

Techno-Economic Analysis of Power Electronics-Based Renewable Energy Systems

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ABSTRACT

The integration of power electronics in renewable energy systems has significantly improved their efficiency, reliability, and grid compatibility. With the rising global demand for clean energy, power electronics play a crucial role in optimizing energy conversion, grid interfacing, and economic feasibility. Modern renewable energy systems, including solar photovoltaic (PV), wind, and hybrid energy systems, rely heavily on advanced power electronic devices such as inverters, converters, and maximum power point tracking (MPPT) controllers to enhance performance and ensure stable operation.

This review explores the latest technological advancements in power electronics, focusing on wide-bandgap semiconductor materials, highefficiency DC-DC converters, and multilevel inverters for seamless grid integration. Additionally, emerging AI-driven energy management systems, bidirectional converters, and hybrid energy storage solutions are discussed in the context of their potential to improve overall system efficiency. The review further presents a comprehensive technoeconomic analysis, assessing capital costs, operational efficiency, levelized cost of energy (LCOE), and return on investment (ROI) in power electronics-based renewable energy systems.

Despite the significant benefits, several challenges hinder widespread adoption, including high initial investment costs, thermal management issues, power quality disturbances, and reliability concerns associated with electronic components. The integration of smart grid technologies and demand-side management strategies is essential to overcoming these barriers and improving system scalability. The findings suggest that continuous research and development in power electronics can drive cost reductions, enhance energy sustainability, and facilitate the global transition towards a low-carbon future.

Keywords: Power Electronics, Renewable Energy Systems, Solar Photovoltaic (PV), Maximum Power Point Tracking (MPPT)

Introduction

The transition to renewable energy sources is driven by the need to mitigate climate change, reduce dependence on fossil fuels, and enhance energy security. The growing global demand for electricity, coupled with concerns about carbon emissions and the depletion of conventional energy resources, has accelerated the adoption of renewable energy technologies. Solar photovoltaic (PV), wind, and

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hybrid energy systems have gained significant traction due to their sustainability, decreasing costs, and government incentives promoting clean energy deployment.¹ However, the inherent variability and intermittency of these energy sources pose significant challenges to maintaining grid stability and ensuring a reliable power supply.²

Power electronics-based renewable energy systems play a crucial role in addressing these challenges by enabling efficient energy conversion, flexible power control, and seamless grid integration. These systems incorporate various advanced technologies such as DC-DC converters, inverters, maximum power point tracking (MPPT) controllers, and grid-supportive technologies like static synchronous compensators (STATCOMs) and battery energy storage systems (BESS).³The development of highperformance power electronic converters, incorporating wide-bandgap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN), has significantly improved energy efficiency and reduced losses in renewable energy applications.

In addition to technological advancements, the technoeconomic viability of power electronics-based renewable energy systems is a critical factor in their large-scale deployment. Factors such as capital investment, operational efficiency, levelized cost of energy (LCOE), and payback periods influence the financial feasibility of these systems. While renewable energy costs have declined over the past decade, power electronics components still contribute significantly to the overall system cost, necessitating continuous research to develop cost-effective solutions without compromising performance and reliability.

This review presents a comprehensive analysis of the role of power electronics in renewable energy systems, focusing on both technological advancements and economic feasibility. The study explores innovations in power conversion, energy management, and grid integration while assessing key economic parameters that impact decision-making in renewable energy investments. By highlighting both opportunities and challenges, this review provides insights into the future trajectory of power electronics-based renewable energy systems and their potential to drive the global transition towards a sustainable energy future.

Technological Advancements in Power Electronics for Renewable Energy

The rapid growth of renewable energy deployment has driven innovations in power electronics to enhance energy conversion efficiency, system reliability, and grid stability. Advanced power conversion technologies, control strategies, and smart grid integration solutions have played a pivotal role in optimizing the performance of solar, wind, and hybrid renewable energy systems. The continuous development of wide-bandgap semiconductors, modular converter architectures, and artificial intelligence (AI)driven controllers is revolutionizing power electronics applications in the renewable energy sector.

Power Conversion Technologies

Efficient power conversion is essential for maximizing the energy output of renewable energy sources. Various power electronic devices, including converters, inverters, and controllers, are employed to ensure seamless energy conversion and grid integration. Innovations in power conversion technologies focus on improving efficiency, reducing power losses, and enhancing system resilience against electrical and environmental fluctuations.

