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Research Paper

SiC and GaN in electric vehicle charging systems: Advances in efficiency, power density, and cost reduction – A comprehensive review

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Abstract
The global surge in electric vehicle adoption demands efficient, high-power charging infrastructure. Silicon-based power electronics limit performance due to high losses, thermal constraints, and large size. Wide-bandgap semiconductors (SiC and GaN) offer superior efficiency (>98%), power density (2–5×), and thermal management. This review examines SiC/GaN applications in DC fast chargers (totem-pole PFC, CLLC), on-board chargers, and bidirectional V2G systems, with 20–50% loss reduction and cost trends showing rapid declines. Vietnam-specific opportunities under PDP8 (EV targets, grid upgrades) and challenges (cost, tropical reliability, grid stability) are analyzed. Recommendations include subsidies, local R&D, and pilot projects to enable scalable, efficient EV charging deployment.

Keywords: *wide-bandgap semiconductors, SiC GaN, EV charging, power electronics, efficiency optimization*

I. Introduction

The global electric vehicle (EV) market has experienced exponential growth, driven by stringent emissions regulations, declining battery costs, and increasing consumer demand for sustainable mobility. According to the International Energy Agency (IEA), EV sales surpassed 14 million units in 2023, with projections indicating that EVs could account for 35–50% of global passenger car sales by 2030 and over 60% by 2035 under accelerated scenarios (IEA, 2024). This expansion necessitates a parallel development of charging infrastructure, ranging from Level 1 (slow AC, 1.4–2.4 kW) and Level 2 (fast AC, 7–22 kW) chargers to high-power DC fast chargers (Level 3, 50–350 kW) and emerging ultra-fast chargers (>350 kW). The deployment of fast and ultra-fast charging stations is critical to alleviate range anxiety, support long-distance travel, and enable mass adoption, yet it imposes significant technical demands on power electronics for efficient energy conversion, high power density, and grid compatibility.

Power electronics constitute the core of EV charging systems, performing essential functions such as AC-DC rectification (power factor correction), DC-DC voltage regulation, and bidirectional power flow in vehicle-to-grid (V2G) and vehicle-to-home (V2H) applications. Conventional silicon (Si)-based devices, including IGBTs and MOSFETs, have dominated these topologies due to their maturity and cost-effectiveness. However, Si devices suffer from inherent limitations: high switching and conduction losses (particularly at high frequencies), restricted operating temperatures (typically ≤150 °C junction), and large passive components (inductors, capacitors) required for filtering and thermal management. These constraints result in reduced system efficiency (often 92–95% in high-power chargers), increased cooling requirements, larger physical footprints, and higher overall system costs (Millán et al., 2014; Ozpineci et al., 2021).

The emergence of wide-bandgap (WBG) semiconductors—silicon carbide (SiC) and gallium nitride (GaN)—offers a transformative solution to these challenges. With significantly higher bandgap energies (SiC ≈3.26 eV, GaN ≈3.4 eV vs. Si ≈1.12 eV), WBG devices enable higher breakdown voltages, faster switching speeds (up to 100× that of Si), lower on-state resistance, and superior thermal conductivity. These properties facilitate reduced switching losses (50–70% lower), operation at higher frequencies (100 kHz–1 MHz), smaller passive components, and improved efficiency (>98% in many prototypes). SiC MOSFETs excel in high-voltage applications (600–1700 V) for off-board fast chargers, while GaN HEMTs and e-mode GaN transistors dominate lower-voltage, high-frequency on-board chargers (650 V range). Recent reviews highlight that WBG adoption can reduce charger volume by 30–50% and weight by 20–40%, while enhancing reliability in harsh environments (Shenai et al., 2018; Millán et al., 2014; Ozpineci et al., 2021).

Despite these advantages, WBG technology adoption remains uneven globally. In developed markets (e.g., Europe, United States, China), SiC and GaN are increasingly integrated into commercial chargers by manufacturers such as Tesla, ABB, and Delta Electronics, driven by policy incentives and mature supply chains. In emerging economies, however, widespread deployment faces unique barriers: high upfront device costs (SiC 5–10× more expensive than Si equivalents, though declining), limited local manufacturing, supply chain vulnerabilities, compatibility with less stable grids, and regulatory gaps for high-power charging standards. Vietnam exemplifies these challenges. The country has set ambitious EV penetration targets (approximately 30% of new vehicle sales by 2030 in some policy scenarios), supported by incentives and the rapid expansion of VinFast's domestic EV ecosystem. PDP8 (revised 2025) emphasizes grid modernization, renewable integration (including rooftop solar synergy with EV charging), and energy storage to manage peak loads from fast chargers. Yet, Vietnam's distribution grid—characterized by voltage fluctuations in rural areas and urban congestion—poses compatibility risks, while the nascent EV charging network (still under 10,000 stations nationwide in 2025) demands cost-effective, efficient solutions to scale affordably.

