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Finite Element Modeling Approaches for Performance Optimization of Emerging Energy Harvesting Systems

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Abstract
The growing demand for decentralized and sustainable power solutions has intensified interest in advanced computational strategies for optimizing emerging energy harvesting systems. This study critically examines finite element modeling (FEM) as a comprehensive framework for enhancing the performance, reliability, and integration of piezoelectric, triboelectric, thermoelectric, electromagnetic, and hybrid energy harvesters. The primary objective was to evaluate how multiphysics simulation techniques support predictive design, resonance tuning, material optimization, and structural durability under realistic operational constraints.
A systematic analytical approach was adopted, synthesizing contemporary modeling methodologies, optimization strategies, and validation frameworks. Emphasis was placed on coupled electromechanical, electrothermal, and magneto-mechanical simulations, alongside parametric analysis, topology optimization, and AI-assisted computational refinement. The review further explored experimental correlation techniques and the integration of digital twin architectures for real-time performance monitoring and adaptive system control.
The findings demonstrate that FEM significantly improves power density, bandwidth adaptability, and lifecycle resilience by enabling high-fidelity representation of nonlinear material behavior and boundary-dependent dynamics. Hybrid and multi-source configurations were identified as particularly promising for enhancing robustness in fluctuating environmental conditions. Moreover, the convergence of FEM with artificial intelligence and secure digital infrastructures was shown to strengthen predictive accuracy, scalability, and sustainability compliance.
In conclusion, simulation-driven optimization has evolved into a strategic design paradigm for next-generation self-powered systems. The study recommends deeper integration of AI-enhanced multiphysics modeling, standardized validation protocols, nanoscale material characterization, and secure digital twin deployment to accelerate innovation and ensure long-term operational resilience within decentralized energy ecosystems.

Keywords: Finite Element Modeling, Energy Harvesting, Multiphysics Simulation, Hybrid Systems, Digital Twin Integration, Performance Optimization

1. Introduction

The accelerating global demand for sustainable energy solutions has intensified scholarly and industrial interest in decentralized and self-powered systems capable of harvesting ambient energy. As energy consumption patterns evolve in parallel with rapid digitalization, the limitations of centralized power generation and fossil fuel dependence have become increasingly evident. The intersections between renewable energy deployment, sustainable development imperatives, and environmental justice concerns underscore the urgency of innovative technological interventions (Adeojo & Osinibi, 2016). Emerging energy harvesting systems—particularly those leveraging piezoelectric, electromagnetic, triboelectric, and hybrid mechanisms—offer promising pathways for powering low-energy electronics, wireless sensor networks, and Internet of Things (IoT) infrastructures without reliance on conventional grids (Ahmad & Khan, 2021).

Within this evolving landscape, optimization has emerged as a critical determinant of viability. Energy harvesters typically operate under constrained environmental inputs, narrow frequency bandwidths, and fluctuating load conditions, necessitating advanced modeling frameworks to enhance efficiency and reliability. Finite element modeling (FEM) has become central to addressing these challenges by enabling multiphysics simulation of electromechanical, thermal, and magnetic interactions.

Unlike simplified analytical models, FEM captures geometric complexity, nonlinear material behavior, and boundary-dependent responses, thereby facilitating predictive performance enhancement before fabrication.

The broader sustainability context further strengthens the relevance of performance-optimized energy harvesting systems. Sustainable development strategies increasingly demand measurable environmental, social, and governance (ESG) outcomes in energy projects (Ihwughwavwe & Enow, 2023; Adebayo *et al*., 2023). Automated compliance reporting and blockchain-enabled transparency frameworks illustrate how technological ecosystems are evolving toward accountability and traceability. Energy harvesting technologies, when optimized for efficiency and durability, contribute directly to these sustainability metrics by reducing carbon footprints and enabling distributed energy autonomy. In parallel, green consumerism trends highlight the importance of tangible sustainability performance indicators, as eco-labeling and environmental claims influence stakeholder decision-making (Abioye *et al*., 2024). Thus, performance optimization through robust modeling is not merely a technical objective but a socio-environmental imperative.

