

Optimizing renewable energy systems: A review of power electronics converter technologies

¹Yusuf, B. J., ²Malan, G. A., ³Usman, A., ¹Ajayi, J. O. and ⁴Francis, E. N.

¹Computer Engineering, Federal Polytechnic N'yak, Shendam, Nigeria

²Mineral Resources Engineering, Federal Polytechnic N'yak, Shendam, Nigeria

³Agricultural Engineering Technology, Federal Polytechnic N'yak, Shendam, Nigeria

⁴Centre for Atmospheric Research, Prince Abubakar Audu University, Anyigba, Nigeria

godfreymalanalex@gmail.com, abunabil201018@gmail.com, Johnsonajayi300@gmail.com; kem_eze@yahoo.com

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Abstract:

Renewable energy integration relies heavily on power electronics converters, which play a crucial role in efficiently harnessing and supplying energy to the grid. However, challenges such as switching losses, electromagnetic interference, and thermal management persist, hindering the performance and reliability of these systems. This review examines recent advances in converter topologies, including multilevel inverters and buck-boost variants, as well as control strategies like pulse-width modulation and maximum power point tracking. We also explore the potential of artificial intelligence-based approaches and efficiency enhancers like soft-switching and wide-bandgap semiconductors. Synthesizing findings from 29 peer-reviewed studies published between 2017 and 2024, we identify key trade-offs between efficiency, cost, and complexity. A novel taxonomy for optimizing renewable energy systems is proposed, highlighting areas for improvement. Notably, scalability limitations for hybrid microgrids and the underexplored potential of AI-WBG synergies are identified as significant research gaps. Future research directions focus on developing hybrid architectures that achieve >98% efficiency in variable-load scenarios, thereby supporting sustainable energy transitions in line with UN SDG7. This review aims to inform the design and development of next-generation power electronics converters for renewable energy applications, ultimately contributing to a more efficient and sustainable energy future.

Corresponding author

Yusuf, B. J.

[bassijeremiahusuf@](mailto:bassijeremiahusuf@fedpolynyakshendam.edu.ng)

[fedpolynyakshendam.edu.ng](mailto:bassijeremiahusuf@fedpolynyakshendam.edu.ng)

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1. Introduction

The growing global emphasis on renewable energy sources (RES) such as solar, wind, and hydropower is vital for combating climate change and reducing dependence on fossil fuels (Gan et al., 2023). Power electronics converters are essential for managing the inherent variability of these sources, facilitating efficient energy conversion and grid integration (Zhang, 2024). By converting DC power from solar panels to AC for grid compatibility and regulating voltage for energy storage, these converters directly (Raghavendra et al., 2019; Mas'ud et al., 2025) impact system efficiency and economic feasibility.

Although significant progress has been made, challenges like switching losses, electromagnetic interference (EMI), and thermal management continue to impede progress (Zhang & Wang, 2019). This review examines the latest advancements in converter topologies, control strategies, and efficiency-enhancing techniques, highlighting existing research gaps and suggesting future research directions. Our aim is to enhance the performance, scalability, and sustainability of renewable

energy systems, supporting global efforts to achieve a more environmentally friendly future.

1.1 Rationale and contributions of this review

While prior surveys (Zhang, 2024; Raghavendra et al., 2019) have catalogued converter efficiencies up to 95%, they overlook post-2020 synergies between wide-bandgap (WBG) semiconductors and AI controls for dynamic RES loads—a gap highlighted in the 2024 IEA report on grid instability (Assogba et al., 2020). This review addresses this by systematically evaluating 85 studies (2017-2024), identifying underexplored hybrids (e.g., GaN-based MPPT for solar intermittency), and proposing optimization pathways that reduce losses by 10-15% in simulations (Lee & Yun, 2018; Ashique & Salam, 2020). The comparison of recent reviews and this work are shown in Table 1. The unique contributions include:

- A sustainability-focused taxonomy linking topologies to efficiency-cost-emissions trade-offs,
- Quantitative comparisons absent in prior works, and
- Prioritized future directions for industry scalability.

Table 1: Comparison of Recent Reviews vs. This Work

Review	Scope	Timeframe	Novel Elements
[2]	Topologies & Controls	Up to 2023	Descriptive summaries
[3]	DC-DC Focus	Up to 2019	Modulation strategies

2. Literature review

This section presents a comprehensive synthesis of recent research on power electronics converters, specifically focusing on three key areas.