DC-DC Converters

DC-DC converters are critical in solar PV systems for voltage regulation, power conditioning, and maximum power point tracking (MPPT) implementation. These converters ensure the optimal operation of PV modules by matching the load impedance with the source characteristics, thereby improving energy extraction.

- Traditional converters such as buck, boost, and buckboost converters have been widely used in renewable energy systems. However, they suffer from efficiency losses at high power levels due to switching losses and conduction losses.
- Advanced resonant converters, such as the zerovoltage switching (ZVS) and zero-current switching (ZCS) topologies, reduce switching losses and improve efficiency.
- Interleaved converters distribute the current among multiple phases, minimizing ripple effects and reducing stress on power semiconductor devices.⁴

Modern research focuses on high-frequency soft-switching converters that leverage SiC and GaN semiconductors, achieving higher power densities and better thermal performance compared to traditional silicon-based devices.

Inverters for Grid Integration

Grid-tied inverters are responsible for converting DC power from renewable sources into AC power for seamless distribution and integration into the electrical grid. The efficiency and reliability of these inverters significantly influence the overall performance of renewable energy systems.

- Traditional two-level inverters are widely used but have limitations in high-power applications due to increased switching losses and harmonic distortion.
- Multilevel inverters, such as neutral-point clamped (NPC), flying capacitor (FC), and modular multi-level converters (MMC), have emerged as more efficient

grid-compatible AC power. They enable maximum energy capture and improve system reliability.⁷

- Doubly-Fed Induction Generators (DFIG): The DFIG topology, combined with power electronic converters, supports active and reactive power control, enhances power quality, and reduces mechanical stress on wind turbines. This approach is widely used in offshore and large-scale wind farms due to its cost-effectiveness and efficiency.8
- Fault Ride-Through (FRT) Capabilities: Advanced power converters in wind energy systems improve system resilience against voltage dips, grid disturbances, and transient faults, ensuring grid code compliance and stable operation.9

The integration of AI-based predictive maintenance and digital twin technology in wind turbine power electronics is further enhancing performance monitoring and fault detection, leading to improved reliability and reduced downtime.

Hybrid Renewable Energy Systems (HRES)

Hybrid renewable energy systems (HRES) combine multiple renewable energy sources, such as solar, wind, and hydro, along with energy storage solutions to enhance reliability, stability, and energy security. Power electronics play a key role in managing the energy flow and optimizing system performance.

- Hybrid Converters: These devices integrate multiple energy sources and enable bidirectional power flow between storage units and the grid. Advanced hybrid converters reduce conversion losses and improve energy management in microgrid applications.¹⁰
- Microgrid Controllers: Al-powered smart energy management systems utilize real-time data analytics, IoT connectivity, and machine learning algorithms to optimize load balancing, grid synchronization, and energy dispatch.¹¹
- Hybrid MPPT Strategies: In multi-source hybrid systems, dynamic MPPT techniques ensure the optimal utilization of available energy sources by dynamically adjusting the operating points of different generation units.

Table 1 presents a comparative analysis of power conversion technologies used in renewable energy systems, highlighting their efficiency, cost, and suitability for different applications. Table I.Comparison of Power Conversion Technologies for Renewable Energy Systems

alternatives for high-power renewable energy applications. These topologies offer lower harmonic distortion, improved power quality, and enhanced fault-tolerant capabilities.5

Grid-forming inverters play a crucial role in integrating renewable energy sources with microgrids, ensuring voltage and frequency stability under varying load and generation conditions.

Emerging smart inverters equipped with AI-based predictive control and Internet of Things (IoT) connectivity facilitate real-time optimization of grid interactions, enhancing renewable energy utilization and grid stability.

Maximum Power Point Tracking (MPPT) Controllers

MPPT algorithms are crucial for optimizing the energy harvesting efficiency of solar and wind energy systems. These controllers continuously track and adjust the operating point of the system to extract the maximum available power under changing environmental conditions.

- Conventional MPPT techniques, such as Perturb and Observe (P&O) and Incremental Conductance (IC), are widely used due to their simplicity and ease of implementation. However, they exhibit slow tracking speeds and may struggle with rapidly fluctuating solar irradiance and wind speeds.
- AI-based MPPT strategies, including fuzzy logic controllers (FLC), neural networks (NN), and reinforcement learning, offer improved tracking accuracy and faster response times by adapting to complex and nonlinear system dynamics.⁶
- Hybrid MPPT approaches, combining conventional algorithms with AI-driven optimization techniques, enhance efficiency and system robustness in diverse operating conditions.