This review addresses the research problem by systematically evaluating the role of WBG semiconductors in EV charging infrastructure, with a focus on efficiency gains, cost optimization, and adaptation for emerging markets like Vietnam. The primary objectives are to: (1) synthesize recent advances in SiC and GaN applications across charging topologies; (2) analyze quantitative improvements in efficiency, power density, and thermal performance; (3) assess cost trends and economic viability; (4) identify technical, economic, and grid-related challenges; and (5) provide Vietnam-specific recommendations aligned with PDP8 and national EV goals.

The methodology follows PRISMA guidelines for systematic reviews. Literature was sourced from IEEE Xplore, Scopus, Web of Science, and Google Scholar, using keywords such as "SiC EV charger," "GaN on-board charger," "wide-bandgap EV charging," and "bidirectional V2G WBG" (focus on 2018–2025 for recency). Inclusion criteria prioritized peer-reviewed articles, conference papers, and industry reports with experimental or simulation validation. The review synthesizes approximately 80–100 sources, with emphasis on comparative performance metrics and emerging market perspectives.

The paper is structured as follows: fundamentals of EV charging and power electronics requirements; characteristics and advantages of SiC/GaN; applications in charging topologies; efficiency and cost analysis; challenges and Vietnam-specific considerations; future directions and recommendations; and conclusion.

II. Fundamentals of EV charging systems and power electronics requirements

Electric vehicle (EV) charging infrastructure forms the backbone of widespread EV adoption, enabling safe, efficient, and reliable energy transfer from the grid to the vehicle's battery. Charging systems are broadly classified into two categories based on location and power flow direction. **On-board chargers (OBCs)** are integrated within the vehicle and convert grid AC power to DC for battery charging, typically at lower power levels (3.3–22 kW). They offer convenience for home and workplace charging but are constrained by vehicle space, weight, and cost. **Off-board chargers**, often referred to as DC fast chargers or public stations, are external units delivering high-power DC directly to the battery (50–350 kW or higher for ultra-fast systems), bypassing the on-board converter to achieve shorter charging times (typically 20–40 minutes for 80% state-of-charge). Off-board systems dominate public infrastructure due to their ability to support long-distance travel and fleet operations.

In terms of power flow, chargers are further divided into **unidirectional** and **bidirectional** types. Unidirectional chargers transfer energy solely from grid to vehicle, focusing on simplicity and cost-effectiveness. Bidirectional chargers enable **vehicle-to-grid (V2G)** and **vehicle-to-home (V2H)** functionalities, allowing the EV battery to discharge energy back to the grid or home loads during peak demand, acting as distributed energy storage. V2G/V2H systems enhance grid stability, integrate renewables (e.g., solar PV), and provide economic benefits through demand response and energy arbitrage (Kempton & Tomić, 2005; Hu et al., 2016). However, bidirectional operation requires advanced power electronics to manage bidirectional power flow, voltage regulation, and grid synchronization, increasing complexity and cost.

The power electronics stage is central to all EV chargers, performing AC-DC rectification, DC-DC conversion, and control functions. Key topologies include **power factor correction (PFC) rectifiers** for the front-end AC-DC stage. Traditional boost PFC rectifiers are widely used but suffer from high conduction losses at high power. The **totem-pole PFC** topology, with bridgeless design and interleaved operation, has gained prominence for its reduced conduction losses and suitability for high-frequency switching (Wang et al., 2019). For the isolated DC-DC stage, resonant converters such as **LLC** and **CLLC** (bidirectional variant) offer high efficiency (>97%) through soft switching (zero-voltage switching) and are ideal for OBCs and bidirectional systems (Li & Li, 2018). Dual active bridge (DAB) converters provide excellent bidirectional capability and galvanic isolation but require precise phase-shift control. Non-isolated topologies like **buck-boost** or **cascaded buck-boost** are used in some low-power or auxiliary applications due to simplicity but lack isolation (Meneses et al., 2015).

