manufacturing and industrial sectors, reducing energy consumption and improving the performance of industrial drives, motors, and heavy equipment. WBG technologies also serve as a key enabler for hydrogen generation technologies, which are key in modernizing hard-to-electrify industries.

Focus Area 2: Materials and Devices for WBG PE

The foundation of WBG PE lies in the materials and semiconductor devices used to create high-performance power components. This section outlines the different materials that drive advancements in WBG technologies:

- **Silicon carbide (SiC):** Known for its high breakdown voltage, thermal conductivity, and efficiency, SiC is widely used in power converters, especially in high-voltage and high-power applications such as electric vehicles and grid systems.
- **Gallium nitride (GaN):** GaN is ideal for high-frequency and high-efficiency applications, making it a key enabler in power supplies, RF amplifiers, and consumer electronics.
- **Aluminum gallium nitride (AlGaN) and aluminum nitride (AlN):** These materials are emerging for applications that demand extreme power density, thermal performance, and reliability, particularly in aerospace, military, and other high-stress environments.
- **Gallium oxide:** This newer WBG material offers extremely high breakdown voltages, which could enable future breakthroughs in ultra-high voltage applications like solid-state transformers and HVDC power transmission.

Focus Area 3: Passive Devices and Packaging for WBG PE

While WBG semiconductors are critical, the devices' ultimate performance depends heavily on the passive components and packaging technologies that surround them. This section focuses on:

- **Established packaging and passives:** Traditional packaging solutions and passive components like inductors, capacitors, and transformers are being adapted to handle the higher frequencies, power densities, and temperatures associated with WBG devices.
- **Emerging packaging and passives:** Novel approaches to packaging, such as advanced thermal management techniques and 3D packaging, along with passives designed for ultra-high-speed operation, are being developed to further maximize the performance of WBG technologies.

Focus Area 4: Nontechnical WBG Development Support Areas

In addition to technical innovations, there are crucial nontechnical factors that will drive the successful adoption of WBG technologies. This section examines these broader support areas:

- **Education and workforce development:** As WBG technologies proliferate, there is an urgent need for training programs to develop a skilled workforce proficient in the unique properties and applications of WBG semiconductors. This will ensure that companies can scale and implement WBG technologies effectively.
- **Lifecycle assessment (LCA):** Assessing the environmental impact of WBG PE throughout their lifecycle is essential for promoting sustainable development and meeting global energy efficiency and energy security goals.
- **Technoeconomic analysis:** The widespread adoption of WBG technologies hinges on their cost-competitiveness with established technologies. This area focuses on cost reduction strategies, manufacturing scale-up, and economic models to drive the market penetration of WBG PE.

1 Focus Area 1: WBG PE Applications to Infrastructures

This chapter is split into four broad Infrastructure Areas: Grid Infrastructure, Transportation Infrastructure, Digital Infrastructure, and Industrial Infrastructure. In each area, this chapter discusses the current state of PE, the technical challenges for WBG PE that need to be overcome, and technological innovation pathways available for addressing those challenges.

The following tables summarizes the key metrics driving innovation in each infrastructure where PE has application. While it can be argued that SWaP-C, reliability, and scalability are critical in all PE applications, some metrics matter more in certain contexts. Table 1 below summarizes the priority metrics for each application area discussed in this chapter.

Table 1. Priority Metrics for PE Used in Various Infrastructures and Applications

	Size, Weight, Power Density	High Voltage and High Power Operation	Low Cost Components	High Reliability Circuits	Scalability	High-Efficiency Power Conversion
Grid Infrastructure						
Photovoltaics		X	X	X	X	
Wind Energy	X	X	X	X		
Energy Storage		X	X	X	X	X
Solid-State Transformers	X	X		X		
Transportation Infrastructure						
Light-Duty Vehicles	X		X	X		
Heavy-Duty Vehicles	X		X	X		
Electric Rail	X	X		X		
Digital Infrastructure						
Datacenters	X			X	X	X
Industrial Infrastructure						
Hydrogen Production		X	X			X

2.1 Grid Infrastructure

Since its formulation in the late 1800s, the electrical grid has been dominated by generation, transmission, and conversion equipment that is electromechanical in nature rather than PE-based. This has yielded the grid that we know today, which is frequently called the largest and most complex machine that mankind has ever devised.[14]

The existential threat of climate change and the subsequent need for a modern and secure electrical grid require a more efficient, resilient, and cost-efficient electrical grid that enables flexibility at both load and generation.

The future grid of 2035 requires the addition of hundreds of GW of solar, wind, and other renewable resources. Much of this energy will be generated locally, near load centers, and will be interfaced into the electrical grid through PE converters. Significant portions of this new renewable generation will be focused in high-value areas with abundant resources, such as the desert Southwest (for solar), Midwest (for on-shore wind), and Atlantic seaboard (for off-shore wind). Efficient transmission of electricity from these areas to load centers will require multi-terminal HVDC interconnections, which are enabled by PE conversion. To mitigate short-term and long-term variability, generation resources will need hundreds of GW and GW-hrs of both short-term and long-duration (> 4 hour) energy storage. Each generation and storage asset will be interfaced into the electrical grid via PE.

The PE uptake in generation and transmission will be matched by PE penetration at the load side. Increased efficiency has driven PE-mediated load over the past 10 years, and this trend will continue until all loads are PE-based. Additionally, as transportation (light- and heavy-duty EVs, aviation, etc.) and heavy industry become increasingly electrified, the amount of load on the system will significantly increase over the next several decades. The growth of high-power loads—through charging stations to support electrified transportation, proliferation of data centers, and increased industrial electrification—combined with more extreme weather events will also mean that the level of flexibility and resiliency in the grid will need to significantly increase.

2.1.1 Grid Infrastructure Application Areas

Application Area 1: Photovoltaics

The modernization of the electrical grid is projected to require 20-50%[15] of all electricity generation to come from PV sources for a total power level of 1 TWAC. While 15 GW of PV was installed in 2020,[16] an increase in rate of 2-5 times is required to achieve 1 TW.

To achieve this sort of year-over-year increase in PV installation economically requires an extreme reduction in the LCOE of PV implementations through the reduction of Day 1 costs for PV installations, reduction in long-term operations and maintenance costs, and extension of lifetime for PV system. The DOE Solar Energy Technology Office (SETO) targets an LCOE of < 0.03 $/kW-hr for utility-scale installations by 2030.[17] This requires a PV Balance of System cost of 0.54 to 0.62$/W with a fielded service lifetime of 30-50 years.

Application Area 2: Wind Energy

Wind energy currently supplies more than 10% of U.S. electricity and is now the largest single technology contributor to U.S. renewable electricity after wind generation surpassed hydroelectric generation in 2019.[18] While land-based wind generation is predominant, offshore wind development is growing as the ability to generate wind energy near coastal population centers and site plants in areas with excellent capacity factors promises future economical deployment. Significant additional capacity of both land-based and offshore wind is expected to meet clean energy targets for the U.S. electrical grid by 2035 and beyond.

Application Area 3: Energy Storage

The deployment of energy storage in the U.S. electric grid is experiencing a near-exponential rise, as measured and reported by the U.S. Energy Information Administration and shown in Figure 5.

Figure 1. Growth in Energy Storage Deployments[19]

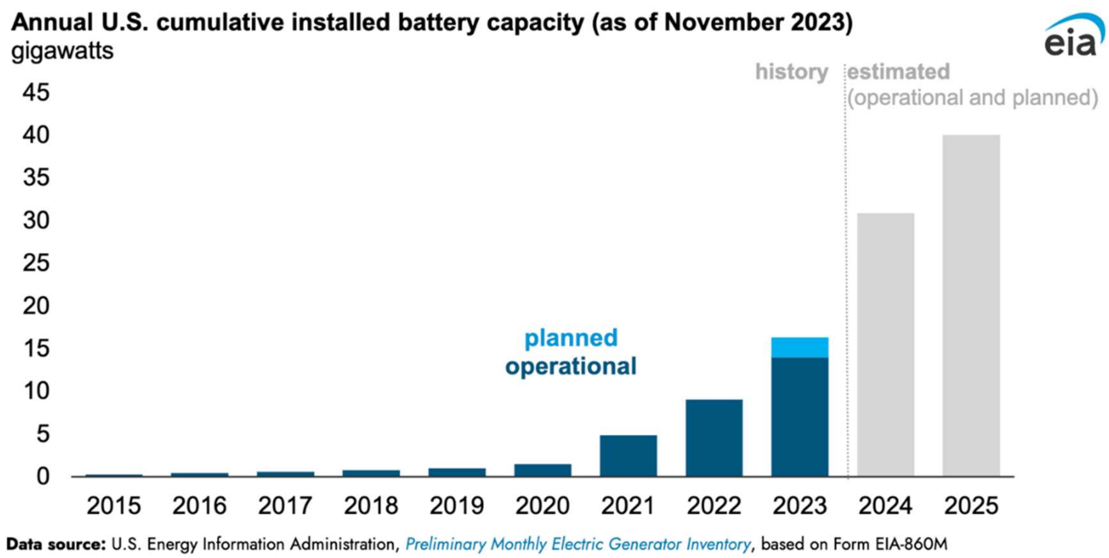

Figure 5. Growth in Energy Storage Deployments[20]

Prior analyses have indicated that the PE used to interconnect batteries to the grid constitute the primary energy loss mechanism in grid-scale battery energy storage systems.[21] This conclusion is represented in Figure 6. In the figure referenced, PCR (primary control reserve), SCR (secondary control reserve), and PV-B (storage of surplus photovoltaic power) represent different applications for energy storage that were tested as a part of the published analysis.

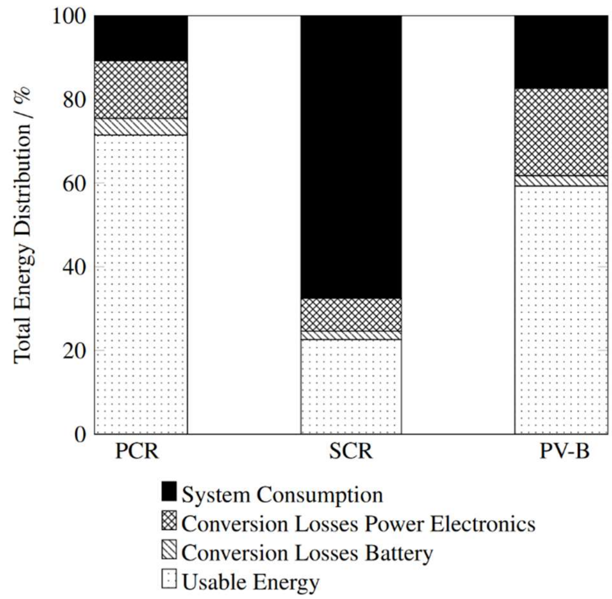

Figure 6. Losses in Battery Energy Storage Systems (BESSs)[22]

BESSs are growing in number, size, and scale. Systems installed in the United States through 2022 ranged in size from less than 1 MW to over 400 MW.[23] Systems scheduled for deployment through 2025 have planned capacities exceeding 600 MW.[24] As power capacities increase, BESS developers and utilities look to operate battery systems at higher voltages to reduce system losses. Advancements in PE will be critical to ensuring that energy storage can be successfully deployed in support of grid modernization efforts. This section explores the challenges, innovation pathways, and recommendations related to WBG PE advancements for energy storage systems.

Application Area 4: Solid-State Transformers

Solid-state transformers offer the functional benefits of large power transformers (high voltage conversion ratios, galvanic isolation) with the added benefit of being lightweight and offering small physical footprints. In addition, solid-state transformers provide functionality that cannot be performed by conventional transformers. Though solid-state transformers have vast potential for impacting the future grid, they have mainly been deployed in niche applications, and have challenges to overcome regarding cost and integration.

2.1.2 Challenges

Challenges for Solar PE Systems

The aggressive cost goals for lowering the LCOE of a utility-scale solar energy system are relevant to PE in that the upfront capital costs of the inverter must be as low of possible, presenting a number of challenges to today's inverter technologies. Reducing inverter costs is typically achieved through simplifying circuit architectures to use a minimum of components to achieve the required power conversion. As such, PV inverters typically are some of the primary beneficiaries from basic component improvements, as there is a distinct trade-off between component and circuit complexity. For example, complex circuits are often used to minimize voltage stress on PE switches. When using WBG PE switches with higher voltage handling capabilities, simpler circuit architectures can be employed.

Similar benefits are achieved from high frequency switching, as this allows for significant decreases in filtering components. Not only do the primary inverter component costs decrease with smaller filtering, but secondary costs also decrease due to the significantly smaller size and weight of the unit. This can reduce both shipping and installation costs. For these reasons, PV inverters were one of the first major entry points for 1.2 kV SiC metal-oxide-semiconductor field-effect transistors (MOSFETs), as they allowed for a significant increase in switching frequency.

Another driver for lowering LCOE is through the increase in service lifetime, which allows for a longer timeframe and extends the operation of the unit beyond the payback period. In general, the simple circuit architectures tend to reduce the number of components that can fail. However, they also tend to exacerbate stresses compared to complex architectures or switching schemes. For example, the H-bridge configuration is the simplest DC/AC architecture, but also requires hard switching, which can exacerbate failure mechanisms compared to soft-switching techniques.

Aside from reducing inverter costs, additional PE devices are being used in more complex PV systems. PV is an inherently variable generation source and is increasingly being paired with energy storage to mitigate both short term and seasonal variability as well as to enable enhanced dispatchability. This PV and energy storage (PV+Storage) concept, which has become increasingly dominant over the past decade, typically integrates PV and energy storage in a DC-coupled manner, where the energy storage and PV have independent DC/DC converters, but flow through the same inverter. These multi-terminal or multi-source power converters are beginning to propagate through new PV plants, and significant research is needed to increase performance and reduce costs in these converter topologies.

Other challenges result from the consequences of leveraging the ability of WBG PE to operate at higher switching frequencies. These higher switching frequencies can reduce passive component sizing, leading to size and cost savings in the converter. However, the increased switching frequency can also introduce added complication due to the higher dv/dt than is experienced in Si-based insulated-gate bipolar transistor (IGBT) devices. This can exacerbate electromagnetic interference (EMI) issues as well as lowering the effective hold-off voltage of the circuit and leading to partial discharge at lower voltages. So, while high voltage switches can enable simpler, more cost effective medium voltage and high voltage power converters, a simple drop-in replacement for Si based devices may not be practical, due to other factors involved in system design and optimization.

Challenges for Wind Energy PE Systems

PE converters for wind energy are high-capacity devices because individual wind turbine generators (WTGs) benefit from an economy of scale from a mechanical perspective and thus individual machine capacities have increased over the past decade to 3-5 MW for individual turbines. Wind plants also tend to have higher capacity from a collector system and total plant perspective. Due to their high capacities, the common standard voltages are higher. For instance, 34.5kV, AC is considered a medium voltage rating for 100+ MW wind plants.

Grid interconnection becomes increasingly difficult as more wind energy is integrated onto the system. Wind energy inherently relies more on the transmission system to deliver power due to several factors, including that the best wind resource areas are often far from load centers, wind energy's relative difficulty to integrate into the urban or suburban environments compared to solar PV, and the economy of scale realized with 100+ MW wind plants.

As more wind energy systems are being deployed offshore, their power conversion systems also require high power density and small footprints. Even more, they must operate with high reliability in harsh environments, as serviceability becomes difficult in remote environments. For these reasons, wind energy systems benefit from higher voltage PE switches, smaller passive devices and filters, low parts count systems, and simple thermal management approaches.

Challenges for Energy Storage PE Systems

In BESSs, higher voltage operation is achieved conventionally by connecting battery modules in a series configuration. Achieving higher voltage operation requires more modules. System reliability decreases with the addition of new components, and when connected serially, a single battery module failure can compromise the operation of the entire system. For these reasons, new approaches are needed to enable higher voltage operation for BESSs to support system efficiency, reliability, and scaling.

Lithium-based electrochemical batteries, which are most commonly applied in grid-scale applications, are manufactured using highly flammable materials. Thermal management is a primary concern when conducting BESSs with high power densities and small footprints. PE are key in the development of protection and control systems that ensure the safety of battery energy storage systems.

Challenges for Solid-state Transformer PE

Current solid-state transformer technologies rely on four quadrant switches (FQS), which can be made using two drain connected MOSFETs controlled as one switch. This back-to-back configuration of MOSFETs enables the full operation of the FQS. Even though this functional workaround meets the performance need, it is not currently cost effective, because there are twice as many switches needed to do the same job as a single FQS. In addition, the parasitic elements that exist between the pair of devices affect the switching characteristics of the topology as a whole, which means more protection and filtering circuitry is needed to achieve acceptable levels of power quality. The development of new PE switches and simplified topologies can drive innovations in solid-state transformer technology.

Conventional large power transformers are designed to operate for 30 years, and many transformers exceed their expected lifetime. Efforts to date to develop solid-state transformers have not yet resulted in devices that exceed the reliability of conventional transformers.[25] Furthermore, solid-state transformers developed to date suffer from high costs and poor efficiencies. Continued research is needed to realize the promise of solid-state transformers.

2.1.3 Innovation Pathways

The advent of WBG devices such as SiC and gallium nitride (GaN) have allowed for converter topologies to significantly increase operational switching frequencies compared to that of Si-based switches. WBG-based circuits can operate at very high frequencies (hundreds of kHz to a few MHz). The requirements for energy storage, which buffer on-off switch transitions, ideally decrease with the square of the switching frequencies. So, the high switching frequencies of WBG devices significantly shrink the requirements of passive components (capacitors and inductors) at a very rapid rate. Smaller passives and more power dense circuits means less materials have to be used, which inevitably leads to reduced costs.

Most three-phase grid-connected devices operate at < 20 kHz switching frequencies. To impact the grid, high frequency operation must be demonstrated in operational units at higher power level with an ideal of > 500 kHz at power levels > 500 kW demonstrated by 2035. However, high frequency operation enabled by semiconductor switches can shift issues over to passive components, so passive components that can operate with low-loss at high switching frequencies are required. More detail is given in the Packaging and Passives Section of this framework.

An alternative approach for scaling PE to achieve higher power and voltage levels involves the use of PE Building Blocks, wherein PE circuits are developed for providing specific functions. These circuits can be combined to stack functions, producing more complex systems.[26] Each circuit represents a building block with a distinct purpose, known operating parameters, and a standardized interface. Building blocks can be stacked to achieve higher voltage and power levels with reduced component stress.[27] By standardizing simple components, PE Building Blocks can be manufactured in bulk, supporting scalability, reliability, and cost effectiveness. Hot-swappable PE Building Blocks increase reliability and lower O&M costs. PE Building Blocks reduce supply chain risk and enhance manufacturability at scale.

To overcome the impact of a constrained transmission system, more transmission capacity will be needed in some regions to further develop wind resources. HVDC systems will play an important role in overcoming this challenge but present their own challenges too. The development of affordable HVDC conversion technology and controls for multi-terminal HVDC systems (MTDC) could allow regional HVDC backbones to become a reality, particularly if built using existing AC transmission rights-of-way. Advancing MTDC technology will require breakthroughs in DC protection and control systems, including solid-state DC circuit breakers that operate at transmission voltages and power levels. Furthermore, HVDC system costs need to improve. To this end, DOE has established an initiative to reduce the levelized cost of HVDC converter stations by 35% by 2035.[28] Broader adoption of HVDC technology will also require improvements to voltage-source converter technology, including improvements in power capacity, voltage limits, size and power density, lifespan, and reliability.[29]

Innovative voltage conversion approaches can support efficiency, reliability, and scaling for energy storage systems. Approaches are needed to increase the DC operating voltage of energy storage systems without increasing the number of series-connected battery models. In addition, approaches are needed for interconnecting BESSs at higher AC system voltages (e.g., medium voltage, direct grid interconnection). WBG PE devices can enable higher voltage operation with lower losses, compared to Si-based switching devices.