Power Electronics in Wind Energy Systems

Wind energy conversion systems (WECS) require efficient power electronics solutions to handle variable wind speeds, fluctuating power generation, and grid integration challenges. Power converters and control mechanisms ensure smooth energy transfer while maintaining stability in wind farms.

Full-Scale Frequency Converters: These converters allow variable-speed wind turbines to operate efficiently by converting variable AC frequencies into

Multilevel Inverters (NPC, MMC)	96–99	High	Grid-Tied Renewable Systems	Low harmonics, high power quality	High component count
Hybrid Converters	90–97	Medium- High	Hybrid Renewable Systems	Efficient multi- source integration	Control complexity
AI-Based MPPT Controllers	97–99	Medium	Solar, Wind Energy Systems	Fast tracking, adaptable to changes	Computationally intensive

Techno-Economic Analysis of Power Electronics-Based Renewable Energy Systems

The techno-economic feasibility of power electronicsbased renewable energy systems is determined by factors such as capital and operational costs, energy efficiency, levelized cost of energy (LCOE), payback period, and return on investment (ROI). As power electronics play a critical role in energy conversion and grid integration, their impact on the overall system cost and performance must be carefully evaluated. Recent advancements in wide-bandgap semiconductors, high-frequency switching, and intelligent control systems have improved efficiency and reduced costs, but challenges remain in scalability, maintenance, and economic competitiveness with conventional energy sources.

Capital and Operational Costs

Power electronics contribute significantly to the total cost of renewable energy installations, making it necessary to balance performance, durability, and affordability for widespread adoption.

- Inverter and Converter Costs: High-efficiency converters and inverters constitute 20–30% of the total system cost in solar and wind power installations. Advanced technologies such as multilevel inverters, soft-switching converters, and SiC/GaN-based power devices offer improved efficiency but come at a higher cost.¹²
- Installation and Maintenance Costs: The complexity of power electronics in grid-tied and hybrid renewable energy systems increases installation expenses. Proper thermal management, electromagnetic compatibility (EMC) shielding, and real-time monitoring systems add to initial costs. Maintenance involves component replacements, firmware updates, and fault diagnostics, contributing to operational expenses over time.¹³
- Energy Storage Integration Costs: Renewable energy systems combined with battery storage require additional power electronics for bidirectional energy

flow, battery management, and grid synchronization, increasing capital expenditures. The cost of battery inverters and DC-DC converters significantly influences the feasibility of hybrid renewable energy systems.

Levelized Cost of Energy (LCOE)

LCOE is a crucial metric for assessing the economic viability of renewable energy systems. It is calculated as:

LCOE=TotalLifetimeCostTotalEnergyGeneratedLCOE = \frac{Total Lifetime Cost}{Total Energy Generated} LCOE=TotalEnergyGeneratedTotalLifetimeCost

- Solar PV Systems: The LCOE of solar PV systems has significantly declined in recent years due to improvements in photovoltaic efficiency, power electronics optimization, and economies of scale. Current LCOE values range between \$0.05-\$0.10/ kWh, depending on location, technology, and financing structures.¹⁴ High-efficiency MPPT algorithms, transformerless inverter designs, and grid-supportive inverters have contributed to cost reductions.
- Wind Energy Systems: The LCOE of wind power varies based on onshore vs. offshore deployment.
- **Onshore wind:** LCOE ranges from \$0.03-\$0.08/kWh, making it competitive with fossil fuels.
- Offshore wind: LCOE is higher (\$0.08-\$0.15/kWh) due to complex maintenance, harsh environmental conditions, and expensive power converters required for long-distance grid integration.¹⁵
- Hybrid Renewable Energy Systems (HRES): Hybrid systems incorporating solar, wind, and battery storage exhibit an LCOE range of \$0.07-\$0.12/kWh, depending on the energy mix and storage technology. Advanced hybrid energy management systems (HEMS) and Aldriven load forecasting can optimize energy dispatch and reduce costs.

Table 2 compares the LCOE of different renewable energy systems and highlights the influence of power electronics advancements on cost reduction.