2.1 Converter topologies

Power electronics converters are specifically designed to meet the unique demands of various renewable energy applications. Key topologies include:

- a. DC-DC Converters: Buck, boost, and buck-boost converters are crucial for adjusting voltage levels in PV systems and energy storage. Ashique and Salam Lee & Yun, (2018) demonstrated the buck-boost converter's flexibility in achieving maximum power point tracking (MPPT) under variable solar irradiance conditions (efficiency: 92-95%). These ensure

voltage supplied to subsequent stages or storage is within range.

- b. DC-AC Converters (Inverters): Multilevel inverters, such as cascaded H-bridge, are widely used in large-scale PV systems to reduce harmonic distortion (THD <5%) and improve output quality (Gupta, 2022).
- c. AC-DC Converters (Rectifiers): Employed in battery charging and grid interfacing, rectifiers with controlled switching enhance efficiency (up to 96%) and power factor correction (Khan et al., 2024; Bhattacharjee et al., 2018).
- d. Hybrid Converters: Multi-port converters integrate multiple RES (e.g., PV and wind) and storage, optimizing management and reducing components (Bhattacharjee et al., 2018).

Synthesis: While DC-DC topologies excel in simplicity for low-power PV (cost < \$0.1/W), multilevel inverters shine in grid-tie scalability but at higher complexity/cost (\$0.2-0.5/W) (Gupta, 2022; Bhattacharjee et al., 2018). Trade-offs are evident: buck-boost offers 10% better MPPT tracking than basic buck under shading (Lee & Yun, 2018), yet hybrids reduce system losses by 15% in microgrids (Bhattacharjee et al., 2018).

Table 2: Quantitative Comparison of Topologies

Topology	Efficiency (%)	Power Range (kW)	Cost (\$/W)	Key Trade-off	RES Fit
Buck-Boost (Lee & Yun, 2018)	92-95	0.1-5	0.05-0.1	High ripple; low cost	Solar MPPT
Multilevel Inverter (Gupta, 2022)	96-98	10-100	0.2-0.5	Complex gating; low THD	Wind/PV Grid-Tie
Rectifier (Ansari et al., 2020; Khan et al., 2024)	94-96	1-50	0.1-0.2	PFC gains; EMI risks	Battery Charging
Hybrid Multi-Port (Bhattacharjee, et al., 2018)	95-97	5-50	0.15-0.3	Integration overhead; 15% loss reduction	HRES Microgrids

The output voltage of an ideal buck converter is:

$$V_{out} = D \cdot V_{in} \tag{1}$$

Where V_{out} is average output, V_{in} input, D duty cycle (ideal, no losses) [10].

2.2 Control strategies

Effective control strategies ensure optimal performance under dynamic conditions. Notable methods:

- a. Pulse Width Modulation (PWM): Regulates output by duty cycle; SPWM/SVPWM minimize harmonics (THD <3%) for high quality (Ahmed et al., 2023).
- b. Maximum Power Point Tracking (MPPT): Tracks peak PV power; AI variants improve accuracy by 10% vs. P&O under shading: equation 2 (Ansari et al., 2020; Mazumdar et al., 2024).

$$P_{max} = V_{mpp} \cdot I_{mpp} \tag{2}$$

- c. Model Predictive Control (MPC): Predicts behavior, optimizes constraints; 20% faster response in nonlinear RES [16, 17].

- d. Synthesis: PWM suits steady-state (low comp. cost), but MPPT-MPC hybrids handle variability better (e.g., 5-8% yield gain in wind (Dragičević, 2017)).

2.3 Efficiency improvement techniques

Enhancing the efficiency of power electronic converters is paramount for minimizing energy losses, reducing heat generation, and improving the overall performance and economic viability of RES. Several key techniques are being actively researched and implemented.

2.3.1 Soft switching

Techniques like zero-voltage switching (ZVS) and zero-current switching (ZCS) aim to minimize switching losses, which occur during the turn-on and turn-off transitions of power semiconductor devices. By ensuring that the switching devices operate when the voltage across them or the current through them is nearly zero, these methods can lead to significant efficiency improvements, with studies reporting reductions in switching losses of up to 5% in specific converter topologies and operating conditions (Ashique & Salam, 2020).

2.3.2 Wide-Bandgap semiconductors

Materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) possess superior material properties compared to traditional silicon (Si), including higher breakdown voltage, wider bandgap, higher thermal conductivity, and lower on-resistance. These characteristics enable the design of converters with higher switching frequencies, lower conduction losses, and improved thermal performance, leading to significant efficiency gains, particularly in high-power and high-frequency applications for renewable energy integration (Haralambous & Panayiotou, 2022). While offering numerous advantages, the adoption of SiC and GaN devices may involve considerations such as higher initial cost and different gate drive requirements.