String converters represent an option for increasing series voltage. High voltage ratio converters, including those that utilize high-frequency transformers, can be used to achieve MV interconnection, while improving overall system cost and footprint through elimination of the 60 Hz step-up transformers that are common in grid-connected BESSs and PV installations. This can reduce overall system cost while maintaining reliability and facilitating interconnection.

In MV and HV grid applications, the use of high voltage power electronic switches will enable power conversion at higher voltage levels, driving efficiency through lower current losses, and driving reliability by reducing the overall number of circuit components needed. Recently, 3.3 kV devices have been commercialized for a variety of power converter applications to increase system power density and efficiency. It is expected that SiC MOSFETs will follow a natural progression of increasing voltage ratings over time, as driven by industry needs.

Reductions in switching and conduction losses can be achieved by using WBG PE switches in BESSs. Doing so can reduce the BESS conversion losses attributed to PE, increasing overall roundtrip efficiency, a key metric for evaluating the effectiveness of BESSs. Loss reductions also improve operating costs for BESSs.

Improvements are needed in BESS protection and control systems. PE converters can work in tandem with battery management systems to identify thermal issues, quickly isolating impacted battery modules, preventing cascading thermal management incidents. In addition, PE and controls can be used to quickly re-optimize the performance of a BESS when individual battery modules are taken out of service. PE improvements may enable the development of hot-swappable battery modules, improving system reliability and serviceability.

There are current R&D efforts intended to provide short-term and long-term solutions to the challenges facing current solid-state transformer technologies. In particular, appropriate switching devices, magnetic materials, and circuit topologies are needed, as well as control systems that provide appropriate functionality for tailored applications. Technoeconomic analysis is important for promoting solid-state transformer adoption, as solid-state transformers can provide unique benefits to end-users, and these benefits require proper accounting when considering solid-state transformer deployment.

2.1.4 Recommendations

The following recommendations outline actions the U.S. government, AMMTO, and the broader ecosystem can support to advance the adoption and integration of PE to modernize and secure the nation’s electric grid:

1 Support pre-competitive R&D activities for advanced PE technologies

WBG devices offer superior performance at high switching frequencies and voltages, enabling more compact and efficient power converters. Pre-competitive R&D support from both the public and private sectors can accelerate the deployment of WBG-based PE across the grid infrastructure, improving grid stability and lowering the costs of integrating renewable energy.

2 Focus on further development of the emerging WBG technologies such as solid-state transformers, multilevel modular converters for MVDC and HVDC systems, and PE Building Blocks

Solid-state transformers can facilitate the seamless integration of distributed energy resources (DERs), enhance fault management, and reduce power losses. Supporting solid-state transformer technology will help overcome the limitations of conventional transformers and enable greater flexibility in grid operations.

HVDC systems are crucial for transmitting large volumes of renewable energy from remote generation sites (e.g., offshore wind and desert solar) to urban load centers. MVDC technology can support medium-voltage interconnections and improve efficiency in distributed grid applications.

PE Building Blocks offer the potential for hot-swappable modules, enhancing system reliability, reducing operation and maintenance (O&M) costs, and decreasing supply chain risks. Promoting their adoption will enable faster deployment of PE solutions and enhance grid resilience.

3 Support innovation in passive components & packaging to handle higher frequency PE operation

High-frequency operation enabled by WBG devices reduces the size and cost of passive components, making power converters more compact and efficient. Developing passives that match the performance of advanced semiconductors is essential for achieving optimal system performance.

4 Identify and support opportunities for field-relevant demonstration projects for emerging PE technologies

Demonstration projects can validate the performance and reliability of new technologies, providing critical data for widespread deployment. They also offer a platform for testing interoperability and scalability in real-world grid conditions.

2.2 Transportation Infrastructure

The U.S. Environmental Protection Agency (EPA) reported in 2021 that the transportation sector accounted for the largest portion, nearly one-third, of greenhouse gas emissions.[30] Automobiles account for over 80% of the transportation portfolio, which is mostly light-duty personal vehicles. There are many reasons that led to the dominance of the automotive sector in the United States, including early advances in assembly line manufacturing, globalization of the automotive industry, tight coupling with the oil industry and its political influence, suburban sprawl, a shift from single-earner to dual-earner households, and a rise of consumer goods home-deliveries, among other important factors. Efforts are underway to modernize, secure, electrify, and balance U.S. transportation technologies.[31] PE are a key enabler for electrified transportation systems: both on-board to enable electric powertrains as well as an interface into the electrical grid for charging those systems. Given the scale of transportation needs, the incremental improvement of advanced components like semiconductors and passives will have the most significant impact to improve our transportation technologies.

2.2.1 Transportation Infrastructure Application Areas

Application Areas 1: Light-Duty Vehicles

Light-duty vehicles lead the transportation sector with 58% of the emissions profile.[32] At present, light-duty vehicle electrification is well underway with 1.1 million units being sold in 2023 in the North American market, accounting for 7.2% of new light duty vehicle sales.[33] Full-year 2023 global light duty vehicle sales are projected to reach nearly 86 million units with a 2024 forecast to exceed 88 million.[34] Even though the EV market share is still a small percentage of the overall light duty vehicle market, safe and reliable mass production of EVs and their PE components will be critical to achieve a zero-emission future. PE are at the heart of this shift to battery electric vehicles (BEVs). They are responsible for the control of the electric powertrain, battery pack utilization and management, and charging interface.

Application Area 2: Heavy-Duty Vehicles

According to Figure 7, medium and heavy-duty vehicles currently account for nearly one quarter of transportation-based emissions. Due to the more demanding workloads of heavy-duty vehicles, a pure BEV with current battery technology is very challenging given the range/weight trade off. From a PE standpoint, the needs are similar to the light-duty vehicle sector, although scaled up to meet the higher torque and power demands. Furthermore, charging/refueling infrastructure must be frequent and robust to account for the high throughput needs of heavy-duty vehicles.

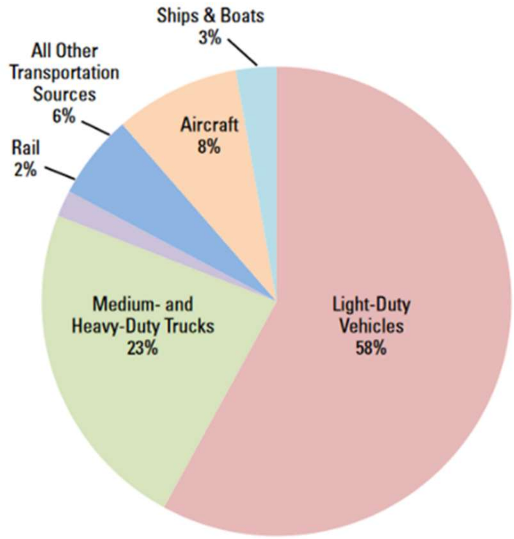

Figure 7. Share of transportation sector emissions by source[35]

Application Area 3: Electric Rail

Although the rail industry only accounts for 2% of the transportation greenhouse gas (GHG) emissions, considerations must be made to the freight industry's reliance on diesel and the effect extreme climate events can have on critical rail infrastructure.[36] While electric rail infrastructure is ubiquitous worldwide, the United States is almost exclusively reliant on diesel locomotives. This is partially due to the fact that the United States has the largest rail network in the world, much of which covers long-distance, low-population areas.[37] Electric passenger rail, on the other hand, represents less than 5% of the current rail network. Rail modernization in the United States can leverage infrastructure electrification and electric powertrain technologies, as well as hydrogen and biofuel options.[38]

2.2.2 Challenges

Meeting the demands of the consumer automotive market—safety, cost, range, and charge times—presents significant challenges for automakers. Some of the key barriers to the widespread adoption of EVs are the current limitations within the semiconductor supply chain, as well as gaps in EV infrastructure, particularly in charging and grid capabilities. Additionally, high-voltage, high-power, and high-frequency components are still in development, and these factors will likely slow the adoption timeline for EVs.

Another critical challenge is managing thermal loads and cycling effectively to ensure the safety and reliability of passenger vehicles. These concerns are closely related to the performance of batteries, which remain the most significant barrier to further technological progress. Batteries will need sophisticated electronics and control systems to ensure they are safe and long-lasting, which is essential for consumer confidence and the vehicle's lifespan.

Automakers must also secure a reliable supply chain not only for lithium-based batteries but also for semiconductors and high-rated passive components, which are needed for building various power converters (see Figure 8). Among these critical technologies, WBG semiconductors, particularly SiC and GaN, are in high demand for large-scale production and are crucial for achieving the reliability and efficiency needed in electric powertrains.

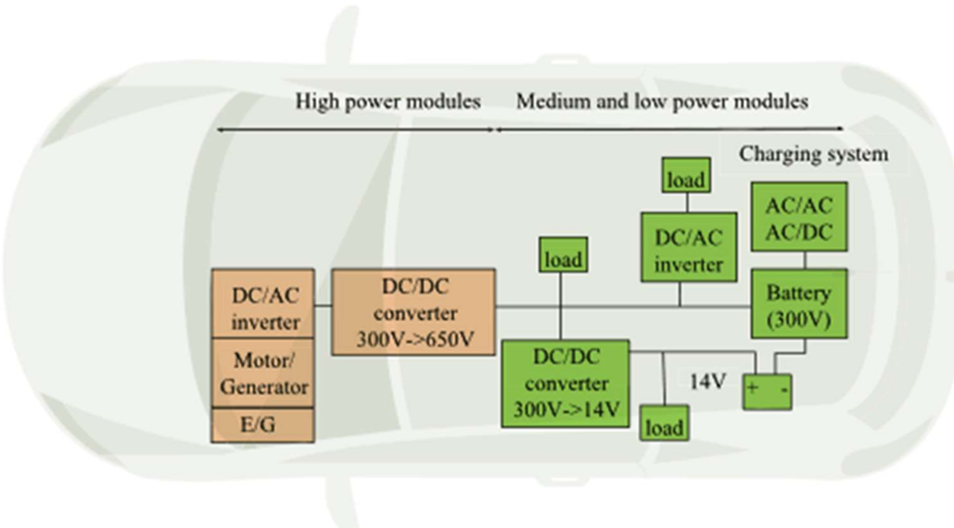

Figure 8. PE components in a BEV[39]

In the electric powertrain, PE will need to prioritize high performance with effective thermal management, switching frequencies in the 10-50 kHz range, and maximum efficiency, all while keeping costs low. Onboard charging modules will also need to support DC fast-charging capabilities to address consumer concerns about range. Since these modules are not constrained by the dynamics of electric motors, their switching frequencies should ideally operate in the hundreds of kHz range, significantly improving charging performance (see Figure 9).

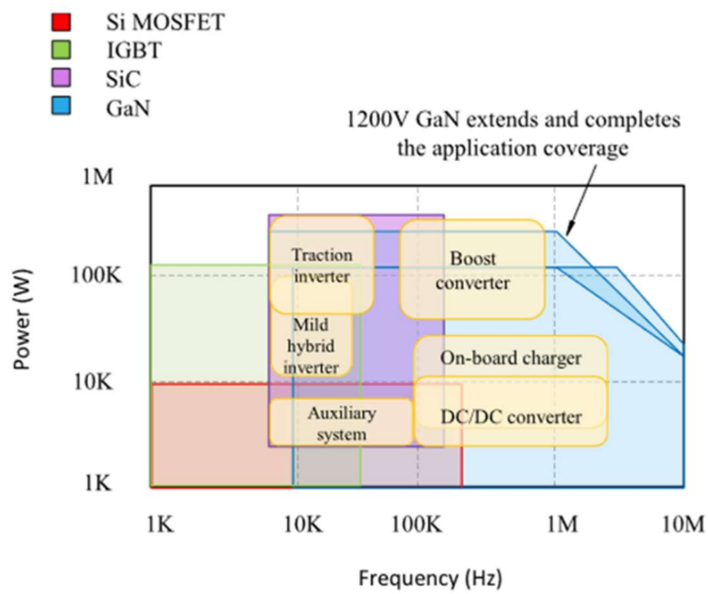

Figure 9. Power vs frequency comparison of different semiconductor technologies for EV power converters[40]

The PEs used in battery management systems will be pivotal for the safety and longevity of battery packs, which, in turn, are critical to the overall lifetime of the vehicle. These systems must ensure proper monitoring and management of the batteries to maximize their performance and ensure they meet stringent safety standards. As such, improving PEs across these areas will be essential for overcoming the current barriers to EV adoption and ensuring the industry can meet future market demands.

WBG semiconductors and passive components will need to meet the higher power demands, particularly in terms of current, required by heavy-duty vehicles. In addition to these electrical demands, thermal management systems must also be designed to handle the increased power loads, ensuring safe and efficient operation under heavy-duty conditions. For hybrid systems, different solutions will be necessary to balance the use of secondary propulsion or energy sources, which may require distinct power management strategies.

Fast-charging technology will also play a crucial role in enabling the transition to a more electrified heavy-duty vehicle fleet, especially for high-throughput applications that require minimal downtime. Ensuring that these charging systems can deliver high power efficiently and quickly is critical for the practical use of electric heavy-duty vehicles. Lastly, reliability will be a significant factor in the success of these future technologies. Both the electrical and thermal systems must be highly durable and capable of withstanding the demanding operating conditions of heavy-duty applications to ensure long-term vehicle performance and safety.

	Charging Technologies of HD-EVs	Pros	Cons
Conductive charging	Manual connector charging (power: 50 to 150 kW)	Good efficiency and less exposure to electromagnetic field compared to the inductive charging.	Maintenance costs because of the physical contact. For manual charging, need for dedicated staff to perform the charging. Visual impact, depending on the solution chosen and its location.
Conductive charging	Charging with automatic connection devices (ACD) (power: 150 to 600 kW): Infrastructure mounted ACD; Roof-mounted ACD; ACD connected to side or on roof of vehicle; Ground-based ACD		
Conductive charging	Catenary	Small battery can be used in the vehicle, which decreases vehicle cost. Flexibility in terms of route and network design.	Installation of new overhead lines can be costlier than other conductive charging. Visual impact (no impact while running without wires).
Inductive charging	Static inductive	Better visualization compared to conductive charging.	Lower efficiency as compared to conductive charging.
Inductive charging	Dynamic inductive	Small battery can be used in the vehicle, decreases vehicle cost.	Lower efficiency compared to conductive charging. Heavy and costly construction works.
	Battery swap (not very common for HD-EVs in Europe)	Reduces the high upfront price of EVs by separating battery ownership and cost [5].	Complex and expensive infrastructure. A high level of standardization for the battery packs. High capital expenses of additional battery packs [6].

Figure 10. Heavy duty vehicle charging technologies overview[41]

A significant hurdle to heavy-duty vehicle electrification is the charging infrastructure. Some bottlenecks to address include lack of standardization, maximum achievable power, and safety concerns.[42] From a PE perspective, an industry standard would help better define the design space for the associated on-board charging PEs. Figure 10 illustrates the variety of charging solutions that exist for heavy-duty vehicles. The electric powertrain PEs will have overlapping needs from the light duty sector—high-frequency WGB devices that shrink the overall footprint and power density and thermal management of the converter.

2.2.3 Innovation Pathways

Improvements in electrified transportation will come from a combination of factors, including increasing domestic manufacturing capacity, further reducing the size and weight of drivetrain components, increasing power levels for EV charging equipment, extending service lifetimes for all PE components, and reducing costs in every way possible.

Improving the efficiency of electric powertrains is a critical step in advancing zero-emission vehicle technologies. Currently, electric powertrains are more than 90% efficient, a significant improvement compared to the roughly 30% efficiency of internal combustion engine (ICE) vehicles. Future efficiency improvements will primarily come from increasing the switching frequency of PE components, which reduces their size and weight. WBG semiconductors, such as SiC and GaN, offer superior performance at higher switching frequencies, making them key to further advancements in electric powertrain efficiency. In addition to WBG semiconductors, improvements in passive components such as magnetics and capacitors will further drive system-level improvements.

To achieve the vision of zero-emission transportation, the focus must be on maturing WBG semiconductors and advancing battery technologies. As electric powertrains trend towards faster switching speeds and reductions in size and weight, the mass production of highly reliable components will be critical. Currently, 800V electric powertrain systems are available to consumers, addressing concerns about range and charging times. By moving to higher voltage levels and increasing switching frequencies, manufacturers can reduce the size and mass of PE components, optimizing overall system integration.

High-reliability WBG semiconductors will also play a crucial role in electric powertrains and onboard charging modules. Additionally, PE converters must manage high-cycle battery packs both safely and efficiently, which is essential for the electrification of heavy-duty vehicles. Much like light-duty vehicles, the electrification of medium- and heavy-duty vehicles will depend on the continued development of electric powertrains, onboard chargers, battery technology, and a robust national charging infrastructure. However, heavy-duty vehicles confront higher torque and power demands and have longer performance lifetime expectations, though they may be less sensitive to cost pressures.

Because many of these advancements are contingent upon improvements in the underlying materials and devices, further research and development pathways for achieving these innovations are discussed in the materials and devices section of this framework (see Focus Area 2: Materials and Devices for WBG PE). This continued focus on R&D will be pivotal in ensuring that the necessary advancements in PEs and battery technology can support the future of electrified transportation.

2.2.4 Recommendations

Given the transportation sector's substantial contribution to GHG emissions, supporting the successful application of PEs is critical to advancing vehicle electrification and modernizing transportation infrastructure. The U.S. government can help accelerate the shift towards electric and zero-emission vehicles by considering the following recommendations:

1 Focus on durability and reliability of WBG PE for transportation applications

Support research that improves the durability and efficiency of battery technologies, PEs, and thermal management systems for light-, medium-, and heavy-duty vehicles. An inherent strength of WBG PE is their smaller footprint, higher efficiency, and ability to provide power at levels most useful for transportation applications. By developing more robust battery management systems and efficient power converters, EVs can achieve longer lifespans, improved safety, and better overall performance, especially in high-throughput applications such as freight and logistics.

2 Strengthen supply chain resilience for EV components

Ensuring a reliable supply of critical materials and power components for the industry will mitigate bottlenecks in EV production, prevent delays in the electrification transition, and support national energy security.

3 Encourage hybrid power management systems for heavy-duty vehicles

Hybrid power management strategies will provide flexibility for heavy-duty applications, optimizing performance while reducing emissions, especially in sectors where full electrification is not yet feasible due to weight or range limitations.

4 Develop WBG systems for electric rail infrastructure

Rail modernization will expand the transportation sector's range of power options while increasing the energy efficiency of freight and passenger rail systems.

By implementing these recommendations, the U.S. government can accelerate the adoption of electric and hybrid technologies across the transportation sector, reducing GHG emissions, enhancing energy efficiency, and ensuring the reliability of PEs for future electric transportation systems.

2.3 Digital Infrastructure

Electricity is the lifeblood of the digital economy. As more aspects of consumer life and modern industry are digitized, electricity demand continues to increase as well as reliance on PE technologies. This section explores PE needs for powering the digital economy.

2.3.1 PE Applications for Data Centers

In recent years, the use of electricity by data centers has seen sharp growth, driven by ongoing efforts such as cloud-based computing, AI language models, and cryptocurrency mining. Estimated global data center electricity consumption in 2022 was 240-340 TWh,[43] or around 1-1.3% of global electricity demand. This is the equivalent to 0.9% of energy-related GHG emissions (or 0.6% of total GHG emissions).[44] These numbers for data centers exclude energy used for cryptocurrency mining, which was estimated to be around 110 TWh in 2022, or an additional 0.4% of annual global electricity demand, according to the University of Cambridge Bitcoin Energy Consumption Index.[45] This proportion does not even encompass the electricity use of the entire digital communication infrastructure (e.g., data transmission, wireless and satellite communication, mobile consumer devices, autonomous and other Internet of Things [IoT] systems) and is expected to continue growing significantly over the next few years as data collection and analysis, aided by AI and ML, is leveraged in increasing aspects of modern life. Mitigation of the electricity usage of these digital information communication networks to ensure the electrical grid can meet future requirements will necessitate, at a minimum, more energy-efficient data centers that utilize new methods of power routing and usage, enabled by advancements in PEs.