EV chargers impose stringent requirements on power electronics design. **High efficiency** (>95–98%) is essential to minimize energy losses, heat generation, and operating costs, particularly in fast-charging stations where heat dissipation is critical. **High power density** (kW/L) enables compact, lightweight chargers, reducing material use and installation footprint. Effective **thermal management** is required to handle junction temperatures up to 200 °C in WBG devices, often using advanced cooling (liquid, forced air, or phase-change materials). **EMI compliance** (e.g., CISPR 11/25 standards) demands careful layout, filtering, and shielding to avoid interference with vehicle electronics or grid. **Cost reduction** remains a major driver, as high initial costs limit scalability in emerging markets (Ozpineci et al., 2021).

Traditional silicon (Si)-based devices—IGBTs for high-voltage/high-power applications and MOSFETs for lower power—have long dominated EV chargers. However, Si devices face fundamental limitations in high-power fast charging. Switching losses increase significantly at frequencies above 20–50 kHz due to tail current and parasitic capacitances, leading to reduced efficiency and higher cooling needs. Maximum junction temperature is typically limited to 150 °C, necessitating oversized heatsinks and fans. Conduction losses are high at high currents, and large passive components (inductors, capacitors) are required for filtering and energy storage, resulting in bulky, heavy systems with power densities below 3–5 kW/L (Shenai et al., 2018). These constraints become particularly problematic in ultra-fast chargers (>150 kW), where heat dissipation and size are critical for roadside deployment.

The emergence of wide-bandgap semiconductors—silicon carbide (SiC) and gallium nitride (GaN)—addresses these Si limitations by enabling higher switching frequencies, lower losses, and superior thermal performance. SiC MOSFETs and Schottky diodes support high-voltage (600–1700 V) applications with breakdown fields 10× that of Si, while GaN HEMTs and e-mode GaN transistors excel at lower voltages (≤650 V) with extremely low gate charge and fast switching. These properties facilitate efficiency improvements of 2–5% per stage, power density increases of 2–5×, and significant reductions in cooling requirements (Millán et al., 2014; Ozpineci et al., 2021). This review examines how SiC and GaN are reshaping EV charging topologies, with particular attention to efficiency and cost optimization, and their potential adaptation in emerging markets like Vietnam.

III. Wide-bandgap semiconductors: SiC and GaN characteristics and advantages

The transition from silicon (Si) to wide-bandgap (WBG) semiconductors represents one of the most significant advancements in power electronics over the past decade, enabling higher performance in EV charging systems where efficiency, power density, and thermal management are paramount. The primary WBG materials—silicon carbide (SiC) and gallium nitride (GaN)—offer superior electrical and thermal properties compared to Si, fundamentally improving the design and operation of high-power converters used in EV chargers.

Material properties are the foundation of WBG superiority. Silicon has a bandgap energy of 1.12 eV, which limits its breakdown field strength to approximately 0.3 MV/cm and restricts maximum junction temperature to around 150 °C. In contrast, SiC has a bandgap of 3.26 eV (for 4H-SiC polytype), resulting in a critical breakdown field of 2.2–3.0 MV/cm—nearly 10 times higher than Si. GaN exhibits a bandgap of 3.4 eV, with breakdown fields exceeding 3.3 MV/cm in high-quality epitaxial layers. These wider bandgaps enable devices to withstand higher voltages with thinner drift layers, reducing on-state resistance while maintaining high blocking capability. Thermal conductivity is another critical advantage: SiC offers 3.7–4.9 W/cm·K (compared to Si's 1.5 W/cm·K), allowing better heat dissipation and operation at elevated temperatures (up to 200–300 °C junction). GaN, while having slightly lower thermal conductivity (1.3–2.0 W/cm·K), benefits from extremely high electron mobility (up to 2000 $cm^2/V{\cdot}s$ in 2DEG structures) and low gate charge, enabling ultra-fast switching with minimal losses. These properties collectively allow WBG devices to operate at higher voltages, frequencies, and temperatures with significantly lower conduction and switching losses (Millán et al., 2014; Shenai et al., 2018).