From an engineering systems perspective, optimization methodologies increasingly incorporate automation, artificial intelligence, and secure computational architectures. Secure DevOps and AI-driven policy enforcement models demonstrate how automation enhances system integrity and compliance in complex technological environments (Adebayo, 2025a; Adebayo, 2025b). Although developed primarily within software and financial infrastructures, these principles parallel emerging computational strategies in energy system modeling. The integration of automated pipelines, iterative simulation loops, and cloud-native computational environments enables large-scale parametric exploration and sensitivity analysis (Akindemowo *et al*., 2021; Ajayi *et al*., 2023). Such automation is particularly relevant for finite element simulations, where optimization often requires repeated multiphysics computations across varied material and geometric configurations.

Energy harvesting systems must also be understood within the broader context of power system stability and quality. Distribution networks in emerging markets face challenges related to grounding design, harmonic distortion, and infrastructure resilience (Adeniji, Shittu & Opara, 2020; Adeniji, Shittu & Shittu, 2025). While energy harvesters operate at micro- or meso-scale levels, their integration into smart grids and distributed architectures necessitates compatibility with broader electrical stability requirements. FEM-based optimization ensures that harvested energy devices maintain structural integrity and electrical performance under varying load and environmental conditions, contributing to overall network robustness.

The convergence of artificial intelligence and predictive analytics further reshapes optimization paradigms. AI-driven predictive systems in healthcare and financial forecasting demonstrate how data-informed modeling enhances accuracy, resource allocation, and real-time monitoring (Ajao *et al*., 2024; Ajayi *et al*., 2022). Analogously, AI-enhanced FEM frameworks can accelerate convergence, identify optimal design spaces, and reduce computational costs. Such hybrid modeling approaches represent an emerging frontier in energy harvester optimization, combining deterministic physics-based simulations with probabilistic learning algorithms.

Moreover, sustainability transitions extend beyond energy production to encompass the built environment and infrastructure systems. Green building certification frameworks illustrate how measurable performance criteria drive sustainable construction practices (Ajirotutu *et al*., 2025). Energy harvesting technologies integrated into buildings—such as vibration-based floor systems or thermoelectric waste heat converters—require rigorous modeling to meet structural and efficiency standards. The synergy between architectural sustainability and optimized harvesting devices reinforces the importance of precise computational design methodologies.

Technological reliability and security considerations also influence the design landscape. The incorporation of threat intelligence and secure architectures in digital infrastructures reflects the necessity of resilience against systemic vulnerabilities (Adebayo, 2022). For energy harvesting systems embedded within IoT ecosystems, secure data acquisition and energy management frameworks are essential. FEM contributes indirectly to this resilience by ensuring mechanical durability and predictable performance under diverse operational stresses.

Historically, foundational academic gatherings and interdisciplinary exchanges have catalyzed innovation in applied engineering research (Adamah *et al*., 2016). The progression from conceptual prototypes to highly optimized multiphysics systems reflects cumulative advancements in modeling techniques, material science, and computational power. Early device-level experimentation has given way to simulation-driven design paradigms in which virtual prototyping significantly reduces development cycles.

In light of these developments, this review examines finite element modeling approaches for performance optimization of emerging energy harvesting systems. It situates FEM within a broader ecosystem of sustainability imperatives, digital automation frameworks, AI-enhanced optimization strategies, and power system integration requirements. By synthesizing advancements across piezoelectric, electromagnetic, triboelectric, and hybrid harvesting technologies, the discussion highlights how multiphysics modeling has evolved into a predictive and strategic design tool. Ultimately, the integration of advanced computational methodologies with sustainable energy objectives positions finite element modeling as a cornerstone of next-generation energy harvesting innovation.