The advent of cloud computing has resulted in an explosion of systems that store, process, and network data, all of which are inherently electrical processes and none of which are 100% energy efficient. Fundamentally, the power architecture of a data center is that of multiple levels of series voltage down conversion from the sub-transmission level to the chip level. Data centers couple into the electrical infrastructure at the medium voltage level. However, the majority of energy is utilized at the 5V logic level, requiring multiple stages of conversion in which voltage is decreased and current is increased and at least one stage where AC is rectified to DC. Depending on where these conversion stages occur and how long routing distances are at lower voltages, this can lead to significant Ohmic losses, especially on the low voltage side where current draw can be significant.

2.3.2 Challenges

The needs for transitioning from a medium voltage interconnect (either AC or DC) to logic level voltages (5V) in an energy-efficient manner requires the use of high efficiency DC/DC and AC/DC converters. Additionally, the number of these conversion stages should be minimized as much as possible, which requires the highest conversion ratio for each stage that can be achieved. High conversion and low-loss converters require very fast switching, in the pseudo-radio frequency (RF) regime.

2.3.3 Innovation Pathways

High-voltage conversion ratios above ~4x are difficult for non-isolated converters. Achieving higher conversion ratios typically requires isolated topologies where very high conversion ratios can be accommodated using high frequency transformers. These isolated topologies (such as a dual active bridge) that can achieve high frequency switching operation simultaneously with high-voltage conversion are ideal pathways for future data centers. Medium voltage direct current (MVDC) applications utilizing multiple modules of these dual active bridge topologies can also achieve high voltage input with high current output via series input, parallel output (SIPO) circuit configurations.

Very high voltage ratio conversion in a single stage from MVDC to chip-level voltages is the highest efficiency configuration possible for a data center. However, the maximum conversion ratio is ultimately determined by voltage isolation at the high-frequency transformer. Achieving even higher voltage conversion ratios may require new high-frequency transformer designs or isolation methods. Additionally, to increase power density while simultaneously maximizing efficiency, the converter must operate at high switching frequency and little loss under all operational loading levels. Certain topologies may have difficulty in maintain zero-voltage or zero-current switching under all operational conditions, which may require either methods to ensure they remain in the low-stress switching regime (e.g., by altering the system to change their loading) or new switching algorithms that can extend this region.

The Advanced Research Projects Agency–Energy (ARPA-E) and other organizations have suggested that turning the distribution system inside of data centers from an AC-based system into DC-based system could significantly decrease total energy consumption by leveraging on-site DERs, reducing the number of conversion stages, and utilizing higher efficiency converters. The main goal of data center advancement is to make the data center more efficient while maintaining effectively zero downtime.

The use of DC distribution would allow for 1) DC lighting and loads to reduce conversion losses and 2) the coupling of on-site DERs, which could reduce the effective CO_2 emissions of data centers, enable higher reliability through microgrids, and allow for providing grid-support services during low-load conditions. Due to the large amount of power required for modern data centers, this DC-bus would most likely be at the MVDC level. This approach would require advances in DC protection and control.

2.3.4 Recommendations

As data centers continue to grow in number and energy consumption, driven by the rapid expansion of cloud computing, AI, ML, and the rise of digital communications, advancements in PEs will be crucial to meeting future energy efficiency and sustainability goals. The U.S. government can play a pivotal role in fostering the development and application of PEs in these critical areas by considering the following recommendations:

1 Promote R&D for developing high-efficiency power converters for data centers

High-efficiency converters with fewer conversion stages, including high-efficiency AC/DC and DC/DC converters with high voltage conversion ratios such as high-frequency transformers and isolated topologies like dual active bridges, will reduce energy losses in data centers, lowering overall power consumption as demand continues to grow.

2 Work with industry partners to explore a transition to DC distribution systems in data centers

A DC distribution system would improve energy efficiency and reliability in data centers, allowing them to contribute to grid stability without curtailing their use. This switch would need to be paired with improvements in DC protection and control technologies. Support for DC fault detection, isolation, and control systems will be essential to ensure safety and operational continuity through such a transition.

3 **Support the development of grid-interactive data centers**

Work with industry partners to develop WBG PE technologies that enable integrating data centers in a more flexible and responsive way, i.e., through microgrid configurations that leverage on-site DERs. Grid-interactive data centers will enhance grid reliability, provide additional revenue streams for data center operators, and reduce overall CO2 emissions by optimizing energy use.

4 **Develop efficiency metrics and benchmarks**

Establish industry-wide standards for PE performance in data centers, including efficiency benchmarks for power converters and energy metrics for facilities. Standardizing efficiency metrics and performance benchmarks will drive innovation and ensure that data centers implement the most energy-efficient solutions, accelerating progress toward sustainability targets.

5 **Increase partnerships & co-design opportunities with end-users**

Collaboration, especially with current and potential customers of WBG PE systems, will accelerate the development of advanced PE technologies that can be implemented in data centers, helping to meet the growing energy demands of digital infrastructure while improving sustainability.

By implementing these recommendations, the PE industry can help ensure that data centers and other digital infrastructure evolve to meet the increasing demands of modern computing while minimizing their environmental impact. Advancements in PEs will play a crucial role in improving energy efficiency, reliability, and sustainability in this critical sector.

2.4 Industrial Infrastructure

As the industrial sector transitions toward greater electrification to meet global sustainability goals, PE is emerging as a critical enabling technology. PEs serve as the backbone for converting, controlling, and managing electrical power across a wide range of industrial applications, including renewable energy integration, EVs, grid modernization, and hydrogen production. The adoption of WBG semiconductors, such as SiC and GaN, is accelerating this transition by offering higher efficiency, improved thermal management, and the ability to operate at higher voltages and frequencies compared to traditional Si-based devices.

In industrial applications, such as hydrogen production via water electrolysis, PEs are fundamental to achieving the necessary energy efficiency and cost reductions required for large-scale deployment. Electrolyzers, which are key to producing green hydrogen from renewable electricity, require efficient conversion of AC to DC. Innovations in PEs are critical for optimizing these processes and reducing the overall energy consumption of the industrial sector. As the demand for clean energy solutions continues to grow, the development and deployment of advanced PEs will be crucial for ensuring the industrial sector can meet its electrification and modernization goals.

DOE and other government agencies have an important role to play in supporting the PE industry as it develops the technologies and infrastructure necessary for this transition. Ensuring the U.S. remains a leader in PEs will not only strengthen the country's energy independence but also position it to lead in the global clean energy market.

2.4.1 Hydrogen Technologies in Industrial Applications

In sectors where electrification is difficult due to the need for high heat, such as in blast furnaces and kilns, hydrogen can serve as a direct replacement for fossil fuels. Additionally, hydrogen can be used as a feedstock in processes like ammonia synthesis, further broadening its potential applications in industrial settings. As the production of green hydrogen through renewable energy-powered electrolysis becomes more cost-competitive, the adoption of hydrogen as a clean alternative to fossil fuels is expected to accelerate, helping industries meet ambitious emissions reduction targets while ensuring energy reliability and security.

According to a roadmap by the Hydrogen and Fuel Cell Technology Office (HFTO),[46] clean hydrogen production is expected to increase to 10 million metric tons (MMT) by 2030 and 20 MMT by 2040. The production costs are also expected to reduce to $1 per kg by 2031. The onboard storage costs are expected to reduce to $9 per kWh (700-bar) by 2030 and delivery and dispensing costs are expected to be around $2 per kg by 2030.

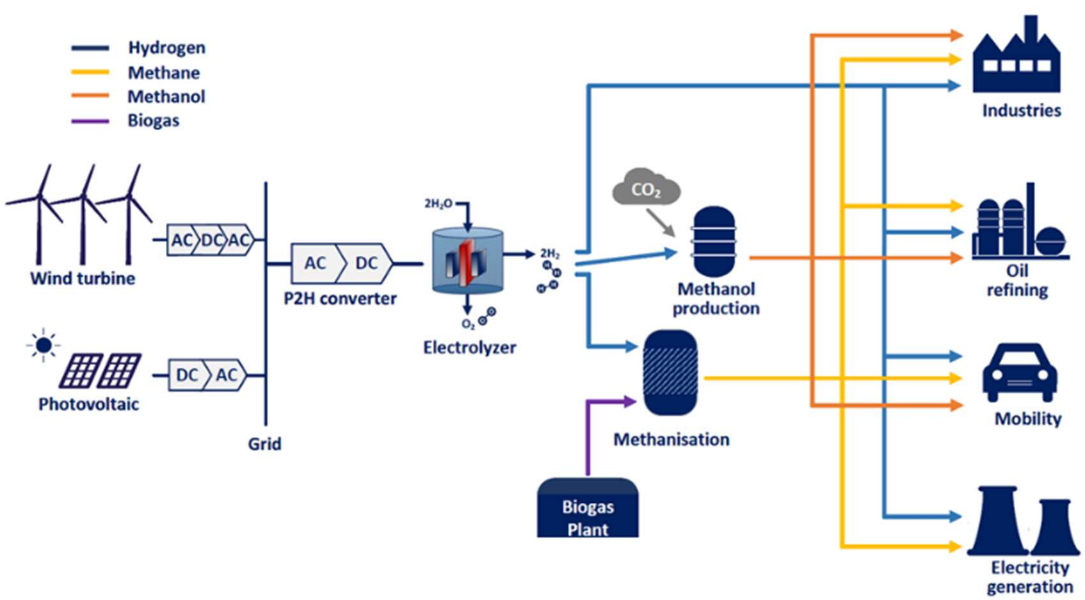

Figure 11. Architecture of power-to-hydrogen (P2H) with renewable energy input for industrial utilization[47]

Hydrogen can be produced at high purity utilizing water electrolysis but has high cost of electrolyzer and electricity, as well as low energy efficiency. The electrolyzers require a supply of DC voltage (ranging from tens to hundreds of volts) and DC currents (hundreds to thousands of amperes). To obtain DC power from an AC power grid requires the utilization of an AC-DC converter/rectifier. The rectifiers needed for this application require careful design with consideration of reactive power compensation due to power quality issues. However, they provide the advantage of adjustable DC output voltages by changing the firing angle. Other types of electrolyzers that use diode-based rectifiers can only provide fixed DC voltages dependent on the AC voltages requiring an additional DC chopper circuit.

2.4.2 Challenges

The main challenges for hydrogen technologies relate to the efficiency and the cost of the system. Efficiency can be achieved through improvement in device and converter technologies enabled by medium voltage WBG technologies such as 10kV SiC and upcoming device technologies such as UWBG devices, including Ga_2O_3. For hydrogen to be an enabler for energy transition at high energy volumes, the cost of the above-mentioned devices and the power conversion designs enabled by these devices must mature for the needs of the industry.

2.4.3 Innovation Pathways

To support adoption of hydrogen, it will be important to demonstrate active power conversion using WBG technology to replace conventional diode-thyristor based rectification at medium voltage scale at power levels in excess of 100kW.

2.4.4 Recommendations

1 Leverage demonstration projects for WBG PE in industrial applications

Demonstration projects can de-risk new technologies and provide real-world data that helps accelerate commercialization and adoption across the industrial sector.

2 Establish standards and guidelines for PEs in industrial applications

PE and industrial equipment manufacturers should work with industrial users as well as government and academic stakeholders to establish standards and guidelines for the application of WBG and UWBG devices in industrial settings. This includes creating frameworks for reliability testing, performance evaluation, and safety in mission-critical applications like hydrogen production and manufacturing processes. Standardization will reduce barriers to adoption by ensuring that new PE technologies meet the needs of industrial users and comply with regulatory requirements.

Through these strategic initiatives, the PE industry can ensure that electrification of the industrial sector happens quickly and efficiently, supporting both economic growth and environmental sustainability.

2 3 Focus Area 2: Materials and Devices for WBG PE

The purpose of the following section is to identify critical areas in research of semiconductor materials and devices expected to be key aspects of next-generation PE systems. **Error! Reference source not found.** presents a brief introduction to some key topics discussed in the following sections, along with a general framework for maturity and application space for each material system based on voltage class and Technology Readiness Level (TRL). The framework starts with higher-maturity materials like SiC and GaN, which are categorized as Established Materials and Devices. Following this, the framework will discuss Next-Generation Materials and Devices, which include Al(Ga)N and Ga_2O_3. This framework does not reflect cost, nor does it account for other performance parameters such as frequency range.

3.1 Silicon Carbide

Within the next decade, several performance and manufacturing gaps must be targeted to expeditiously maximize the modernization impacts of the SiC material system (see Figure 12).[48,49] Compared to Si-based devices, SiC systems offer faster switching capabilities and enhanced chip-level thermal conductivity, leading to increased system efficiency and reduced costs of the system passives and cooling. In addition, SiC MOSFETs are less prone to thermal runaway than Si IGBTs, possibly offering a reliability improvement in harsh operating environment applications, such as electrified transportation and other high-voltage motor drives. However, the lack of SiC-specific packaging strategies limits device operating temperatures to ranges similar to Si-based devices, thereby throttling one of the most promising aspects of SiC technology. Nevertheless, overall system performance and reliability can be increased while costs can be reduced by transitioning to SiC-based devices. Recently, 3.3 kV devices have been commercialized for a variety of power converter applications to increase system power density and efficiency. SiC MOSFETs will likely follow a natural progression of increasing voltage rating led by industry.

3.1.1 Challenges

Despite these advantages, SiC MOSFETs only claim a small portion of the commercial market. This is, in part, due to the higher associated device cost, which is a function of the growth and fabrication processes as well as the substrate size. These areas are under continuous improvement by industry and will naturally reduce costs over time. With a vested interest in increasing profits, SiC device manufacturers are the primary drivers of increasing wafer size and improving material quality (i.e., reducing the defect density and increasing yield). Consequently, these issues will not be discussed at length. However, in addition to industry, numerous research groups are working to address the device design related challenges required to achieve high-performance SiC MOSFETs and IGBTs. Such performance challenges related to device-level architectures are the primary focus of this section, which is divided into several thrusts: 1) improvement of the SiC MOSFET on-resistance for < 10 kV applications where it is primarily limited by the channel and substrate resistances; 2) an overview of > 10 kV architectures (i.e., IGBT and superjunction MOSFET) where the MOSFET on-resistance becomes problematic; and 3) advancing SiC-specific ion implantation techniques to reduce manufacturing costs.

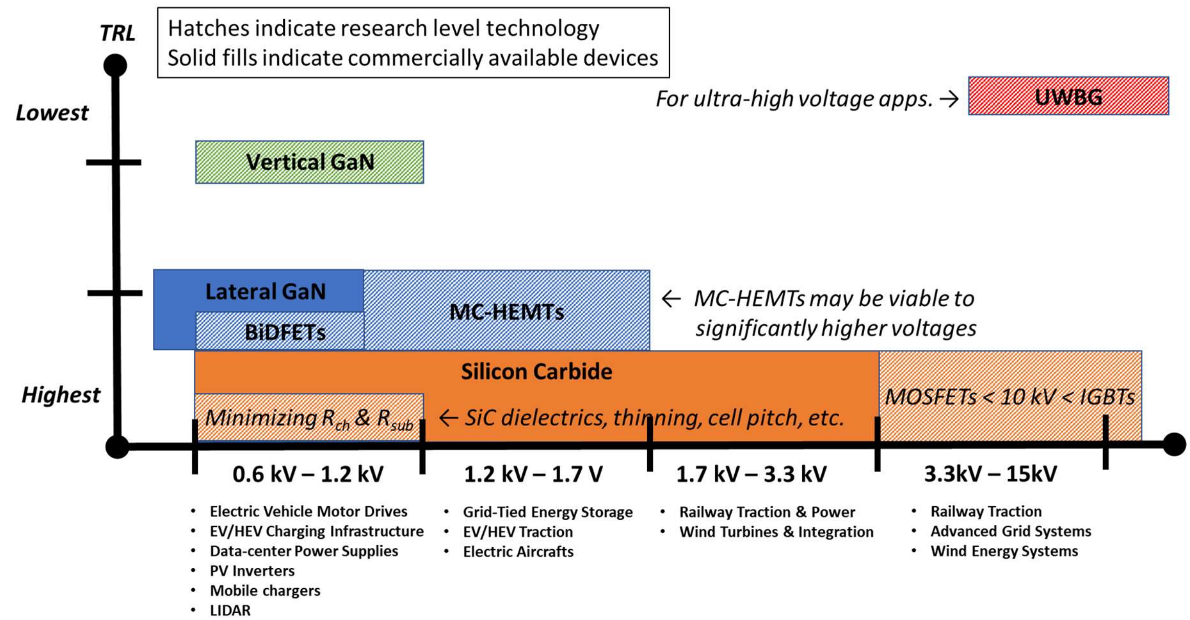

Figure 12. Technology maturity and application space chart for various material systems showing select highlighted research areas considered to be impactful

For 600 V – 1.7 kV SiC MOSFETs, key limiting factors in reducing on-resistance to increase on-state performance include the channel resistance (RCH) and substrate resistance (RSUB).[50] These resistances increasingly dominate the overall device on-resistance as the voltage rating is reduced. For n-type SiC, bulk mobilities of 600–1000 cm^2/Vs corresponding to doping levels of 10^{17}–10^{14} are common in the drift region. However, issues at the SiO_2/SiC interface reduce the effective channel mobility to around 25cm^2/Vs in SiC DMOSFETs and around 35 cm^2/Vs in SiC trench MOSFETs for practical doping levels.[51] While this parameter has been improved through various methods,[52,53] there is still substantial room for impactful improvement of the channel mobility. For either device type, this would enable a substantial reduction in device on-resistance at the 1.2 kV voltage class. These benefits become more pronounced as the voltage class reduces.[54] SiC substrates offer mechanical strength during the fabrication process but add extra electrical and thermal resistances. The typical resistivity of 4H-SiC substrates is in the range of 0.015–0.025 Ohm×cm^2 for a thickness of approximately 360 µm.

As the voltage rating increases, the on-resistance of a MOSFET increases proportionally and is dominated by the thickness of the drift region. This trade-off can no longer be ignored or accommodated in SiC beyond 10 kV[55] where the increased device on-resistance leads to excessive heat-dissipation and electrical losses in the on-state due to the drift region resistance. Furthermore, a simple scaling up of the device area to reduce the resistance leads to high chip costs and capacitances. Thus, device applications that rely on voltage ratings well beyond 3.3 kV would critically benefit from a less resistive device architecture. To this end, SiC-based IGBTs and superjunction MOSFETs could alleviate the performance degradation issues.[56,57]

An additional challenge to the materials costs facing the SiC industry is that of the relatively higher cost of ion implantation. Current ion implantation techniques require high-temperature implants that necessitate a time-consuming temperature ramp-up and ramp-down, which throttles manufacturing throughput.