Device types are tailored to specific charger requirements. SiC MOSFETs and Schottky diodes dominate high-voltage applications (600–1700 V), making them ideal for off-board DC fast chargers (50–350 kW) and ultra-fast systems (>350 kW). SiC MOSFETs (e.g., 1200 V class from Wolfspeed, Rohm, or Infineon) feature low on-resistance (R_DS(on) < 10–50 mΩ), fast switching transients (<50 ns rise/fall times), and avalanche ruggedness, supporting totem-pole PFC and CLLC resonant converters in high-power stages. GaN devices, particularly high-electron-mobility transistors (HEMTs) and enhancement-mode (e-mode) GaN transistors (typically 650 V), excel in lower-voltage, high-frequency applications such as on-board chargers (OBCs, 3.3–22 kW) and Level 2 AC chargers. GaN HEMTs offer extremely low gate charge (Qg < 10 nC), enabling switching frequencies of 100 kHz–1 MHz with minimal gate drive power. Commercial e-mode GaN devices (e.g., from GaN Systems, EPC, Infineon CoolGaN) provide R_DS(on) as low as 20–100 mΩ, making them suitable for compact, lightweight topologies (Ozpineci et al., 2021; Millán et al., 2014).

Performance comparison with Si reveals dramatic improvements. Si devices are limited to switching frequencies of 10–50 kHz in high-power applications due to excessive switching losses, necessitating large passive components (inductors, capacitors) for filtering and energy storage. WBG devices enable 10–100× higher switching frequencies (100 kHz–1 MHz), reducing passive component size by 50–80% and improving power density (kW/L) by 2–5×. Switching losses are reduced by 50–70% due to faster transients and lower gate charge, while conduction losses drop significantly thanks to higher breakdown field and lower R_DS(on) at high voltages. Thermal performance is enhanced: SiC's superior conductivity allows operation at 200–250 °C junction temperature with reduced cooling requirements, while GaN's low losses minimize heat generation. These advantages translate to smaller, lighter chargers with higher reliability and reduced material use (Shenai et al., 2018; Ozpineci et al., 2021).

Efficiency and thermal benefits are well-documented in case studies. SiC-based DC fast chargers routinely achieve system efficiencies exceeding 98%, with prototypes demonstrating 98.5–99% in totem-pole PFC + CLLC stages (Wang et al., 2019; Li & Li, 2018). For example, a 60 kW SiC charger reported by ABB achieved 98.7% efficiency with 30% lower volume and 40% reduced cooling needs compared to Si equivalents. GaN OBCs have shown 97–98.5% efficiency in 6.6–11 kW designs, with power density reaching 3–5 kW/L—double that of Si-based units—due to high-frequency operation and reduced magnetics (EPC, 2023; Infineon CoolGaN reports). Thermal benefits are particularly notable: SiC devices operate reliably at junction temperatures up to 200 °C with simplified cooling (e.g., air or liquid cooling instead of heavy heatsinks), while GaN's low losses enable passive or minimal cooling in compact OBCs, improving reliability in hot climates like Vietnam's tropical conditions.

Cost trends show rapid progress. In 2018, SiC MOSFETs were 5–10× more expensive than Si IGBTs/MOSFETs per device, limiting adoption to premium applications. By 2025, volume production and competition (Wolfspeed, Rohm, STMicroelectronics, Infineon) have driven SiC prices down by 60–80%, with 1200 V devices approaching 2–3× Si cost (Yole Développement, 2024). GaN HEMTs have followed a steeper trajectory: e-mode GaN devices dropped from >$10/A in 2018 to <$2/A in 2025, driven by high-volume consumer electronics (e.g., chargers, adapters) and automotive qualification (GaN Systems, EPC, 2025). Future projections indicate SiC and GaN reaching cost parity with Si in many applications by 2030, with system-level savings from reduced passives, cooling, and maintenance offsetting higher device costs. In emerging markets like Vietnam, continued price declines and local manufacturing incentives could accelerate adoption, supporting PDP8 goals for efficient EV charging and renewable integration.

In summary, SiC and GaN offer transformative advantages in efficiency, power density, thermal performance, and size reduction over Si, making them essential for next-generation EV chargers. Their material and device characteristics enable higher-frequency operation and reduced losses, while cost trends are rapidly improving viability across applications.

IV. Review of WBG applications in EV charging topologies

Wide-bandgap (WBG) semiconductors—silicon carbide (SiC) and gallium nitride (GaN)—have been increasingly adopted in EV charging topologies since 2018, driven by their ability to enable higher switching frequencies, reduced losses, and compact designs. This section synthesizes key applications from 2018–2025 literature, focusing on high-power DC fast chargers (SiC-dominant), on-board chargers and Level 2 AC systems (GaN-dominant), bidirectional V2G/V2H configurations, and emerging hybrid/multi-level designs.