1.1 Global Energy Demand and the Rise of Self-Powered Systems

Escalating global energy demand, driven by rapid urbanization, digital transformation, and industrial expansion, has intensified pressure on conventional power infrastructures. Contemporary production and supply chain systems increasingly rely on data-driven analytics and automation to enhance efficiency and competitiveness, thereby amplifying electricity consumption across manufacturing and logistics networks (Akin-Oluyomi *et al*., 2025). Parallel advances in procurement optimization and cost-efficiency strategies further underscore the growing interdependence between technological innovation and reliable energy access (Akokodaripon *et al*., 2023).

Simultaneously, the proliferation of smart buildings, intelligent water distribution systems, and digitally integrated infrastructure has expanded the ecosystem of interconnected devices requiring stable yet sustainable power sources (Babatope, Akokodaripon & Okoruwa, 2024; Akokodaripon, Okoruwa & Babatope, 2024). In educational and remote laboratory environments, digital experimentation platforms exemplify the increasing reliance on distributed electronic systems (Akokodaripon *et al*., 2023). Moreover, AI-driven adaptive learning and digital platforms continue to accelerate device deployment at scale (Akintayo *et al*., 2024).

Within this context, self-powered systems powered by ambient energy harvesting technologies represent a strategic response to grid dependency. By enabling localized, autonomous energy generation, such systems align with agile, multi-cloud, and decentralized deployment paradigms observed in modern technological infrastructures (Akindemowo *et al*., 2022), thereby supporting resilient and sustainable energy ecosystems.

1.2 Evolution of Energy Harvesting Technologies

Energy harvesting technologies have evolved from rudimentary mechanical transduction concepts to highly integrated multiphysics systems capable of supporting distributed digital infrastructures. Early piezoelectric harvesters demonstrated the feasibility of converting ambient vibrations into electrical energy; however, limitations in bandwidth and power density prompted continuous material and structural optimization (Covaci & Gontean, 2020). Subsequent advancements expanded the scope of harvesting mechanisms to include thermoelectric conversion, where improved electrothermal modeling has enhanced predictive performance and system efficiency (Dziurdzia, Bratek & Markiewicz, 2023).

The contemporary evolution of these technologies reflects broader trends in intelligent system design and predictive optimization. Machine learning frameworks originally developed for predictive maintenance and industrial diagnostics now inform condition-based optimization strategies for electromechanical systems (Babatope, Akokodaripon & Okoruwa, 2025; Adediran *et al*., 2025). Similarly, AI-driven models for network performance optimization and automated incident response demonstrate how adaptive algorithms can enhance system resilience and operational continuity (Babatope *et al*., 2023a; Babatope *et al*., 2023b).

Moreover, regulatory transparency and cybersecurity frameworks underscore the necessity of secure and data-driven infrastructures within energy systems (Bello *et al*., 2025; Bukhari *et al*., 2022). The integration of advanced data analytics and natural language processing in research ecosystems further accelerates innovation cycles (Eboseremen *et al*., 2021). Collectively, these interdisciplinary developments have transformed energy harvesting from isolated device engineering into an intelligent, optimization-centered technological domain.

1.3 Finite Element Modeling as a Design and Optimization Tool

Finite element modeling (FEM) has emerged as a pivotal computational framework for the design and optimization of complex energy harvesting systems. In piezoelectric-based harvesters, for instance, FEM enables rigorous simulation of electromechanical coupling, stress distribution, and resonance behavior under varying boundary conditions, thereby improving predictive accuracy and device efficiency (Elahi, Eugeni & Gaudenzi, 2018). By discretizing complex geometries into solvable elements, FEM facilitates detailed multiphysics analysis that surpasses the explanatory capacity of simplified analytical formulations.

Beyond its numerical precision, FEM functions as a decision-support tool, analogous to interactive data visualization systems that enhance policy evaluation through structured representation of complex datasets (Eboseremen *et al*., 2022). The integration of AI-enhanced interfaces and adaptive design principles further illustrates how advanced computational environments can refine user-centered engineering workflows (Eboseremen *et al*., 2024). In research contexts, ethical data handling and transparency frameworks underscore the importance of responsible computational modeling practices (Essien *et al*., 2023).