3.1.2 Innovation Pathways

Pathway 1: Channel Mobility

Thermally deposited SiO_2 is universally used as the gate dielectric due to high reliability and ease of manufacturing. However, to overcome the low channel mobility issue, a paradigm shift in the gate dielectric may prove helpful. Although there have been many iterations on doping SiO_2,[58] there have been limited studies on atomic layer deposited (ALD) high-k dielectrics,[59,60,61] and research on laminate stacks is nearly non-existent. Further investigation of novel gate-dielectrics coupled with improved batch manufacturing of ALD dielectrics may prove fruitful for improving channel mobility without sacrificing device reliability. In addition, emerging device architectures with deeply scaled dimensions that rely on the FinFET effect have been shown to improve channel mobility by as much as 18-fold.[62,63,64] There have also been reports of devices that reduce on-resistance by increasing the channel density or providing additional current-carrying pathways, such as the IMOSFET and tri-gate MOSFET.[65,66] Nevertheless, it is important to note that demonstrated devices still have mobilities significantly lower than the bulk material and current SiC foundries do not operate at the necessary node sizes for sub-100 nm device features. Hence, further research into these architectures should parallel that of the gate dielectric material.

Pathway 2: Substrate Resistance

Grinding and polishing of the substrate is widely used to reduce both electrical and thermal resistance contributions of native SiC substrates by about 70%. However, this severely compromises the mechanical strength leading to yield issues from wafer breakage. Taking the research into a new direction, recent engineered substrates based on polycrystalline SiC with a bonded crystalline layer to facilitate epi-growth has been shown to reduce the substrate resistance by around threefold with less wafer deformation, enabling both mechanical robustness and low resistivity.[67] Additional research into the durability of devices on such wafers is of great interest, as well as research into other engineered substrate types.

Pathway 3: Superjunction MOSFETs

For superjunction MOSFETs, increased control during manufacturing over the doping precision and width of the n- and p-pillars to achieve < 10% charge imbalance and novel methods for forming deep pillars are required for > 10 kV devices.[68] Due to this requirement, superjunction MOSFET designs at these voltages are challenging. The repeated implant epi-growth method used for Si-based devices would require over 30 cycles for 10 kV class SiC-based devices, making this method impractical. For implanted devices, as the required implant depth increases, so too does the energy and the associated damage to the SiC material, resulting in performance and reliability concerns. Both the pillar width and doping precision difficulties must be handled for commercialization of such devices. Hence, there is a desire for research in the direction of advanced implantation schemes like channeled implants, as well as sidewall implantation to reduce associated damage while maintaining a high degree of dose precision.[69,70] Alternatively, a revolutionary advancement of the trench-refill technique enabling precise charge balance may lead to commercial viability of such devices.

Pathway 4: IGBTs

In recent years, improved epitaxial growth quality of the drift region layer and a reduction in carrier lifetime killers has increased the ambipolar carrier lifetime from < 1 μs (as-grown) to over 30 μs, a requirement for 10–30 kV class IGBTs with low conduction losses.[71] However, as the carrier lifetime increases, the modulation frequency decreases. In addition, the resistance contribution of p-type substrates to the overall device on-resistance is significant, and there are limited commercial offerings. Hence, for SiC IGBTs, studies on the performance trade-offs associated with these devices coupled with bespoke device architectures and methods for producing large diameter, low-resistance, and low-defect density p-type substrates are necessary to rapidly commercialize. Flip-wafer IGBTs utilizing an n-type substrate were reported as an alternative approach to p-type substrates.[72] However, for such devices, foundry efforts must be made to develop a mass manufacturable fabrication process. For either substrate type, the turn-on voltage of SiC devices is roughly 2V higher than their Si-based counterparts, leading to comparatively higher power losses in the on-state for the same current level. This, in conjunction with the ambipolar carrier lifetime consideration, leads to a design trade-off between faster-than-Si switching times and extremely high conductivity modulation to minimize losses.[73] Considering this trade-off, further application-specific research into IGBT architectures that minimize either the switching or conduction losses is of great interest. To address the relatively high p-type substrate resistance, research toward improved doping methods, dopant activation, hole mobility, or techniques like waffle patterning to reduce substrate resistance are desired.

Pathway 5: Room-Temperature Implantation

Room-temperature ion implantation is needed to reduce manufacturing costs; however, limited research on the topic exists.[74,75,76] Further research on this process and the resulting device characteristics could reduce SiC chip cost.

3.1.3 Recommendations

1 Develop novel gate dielectric approaches for SiC devices

For 600–1700 V class SiC MOSFETs, channel and substrate resistance inhibit these devices from reaching their theoretical maximum performance. Novel gate dielectrics including high-k materials and laminate stacks, which are ubiquitous in modern Si technology, are a relatively unexplored pathway for improving the quality of the dielectric-SiC interface.

2 Develop SiC IGBTs for high voltage applications

For future applications that would benefit from devices with a voltage rating of 10 KV and higher, like advanced grid systems, wind energy, and railway traction drives, development of SiC IGBTs is critical. Low-resistance, low-defect p-type substrates are needed for these devices.

3 Develop SiC superjunction MOSFETs for high voltage applications

In addition to IGBTs, SiC superjunction MOSFETs would also enable 10 kV+ applications. Various approaches to fabricating a SiC superjunction drift region have been investigated using epitaxial regrowth, trench etching, and ion implantation processes. Continued investment in alleviating the fabrication difficulties and improving manufacturability can help.

4 Reduce material costs for SiC technologies

Despite clear performance and reliability advantages over Si-based PE, SiC adoption continues to be slowed by its significantly higher costs compared to Si and even GaN technologies. Development and integration of process innovations to lower the costs and increase the yield of SiC device manufacturing will significantly improve market adoption.

SiC MOSFETs are continuously expanding their market share in electrified transportation and industrial motor drive applications and are expected to be a key enabling technology of grid-based inverters as the voltage class of commercialized components continues to increase. SiC devices and power modules offer not only the opportunity to reduce our nation's carbon footprint, but also significant systems-level cost savings due to reduced size, weight, and increased power density. If these challenges are addressed, SiC technology will provide significant benefits in the areas of carbon reduction, energy efficiency, and system-level costs across the application sectors of electrified transportation, the electrical grid, and industrial motor drives.

2.1 Gallium Nitride

GaN has higher-saturation electron drift velocity, electron mobility, and a lower dielectric constant than both Si and SiC. These features of GaN facilitate faster switching speeds and low conduction losses.[77,78] In addition to performance benefits, GaN-on-Si has potential to reduce overall system costs when compared to SiC. While SiC devices currently have smaller dies than GaN, yielding more chips per wafer, this attributes to only part of the total cost.[79] SiC substrates account for 50% of device cost, while GaN devices are often grown on standard and readily available Si substrates.[80,81,82,83] Additionally, SiC devices generate a larger carbon footprint during fabrication, attributed to high-temperature processing.[84] In addition, the transparent substrates necessitate specialized metrology equipment.[85]

GaN technologies have implications across a broad range of industries. With the high switching speeds and low losses of GaN-based wall chargers, GaN has already solidified itself as a leading material in lower-power markets.[86] In 2022, a GaN-based charger made through a collaboration between Anker and Infineon achieved 21% lower loss compared to Si-based counterparts with a 53% reduction in size.[87,88] High-frequency switching and low parasitic loss make GaN an excellent candidate to improve system-level power density and efficiency in on-board charging applications.[89,90] As inverters for photovoltaics, the two-dimensional electron gas (2DEG) channel of GaN transistors allows them to behave in the reverse direction like a conventional diode, eliminating the need for an additional freewheeling diode.[91,92] This enables a single-stage inverter instead of the conventional two-stage inverter, reducing costs and lending a smaller form factor. In server and telecom applications, currently dominated by Si-based superjunction devices,[93] GaN is predicted to represent almost 45% of the total market by 2028 according to Yole group.[94] GaN transistors can also be configured as bidirectional switches, which are used for overvoltage protection, switching circuits with multiple power sources, and high side load switches. Commonly, two n-type Si MOSFETs in common source connection form the switch (Figure 13).[95,96,97] The 2DEG channel of a GaN HEMT is current bi-directional. In 2022, Innoscience Technology announced their Bi-GaN series of bi-directional GaN HEMTs. One Bi-GAN replacing back-to-back MOSFETs reduces on-state resistance by 50%, chip size by 70%, and temperature rise by 40%.[98]

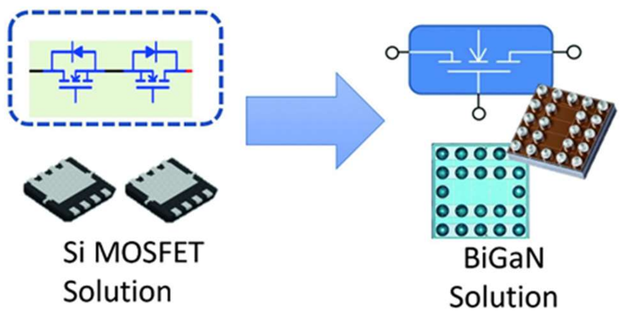

Figure 13. Innoscience BiGaN can replace two back-to-back Si MOSFETs[99]

3.1.4 Challenges

Despite the advantages of GaN, the material system is several steps behind SiC in terms of achievable power levels and standardization, hindering its integration in several real-world applications.

Commercially available power GaN is based on lateral transistors and is successful due to the incredibly fast 2DEG channel that forms at the interface between GaN and AlGaN. The 2DEG channel of GaN HEMTs forms spontaneously without external gate bias resulting in normally-on depletion-mode devices that require a negative gate voltage to cut-off the channel and turn off the transistor. As lateral devices, GaN HEMTs are voltage limited by gate-to-drain spacing. The device size necessary for higher blocking voltages results in increased on-resistance, chip real-estate, and production costs, effectively limiting the usefulness of HEMTs to low-voltage applications (<650 V). Because of the voltage limitations imposed by lateral architectures, commercial adoption of GaN has lagged SiC MOSFETs outside of mobile charging applications. To compete in EV and power grid applications, the voltage capabilities of GaN must extend to 1.2 kV and beyond. Vertical GaN transistors have the potential to operate at higher voltages but have a low technology level readiness and high cost, largely due to the challenges associated with GaN substrates. While the primary challenge for vertical GaN is cost, another concern relates to the performance advantage of GaN over SiC. Recent reports on WBG material characteristics suggest that the advantage in unipolar figure-of-merit (UFOM) for GaN over SiC is less than what was thought a decade ago (Figure 14). Early reports on the UFOM reported a favorable outlook for GaN,[100] while a recent updated UFOM from Kaplar[101] showed little advantage for GaN over SiC. Even when comparing the aggregate of data reported for SiC and GaN from Cooper,[102] there appears to be a negligible performance difference between the two. Based on this, it becomes evident that for UFOM-limited devices, GaN may offer little or no advantage over SiC. In addition, differences in how these materials behave can further compound the challenge in reaching the theoretical performance limit of vertical GaN. For example, currently there are significant challenges in selective area doping for GaN, and no processes yet for self-aligned ohmic contacts analogous to the silicide process in SiC. Both challenges have a direct negative impact on cell pitch, and every disadvantage pushes the technology farther from the theoretical limit.

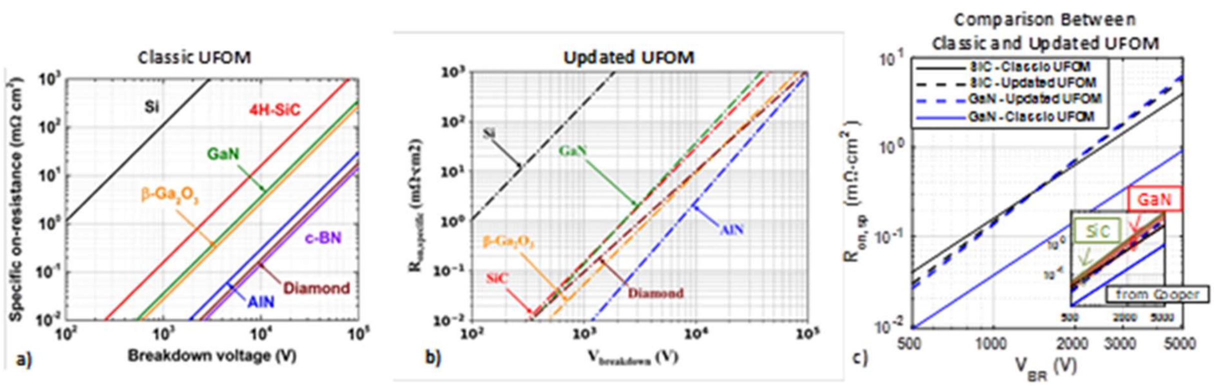

Figure 14. Comparison of various unipolar figure-of-merit (UFOM) plots: (a) “classic” plot,[103] which shows an incredibly favorable outlook for GaN, (b) an updated UFOM,[104] and (c) direct comparison between the classic and updated UFOMs[105]

The other major hurdle confronting GaN HEMTs is a lack of a standard structure. Most applications require power switches to be normally-off or enhancement-mode (e-mode). SiC MOSFETs operate in e-mode and are controllable with +15/-5V gate standards imposed by IGBT devices, easing adoption in applications occupied by Si.[106] There are two avenues to normally-off GaN: 1) the cascode structure, where a low-voltage Si MOSFET is used to modulate the gate of the GaN HEMT, and 2) e-mode HEMTs with a modified gate structure. Cascode GaN is favored by industry for safe threshold voltages (2.5-4 V), automotive grade ratings, and standard gate drivers. However, the Si MOSFET in the cascode structure increases the achievable on-resistance and introduces significant switching loss.[107,108] This makes cascode GaN particularly difficult to use in hard-switching applications like motor drive.[109,110,111,112] The alternative to the cascode structure is e-mode HEMTs with gate architectures that are modified to reduce the charge density of the 2DEG channel to yield a positive threshold voltage. The threshold voltages of e-mode HEMTs are still quite low (1-2 V) and often require a negative gate drive that causes additional power loss and design challenges. Diverse packaging and gate drive solutions add complexity to industry adoption of e-mode HEMTs.

A significant supply chain issue affecting all gallium (Ga)-based devices is the United States' dependence on the foreign supply of Ga with China accounting for 98 percent of the world's raw supply.[113,114,115] In July 2023, China's Ministry of Commerce announced plans to impose new restrictions on exports of Ga. These measures went into effect in August and require exporters to request a government license explicitly naming the end users.[116] The new Ga export controls will likely have major economic implications in the United States. A 2022 analysis by U.S. Geological Survey (USGS) found that a 30% supply disruption of Ga could cause a $602 billion decline in U.S. economic output, or 2.1% of GDP.[117,118] In addition, impacts on industrial production could cause major setbacks for defense firms as many of the U.S. military's key suppliers of GaN chips rely on revenue from sales to civilian customers [36]. However, while export controls could likely have major economic implications in the United States, new policy in China is unlikely to kill the Ga supply.

Chinese efforts to develop Ga-based chips are aimed at leapfrogging the United States, Europe, and Japan. As the semiconductor industry shifts from Si to Ga, China is preparing to take the lead position accounting for over 40% of all related patent applications between 2019 and 2020 (compared to 23% for the United States).[119]

3.1.5 Innovation Pathways

Pathway 1: Gallium sourcing and domestic GaN HEMT manufacturing capacity

Dependence on foreign sources of Ga and overseas mature node Si foundries for GaN-on-Si capacity are both economic and national security risks. Improving GaN HEMT device performance is a risk to the large investment already made in SiC devices. These supply chain issues must be addressed to mitigate the risks associated with ever-improving GaN devices.

Pathway 2: Optimization and standardization of single-channel HEMTs

Single-channel GaN HEMTs trail SiC devices in terms of TRL level. This is partly due to the different approaches being taken to achieve normally-off operation. Further development of e-mode GaN HEMTs to achieve robust operation would mitigate the need for a cascode topology while improving performance. Alternatively, optimization of cascode GaN to reduce on-resistance and switching losses could expand adoption in new applications.

Pathway 3: Polarization Super Junction and Multi-Channel HEMTs

Like SiC, a charge balanced drift region has also been proposed for GaN HEMTs that reduces the on-resistance of the device for a given breakdown voltage. In the polarization super junction (PSJ) concept, either two-dimensional gas charge (electrons and holes) or ionized doping (n-type and p-type) within the heterostructure are balanced to flatten the electric field profile within the drift region thus improving the figure of merit.[120] Another method to improve the figure of merit is the multi-channel HEMT (MC-HEMT), which integrates multiple vertically stacked 2DEG channels. The multiple channels of MC-HEMTs allow for much higher total carrier densities without impeding mobility. This results in excellent on-resistance for a wide range of blocking voltage classes up to 10 kV and a FOM that exceeds the SiC material limit.[121] Traditional planar gates used in single-channel HEMTs are unable to deplete the multiple channels of MC-HEMTs due to field shielding from the topmost channels and distance from the lower channels.[122] The result is very negative threshold voltages and early breakdown of the gate.[123] Three-dimensional or FinFET gate architectures can more effectively modulate the gate and have been used to demonstrate positive threshold (Vth=1.8 V) e-mode operation. The fin width must be extremely narrow (15 nm) to realize threshold values in this range, which is an unrealistic expectation for industrial scale manufacturing.[124,125] An alternative approach to e-mode MC-HEMTs was demonstrated in 2021 using an integrated Cascode structure.[126] The structure, called Multi-Channel Monolithic-Cascode HEMT (MC2-HEMT), monolithically integrates a high-voltage MC-HEMT and low-voltage single-channel HEMT in a Cascode connection. MC2-HEMTs relax the lithography requirement presented by fin-gate architectures. This is the first report of e-mode operation in 3kV+ GaN devices and has set a new record in Baliga's FOM for medium-voltage transistors.

Traditional AlGaN based barriers are lattice mismatched to GaN and introduce strain. In MC-HEMTs, the lattice-mismatch effectively limits the total number of channels. InAlN barriers present an interesting opportunity, as it can be lattice-matched with GaN and in principle enable the growth of as many channels as desired without strain-related issues or cracking.[127,128] In the case of FinFET gate architectures, the number of channels would then be limited only by the minimum stack height necessary to facilitate fabrication of the narrow trenches. To this point, the larger polarization fields of InAlN or AlN barriers can achieve larger carrier densities with reduced stack thickness.[129] If the number of channels is unrestricted, it would enable devices with an on-resistance that is arbitrarily small.[130] Developments in Metal-Organic Chemical Vapor Deposition (MOCVD) growth of InAlN and AlN barriers in MC-HEMTs, particularly improvements in channel mobility and growth quality, have tremendous potential to further the already impressive qualities of MC-HEMTs.

Pathway 4: Vertical GaN Device Architectures

Vertical architectures enable much higher voltage ratings by increasing the drift layer thickness without enlarging the device size. While some companies claim to be able to manufacture vertical normally-off GaN transistors, they are not commercially available. The primary hurdle is the cost of native substrates. Compared to SiC, GaN wafers are not yet competitive in terms of cost ($100/cm^2 for 2-in GaN wafers compared to $10/cm^2 for 4-6 in SiC) and quality (dislocation densities of 10^4-10^6 cm^{-2}).[131,132,133] Engineers at Nagoya University, Japan have demonstrated vertical GaN diodes grown by hydride vapor-phase epitaxy (HVPE), a technique conventionally used to grow free-standing GaN substrates.[134] They estimate a switch from MOCVD growth to HVPE has the potential to yield a near sevenfold reduction in total manufacturing costs if reactors can be developed for high-volume manufacturing.[135]

Vertical GaN-on-Si can dramatically reduce material costs and enable large-area processing.[136,137] The difficulties of epitaxial growth of thick layers on foreign substrates has led to much of the research of vertical GaN-on-Si to focus on quasi-vertical structures with thin drift layers and low breakdown voltage.[138,139] The first fully vertical GaN-on-Si MOSFET was demonstrated in 2019 with a 520 V blocking voltage.[140]

Regardless of substrate, recent analysis has questioned the performance advantage of a unipolar vertical GaN device relative to SiC.[141,142] Demonstration of an actual advantage, either theoretically or experimentally, is needed to validate vertical GaN as viable pathway.