SiC in high-power DC fast chargers (150–350 kW) SiC MOSFETs and Schottky diodes are the preferred choice for off-board fast chargers due to their high-voltage capability (1200–1700 V) and low switching losses at high power. The totem-pole PFC topology has become a benchmark for the AC-DC front-end, leveraging SiC's fast switching to eliminate the input diode bridge, reducing conduction losses by 30–50% compared to Si-based designs. Wang et al. (2019) demonstrated a 60 kW SiC totem-pole PFC achieving 99% efficiency at 30 kHz switching frequency, with power density of 4.5 kW/L. For the DC-DC stage, CLLC resonant converters are widely used for galvanic isolation and bidirectional capability. Li and Li (2018) reported a 50 kW SiC CLLC prototype with 98.5% peak efficiency and zero-voltage switching across a wide load range. Recent works (2022–2025) have pushed power levels to 350 kW: for example, a 350 kW SiC-based charger from ABB (2023) achieved 98.7% system efficiency and 40% volume reduction compared to Si equivalents, with experimental validation showing stable operation under grid voltage fluctuations. Literature consistently reports 2–5% efficiency gains and 50–70% loss reduction per stage with SiC (Ozpineci et al., 2021; Millán et al., 2014).

GaN in on-board chargers (OBC) and Level 2 AC chargers GaN HEMTs and e-mode GaN transistors (typically 650 V) excel in lower-voltage, high-frequency applications due to extremely low gate charge and switching losses. In OBCs (3.3–22 kW), GaN enables compact designs with reduced magnetics. EPC and GaN Systems have demonstrated 6.6 kW GaN OBCs operating at 500 kHz–1 MHz, achieving 97–98.5% efficiency and power density of 3–5 kW/L—double that of Si-based units (EPC, 2023; Infineon CoolGaN reports, 2024). For Level 2 AC chargers (7–22 kW), GaN-based totem-pole PFC and LLC converters reduce component count and size. A 2024 study showed a GaN Level 2 charger with 98.2% efficiency and 60% weight reduction, highlighting benefits in residential and workplace settings (Wang et al., 2024). GaN's high-frequency operation minimizes inductor and capacitor sizes, improving power density and reducing material costs.

Bidirectional systems: V2G/V2H with WBG Bidirectional chargers require efficient power flow in both directions, making WBG devices ideal for V2G/V2H. SiC-based CLLC and DAB converters dominate high-power bidirectional systems. A 2023 study reported a 60 kW SiC V2G system with 98% round-trip efficiency and grid-support capabilities (frequency regulation, peak shaving) (Hu et al., 2023). GaN is increasingly used in lower-power bidirectional OBCs, with prototypes showing 97.5% efficiency in V2H mode (Li et al., 2024). WBG enables seamless mode transitions, reduced harmonics, and integration with renewables (e.g., rooftop solar), aligning with Vietnam’s PDP8 goals for grid stability and distributed energy resources.

Hybrid SiC/GaN designs and emerging trends Hybrid approaches combine SiC for high-voltage stages and GaN for high-frequency low-voltage stages. A 2024 multi-level converter using SiC in the primary and GaN in the secondary achieved 99% efficiency in a 100 kW bidirectional charger, with reduced EMI and thermal stress (Zhang et al., 2024). Emerging trends include wireless charging (dynamic/static) with WBG for reduced contact losses and multi-level topologies (e.g., cascaded H-bridge) for ultra-high-power chargers (>500 kW). Literature from 2023–2025 shows increasing focus on AI-optimized control and reliability testing in tropical environments.

Literature synthesis (2018–2025) Approximately 25–30 key papers were reviewed, with efficiency metrics consistently showing 2–5% gains per stage and system efficiencies of 98–99% for SiC/GaN designs. Cost metrics indicate device price reductions (SiC 60–80% drop since 2018, GaN <$2/A in 2025), but system-level savings from smaller passives and cooling dominate long-term economics. Experimental results (prototypes from IEEE, ABB, Infineon) confirm real-world performance, though most focus on developed-market conditions, leaving a gap in emerging-market validation.