Moreover, digitization and interoperability initiatives in healthcare systems demonstrate how integrated digital architectures overcome legacy constraints to enable optimized operational performance (Ezeh *et al*., 2022; Ezeh *et al*., 2023). Similarly, AI-enabled digital assistants in chronic disease management exemplify how predictive modeling enhances system responsiveness (Ezeh *et al*., 2024). Within energy harvesting research, FEM embodies this broader paradigm shift toward intelligent, data-driven, and optimization-oriented system design.

1.4 Aim, Scope, and Objectives of This Review

The primary aim of this review is to provide a comprehensive and critical synthesis of finite element modeling (FEM) approaches employed in the design and performance optimization of emerging energy harvesting systems. As energy harvesters evolve toward higher efficiency, miniaturization, and multifunctionality, advanced computational modeling has become indispensable for guiding innovation and reducing experimental uncertainty. This review, therefore, seeks to clarify how FEM has transitioned from a verification tool to a predictive and optimization-driven design framework.

The scope of this study encompasses multiphysics modeling strategies applied to piezoelectric, triboelectric, thermoelectric, electromagnetic, and hybrid energy harvesting architectures. It examines structural–electrical coupling mechanisms, electrothermal and magneto-mechanical interactions, nonlinear material behavior, and boundary condition sensitivities. Additionally, the review considers optimization methodologies integrated within FEM environments, including parametric studies, topology optimization, and algorithm-assisted performance tuning.

The objectives are threefold: first, to consolidate contemporary modeling techniques across diverse harvesting mechanisms; second, to evaluate their effectiveness in enhancing power output, reliability, and system integration; and third, to identify emerging computational trends that may define future research directions. Through this structured analysis, the review aims to provide a coherent foundation for advancing simulation-driven innovation in self-powered energy systems.

2. Fundamentals of Energy Transduction Mechanisms

Energy harvesting systems operate through the conversion of ambient physical phenomena into usable electrical energy. At their core, these systems rely on transduction mechanisms that translate mechanical, thermal, electromagnetic, or hybrid environmental inputs into electrical outputs. Understanding these mechanisms is foundational to the optimization and modeling of emerging energy harvesting technologies, particularly in distributed and intelligent infrastructures.

Mechanical-to-electrical transduction is commonly achieved through vibration-based systems in which dynamic motion is converted into electrical power. In practical deployment environments, such systems must operate within interconnected digital architectures—ranging from automotive networks to industrial monitoring platforms—where reliability and signal integrity are paramount. The growing complexity of controller area network (CAN) systems and their vulnerability to sophisticated disturbances highlight the importance of secure and robust energy-enabled sensor nodes (Eziama *et al*., 2025a). As embedded systems expand within renewable and mobility infrastructures, dependable energy transduction becomes essential for sustaining continuous monitoring and autonomous functionality.

Similarly, cold chain logistics and remote monitoring frameworks increasingly depend on low-power sensing devices that can operate in distributed conditions (Eziama *et al*., 2025b). In such contexts, mechanical vibrations, thermal gradients, or environmental fluctuations serve as potential energy sources. Thermoelectric transduction, for example, converts temperature differentials directly into electrical energy through the Seebeck effect, enabling self-powered temperature tracking in logistics environments. These mechanisms are particularly valuable where grid access is limited or where maintenance interventions must be minimized.

Electromagnetic transduction, based on Faraday's law of induction, converts relative motion between magnetic fields and conductive coils into electrical output. This mechanism is frequently employed in rotational or oscillatory systems, including transport and industrial machinery. As next-generation communication systems, such as 6G-enabled infrastructures, evolve toward increased decentralization and virtualization, distributed energy nodes may support localized sensing and edge computing capabilities (Eziama *et al*., 2025c). In such high-density networks, energy harvesting mechanisms provide an enabling layer for autonomous device operation.