3.1.6 Recommendations

1 Increase domestic GaN supply chain presence in the United States

The ease of manufacturing GaN-on-Si wafers within Si foundries has resulted in significant GaN foundry capacity outside of the United States. GaN foundries within the country should be supported to ensure competitiveness in this material system.

2 Increase operational voltage ranges for GaN devices

To compete in EV and power grid applications, the voltage capabilities of GaN must extend to 1.2 kV and beyond while maintaining competitive on-resistance and cost. Vertical architectures can serve to improve the voltage capabilities of GaN. Polarization super junction (PSJ) and multi-channel (MC) HEMTs are promising approaches for extending the voltage range of lateral single-channel HEMTs by providing excellent on-resistance for a wide range of blocking voltages. These innovations have the potential to reframe GaN from a low-voltage material to one that competes with SiC in medium- and high-voltage power applications.

GaN HEMTs have established a niche in mobile charging and are predicted to take significant space in server and telecom applications in the coming years. Additionally, the bi-directional nature of the 2DEG channel enables unique opportunities for single-stage inverters and improved bi-directional switches. However, application of GaN devices at voltages greater than 650V requires innovations at the device level.

3.2 Ultrawide Bandgap Materials: Aluminum Gallium Nitride and Aluminum Nitride

AlN has a bandgap of 6.0-6.2 eV (depending on the reference), placing it at the high end of the UWBG semiconductor bandgap range, resulting in commensurately higher breakdown electric field in the 10-15 MV/cm range (similarly, depending on the reference and method of evaluation).[143,144] A recent analysis that expands upon the unipolar FOM approach indicates that AlN has the lowest specific on-resistance for a given breakdown voltage among several UWBG semiconductors (Figure 15).[145]

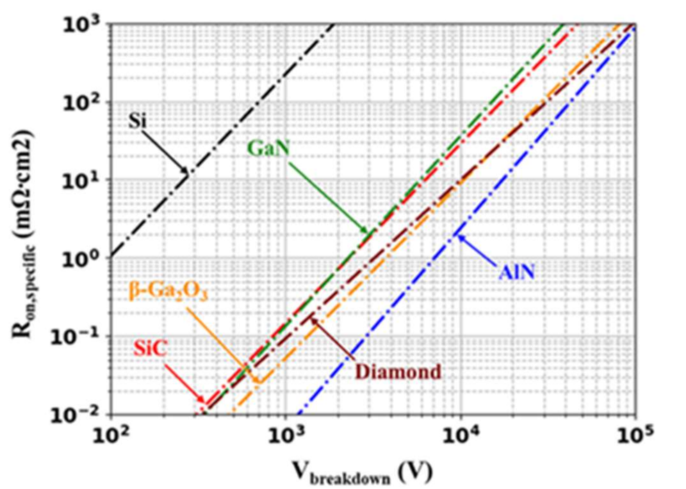

Figure 15. Calculated unipolar figure of merit lines for Si and several WBG and UWBG semiconductors[146]

AlN also has reasonable electron mobility (~425 cm^2/Vs) and good thermal conductivity (~320 W/m-K).[147] In addition, UWBG nitride semiconductors may be alloyed (e.g. AlGaN), allowing for great flexibility in device design, including the formation of heterostructures and graded-composition structures. In general, heterostructure-based devices have lateral geometries similar to traditional AlGaN/GaN HEMTs, although details such as layer compositions and thicknesses may vary significantly. Structures with continuously graded regions rather than abrupt heterojunctions are also possible. Much progress has been made in recent years on the fundamental building blocks of such devices, such as low-resistivity Ohmic contacts (discussed below) and positive threshold gate structures, and a key challenge now is to effectively combine these pieces.

3.2.1 Challenges

It is critical to continue experimental validation of the key material parameters, such as mobility, thermal conductivity, and the impact ionization coefficients / critical electric field, and their dependence on factors such as alloy composition (to be discussed below), doping, and temperature. The predicted performance metrics such as shown in Figure 15 sensitively depend on these.

AlN substrates are readily available at price parity with 2 in. diameter GaN substrates, and 4 in. diameter AlN substrates are being sampled; however, the substrates are insulating, which limits vertical device architectures. No true vertical Al-rich, AlGaN power devices have been demonstrated; rather, they are limited to quasi-vertical structures with the cathode contact on the top surface of the wafer laterally displaced from the main portion of the device. Such quasi-vertical devices are ultimately not viable due to the additional resistance of the lateral transport path.

Key challenges for Al(Ga)N can be grouped into the following categories: 1) doping and contacts, 2) gate dielectrics, and 3) novel/virtual substrates.

Historically, n- and p-type impurity doping is challenging for Al-rich nitride materials. However, significant progress has recently been made in this area. The UWBG nitride semiconductors may be alloyed (e.g., AlGaN), allowing for great flexibility in the formation of heterostructures and graded-composition structures. This, coupled with the polar nature of these materials, allows them to be polarization-doped, providing a means to circumvent the difficulties with impurity doping common to all UWBG materials to achieve both n-type[148] and p-type[149] conductivity. Such properties have resulted in very impressive results for Al-rich AlGaN heterostructure-based devices. A comprehensive review of AlGaN-channel transistors is provided in the review article "Al-rich AlGaN based transistors".[150] The formation of Ohmic contacts on Al-rich AlGaN (and other UWBG semiconductors) has also historically been a challenge, due to the high barrier heights of most metals on the semiconductor.

UWBG semiconductors inherently have challenges with integrating gate dielectrics that exhibit low leakage and high capacitance. Bandgap and dielectric constant for dielectrics are inversely proportional, leading to lower dielectric constant films at higher and higher bandgaps. This poses a challenge, as a dielectric needs a sufficiently high-band offset from the semiconductor to suppress leakage. At the same time, a high dielectric constant is required for MOS devices to get sufficient channel inversion (gate capacitance).

There are several suitable substrates for laterally conducting transistors (HEMTs, polarization-doped field effect transistors [POLFETS], metal-semiconductor field-effect transistors [MESFETs], etc.) including commercially available AlN substrates, SiC, Si, and sapphire. However, SiC and AlN offer significantly higher thermal conductivity but are more costly. Unfortunately, realizing vertically conducting device architectures is a significant research challenge that has not been resolved. The insulating nature of AlN substrates precludes the typical approach of using conducting, native substrates. While vertical device structures using n-SiC are possible, the combination of several micron thick AlGaN device layers and the mismatch in the coefficient of thermal expansion (CTE) results in highly cracked films. In addition, while conducting GaN substrates are commercially available, the smaller lattice constant of UWBG AlGaN epilayers results in highly tensile strained films and highly cracked films.

3.2.2 Innovation Pathways

Pathway 1: Experimental validation of material parameters

The experimental validation of the key material parameters must be continued, as the predicted performance metrics such as those shown in **Error! Reference source not found.** are strongly dependent on these parameters.

Pathway 2: Novel/Virtual Substrates

AlN substrates are insulating; thus, new approaches (e.g., epi-layer liftoff/substrate removal, heteroepitaxy on strain relief patterned substrates, conductive substrates) are required to realize vertical device architectures based on Al-rich AlGaN materials. However, Al(Ga)N may be grown on non-native substrates such as sapphire and SiC, making it compatible with existing processing lines and providing an advantage in terms of manufacturability compared to other UWBGs. For example, AlGaN-based ultra-violet light emitting diodes (UVC-LED) are in commercial production in the United States, Europe, and Asia, demonstrating manufacturability of high Al content AlGaN alloys that would be used in UWBG AlGaN power devices.

Pathway 3: Doping and Contacts

For n-type doping in AlGaN, the Si dopant becomes deep for Al compositions greater than approximately 85%, and compensation effects can significantly influence the free carrier density. Si ion implantation followed by annealing has been successfully used to achieve shallow n-type dopants (70 meV) in near-surface regions.[151,152] Further, metal-modulated epitaxy (MME, a variant of MBE) has been utilized to achieve Si doping of bulk AlN films.[153,154] Perhaps even more significantly, MME has been used to achieve p-type conductivity of AlN using Be doping,[155,156,157] which is an alternative to the standard Mg doping in nitrides (Mg has an activation energy of 500-600 meV in AlN, compared to 37 meV estimated for Be). These approaches to doping have resulted in the demonstration of AlN p-n diodes. A key advantage of AlGaN compared to other UWBG semiconductors is that as an alternative to impurity doping, compositional grading can be used to induce conductivity via polarization, which has successfully been utilized to demonstrate both n-type[158] and p-type[159] conductivity and a variety of devices such as polarization-doped field-effect transistors.[160,161] Significant progress related to contacts has also been made in the past few years, primarily through the use of grading from Al-rich to Ga-rich material and very high n-type doping concentrations. For example, recent work utilizing regrowth has resulted in specific contact resistivities in 10^{-6} - 10^{-7} Ohm cm^2 range,[162,163,164] which is an improvement of several orders of magnitude compared to work published several years earlier and compares favorably to the resistivity of ohmic contacts to conventional GaN-channel HEMTs.

Pathway 4: Gate Dielectrics

More research is required to identify the best dielectric thin films that optimize the tradeoff between band offset and dielectric constant. These dielectrics also have other uses in AlGaN-based devices. For example, a high-breakdown electric field of 8.5 MV/cm has been demonstrated in a $BaTiO_3/Al_{0.58}Ga_{0.42}N$ heterostructure.[165]

3.2.3 Recommendations

1	**Develop processes for reliably producing AlGaN on virtual substrates for PE applications**

The ability to grow AlGaN on non-native substrates such as sapphire and SiC using industrially relevant processes is a significant opportunity to create devices that leverage this UWBG material system. Focused R&D on leveraging known processes and developing new devices made with them for high-voltage applications could accelerate the expansion of PE technologies into higher voltage ranges.

2	**Innovate on device designs that leverage AlGaN characteristics for high-voltage applications**

The unique characteristics of the Al(Ga)N material system offer the potential for high performance, high voltage devices. Increasing the understanding of processes critical to device architecture and fabrication such as doping, contacts, and dielectrics will allow practical devices to be conceived and developed.

3 Identify optimal gate dielectrics for use with AlGaN

The development of gate dielectrics for UWBG semiconductors presents unique challenges due to the tradeoff between band offset and dielectric constant. UWBG materials in general will benefit from the development of advanced gate dielectrics suitable for use with these material systems.

In summary, Al(Ga)N is a promising UWBG semiconductor that builds upon more mature GaN technology.

3.3 Ultrawide Bandgap Materials: Gallium Oxide

β-Ga_2O_3 stands out with an UWBG of nearly 5 eV,[166] with a higher breakdown electric field (8 MV cm^{-1})[167,168] and improved Baliga's figure of merit (BFOM).[169,170] This unique combination has sparked enthusiasm in power devices with a potential to outperform SiC and GaN. Advancements in materials synthesis and design optimization are now essential for large-scale production. Being the only WBG material grown from a melt,[171] β-Ga_2O_3 enables cost-effective production with exceptional crystalline quality compared to (bulk) GaN, SiC, AlN, and diamond. Besides cost effectiveness, theoretical calculations indicate roughly three times higher R_{ON}*Q_{OSS} and R_{ON}*E_{OSS} compared to 4H-SiC, and approximately 1.2 times higher than GaN,[172] where R_{ON} is on-resistance, Q_{OSS} is output charge, and E_{OSS} is output energy.

Figure 16 shows an example of one such device, a vertical transistor employing a p-type oxide layer to form a junction field-effect transistor (JFET) or an extreme high-*k* dielectric layer to form a MOSFET.[173] Detailed understanding of the interfaces in β-Ga_2O_3 based heterostructures can further improve device performance by controlling the deleterious effect of interface recombination and misfit dislocation on the device transport properties. Demonstrated Ga_2O_3 device types include Schottky barrier diodes,[174,175,176] NiO and $NiGa_2O_4$ heterojunction p-n diodes,[177,178] lateral δ-doped[179,180] and modulation doped FETs,[181,182] including those with β-$(Al_xGa_{1-x})_2O_3$ heterojunctions, and HEMTs.[183]

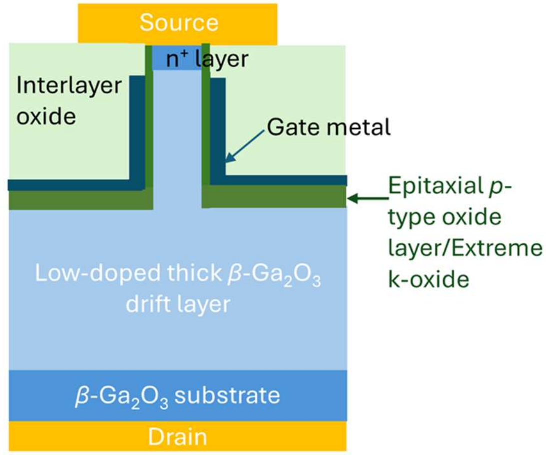

Figure 16. Schematic of vertical β-Ga_2O_3 based transistor[184] employing an integrated epitaxial p-type layer (JFET) or an extreme k-dielectric oxide (MOSFET) towards > 5kV breakdown voltages

3.4.1 Challenges

Despite the potential for high performance, challenges exist for economically viable β-Ga_2O_3-based power devices in real-life power switching applications. The notably low thermal conductivity (eight times lower than bulk GaN and around 30 times lower than SiC)[185,186] necessitates extensive research into better thermal stability of the Ga_2O_3 device interfaces, and new heat removal techniques and wafer thinning, especially as Ga_2O_3-based devices are expected to have significantly smaller die size. The next challenge is to enable normally-off operation and avalanche dielectric breakdown by functional p-type doping and full active layer depletion, achieved through heteroepitaxial growth and/or heterogeneous integration. The absence of native p-type doping[187] of Ga_2O_3 requires novel approaches to overcome this fundamental limitation. Finally, large-area substrates with different orientations and thick low-doped epitaxial layers are needed for circuit and application demonstrations (Figure 17). Advances in MOCVD and HVPE are expected to yield improved epitaxial growth rates and thicknesses while maintaining low unintentional doping concentration and high mobility. Advances in bulk growth will yield large-area (010) oriented gallium oxide wafers. Commercialization of very high voltage gallium oxide devices for advanced energy distribution, grid-tied storage, and heavy vehicle drive applications requires thick and homogeneous drift layers to be manufactured at scale. High epitaxial growth rates and large-area substrates are both necessary for large-scale deployment. An additional challenge is the need for controllable low n-type doping (~1×10^{15} cm^{-3}) to achieve high breakdown voltages.

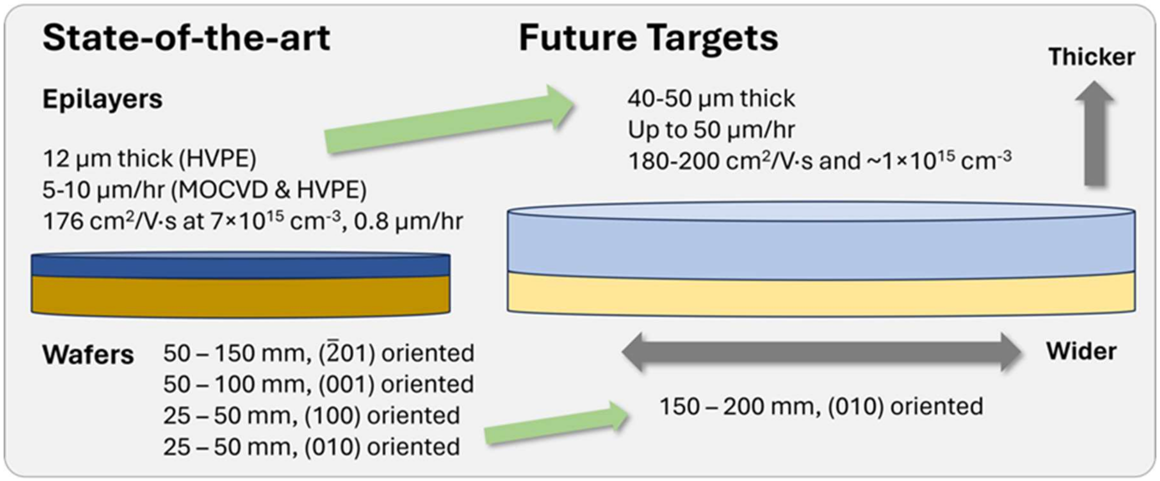

Figure 17. Advances in Ga_2O_3 epitaxy and bulk growth are both necessary for large-scale deployment

3.4.2 Innovation Pathways

Pathway 1: Ga_2O_3 bulk crystal growth

Advances in bulk growth, including Czochralski (CZ), edge-defined film-fed growth (EFG), and vertical Bridgman techniques[188] are expected to scale substrates from the currently commercially available 100 mm, through the 150 available in R&D stage, and eventually to 200 mm diameter[189] in the (010) orientation required for large-scale commercialization. A key aspect of this effort will be sourcing suitable crucible materials and extending their working life, as many bulk growth techniques currently utilize rare and expensive elements such as Ir, Rh, and Pt,[190] and since Ga itself has been recently emphasized as a critical element by DOE.

Pathway 2: Ga_2O_3 epitaxy

Advances in MOCVD[191] and HVPE[192,193] are expected to address the need for high Ga_2O_3 growth rates and low doping, enabling economical production of 40 - 50 μm thick layers.

Pathway 3: Novel approaches to p-type doping

Controllable and reproducible heterostructural[194,195,196,197,198] or iso-structural alloying to tune the valence band of β-Ga_2O_3 to promote shallow acceptor doping is required to achieve p-type conducting β-Ga_2O_3 (with p ~10^{17} -10^{20} cm^{-3}).[199] Material exploration can also focus on heterogenous integration to achieve developing novel lattice-matched p-type materials that can be epitaxially integrated to n- β-Ga_2O_3.[200,201,202,203]

Pathway 4: Extreme permittivity dielectrics

Advances in extreme permittivity oxide dielectrics with breakdown strength higher than β-Ga_2O_3 to enable breakdown fields approaching the theoretical limit in β-Ga_2O_3 are required to achieve high performance devices as outlined in the section on dielectrics for UWBG devices.

Pathway 5: Thermal management

Advances needed in semiconductor material science include thermodynamically stable and electrically conductive interfacial modifications[204] that would prevent reaction and interdiffusion of adjacent layers up to 400-600 °C junction temperature. Progress is also required in development of high-temperature package components such as metalized ceramic casing, as well as electrically insulating epoxies and electrically conducting solders that can withstand 200-400 °C package temperature. Aggressive thermal management solutions, such as double-sided water cooling or single-sided water ethylene glycol cooling are needed.[205] Potentially attractive options to improve the reliability include elimination of some of the packaging layers to minimize the number of high thermal resistance and low-reliability interfaces and moving from wire-bonded to wire-free packaging solutions. Device removal from the native Ga_2O_3 substrate and high-yield transfer on the foreign support with high thermal conductivity may be also beneficial.[206]

3.4.3 Recommendations

1 Improve and scale up Ga_2O_3 manufacturing processes for high voltage applications

Ga_2O_3 ranks highest among the emerging UWBG materials for TRL, with commercially available 100 mm diameter substrates grown from melt and epitaxial thin film growth demonstrated by techniques including high-throughput HVPE and MOCVD processes. Continuing to improve and scale up manufacturing processes to yield large-area Ga_2O_3 wafers and epitaxial growth rates exceeding 10 μm/hr are critical to unlocking the commercial potential of this UWBG material and enable a new option for PE technologies in higher voltage applications.

2 Develop doping approaches and device architectures to overcome existing material system limitations

For Ga_2O_3 to realize its full potential in grid and industrial applications, fundamental limitations in doping must be overcome. These limitations cannot be addressed by incremental improvements to existing processes and instead require the adoption of novel device architectures, such as those utilizing heterogeneous integration with p-type materials and/or isovalent alloying.