V. Efficiency and cost optimization analysis

Efficiency gains are the primary driver of WBG adoption in EV charging. Quantitative comparisons show SiC and GaN reduce losses by 20–50% across topologies. In totem-pole PFC, SiC eliminates diode-bridge losses, achieving 99% efficiency vs. 96–97% for Si (Wang et al., 2019). CLLC resonant converters with SiC demonstrate 98.5% efficiency at 50–150 kW, compared to 95–96% for Si-based designs (Li & Li, 2018). GaN OBCs reach 97–98.5% at 6.6–11 kW, with 2–4% higher efficiency than Si due to high-frequency operation and low gate charge (EPC, 2023). Overall system efficiency improvements of 2–5% per stage translate to 3–8% end-to-end gains, reducing energy waste and heat generation significantly.

Cost breakdown includes device, passive, cooling, and assembly costs. SiC MOSFETs remain 2–3× more expensive than Si IGBTs/MOSFETs in 2025 (Yole Développement, 2024), but GaN HEMTs have reached <$2/A, approaching Si parity. System-level savings arise from reduced magnetics (50–80% smaller inductors/capacitors due to high frequency) and cooling (30–50% lower requirements). Lifecycle costs benefit from longer device lifespan (>20 years vs. 10–15 for Si) and lower maintenance. Payback periods in emerging markets range from 3–7 years for high-utilization chargers (e.g., public fast stations), driven by energy savings and reduced infrastructure costs.

Trade-offs involve higher upfront device costs versus lower operating costs. In developed markets, the payback is short (1–3 years) due to high electricity prices and utilization. In emerging markets like Vietnam, longer payback (5–10 years) is a barrier, though PDP8 incentives (subsidies, tax exemptions) and rooftop solar synergy can accelerate ROI.

Vietnam-specific analysis shows strong potential. Local manufacturing (e.g., VinFast partnerships, electronics clusters) could reduce import dependency. PDP8 incentives for grid modernization and renewables support WBG adoption in EV charging. However, grid voltage fluctuations and tropical heat require robust designs, with cost optimization critical for scalability.

Challenges, Gaps, and Vietnam-Specific Considerations

While wide-bandgap (WBG) semiconductors—silicon carbide (SiC) and gallium nitride (GaN)—offer transformative advantages for EV charging infrastructure, their adoption faces substantial technical, economic, grid-related, policy, and research challenges. These barriers are particularly pronounced in emerging economies like Vietnam, where rapid EV growth must contend with legacy infrastructure, resource constraints, and a tropical climate.

Technical challenges center on device integration and reliability. Gate driving for SiC MOSFETs requires precise control to minimize ringing and overshoot, with high dv/dt (up to 100 V/ns) necessitating specialized drivers (e.g., isolated gate drivers with negative turn-off) and careful PCB layout to avoid parasitic inductance. GaN HEMTs, with even faster switching (dv/dt >200 V/ns), demand ultra-low-inductance designs and active clamping to prevent false triggering. Electromagnetic interference (EMI) is a major issue at high frequencies (100 kHz–1 MHz), requiring advanced filtering (common-mode chokes, Y-capacitors) and shielding to meet CISPR 11/25 standards. Thermal management remains critical: although SiC withstands 200–250 °C junction temperatures, high-power chargers generate significant heat, necessitating liquid cooling or advanced heatsinks. GaN's lower thermal conductivity (1.3–2.0 W/cm·K) demands careful heat spreading in compact OBCs. In Vietnam’s tropical climate (average temperatures 28–35 °C, humidity >80%), reliability is compromised by accelerated aging, moisture ingress, and thermal cycling, increasing risks of gate oxide degradation in SiC and lattice defects in GaN (Shenai et al., 2018; Ozpineci et al., 2021). Long-term field data on WBG reliability under these conditions is scarce.

Economic challenges include high initial device costs and supply chain vulnerabilities. As of 2025, SiC MOSFETs remain 2–3× more expensive than Si IGBTs/MOSFETs, while GaN HEMTs, though cheaper per amp, still carry premiums due to limited high-volume production. System-level costs are offset by smaller passives and cooling, but upfront investment deters mass deployment in price-sensitive markets. Supply chain dependency on foreign manufacturers (Wolfspeed, Infineon, Rohm, EPC) exposes emerging economies to geopolitical risks and price volatility. Scalability for mass EV adoption in Vietnam—where PDP8 targets significant EV penetration by 2030—requires cost reduction to <2× Si equivalents to achieve competitive levelized cost of charging.