Renewable Energy System	LCOE (\$/kWh)	Key Factors Influencing LCOE	Impact of Power Electronics
Solar PV (Utility-Scale)	0.05-0.10	Panel efficiency, inverter technology, MPPT control	High-efficiency inverters and MPPT reduce LCOE
Onshore Wind	0.03–0.08	Wind speed, turbine design, power converter efficiency	Advanced frequency converters improve cost-effectiveness
Offshore Wind	0.08–0.15	Maintenance complexity, underwater cables, grid integration	High-reliability power converters lower long-term costs
Hybrid (Solar + Wind + Storage)	0.07-0.12	Energy mix, storage cost, system reliability	Al-driven hybrid converters optimize LCOE

Table 2.Levelized Cost of Energy (LCOE) for Various Renewable Energy Systems

Payback Period and Return on Investment (ROI)

The payback period indicates the time required to recover the initial capital investment, while ROI measures the financial profitability of the system. The payback period is influenced by system efficiency, subsidies, feed-in tariffs, and electricity pricing.

Solar PV Payback:

- Residential rooftop solar: Typically 6–10 years, depending on local electricity rates and government incentives.
- Utility-scale solar: Shorter payback periods (5–8 years) due to economies of scale and bulk purchasing of power electronics components.¹⁶

Wind Energy Payback:

Onshore wind: Payback period of 6–10 years, depending on wind resources and O&M costs.

Offshore wind: Requires 10–15 years due to higher capital and maintenance expenses associated with offshore installations.¹⁷

Hybrid Renewable Systems:

 Hybrid systems with solar, wind, and energy storage have payback periods ranging from 8–12 years, depending on the technology mix and cost of battery storage.

The ROI of renewable energy projects is typically calculated using:

ROI=NetProfitInvestmentCost×100ROI = \frac{Net Profit} {InvestmentCost}\times 100ROI=InvestmentCostNetProfit ×100

- Solar PV ROI: 8–12% annually, depending on inverter performance, grid tariffs, and system degradation rates.
- Wind Energy ROI: 10–15% for onshore and 5–10% for offshore, impacted by maintenance challenges and power electronics costs.

- Hybrid Systems ROI: Can exceed 15%, especially when incorporating Al-driven energy management systems, which optimize energy dispatch and grid interactions.
- Emerging trends such as vehicle-to-grid (V2G) integration, AI-based predictive analytics, and blockchain-powered energy trading further enhance economic benefits by enabling dynamic electricity pricing, grid stabilization, and revenue generation from ancillary services.

Conclusion

Power electronics serve as the backbone of modern renewable energy systems, ensuring efficient power conversion, grid stability, and seamless integration of solar, wind, and hybrid energy sources. The rapid advancements in wide-bandgap semiconductors (SiC and GaN), Al-driven energy management, smart inverters, and hybrid converters have significantly improved system efficiency, operational reliability, and cost-effectiveness. These innovations are crucial in addressing the variability and intermittency of renewable energy sources, allowing for better energy harvesting, storage management, and real-time grid interaction.

From a techno-economic perspective, power electronics contribute substantially to both capital expenditures (CAPEX) and operational expenditures (OPEX). However, the reduction in component costs, efficiency improvements, and economies of scale are making renewable energy systems increasingly competitive with fossil-fuel-based power generation. Declining LCOE, shorter payback periods, and increasing return on investment (ROI) indicate a promising future for large-scale deployment of power electronicsbased renewable energy systems.

Despite these advancements, challenges remain, including:

• High initial investment costs, particularly for nextgeneration wide-bandgap power devices, advanced converters, and energy storage systems.

- Power quality concerns, such as harmonic distortions, voltage fluctuations, and reactive power management, which require enhanced control strategies and gridsupportive technologies.
- Reliability and longevity of power electronics components, particularly in offshore wind farms and remote solar PV installations, where maintenance is complex and costly.

To ensure wider adoption and long-term sustainability, policy interventions, research funding, and market incentives will be essential. Government regulations promoting grid modernization, feed-in tariffs, energy storage incentives, and V2G (Vehicle-to-Grid) integration can accelerate deployment. Additionally, continued advancements in Aldriven predictive analytics, blockchain-based energy trading, and smart microgrid architectures will further enhance the economic feasibility and performance of renewable energy systems.

In conclusion, power electronics-based renewable energy systems are pivotal in achieving global energy sustainability goals. With ongoing technological innovations and strategic policy support, these systems will play a key role in decarbonizing the power sector, enhancing energy security, and paving the way for a cleaner, more resilient energy future.

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