3 Innovate device design to overcome Ga_2O_3 thermal conductivity limitations

Many innovations in the area of thermal control can help address the largest weakness of Ga_2O_3 devices for PE applications. Thinner device active regions and improved interfacial stability offer synergistic benefits to high-temperature device operation.

3 4 Focus Area 3: Passive Components and Packaging for WBG PE

Passive components (sometimes called "passives") and device packaging are critical for realization of power conversion systems. Passive components provide functions such as storage, filtering, and dissipation of electrical energy. Examples of passives include resistors, capacitors, inductors, and transformers. Packaging, at the most basic level, provides an enclosure to give mechanical stability and protect semiconductor chips from the environment. But packaging also plays a vital role in electrical interconnection, thermal management, voltage isolation, and several other functions central to the overall function of the power device. Because of this, packaging has become one of the most important elements of PE product-level design.

Passive components and packaging technology must advance at a pace at least commensurate with WBG power device technology to avoid limiting performance of practical PE systems. More specifically, with WBG semiconductors enabling increases in switching frequency, operating temperature, and power density, a concerted focus on capacitors, inductors, heat sinks, die attach, and system-level cooling is required.

4.1 Passive Components

To meet the needs of PEs and electric machines in the next 10 years, the following need to be addressed: 1) reduction in losses, 2) reduction of mass, and 3) higher temperature operation. In some applications, requirements for tunability (particularly in the case of inductors) also exist. These challenges can in many cases be at least partially met through improvements to existing materials. However, significant breakthroughs and advances will require new materials and/or manufacturing processes.

Inductors, sometimes called inductor coils, are passive components consisting of wire wrapped around a ferrite core. Inductors are used to remove current and voltage fluctuations, ensuring a stable DC power supply.

Capacitors play a crucial role for PEs and are vital for power decoupling and filtering, as well as gate-driver and signal-conditioning circuits.

Printed circuit board (PCB) inductors are distinct from conventional discrete magnetic components since they feature traces as windings and onboard planar-shaped cores. PCBs greatly facilitate efforts for compactness and the streamlining of fabrication and are a major focus of research and development in PE applications.

4.1.1 Challenges

Core losses such as hysteresis and eddy current increase exponentially with frequency and can greatly reduce the efficiency of power inductors. High-frequency designs thus require optimization of magnetic core materials. Magnetically, soft ferrites remain competitive because of their low cost and near-insulating properties (electrical resistivity or r = 10 - 10^8 μΩ×m).[207] However, ferrites suffer from low saturation magnetizations. Most efforts to improve soft ferrite performance at high frequency are through grain boundary engineering approaches.[208] Amorphous and nanocrystalline alloys are considered state-of-the-art material at frequencies in the tens of kHz due to their relatively high magnetizations, modest resistivities, and very thin (5 to 50 μm) laminations.[209] At even higher frequencies (hundreds of kHz and into the MHz range), materials with high resistivities are desired. Soft magnetic composites (SMCs) show promise in this frequency range, with values of r ranging from 0.1 to 1200 μΩ×m.[210,211] However, these electrical resistivities still fall short of what is required, sometimes significantly, at the highest frequencies. In this case, improved approaches to SMC fabrication and magnetic feedstock are required. Additive manufacturing (AM) processes can streamline fabrication but present challenges in achieving the desired microstructures and therefore material performance targets.

Thermal design is a related challenge. While passive miniaturization is a key benefit of high-frequency WBG power systems, the reduced component size means higher heat flux and presents challenges for thermal management.

PCB inductors present several challenges to designers. Their compactness implies less exposed surface area for cooling, making thermal analysis and optimization particularly important. On the other hand, onboard layout may lead to alternative geometries for both windings and cores to conventional designs, and board dielectric materials are often coupled with the magnetic loops, all complicating the electromagnetic (EM) footprint. Also, other circuit elements in the vicinity are more susceptible to EM interference (EMI).

The growing demand for high-temperature capacitors in, for example, downhole drilling, aerospace, defense, and automotive applications, necessitates advancements in capacitor technologies. Moving capacitors closer to WBG semiconductor active components can minimize trace equivalent series resistance (ESR) and equivalent series inductance (ESL), but often leads to increased operating temperature. Further, ambient temperatures found in downhole drilling, industrial electrification, and some military applications can exceed 200 °C. WBG semiconductor devices are increasingly able to handle such higher junction temperatures, but common capacitor technologies are often limited to 125 °C or below. Thus, the capacitors can impact overall power system design and/or require additional cooling, degrading some of the advantages of WBG PEs.

Polymer films are under investigation and development for commercialization, which should allow for higher temperature capability. However, even capacitors made with these “high temperature” dielectrics typically are rated to no greater than ~150 °C. Polyimide and polytetrafluoroethylene (PTFE) film capacitors are rated to 200 °C and may offer attractive energy density, although a critical challenge is designing high-temperature films that retain self-clearing capabilities.[212]

There is extensive academic research on approaches to higher-temperature, higher-energy-density polymer dielectrics. Unfortunately, many of these approaches are not suitable for scale-up and commercialization, whether due to cost, infeasible manufacturing techniques, or materials complexity.

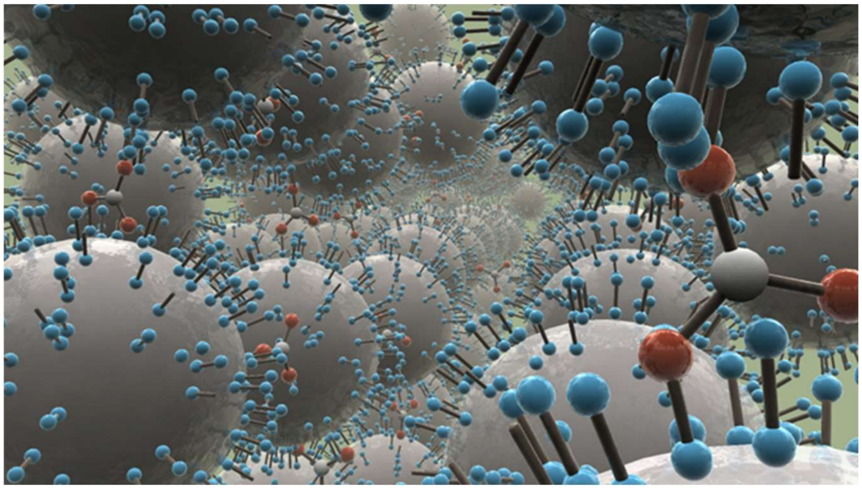

Figure 18. Artist's rendition of an inorganic/organic soft magnetic nanocomposite[213]

High temperature multilayer ceramic capacitors focusing on $Bi(M)O_3$-$BaTiO_3$ dielectrics are under investigation. These dielectrics retain high dielectric constants at temperatures exceeding 300 °C; however, challenges exist regarding component lifetime and integration of cost-effective electrodes. Despite these advancements, ceramic capacitors lack self-healing capabilities and fail short.

Electrolytic capacitors have found primary use as DC-link capacitors in multistage power converters for power decoupling and also find applications in renewable energy applications and motor-drive systems,[214] but reliability issues of electrolytic capacitors[215] have led to increased use of film capacitors in power conversion applications.

4.1.2 Innovation Pathways

The greatest opportunity for reduction in losses is through improved core materials. Existing or emerging materials that show promise for low loss over frequencies ranging from tens of kHz to several MHz include soft ferrites, amorphous and nanocrystalline alloys, soft magnetic composites (SMCs), and SMCs based on nano-sized magnetic powders (nanocomposites).[216,217] Pathways for these materials include grain boundary engineering in ferrites, improving magnetization in amorphous and nanocrystalline alloys while increasing maximum tape thickness, and increasing magnetization while decreasing losses in SMCs. Some present work has enabled better integration, such as ferrites compatible with low-temperature co-fired ceramic processes. Also, utilization of magnetic nanoparticles as shown in Figure 18 (versus mm-sized particles) can significantly reduce both hysteresis and eddy current losses.[218]

In the area of mass reduction, there is some overlap between the requirements for lightweight inductors and those of low-loss inductors. However, the need for lightweight inductors places greater emphasis on high magnetization. In addition to inductor core materials, other factors that can also have a significant impact on inductor mass include compact, integrated, and on-chip inductor designs.[219] Due to their low magnetizations, soft ferrites are no longer a leading candidate core material for lightweight devices. Amorphous alloys, nanocrystalline alloys, and SMCs[220] do remain strong candidate core materials in the design of lightweight inductors. Owing to their high magnetization, high Si (up to 6.5 wt.%)-content steels are an additional possible core material.[221]

To perform at high temperatures, magnetic core materials must not exceed their Curie temperature (T_c). Therefore, inductors operating at high temperatures often require cobalt or Co-based alloys since Co has the highest T_c of the magnetic transition elements (T_c = 1,121 °C).[222,223] If the maximum operating temperature can be limited to a few hundred °C, many more options become available. For example, some SMCs can operate at temperatures ≥500 °C. Additionally, some approaches for the fabrication of integrated or on-chip inductors have also addressed high-temperature operation.[224,225]

Rapid consolidation methods that preserve desired SMC microstructures, such as spark plasma sintering, have demonstrated some initial benefits to both performance and manufacturing efficiency. However, these methods should be further developed.

Future trends include the development and implementation of new materials such as nitrides and superparamagnetic nanocomposites. Work to date in this area has been rather limited. The relatively nascent push toward greater integration and compact on-chip designs should gain momentum due to the requirements for improved SWaP.

The entire design space for soft magnetic materials has not been explored and could potentially open up broader operational windows for inductors. High-entropy alloys are one example of complex compositions with much potential as soft-magnetic-core materials.[226] Computational tools could be quite helpful in exploring the space of potential soft magnetic materials.[227] Additionally, some new promising compositions have recently emerged using nitrides and carbides[228,229,230,231,232] and should be explored.

High-cost elements, such as cobalt, should be used sparingly and only when absolutely necessary to achieve performance targets. For example, the limited use of cobalt may be acceptable in soft magnetics for aviation. Implementing materials and processes that streamline integration of soft magnetic materials with other components (PCBs or other substrates, capacitors, and semiconductors) or into overall electrical machine design should be further explored.

Polymer multilayer capacitors represent a critical technology development pathway. The extreme thinness of the dielectrics combined with relatively high dielectric constants (for polymers) enable significantly improved energy densities relative to polymer film capacitors while maintaining high operating voltages, reliability, and self-clearing capabilities.[233]

Aluminum (Al) electrolytic capacitor with polymer electrodes is another alternative, decreasing ESR and increasing the high-temperature operability.

Adaptation of successful innovations to new materials will also have the potential to provide breakthroughs that can have near-term impact for commercial applications. For example, developing approaches to deposition of low defect density, ultrathin variants of existing dielectric polymers, in a scalable manner, could enable adaptation of the PML geometry to new dielectrics.

High-temperature capacitor technologies will be of benefit to PE systems for multiple industries and should be an area of concerted research focus. Operating temperatures above 200 °C with suitable energy density should be targeted such that capacitor and WBG active component junction temperature ratings are similar. This will avoid the need for de-rating below the inherent capabilities of WBG power devices and may also reduce the need for cooling, thus increasing overall system efficiency.

Approaches to develop new, high-performance dielectric materials that also provide a feasible path to commercialization are needed. Polymer film capacitors are promising, and synthesis of high-temperature films with suitable energy density and self-clearing capabilities should be pursued. Cost remains an issue for certain novel polymeric materials of interest, and cost-effective manufacturing methods should be further explored.

Self-healing materials are a bio-inspired class of synthetic materials that can repair and spontaneously recover functionality. Currently, these materials are being primarily investigated for applications in the field of flexible electronics, sensors, energy harvesting, and storage devices.[234] The introduction of self-healing materials as bonded interfaces in PEs could lead to significant reliability improvements and additional research is warranted.

4.1.3 Recommendations

1 Focus on increasing the operational temperatures of inductors and capacitors for PE applications

The maximum operational temperature of passive components is becoming a performance bottleneck in some PE applications. Innovations, whether through new material development and integration or improved design, to enable higher temperature operation of inductors and capacitors can have significant impacts on the performance improvement of overall WBG PE systems, in some cases enabling the use of WBG devices in new cases/environments.

2 Integrate new materials into inductor and capacitor designs to improve performance and system energy densities

R&D and design innovation, including high-throughput computational and experimental approaches to identify and integrate new materials such as those mentioned in the above section will help increase the lifetime and performance capabilities of inductors and capacitors. These improvements, in turn, will help match some of the higher voltage, higher temperature, and more stringent application requirements, as well as enable decreases in inductor sizes. This would help improve the overall energy density and SWaP of WBG PE systems, making them more commercially competitive, and would help accelerate their adoption across a range of applications, particularly those with volumetric constraints.

3 Increase scale of electro-thermal analysis and modeling

Large-scale electro-thermal co-analysis and co-optimization have been scarce in the PE stakeholder community and should be a focus of upcoming research and development. Additionally, modeling, analysis, and optimization of passive EM properties is of critical importance for their implementation in WBG power systems. The larger scale understanding of electro- and thermal- dynamic interactions between devices can lead to more accurate prediction of expected performance and failure mechanisms and can enable system-level design innovations.

4.2 Packaging

PE designs are rapidly evolving to achieve high power density, high efficiency, high temperature operation, minimal parasitics, and improved reliability under harsh operating conditions. All of these are impacted by packaging technology. Figure 19 illustrates components of a typical power device package and defines some of the package-related requirements/advancements required for WBG PE systems.

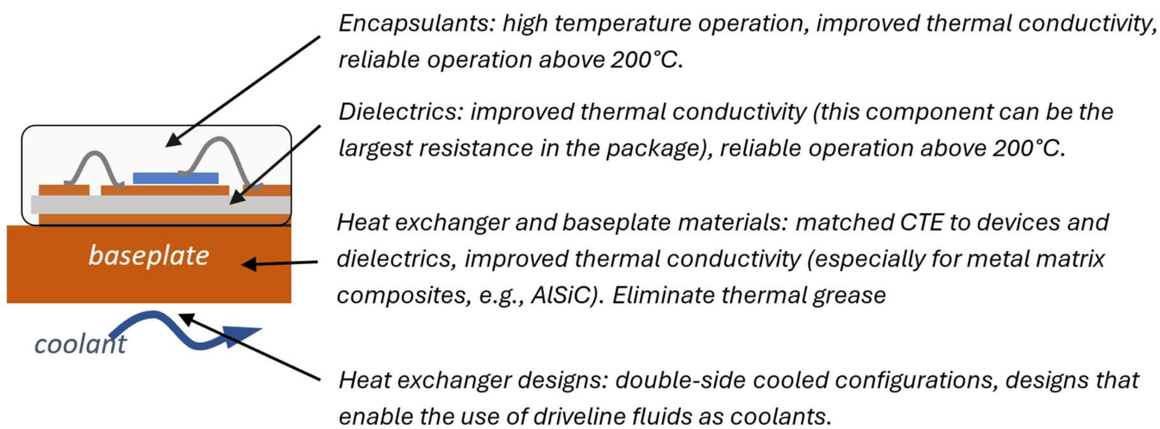

Figure 19. Power device package with associated requirements

Thermal design is of paramount importance for PE packaging due to high dissipated power. Single-sided cooling designs have low material costs and high technical maturity, but limit heat dissipation capacity and exhibit relatively high-power loop parasitic inductance, limiting power density potential.[235,236,237,238,239] Double-side cooled power devices use both sides of the semiconductor surfaces for heat dissipation and therefore have significantly higher heat dissipation capacity. Double-side cooled power devices also offer the potential for lower parasitic inductance layouts and, as a result, much higher power density potential.[240,241,242,243,244] These aspects are summarized in Table 2 and Figure 20.

Table 2. Comparison of Single-Sided and Double-Sided Cooling Designs

	Single-Sided Packaging	Double-Sided Packaging
Power Density	Lower	Higher
Thermal performance	Lower	Much higher
Parasitic Inductance	Higher	Much lower
Reliability	Lower	Higher
Layout Flexibility	Lower	Higher
Complexity of Fabrication	Lower	Higher
Available Design Experience	Abundant	Moderate

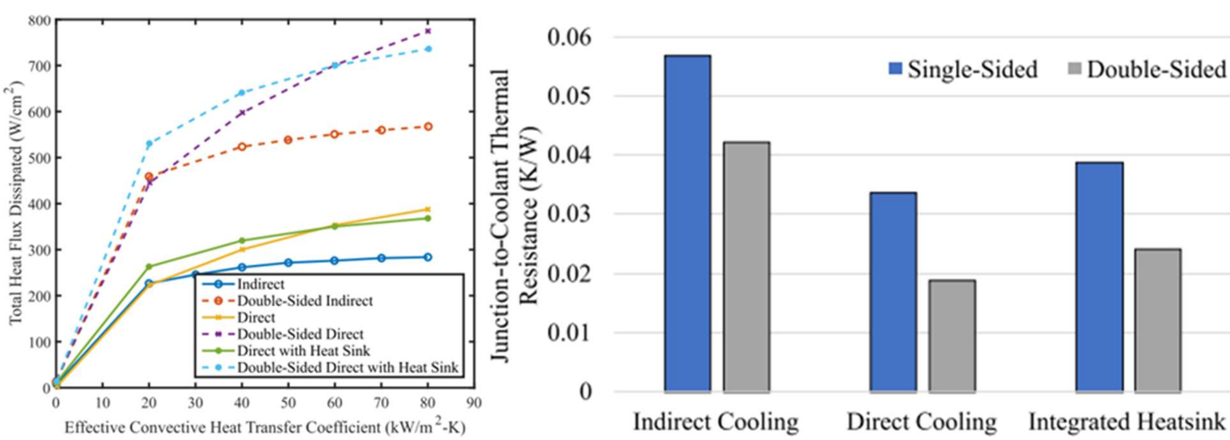

Figure 20. Comparison of heat flux capacity and thermal resistance of different cooling designs[245]

4.2.1 Challenges

Applications requiring high-voltage capabilities, such as solid-state transformers currently being developed for grid-level power conversion, have significant challenges in managing the electric field in not only the semiconductor device, but also inside the package. Standard direct bond copper (DBC) substrates often used in power modules are prone to partial discharge at the point where the ceramic insulator, electrical contacts, and top passivation material meet. Partial discharge can degrade the contacts and material, causing reliability concerns. Additionally, the peak field can often exceed the dielectric breakdown strength of the electrically insulating material, causing catastrophic failure.

The primary motivation for double-sided cooling designs (i.e., higher power density) leads to compactness, which brings new challenges to the layout and fabrication of various internal components. Eliminating material layers between the semiconductor chip and coolant is critical to improve thermal performance and reduce volume (i.e., increase power density). Circulating coolant near or within the devices is a solution that eliminates layers and brings the coolant closer to the heat source and has been shown to provide significant thermal performance enhancements.[246,247,248] This approach also enables 3D packaging of components for improved power density. The challenge with implementing inter/near-device cooling strategies requires collaboration between manufacturers and likely necessitates changes to manufacturing processes and flows.

Production-friendly solutions for PE modules with 3D layouts and multiple heterogeneous materials present major challenges to fully realizing the potential of ultra-compact and high-power density modules. While focus is clearly shifting towards double-sided layout and cooling designs, current power devices mostly have low device count per module, and the electrical layout is still largely based on conventional bonding.[249]

The co-design and co-fabrication of power modules and motherboards presents another major challenge. To achieve converter-level high power density and low loss, designs of the motherboard (PCB) and, especially, the interconnection, are critical for low parasitic inductance and capacitance along with thermal and mechanical benefits. Optimized terminal layout and module orientation bring significant improvements in parasitic performance and converter footprint,[250] and interconnect design has significant implications on both parasitic and thermal performances.[251] The co-optimization of power modules and motherboards is technically challenging and, accordingly, integrated manufacturing is difficult.