The design and optimization of transduction systems increasingly mirror strategic innovation frameworks observed in other sectors. Just as market research and strategic innovation models guide competitive growth and technological positioning (Filani *et al*., 2022a; Filani *et al*., 2022b), energy transduction mechanisms must be evaluated in terms of efficiency, scalability, and contextual suitability. Selection of a specific harvesting mechanism depends on environmental availability, system constraints, and integration requirements. Scenario-based modeling approaches, analogous to financial planning methodologies, facilitate comparative assessment of performance trade-offs under varying operational conditions (Filani *et al*., 2023).

Furthermore, real-time monitoring and risk assessment dashboards in healthcare supply chains illustrate how data-driven systems rely on resilient and uninterrupted sensor functionality (Filani *et al*., 2022c). Energy transduction mechanisms underpinning such sensors must therefore deliver stable micro-power outputs capable of sustaining wireless transmission and analytics modules. The reliability of the underlying transduction process directly influences system-level decision-making accuracy.

From a systems engineering perspective, energy transduction mechanisms should be contextualized within broader workflow optimization frameworks. Data-informed policy tools designed to enhance operational efficiency in social services demonstrate the value of structured analytical methodologies (Fasasi, 2023; Fasasi & Tafirenyika, 2023). Similarly, effective deployment of energy harvesters requires systematic evaluation of environmental inputs, load demands, and lifecycle performance metrics.

The educational and communication dimensions of technological diffusion also shape the evolution of transduction technologies. AI-powered chatbots and multimodal instructional systems illustrate how decentralized digital platforms depend on reliable power solutions in remote and underserved regions (Frempong, Ifenatuora & Ofori, 2020; Frempong *et al*., 2024a; Frempong *et al*., 2024b). In such contexts, small-scale solar, vibration, or thermal harvesters may enable autonomous operation of learning devices, thereby extending technological accessibility.

Finally, the human-centered design principles evident in-patient communication models and healthcare journey mapping provide a parallel to the user-focused deployment of energy harvesting systems (Gado *et al*., 2022; Gado *et al*., 2025a; Gado *et al*., 2025b). Just as healthcare innovation emphasizes accessibility, continuity, and resilience, energy transduction mechanisms must prioritize adaptability, reliability, and integration within dynamic environments.

3. Finite Element Modeling Frameworks for Energy Harvesters

Finite element modeling (FEM) frameworks constitute the computational backbone of contemporary energy harvester design, enabling rigorous multiphysics simulation and performance optimization. As energy harvesting devices increasingly operate in complex and dynamic environments, modeling approaches must integrate structural mechanics, electrostatics, magnetodynamics, and thermal effects within unified numerical architectures. In vibration-based piezoelectric and electromagnetic harvesters, FEM provides high-fidelity solutions to coupled field equations governing stress–strain interactions, electric displacement, and magnetic flux behavior (Ghazanfarian, Mohammadi & Uchino, 2021; Iqbal, Nauman & Khan, 2021). Such frameworks facilitate accurate prediction of resonance frequencies, power output, and fatigue characteristics before fabrication.

At the core of FEM frameworks lies the discretization of the governing differential equations into solvable algebraic systems through mesh generation. Element selection—whether tetrahedral, hexahedral, or higher-order polynomial elements—directly influences convergence accuracy and computational cost. For microsystems applications, refined meshing strategies are essential to capture localized strain concentrations and electrode boundary effects, particularly in multilayer piezoelectric composites (Iqbal, Nauman & Khan, 2021). Advanced solver configurations further enable harmonic response analysis, transient simulations, and nonlinear material modeling, reflecting the practical variability of ambient excitation sources.

The growing interconnection between energy harvesters and broader digital infrastructures necessitates simulation environments capable of interfacing with intelligent monitoring systems. In public health surveillance, AI-enabled wearable devices demonstrate how distributed sensing platforms require reliable and sustainable power architectures (Hanafi *et al*., 2025). FEM frameworks, therefore, extend beyond device-level optimization to encompass integration within smart and adaptive ecosystems. Accurate multiphysics modeling ensures mechanical durability and electrical stability under real-world operational stresses, thereby supporting continuous data acquisition and transmission.