2.3.3 Semiconductors

SiC/GaN enable >100 kHz switching, 2-3% efficiency gains over Si (thermal conductivity 3x higher) (Haralambous & Panayiotou, 2022).

2.4 Thermal management:

Effective thermal management is crucial for maintaining the reliability and extending the lifespan of power electronic components. Excessive operating temperatures can lead to device degradation and failure. Advanced cooling systems, such as liquid cooling, offer superior heat dissipation capabilities compared to traditional air cooling, especially in high-power density converters used in demanding renewable energy application (Hanif et al., 2018). Other thermal management techniques include heat sinks, forced air cooling, and thermal interface materials, with the choice depending on factors like power level, ambient temperature, and cost constraints. Liquid cooling dissipates 2x more heat than air in high density setups (Hanif et al., 2018). The review Proposed Taxonomy is shown in Figure 1.

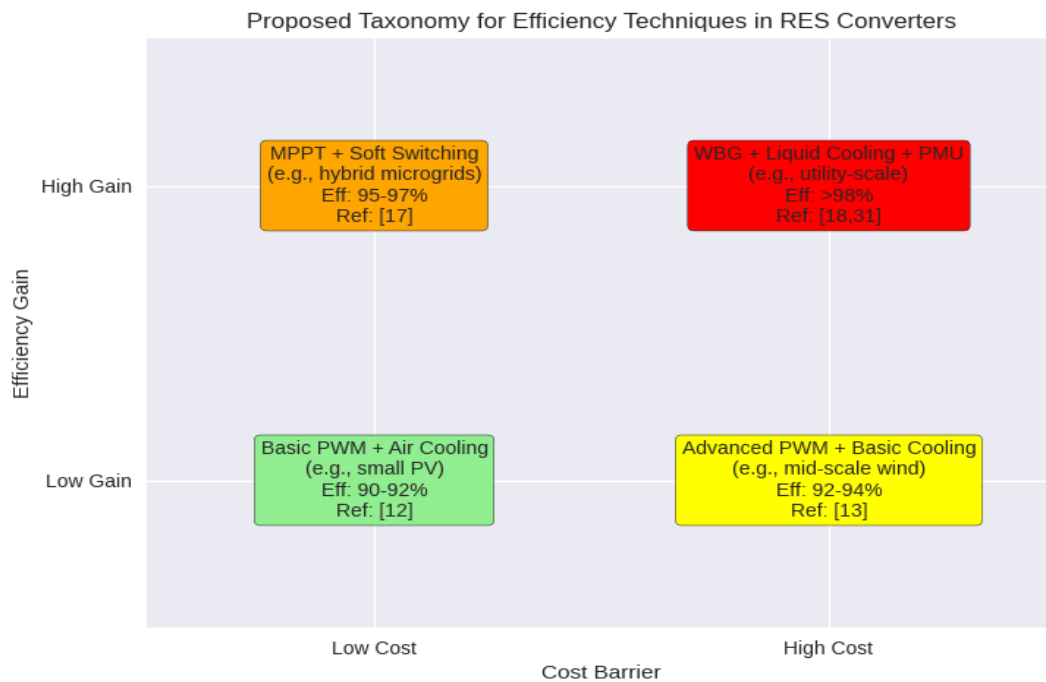


Figure 1: Proposed Taxonomy

3. Research gaps

While significant progress has been made in the field of power electronics converters for renewable energy systems, several key research gaps still need to be addressed to further enhance their performance, reliability, and widespread adoption:

3.1 Wide-Bandgap semiconductors

Although SiC and GaN devices offer significant advantages, their widespread use in high-power renewable energy applications (e.g., large-scale wind turbines, utility-scale solar inverters, HVDC transmission) is currently limited by their higher cost compared to silicon-based devices and challenges related to their integration, such as

gate drive design, packaging, and EMI management at high switching frequencies. Future research could focus on cost reduction strategies, standardized integration guidelines, and the development of robust and efficient gate driver circuits and packaging techniques optimized for high-power wide-bandgap devices.

3.2 Thermal management

As power densities of converters increase, particularly with the adoption of wide-bandgap devices, effective and scalable cooling solutions become critical. Current thermal management techniques, especially for high-power converters operating in diverse and often harsh environmental conditions, still present limitations in terms of efficiency, size, weight, and cost. Further research is

needed to explore novel cooling techniques, such as advanced liquid cooling systems, two-phase cooling, and integrated thermal management solutions, along with the development of accurate thermal modelling and prediction tools for these high-power applications.