AM of thermally conductive polymers has enabled highly optimized baseplate designs that can perform as well as traditional Cu/Al alternatives.[252,253] AM has also been shown to produce intricate packaging structures that allow for electrical isolation while maintaining highly thermally conductive ceramic material in unique 3D architectures.[254] However, the application of AM techniques to power device packaging is currently limited to lab-scale development. Also, metallic and ceramic 3D-printed parts cannot achieve the surface quality offered by conventional manufacturing methods.[255]

Reduction in the weight/volume ratio is crucial for the continued electrification of transportation (e.g., for aviation). However, lightweight components often result in a thermal sacrifice that can lead to de-rating. In some cases, this can outweigh the benefits of the lightweight components.

The reliability of any PE module is, in general, dictated by the performance of the bonded materials and electrical interconnects under harsh conditions. Power device package design has been trending toward configurations without wire bonds,[256,257] which has placed more significant reliability requirements on bonded interfaces. Although sintered silver (Ag), a promising bonded material for high-temperature operation, is now used in SiC-based power modules in electric vehicles,[258] factors such as electromigration, cost, and reliability as a substrate-attach are still a concern.[259,260]

4.2.2 Innovation Pathways

Figure 21 illustrates different packaging schemes adopted for high-temperature SiC device operation. It is evident that all these packages are low-profile, compact, and are amenable to double-sided cooling, with additional benefits such as reduced parasitics and lower thermal resistance. Also, the elimination of the substrate/attach interface improves the reliability of the package, particularly from a thermal cycling standpoint. With respect to insulating substrates, silicon nitride (Si_3N_4) is the preferred choice over aluminum oxide (Al_2O_3) and aluminum nitride (AlN) due to its high flexural strength, which becomes critical at very high temperatures.

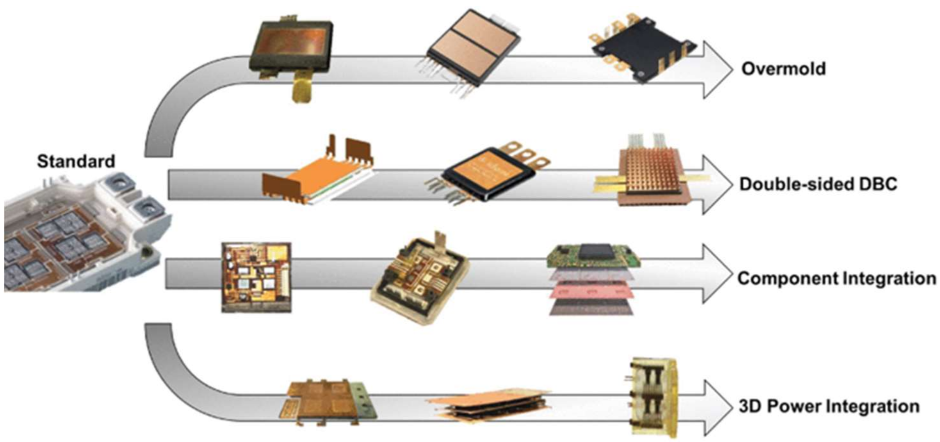

Figure 21. Advanced power module designs for SiC [16]

Compared to single-sided-cooled designs with similar materials, double-sided-cooled designs can usually achieve >=50% lower module-level thermal resistance.[261] This type of design often features replacement of bond wires and novel layouts such as stacking. With the advancement of material and fabrication technologies, more intricate and reliable layouts have been made possible. The resulting high-power density has provided double-sided-cooled modules advantages in power conversion applications for electrified transportation. The use of dielectric fluids as coolants for PEs is a path to improve thermal performance and increase power density. Dielectric fluid coolants enable elimination of the dielectric solid layers (typically ceramics) found in module substrates that can be the single largest thermal resistance in the package. This allows moving the coolant closer to the heat sources (e.g., semiconductor devices) to reduce the junction-to-fluid thermal resistance. Additional thermal performance enhancements can be achieved using dielectric fluids in two-phase heat transfer (e.g., boiling heat transfer). Two-phase heat transfer coefficients can be more than an order of magnitude greater than single-phase heat transfer coefficients, allowing for further reductions to the thermal resistance.

Ceramics are the most common dielectric materials for PE packaging and are most often used as part of the metalized ceramic substrate. Metalized ceramic substates can be DBC, direct-bond-aluminum (DBA), or active metal brazing (AMB).[262] Al_2O_3, AlN, and Si_3N_4 are the most used ceramics. AlN is ideal due to its relatively higher thermal conductivity (170 W/m·K [32]) while Al_2O_3 is a lower-cost solution. Ceramics sheets (i.e., not part of metalized ceramic substrate) have also been used in power modules, and non-ceramic materials have also been used as dielectric materials.

Several trends in packaging design have focused on improving the expected lifetime of packaging components; this is expected to continue in the upcoming decade. Based on historical field failure data, the most common failure locations and failure mechanisms are well understood. Manufacturers have focused on improving several components in PEs to improve overall reliability. Wirebond-free interconnects, solder-free attachment layers, higher-fracture-toughness substrates, and thermal-cycling-resistant thermal interface materials have contributed to additional package lifetime.[263,264,265] Additionally, recent power module designs have focused on simplifying or reducing the complexity in power module construction, such as combining a module baseplate with a cold plate. Designing for CTE mismatches between components greatly relieves thermal stresses that are the most common source of failures.[266,267] While traditional metallized ceramic substrates like Al_2O_3, AlN, or Si_3N_4 have been used in power module design for many years, alternative organic dielectrics promise higher reliability under thermal cycling stresses while also providing improved electrical performance in terms of lower parasitic inductance.[268,269]

The volumetric power density of state-of-the-art commercial inverters lies in the range of 50 kW/L and is projected to reach 200 kW/L in high-frequency power converters. To reach this level, aggressive thermal management solutions will be required, including optimized baseplate materials and cooling solutions. Al and copper (Cu) are still the most used power module baseplate materials. Novel and low-cost materials are needed to improve reliability (e.g., better CTE match to the package), reduce junction temperature (e.g., higher thermal conductivity), and achieve volumetric power density targets. 3D packaging designs with integrated cooling should be explored to bring the coolant close to the devices/chips for improved thermal performance and greater power density. This approach will likely require the use of dielectric fluids as coolants.[270] Package designs that integrate thermal metamaterials (e.g., those that exhibit extreme anisotropy in thermal properties)[271] and electrically insulating, yet thermally conducting substrate materials should also be explored.[272,273]

Package designs that integrate components (e.g., capacitors, gate drivers) on the same substrate to improve electrical and thermal performance can enable cost, efficiency, and weight savings [16] and should continue to be developed. AM at scale may be a viable option to drive down packaging costs by allowing for time-saving benefits when slight modifications from prototype to finished product are required. Multi-material AM should be improved and further explored for the synthesis of PE packages and integration of components.

4.2.3 Recommendations

1 Focus on process improvement and scale-up for double sided cooling designs

To fully support future WBG device operations, especially in grid and industrial applications, thermal management capabilities will need massive improvements. Double-sided cooling approaches show great promise in providing these improvements and focused R&D in this area will enable packaged WBG PE solutions that are not thermally limited (or are much less limited), thereby maximizing the benefits of the wide bandgap semiconductor materials themselves.

2 Innovate and integrate new materials to improve PE packaging across all measures of performance

Packaging performance is closely linked to the performance characteristics intrinsic to the packaging materials. Many candidate material systems, like those mentioned in this section, could significantly improve the performance. Specifically, thermally conductive materials and self-healing materials for improving thermal and mechanical performance appear promising for WBE PE applications of interest.

3 Explore alternative and complementary manufacturing techniques

Following the advanced packaging and heterogeneous integration trends in the microelectronics industry, as well as other advanced manufacturing platforms like AM, there are multiple techniques that can greatly increase the range of system designs and the ability for packages to improve key system performance aspects such as power density, EM shielding, thermal energy dissipation, and/or structural stability. Further work to develop these for PE manufacturing and/or integrate them with current packaging techniques can significantly advance the capabilities of this key stage of the manufacturing supply chain.

5 Focus Area 4: Non-Technical WBG Development Support Areas

The growth and advancement of the U.S. PE industry, particularly in the WBG semiconductor sector, depends not only on technical innovations but also on a robust ecosystem of non-technical support. To ensure the successful development and commercialization of WBG PE technologies, various key support areas must be addressed. These areas focus on fostering cooperation, expanding market opportunities, strengthening industry leadership, setting standards, and providing regulatory and infrastructure support.

1. Ecosystem Support

The PE industry requires a well-connected and cooperative innovation ecosystem. This involves fostering collaboration across industry, academia, government labs, and other stakeholders to create a broad network that supports innovation beyond just semiconductor technology. To achieve this, industry consortia and forums should be established or strengthened to bring experts together, encourage knowledge sharing, and facilitate joint projects. Leveraging existing organizations and enhancing alignment between government labs and industry stakeholders will be key to bridging the gap between academic research and real-world applications. Workshops and other collaborative events can play a critical role in engaging small and medium enterprises (SMEs) and addressing industry challenges.

2. Market Development

Supporting the commercialization of new PE technologies is essential for the industry's growth. Startups and early-stage companies in this sector often face significant challenges during the commercialization process. To help overcome these challenges, dedicated incubators and targeted funding opportunities can assist startups in scaling up their innovations. Developing a long-term domestic manufacturing strategy is also critical, with a focus on bringing PE production back to the United States through investments in advanced device manufacturing.

3. Standards and Reliability

Standardization and reliability are critical for the widespread adoption of new technologies. Collaborating with industry stakeholders to establish standards and guidelines, particularly for emerging technologies such as ultra-wideband gap (UWBG) PE, will help manufacturers align their product development efforts with future market demands. Sharing reliability data, including field failures and testing outcomes, can promote best practices and ensure that new technologies meet the high safety and performance requirements necessary for mission-critical applications.

4. Policy and Regulatory Support

Effective policy and regulatory frameworks are essential to support the PE industry's growth. Strengthening U.S. industrial policy by providing incentives and regulatory support for the domestic supply chain can help stimulate manufacturing and improve supplier diversity. Simplifying the regulatory environment can reduce barriers to innovation and help U.S. companies compete more effectively in the global market. This includes streamlining processes to reduce lead times and making it easier for companies to bring new technologies to market.

5. Availability of Equipment and Facilities

Access to fabrication and testing facilities is crucial for early-stage development and commercialization of PE technologies. The establishment of low-cost prototype fabrication facilities and the expansion of access to national lab foundries will enable companies to move from research and development to production more efficiently. Additionally, supporting specialized boutique fabs that cater to the unique needs of the PE industry will be important for smaller production runs and custom solutions.

By addressing these non-technical needs, the U.S. PE industry will be better positioned to accelerate innovation, improve competitiveness, and contribute to national energy and economic goals.

In addition to the areas described above, particular challenges exist in relation to the U.S. PE workforce, the use of lifecycle assessment within the PE industry, and the application of technoeconomic analysis tools. These topics are described in more detail in the subsequent sections.

5.1 Education and Workforce Development for the U.S. PE Industry

The PE sector is poised for significant growth, as it plays a critical role in advancing American energy independence and securing our power grid. As demand rises for PE development and integration, the industry faces a pressing need for a skilled workforce capable of driving innovation in EVs, renewable energy, and PE manufacturing. However, education and workforce development (EWD) challenges pose a substantial barrier to meeting this demand. From gaps in technical skills and practical experience to barriers in recruitment and retention, the industry struggles with cultivating and sustaining a talent pipeline that can support its rapid evolution. These challenges require a multi-faceted approach, integrating academic partnerships, industry collaboration, and government support to develop solutions that align with the sector's long-term goals.

Addressing these challenges will involve a concerted effort to expand educational pathways, improve hands-on training, and create clearer career trajectories for workers in the field. The industry would benefit from programs that offer alternative credentials, such as trade schools and certification programs, alongside traditional four-year engineering degrees. Additionally, engaging younger students in STEM fields and exposing them to PE concepts early on is essential for building a sustainable workforce pipeline. Industry partnerships are also vital to ensure that curricula keep pace with technological advancements and that employers have access to a pool of workers who are prepared to meet the specialized demands of PE roles. By addressing these education and workforce gaps, the PE sector can better position itself for sustained growth and long-term success in supporting the clean energy transition.

5.1.1 Challenges

The following EWD challenges for the PE industry have been identified through a series of stakeholder engagements held during the development of this framework.

1. Skills Gaps Across the PE Supply Chain

Significant skills gaps exist across various segments of the PE supply chain. This includes gaps in key areas such as the design of experiments, data analysis, work organization, and lab safety. Additionally, there is a shortage of workers skilled in modeling PEs from a power systems perspective, which is an essential skill for understanding PE product behavior, response, and abilities. This shortage makes it difficult for companies to find employees capable of performing these specialized roles.

2. Limitations in Engineering Education

Engineering undergraduates often do not gain sufficient experience outside their core disciplines. PE production requires an integrated knowledge of materials science, chemical engineering, mechanical engineering, and electrical engineering. PE design requires an understanding of modeling and simulation, electricity and magnetism, circuit and control systems design, and other specializations. Existing curricula do not adequately prepare students to work across engineering domains, limiting their flexibility in applying their knowledge to various roles in PEs.

3. Inadequate Preparation in Manufacturing Fundamentals

Another challenge lies in the lack of exposure to fundamental manufacturing concepts and technologies. Current educational programs do not provide sufficient grounding in manufacturing techniques, particularly those applicable to the electronic and non-electronic sectors. This gap affects professionals' readiness to work in advanced manufacturing environments, where an understanding of both electronic and general manufacturing principles is crucial.

4. Disconnect Between Operator and Technician Training Requirements

There is a clear distinction between the skills required for operators and technicians in the PE industry. Current training pathways do not adequately prepare workers for entry or advancement to higher roles. Employers are often looking for workers with basic skill sets who can be internally trained, but they face challenges in identifying, certifying, and advancing these individuals through a structured career path.

5. High Cost of Education and Limited Access to Specialized Training

The high cost of higher education is a major barrier to entry into the PE workforce. This is especially true for learners from underrepresented populations and for smaller companies that cannot afford to hire many engineers or provide ongoing training. There are also funding limitations for training in specialized areas like semiconductors, cleanrooms, and advanced manufacturing processes, making it difficult for students and workers to acquire necessary hands-on skills.

6. Lack of Early Exposure to PEs in Early Education

A significant challenge is the lack of early exposure to PE careers, especially for middle and high school students. Early exposure empowers students to make educational choices that will prepare them for future STEM careers.

7. Barriers to Hiring

Potential candidates who may possess relevant skills but lack traditional qualifications, such as a four-year degree, are often automatically filtered from consideration by automatic employment screening tools. These systems often reject applicants who do not meet rigid requirements, even if they have valuable skills gained from other industries or on-the-job training during prior employment. This is particularly challenging for workers transitioning into the PE sector or veterans returning to the civilian workforce.

8. Insufficient Recruitment for PE Positions

Employers in the PE sector face recruitment challenges, particularly in finding qualified technicians. While there is no shortage of candidates for entry-level operator roles, technicians with specialized training are in short supply.

9. Retention of Skilled Workers and Limited Career Advancement Opportunities

Workers in the PE sector often do not see a clear path for career advancement. This results in high turnover rates, with workers leaving jobs for marginally higher pay in non-technical industries. Workers and managers report that many employers fail to provide skill development and career growth opportunities, or competitive wages. Without structured training and defined career paths, employees are less likely to remain in the industry long-term.

10. Veterans Struggling to Transition to Civilian Roles in PEs

Many veterans with relevant technical skills face difficulties transitioning into the PE industry. Navigating civilian hiring systems and finding pathways into roles that match their military training can be daunting. There are limited programs that help employers tap into this workforce, and without clear guidelines, many veterans are overlooked despite having the technical foundation needed for success in PE roles.

11. Low Engagement Between Industry and Education on Curriculum Development

There is insufficient collaboration between industry and academic institutions to ensure that educational programs meet the evolving needs of the PE sector. Many university programs do not adequately prepare students for the specific technical skills required in PEs. More direct feedback from industry is needed to help universities adjust their curricula to include hands-on training, modeling, and manufacturing fundamentals that are critical for success in the sector.

Addressing these challenges through coordinated efforts among industry, academic institutions, and government bodies will be crucial for growing a skilled workforce to support the future of PEs and the clean energy transformation.

4.1.2 Current DOE PE EWD Efforts

The U.S. government is actively supporting EWD in the PE industry through various initiatives led by DOE/AMMTO. A key strategy under development by AMMTO aims to inspire individuals to pursue and grow careers in advanced manufacturing, including PEs, as part of a broader clean energy transformation. To achieve this, AMMTO is leveraging partnerships with institutes and high-growth industry programs to provide targeted support. For example, ongoing workforce initiatives are being implemented in the battery sector, with similar programs in the early stages for the PE industry. These efforts include identifying skills gaps, gathering input from the industry, and testing employer-based training programs to address workforce needs.

5.2 Techno-Economic Development and Lifecycle Assessment for the U.S. PE Industry

Despite the known benefits of WBG semiconductors, their widespread adoption requires a comprehensive understanding of both their economic viability and environmental impacts. Techno-economic analysis (TEA) and lifecycle assessment (LCA) serve as essential tools for evaluating the overall performance, cost-effectiveness, and sustainability of PE technologies. TEA provides a framework for assessing the cost structures, economic trade-offs, and market competitiveness of WBG devices across different applications. It helps quantify the potential benefits of new technologies in terms of lifecycle cost reductions, system-level performance improvements, and long-term economic impacts. By analyzing key factors such as material costs, manufacturing processes, and operational efficiency, TEA supports decision-making on whether to invest in or scale up WBG technologies.

Meanwhile, LCA examines the environmental footprint of PEs throughout their lifecycle, from raw material extraction to manufacturing, operation, and end-of-life disposal or recycling. This is especially important as industries prioritize sustainability goals and move toward circular economies. LCA allows stakeholders to assess the embodied energy and carbon emissions associated with WBG devices and compare them to traditional Si-based alternatives. Furthermore, it enables the identification of opportunities to reduce environmental impacts by optimizing manufacturing processes, improving material efficiency, or exploring alternative technologies.

Together, TEA and LCA provide a holistic view of both the economic and environmental dimensions of PE technologies. By integrating these analyses, stakeholders—including manufacturers, investors, policymakers, and researchers—can make informed decisions that balance performance improvements with cost reductions and sustainability objectives. For industries like transportation, renewable energy, data centers, and the power grid, where the need for high-efficiency, high-performance PEs is growing, TEA and LCA are invaluable in guiding the path toward a more sustainable and economically viable energy future.

The following sections present preliminary findings related to TEA and LCA for PEs. They then discuss challenges and limitations in performing analyses for PEs and discuss potential solutions and recommendations. By leveraging these insights, the PE industry can accelerate the transition to cleaner, more efficient technologies and help achieve long-term energy security goals.

5.2.1 Current TEA and LCA findings for WBG PE

Embodied Energy and Energy Savings at the Device Level

WBG power semiconductors currently require more energy per unit device area to fabricate compared to conventional Si PEs, but this is vastly offset by the use phase energy savings.