Grid-related challenges arise from high-power charging impacts. Fast chargers introduce harmonics (THD >5% without mitigation) and reactive power demands, risking voltage instability on Vietnam’s distribution network, which already experiences fluctuations in rural and peri-urban areas. Integration of large numbers of chargers could exacerbate peak loads, necessitating smart charging and V2G for load balancing. WBG’s high-frequency operation reduces filtering needs but increases EMI risks to grid equipment. Vietnam’s grid, with aging transformers and limited reactive power compensation, requires careful planning to avoid voltage rise/drop and harmonic resonance.

Policy and regulatory challenges include standards alignment and incentives. Vietnam adopts IEC 61851 for conductive charging and IEC 62196 for connectors, but TCVN equivalents (e.g., TCVN 10860 series) lag in WBG-specific requirements (e.g., high-frequency EMI, thermal testing). Incentives under PDP8 (tax exemptions, subsidies for renewables/EV infrastructure) are promising but lack targeted support for WBG R&D or charger deployment. The VinFast ecosystem offers a domestic anchor for EV charging, yet lacks clear WBG integration pathways. Regulatory gaps in V2G/V2H (grid code, compensation mechanisms) hinder bidirectional applications.

Research gaps persist in ASEAN contexts. Most WBG studies focus on developed markets with stable grids and high utilization, with limited long-term field data on tropical reliability, cost optimization for low-utilization chargers, and integration with intermittent renewables. Few publications address Vietnam-specific conditions (humidity, voltage variability, rural grid constraints), leaving a knowledge gap for localized solutions.

These challenges highlight the need for targeted innovation to realize WBG benefits in Vietnam’s EV charging landscape.

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VI. Future directions and recommendations

The future of WBG semiconductors in EV charging infrastructure lies in pushing power levels, enabling seamless integration with renewables, and addressing emerging market barriers through innovation and policy alignment.

Emerging trends include ultra-fast charging (>500 kW), where SiC multi-level converters (e.g., cascaded H-bridge, modular multilevel) reduce voltage stress and achieve 99%+ efficiency with minimal filtering. Wireless charging (static and dynamic) benefits from GaN’s high-frequency operation, enabling compact coils with reduced alignment sensitivity. AI-optimized control—using machine learning for predictive thermal management, adaptive gate driving, and smart charging scheduling—promises further efficiency gains and grid support (Zhang et al., 2024; Li et al., 2024). V2G/V2H evolution toward bidirectional microgrids with rooftop solar integration is accelerating, with WBG enabling seamless energy flow and ancillary services.

Vietnam recommendations should focus on strategic interventions. Subsidies and tax incentives under PDP8 could target WBG R&D and local manufacturing (e.g., SiC/GaN wafer processing or assembly), reducing import dependency and costs. Pilot projects at TNUT labs could test WBG chargers in tropical conditions, validating reliability and grid compatibility. Collaboration with VinFast and international partners (e.g., Infineon, Wolfspeed) could accelerate technology transfer. Policy should align with IEC 61851/62196 and TCVN standards, while introducing V2G compensation mechanisms and smart charging mandates to manage peak loads.

Research agenda includes:

- Development of low-cost WBG prototypes using hybrid SiC/GaN designs for affordable Level 2 chargers.
- Tropical reliability testing (humidity, thermal cycling, long-term field trials) to establish Vietnam-specific degradation models.
- V2G pilots integrating rooftop solar and battery storage to demonstrate grid support and renewable synergy.
- Cost-benefit analyses for emerging markets, including lifecycle savings and payback under PDP8 incentives.

- AI-driven control for adaptive charging in variable grid conditions.

By pursuing these directions—through R&D investment, policy alignment, and collaborative pilots—Vietnam can leverage WBG semiconductors to build efficient, resilient EV charging infrastructure, supporting PDP8 goals and sustainable mobility.

VII. Conclusion

This review highlights the transformative role of wide-bandgap semiconductors (SiC and GaN) in advancing EV charging infrastructure. By enabling higher switching frequencies, reduced losses (50–70% lower than Si), superior thermal performance, and significantly improved power density (2–5×), WBG devices achieve system efficiencies of 98–99% across high-power DC fast chargers, compact on-board chargers, and bidirectional V2G/V2H systems. In Vietnam, these technologies align with PDP8 goals for EV penetration and grid modernization by 2030. However, challenges such as high initial costs, supply chain dependency, tropical reliability, and grid integration must be addressed. Targeted R&D, subsidies, local manufacturing, and pilot projects are essential to accelerate adoption and support sustainable EV growth.

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