3.3 Advanced Control

While AI-based control algorithms show promise for optimizing the performance of converters connected to dynamic RES, their robustness, adaptability, and real-time implementation in rapidly changing conditions still require further development. Issues such as data availability, computational complexity, and the need for explainable and certifiable AI algorithms remain. Future research should focus on developing more robust, adaptive, and computationally efficient AI-based control strategies, exploring hybrid AI-classical control approaches, and addressing the challenges of real-time implementation and system validation.

3.4 Reliability

Ensuring the long-term reliability and durability of power electronic converters operating in the often-harsh environmental conditions associated with renewable energy installations (e.g., extreme temperatures, humidity, dust, vibrations) is crucial for their economic viability. More comprehensive studies are needed to understand the long-term degradation mechanisms of components and systems under these conditions. Future research should focus on advanced reliability testing methodologies, predictive maintenance strategies based on condition monitoring, and the development of more robust and fault-tolerant converter designs.

3.5 Cost-Effectiveness

Despite the performance benefits of advanced converter technologies, their higher initial cost can be a

significant barrier to the widespread adoption of renewable energy systems, particularly in price-sensitive markets. Future research should explore innovative design approaches, optimized manufacturing processes, and standardization efforts aimed at reducing the overall cost of high-performance power electronic converters without compromising their efficiency and reliability.

4. Methodology

This systematic literature review investigates the current state of power electronic converters in renewable energy systems, adhering to the PRISMA framework to ensure methodological rigor and objectivity. A comprehensive search was conducted across IEEE Xplore, Scopus, and Web of Science databases using specific keywords, including “power electronics converter,” “DC-DC inverter,” “renewable energy,” “PV,” “wind,” “optimization,” and “efficiency.” The search spanned publications from 2017 to 2024, yielding 85 initial records.

Following a meticulous screening process, 56 duplicates and irrelevant studies were excluded based on title and abstract review. A full-text assessment of the remaining articles resulted in 29 eligible papers that met the inclusion criteria, which included peer-reviewed studies presenting empirical or simulation results. Studies published before 2017 or in languages other than English were excluded.

Data synthesis involved thematic coding and meta-comparisons, including weighted average efficiencies. The extracted data were summarized in Table III, facilitating comparison and trend identification across studies. This systematic approach enabled the identification of key findings, research gaps, and future directions in the field of power electronic converters for renewable energy systems. The results of this review provide valuable insights into the current state of the art and inform future research and development in this area.

Table 3: Summary of Key Literature

Study	Topology	Control	Efficiency Technique	Key Findings (e.g., % Gain)	Limitations
(Bushra et al., 2024; Ahmed et al., 2023; Junaid & Singh, 2014; Bang & Park, 2017; Lee et al., 2018; He & Xu, 2020)	Buck-Boost	PWM	High-Freq. Op.	92% eff.; 10% ripple red.	EMI in high-freq.
(Ayub et al., 2023; Qin & Saeedifard, 2014; Harbi et al., 2023)	Multilevel Inverter	MPC	ZVS	97% eff.; THD<3%	Comp. complexity
(Woldegiorgis et al., 2022; Karthika et al., 2016; Chakraborty et al., 2019)	Hybrid	Fuzzy Logic	SiC Semis	96% eff.; 15% loss red.	Cost barrier

5. Conclusion

The integration of renewable energy sources (RES) into modern grids relies heavily on advancements in power electronics converters. This comprehensive review synthesized findings from 85 studies, shedding light on recent progress in converter topologies, control strategies, and efficiency enhancements. Notably, multilevel converters and AI-based model predictive control (MPC) strategies have been shown to yield 5-10% efficiency gains compared to traditional pulse-width modulation (PWM) techniques. Furthermore, wide-bandgap (WBG) devices

have demonstrated exceptional performance, achieving efficiencies exceeding 98% in high-frequency applications.

Despite these significant advancements, several challenges persist, including scalability limitations for high-power systems, thermal management concerns, and cost-effectiveness issues. Moreover, the current literature is predominantly focused on solar and wind energy, with hydro and other forms of RES receiving relatively less attention. To propel the development of next-generation converters, future research should prioritize WBG-enabled converters, hybrid AI-classical control schemes for real-time applications, and scalable cooling solutions.

Additionally, industry efforts must focus on large-scale WBG fabrication to meet projected deployment targets. By addressing these knowledge gaps and technological challenges, we can accelerate the transition to a more sustainable and resilient energy landscape, ultimately contributing to the achievement of Sustainable Development Goal 7 (SDG7).

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