Front-end processing energy inputs for PE and similar architecture devices, which include epitaxial layer growth, lithography, etching, doping, etc., are estimated to range from 7-22 MJ/cm2.[274,275]

A light duty EV application requires on the order of ~20 cm2 of Si semiconductor, which translates to 150-200 MJ of embodied energy in the semiconductor devices (this excludes the large Si diodes needed). For WBG PEs, using SiC as an upper limit, the embodied energy in SiC could be as large as 730 MJ. This is a conservative estimate—the higher operating voltage and efficiency typically require a much smaller total area of WBG power device for a given power application, partially offsetting the differences in energy per area of Si compared to SiC or GaN. However, the total energy within the semiconductor, irrespective of the technology, is negligible when the use-phase is taken into account. Over the lifetime of the EV, a total energy savings of 50 GJ was estimated – a 250x difference between initial energy costs versus operational energy savings. Thus, the additional energy to manufacture SiC PEs makes up, at most, a mere 1.5% of the total energy that is saved by the gain in efficiency. This is demonstrated by Warren et al.'s analysis demonstrating WBGs could have a cumulative energy savings ranging from 2-20 billion GJ between 2015-2050 in light-duty vehicle use.[276]

Similarly, one can estimate the total energy savings for other applications. For example, a 1 MW uninterruptable power supply (UPS) operating at 500 kW continuously over the course of a year would supply approximately 16,000 GJ of energy. Si could provide this power at 94% efficiency, while WBG PEs could operate at 96% efficiency, translating to 350 GJ in energy savings. Again, comparing these savings to 1 GJ or less difference in the embodied energy of the semiconductors highlights that the operational advantages of WBG PEs greatly exceed any differences in embodied energy needed to produce the materials and devices.

Embodied Energy and Energy Savings at the Systems Level

Further energy saving insight is gained by considering the system, not limited to passive components such as additional diodes, capacitors, inductors, and heat sinks as well as active components like fans or pumps for temperature control. Overall, the PE component is a very small component within a full system. WBG PEs operate at higher frequencies than Si devices. The reactance/impedance of inductors and capacitors scale with frequency, so the capacitances and inductances can be proportionally smaller. This translates to physically smaller components with vastly reduced volume and mass of the system. Lower mass means less embodied energy in the overall system (e.g., reducing the ferrite and Cu in the inductor/transformer from 10 kg to 1 kg or less). Additionally, higher efficiency reduces energy lost in the form of heat (up to 50% reductions in heat dissipated in the semiconductor die), meaning less energy needed to cool the system. Third, operating at higher voltages reduces the amount of current for a given power (P = IV). Resistive losses in Cu wire increase more significantly with current than voltage (Ploss = I2/R). Therefore, WBG PEs operating at higher voltages reduce the total mass of Cu needed for a given system. This non-exhaustive list of indirect energy savings is where the major energy, and materials savings lie. Future analysis work is needed to better quantify the benefits of WBG PEs compared to traditional Si PEs accounting for the many knock-on impacts of WBG components from a broader industrial ecology perspective to understand their role in the energy transition.

Circular Economy

In general, the small mass of WBG semiconductors used in a PE device do not make recycling the semiconductor within a package a priority at end-of-life (EoL). However, there are other options to recycle, or rather downcycle, within the semiconductor fabrication process. For example, the large fraction of SiC and sapphire lost as kerf can be downcycled as abrasives, even to be used in the manufacturing of Si. More importantly, the failure mode of WBG PEs does not always damage the semiconductor. Instead, the device fails at various interfaces such as the ceramic/semiconductor interface due to thermal expansion mismatch or repeated partial discharge at high voltages. Therefore, foundational research priority could be given to remanufacturing devices that prematurely reach EoL where the semiconductor die can be recovered, or specifically designing packages to be easily remanufactured.

Implications for TEA and LCA Findings

The opportunities for WBG are well covered by reputable market reports, such as those cited. However, there are areas that could benefit from additional analysis or tools.

As new materials are found to have potential, a full supply chain analysis should be considered. It is important to understand the implications of potentially transformational material choices.

Researchers could benefit from additional bottoms-up cost models provide insights into system-level implications for device-level cost changes. The cost models could be used to explicitly generate a roadmap of research opportunities for cost reduction and inform system-level cost models to determine if higher device capabilities/efficiencies lead to lower system cost.

The current focus on lifecycle impacts highlights the need for either analysis or tools that could be utilized to quantify proposed research's potential impact over the expected lifetime of the device or system. As with cost, the analysis and tools should demonstrate the impact beyond just a material level but extending to embodied and operational energy. Considerations could include questions such as: 1) What is the energy reduction with the footprint shrinkage? 2) What does the efficiency increase enable?

Lastly, circularity and recycling should be more fully evaluated. Given the magnitude of the deployment anticipated to incorporate WBG, the strategies for recycling, remanufacturing, and related activities need to be evaluated to guide where additional research is needed for optimization.

5.2.2 TEA and LCA Challenges for the U.S. PE Industry

1. Lack of Reliable and Standardized Data for Embodied Carbon and Energy

Power sector stakeholders have indicated that they struggle with obtaining accurate and trustworthy data related to the embodied carbon and energy of WBG devices. This lack of reliable data from upstream suppliers, particularly the semiconductor industry, complicates efforts to conduct full LCAs.

Without reliable data, companies cannot accurately compare the environmental impact of different materials or components, such as SiC versus GaN, which hampers their ability to meet corporate sustainability goals or make informed decisions about material selection.

2. Difficulties in Quantifying Use-Phase and Embodied Carbon Comparisons

While the industry has a relatively strong understanding of use-phase energy savings (such as efficiency improvements during operation), quantifying the embodied energy or carbon remains challenging for PE technologies. The lack of standardized methods to compare embodied energy across different materials adds complexity to conducting meaningful comparisons between traditional Si-based devices and WBG materials.

Companies want to understand the trade-offs between the environmental impacts of manufacturing a more efficient WBG device versus its use-phase benefits. Without robust methods to assess embodied energy, organizations risk making decisions based on incomplete or inaccurate information.

3. Cost and Complexity of LCA for PE Manufacturing

Performing a full LCA is resource-intensive, especially when accurate data is lacking. Many companies indicated that the level of effort required to gather comprehensive LCA data (spanning from raw materials to end-of-life recycling) is not always justified by the quality or precision of the results. This complexity increases when considering multi-use factories, where energy and carbon allocation for specific products (e.g., individual PE components) is difficult to assess.

Companies struggle with allocating resources for in-depth LCA studies that have a high margin of error due to data quality issues. This may discourage companies from fully committing to LCAs for their products, which may hinder efforts to make data-driven decisions regarding sustainability and carbon reduction strategies.

4. Granularity of Data Needed for Decision-Making

There is a need for clear guidance on what level of data granularity is most useful for companies in different sectors. While some prefer high-level global averages of carbon and energy data (for easier integration into their own models), others require more granular, component-level data to better understand specific manufacturing impacts.

Without clarity on the appropriate level of granularity (component, system, or application level), DOE and industry stakeholders may invest in data collection that either provides insufficient detail for decision-making or overwhelms users with unnecessary complexity.

5. Difficulty in Applying TEA to Emerging WBG Applications

As PEs become increasingly vital across various sectors (e.g., transportation, renewable energy, data centers), the specific techno-economic benefits of WBG devices are not always clear or well-documented. For example, in some sectors, TEA may focus too narrowly on efficiency improvements without capturing secondary benefits like thermal management or EMI reduction, which are equally important in driving WBG adoption.

Insufficient or incomplete TEA data makes it difficult for industries to justify investments in WBG technologies, especially for high-cost sectors like electric aviation or HVDC systems, where reliability and performance across multiple metrics are crucial.

6. Unclear Metrics and Benchmarks for WBG Adoption

Power sector stakeholders have expressed uncertainty about the specific cost targets or performance metrics that would enable widespread WBG adoption across different applications. While some industries, like EVs, have seen clear trends and projections for cost reduction, other sectors (such as solid-state transformers or AI servers) lack defined benchmarks or targets that would make the adoption of WBG technologies more economically feasible.

Without clear techno-economic metrics, companies may delay WBG adoption because they are uncertain of the long-term cost-effectiveness or whether industry goals can realistically be achieved. This is particularly important for industries looking at long-term sustainability and energy security goals.

7. Uncertainty in Assessing Supply Chain Impacts

Several power sector stakeholders indicated that their ability to perform thorough LCAs is hampered by uncertainty in the supply chain. The price fluctuations of critical materials (such as iridium for crucibles or rare earth materials for WBG devices) add complexity to cost and environmental impact calculations. This is especially important as the industry aims to move toward a circular economy and improve domestic supply chains.

Uncertainty in supply chain availability and pricing makes it difficult to assess the long-term viability of WBG materials. This affects both cost competitiveness and environmental sustainability, making it harder to plan for large-scale adoption.

8. Variability in Use Cases and Applications

WBG materials are used in a wide range of applications, each with different requirements for performance, efficiency, and cost. For example, the needs of EVs differ from those of data centers or the power grid. This variability complicates the development of one-size-fits-all TEA or LCA analyses, as different use cases may prioritize different metrics (e.g., power density vs. efficiency vs. lifecycle cost).

Industries may struggle to apply generalized TEA/LCA results to their specific use cases. This challenge could slow down WBG adoption if companies cannot easily see how the technology will perform in their specific applications.

9. Need for Real-World Case Studies and Prototypes

While TEA and LCA can provide valuable insights, many power sector stakeholders have emphasized the need for specific, real-world case studies and practical demonstrations. These examples would help validate performance claims, such as improvements in efficiency, size reduction, and total cost of ownership (TCO). Without real-world examples, it is difficult to fully capture benefits like improved thermal management or long-term reliability, especially for high-stakes applications like HVDC or aerospace.

Data from TEA/LCA alone may not be sufficient to convince stakeholders or investors to adopt new technologies. Practical demonstrations that quantify secondary benefits could bridge the gap between theory and market adoption, particularly for risk-averse industries.

10. Need for Standardization in TEA/LCA Methodologies

Participants highlighted the need for standardized methodologies for conducting TEA and LCA. Currently, different organizations may use different assumptions or models, leading to inconsistent results that are difficult to compare across the industry. A standard framework for evaluating embodied energy, lifecycle costs, or supply chain impacts would benefit the industry by providing consistency and improving confidence in the results.

Without standardized methods, companies may invest in their own analyses that produce inconsistent or incomparable data, making it harder for the industry to make informed decisions or align with government-led initiatives and roadmaps.

These challenges illustrate the need for more comprehensive and standardized approaches to TEA and LCA in the PE industry, particularly as WBG materials become more critical to achieving energy efficiency and security goals.

5.3 Recommendations to Address Non-Technical WBG Development Challenges

1 Expand industry and academic partnerships

Strengthening partnerships between the PE industry and academic institutions is a critical solution to addressing workforce gaps. Collaboration through cooperative educational programs can align curricula with real-world industry needs and provide students with practical, hands-on experiences. Universities can work closely with companies to offer apprenticeships, internships, and application labs where students and workers can engage in solving real industry problems. Advisory boards with industry leaders can also ensure that programs stay up-to-date with technological advancements and workforce requirements.

2 Support work visas for foreign students

Incentivizing the participation of foreign students in U.S. engineering and PE programs is another important strategy. Expanding support for work visas for international students can help fill critical gaps in the domestic workforce. This will allow the United States to tap into a global talent pool and support diversity in the workforce. Work visa support efforts can ensure that talented individuals are able to enter the PE sector.

3 Develop alternative educational pathways

Creating alternative educational pathways is essential to meet the diverse needs of the PE workforce. Trade school tracks, community college programs, and certification programs should be developed as alternatives to the traditional four-year degree, especially for roles like operators and technicians. These programs can provide targeted skills training and allow for upward mobility within the industry. For example, partnerships with local community colleges can develop bootcamps, certification courses, and micro credentials to help individuals quickly upskill and transition into the PE sector.

4 Create partnerships with international institutions and the U.S. Department of Labor

Collaborating with respected international institutions and engaging the U.S. Department of Labor is vital to enhancing workforce development efforts in PEs. These partnerships can facilitate the exchange of best practices, create global standards for workforce training, and ensure that U.S. programs are competitive on a global scale. Moreover, by involving the Department of Labor, industry and academia can work together to ensure that high school curricula and career technical education (CTE) programs are adequately preparing students for careers in the PE industry.

5 Improve hands-on training and early exposure to PEs

Providing more hands-on training opportunities is crucial for preparing students and workers for the technical demands of PE roles. Programs should focus on integrating cleanroom experience, lab safety, and real-world manufacturing challenges into engineering and technical education. Increasing middle and high school STEM workshops and offering hands-on internships at the undergraduate level will help students gain practical skills early on. Additionally, specialized training for community college instructors and the use of virtual reality (VR) simulations can help create accessible, low-cost training opportunities that scale across the country.

6 Reduce education costs and expand scholarships

To address financial barriers to entering the PE field, the government and industry should continue to expand scholarships and initiatives that reduce the cost of education. Funding should support not only tuition assistance for students but also cover the development of specialized courses and training programs that focus on the emerging needs of the PE sector. Financial incentives can also be extended to companies that sponsor internships and cooperative programs to train students while they complete their education.

7 Implement employer-based training programs and career pathways

Encouraging companies to develop employer-based training programs that are aligned with industry needs is an effective way to close the skills gap. These programs can be validated through partnerships with academic institutions and should focus on providing training in emerging technologies and technical skills like semiconductor manufacturing and power systems modeling. Additionally, creating clear career pathways for workers will help improve retention by offering growth opportunities within companies. This is particularly important for addressing workforce shortages and reducing turnover.

8 Broaden outreach to underrepresented groups and veterans

A key solution for workforce expansion is increasing outreach to underrepresented communities and veterans. Programs that help veterans transition from military roles into civilian positions in the PE industry, such as targeted training and clearinghouses for veteran hiring, should be prioritized. Additionally, recruiting more women, minorities, and workers from disadvantaged backgrounds into STEM fields through outreach programs can diversify the talent pool and bring new perspectives into the industry.

9 Address barriers to employment and improve hiring practices

Employers should address barriers to employment by reforming hiring practices and improving how they identify and evaluate skill sets. Automated screening systems that reject applicants based on rigid qualifications should be adjusted to recognize relevant transferable skills from other industries, veterans, or non-traditional backgrounds. Moreover, creating industry-recognized certifications and skill tags will help workers demonstrate their qualifications even if they lack traditional four-year degrees. Employers should also engage in cross-training workers from adjacent fields to expand the available workforce.

10 Increase early STEM exposure and PE awareness

Broadening STEM outreach efforts in middle and high schools is essential for building long-term interest in PE careers. Supporting high school teachers in incorporating PE-related topics into the curriculum, along with providing exposure to cleanroom environments, manufacturing techniques, and real-world engineering problems, can inspire students to pursue STEM degrees. Creating awareness through industry visits, hands-on projects, and workshops will help students envision future careers in the PE sector and ensure a steady pipeline of future talent.

11 Increase data collection and sharing for energy and environmental footprint of WBG PE technologies

More activities to specifically track and understand energy and environmental footprint of WBG PE production and use – and standardizing such methods -- will improve data reliability and make it easier to compare the environmental impacts of different materials and manufacturing processes across the industry. It also reduces variability in assessments, leading to more trustworthy LCA results. Furthermore, building data repositories and sharing such resources would provide industry stakeholders with an easy-to-use reference for conducting their own analyses, reducing the need for each company to gather data independently. It would also provide a starting point for those conducting more detailed, application-specific LCAs. Tools like the Manufacturing Energy Consumption Survey (MECS), Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET), and Techno-economic, Energy, & Carbon Heuristic Tool for Early-Stage Technologies (TECHTEST) could be adapted to PEs to help estimate energy use and carbon emissions across manufacturing processes.

12 Support supply chain transparency initiatives

Improved supply chain transparency would help companies assess the environmental and economic risks associated with their material choices, allowing for more informed decision-making in both LCA and TEA analyses.

13 Encourage case studies and real-world demonstrations

Demonstrating WBG performance in real-world applications would give the industry concrete examples of how these technologies can be applied successfully. This could help overcome skepticism about theoretical TEA/LCA results and encourage wider adoption by highlighting tangible benefits.

14 Promote collaboration between industry, academic, and government R&D resources

Collaboration across industries and with university and government national labs would give industry access to a wider range of useful data & knowledge, cutting-edge R&D, and advanced analytical tools, speeding up the development of more accurate and comprehensive TEA/LCA methods. This could also foster innovation by creating opportunities for joint research and development, and for sharing best practices.

By implementing these solutions, the PE industry can overcome the current challenges associated with TEA and LCA analyses and accelerate the adoption of WBG technologies. This will help to meet key sustainability and efficiency goals while providing clear, actionable data for decision-making across multiple sectors. Many of the suggested solutions require collaboration between industry, academic institutions, and government agencies, which can enable the PE sector to build a workforce that is prepared to meet the challenges of the rapidly evolving energy and manufacturing landscapes.

6 Path Forward

The power electronics (PE) strategic framework has laid out a clear vision for the transformative potential of wide bandgap (WBG) semiconductor technologies across multiple sectors, from grid infrastructure to industrial applications. Continued advancements are needed to achieve the high-performance, cost-effective, and reliable PE systems required for an energy independent economy.

To drive this progress, this framework highlights several key areas for focus, including the need for pre-competitive research and development, more robust collaboration across sectors, and scaling of manufacturing processes for new materials and devices. WBG power electronics are poised to play a crucial role in enhancing the efficiency of energy systems, reducing greenhouse gas emissions, and supporting the electrification of transportation, industry, and other critical infrastructure sectors.

Overall, this strategic framework identifies the critical importance of collaboration among industry leaders, academic researchers, and government entities to address the technical challenges and non-technical barriers facing the PE sector. By continuing to advance innovation through collaboration, investing in education and workforce development, and implementing supportive policies, the U.S. can ensure its leadership in this vital area and meet its ambitious energy and environmental goals. The future of power electronics will be shaped by these collective efforts, setting the foundation for a cleaner, more efficient, and resilient energy infrastructure.

6.1 Call to Action

The power electronics (PE) industry stands at a pivotal moment, as rapid advancements in wide bandgap (WBG) technologies offer transformative potential for sectors like energy, transportation, and digital infrastructure. To fully realize this potential, a unified and collaborative approach across the entire innovation ecosystem is critical. Researchers, industry leaders, academic institutions, and government agencies must come together to prioritize pre-competitive research and development (R&D) initiatives. This collaboration will not only accelerate the pace of technological breakthroughs but will also enable the broader commercialization of WBG power electronics.

The entire power electronics ecosystem must now take an active role in shaping this future. By focusing on collective innovation, sharing knowledge, and addressing common challenges, we can unlock new capabilities that will drive economic growth, enhance grid stability, and help advance American energy independence. This strategic framework is a call to action for stakeholders to engage in cross-sector partnerships, invest in pre-competitive R&D, coordinate with each other and the DOE to develop a detailed roadmap with timelines and levels of effort needed, and to collectively work toward building a resilient, high-performing power electronics industry that will be essential to the future energy landscape.

This document is a framework to enable industries in different sectors to share what they are learning and in turn accelerate power electronics progress. Collaboration within the broader community will support effective life cycle assessments and techno-economic analysis, which can be useful in defining metrics, targets, and timelines related to the goals laid out in this framework. This can only be achieved through data sharing and cooperative analyses.

Part of this effort will also include finding and/or developing forums for information sharing and collective decision making. In addition, industry also must communicate its nontechnical needs, especially regarding EWD (e.g., hiring, skills, how workers need to be trained, resources needed) to the broader community as well as DOE so that effective support can be provided.

By following the recommendations outlined in this strategic framework and collaborating to share knowledge and communicate industry needs, the PE community can achieve the critical technological innovations and robust nontechnical support framework needed to enable the energy independent economy of future.

End Notes

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Focus Area 1: Wide Bandgap Power Electronics Application Areas

1.1 Grid Infrastructure

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1.3 Digital Infrastructure

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Focus Area 3: Passive Components and Packaging for Wide Bandgap PE

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Focus Area 4: Non-Technical WBG Development Support Areas

4.2 Techno-Economic Development and Lifecycle Assessment for the U.S. PE Industry

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