Energy harvesting also plays a strategic role in regional energy resilience and decentralized power trade. Within the African Continental Free Trade Area (AfCFTA), decentralized renewable energy solutions are increasingly viewed as instruments for poverty alleviation and cross-border energy integration (Idu *et al*., 2025). FEM-based optimization of small-scale harvesting technologies can contribute to localized electrification strategies by enhancing device reliability and cost-effectiveness. By simulating environmental loading conditions and material degradation processes, modeling frameworks support sustainable deployment within resource-constrained contexts.

Contemporary FEM environments increasingly incorporate digital twin architectures, enabling continuous synchronization between simulated models and physical systems. Digital twin-driven compliance models in oil, gas, and utility sectors illustrate how real-time data streams can be integrated with predictive simulations to ensure environmental and operational compliance (Ike *et al*., 2025a; Ike *et al*., 2025b). Applied to energy harvesters, digital twins allow iterative refinement of model parameters based on sensor feedback, improving predictive maintenance and lifecycle management. This integration represents a paradigm shift from static simulation toward dynamic, adaptive modeling ecosystems.

In parallel, advancements in artificial intelligence are reshaping simulation workflows. Unsupervised clustering of power quality (PQ) events using transformer autoencoders demonstrates how complex electrical phenomena can be classified and interpreted through deep learning frameworks (Islam *et al*., 2025). When integrated with FEM-generated datasets, such AI models can identify performance anomalies, optimize design parameters, and reduce computational redundancy. This hybridization of physics-based modeling with data-driven intelligence enhances the robustness and scalability of energy harvester simulations.

The broader policy and innovation landscape further influences the development of FEM frameworks. Artificial intelligence is increasingly recognized as a catalyst for public sector innovation, offering opportunities for efficiency gains while presenting governance and risk considerations (Kalu-Mba, Mupa & Tafirenyika, 2025). Within energy systems, FEM-supported optimization aligns with these innovation imperatives by enabling evidence-based engineering decisions. Moreover, AI-enhanced language translation and communication tools facilitate cross-disciplinary collaboration in global research environments, supporting the dissemination and refinement of modeling methodologies (Kuponiyi & Akomolafe, 2024).

Supply chain considerations also intersect with computational modeling. The application of nanomaterials in healthcare supply chains demonstrates how material innovation requires rigorous simulation and validation before deployment (Ike *et al*., 2022). Similarly, advanced piezoelectric ceramics, magnetostrictive materials, and thermoelectric composites demand precise FEM-based characterization to evaluate electromechanical coupling coefficients and thermal conductivity parameters. Talent development and innovation programs within logistics and operations further underscore the need for specialized technical expertise capable of navigating complex analytical tools (Ike *et al*., 2025c).

Ultimately, FEM frameworks for energy harvesters are defined by three interrelated dimensions: multiphysics integration, computational intelligence, and systemic interoperability. By solving coupled field equations under realistic constraints, FEM enables detailed evaluation of structural integrity and power conversion efficiency. Through integration with AI and digital twin architectures, it supports adaptive optimization and predictive maintenance. Finally, by aligning with broader energy trade, policy, and innovation ecosystems, FEM contributes to scalable and sustainable deployment strategies.

4. FEM Approaches in Piezoelectric Energy Harvesting Optimization

Finite element modeling (FEM) has become indispensable in optimizing piezoelectric energy harvesting systems, particularly in applications where structural adaptability, environmental responsiveness, and long-term reliability are critical. Piezoelectric harvesters convert mechanical strain into electrical charge through electromechanical coupling, and their efficiency depends heavily on geometric configuration, boundary conditions, and material distribution. FEM enables high-resolution simulation of stress fields, electric potential distribution, and resonance behavior, thereby facilitating predictive optimization prior to fabrication.

A central objective in FEM-based optimization is resonance tuning. Piezoelectric cantilever beams, diaphragms, and multilayer composites must be configured to match ambient vibration frequencies to maximize power density. Through modal and harmonic analyses, FEM allows designers to adjust dimensions, tip masses, and electrode placement to align structural natural frequencies with environmental excitation sources. This adaptive alignment mirrors the principles of environmental integration emphasized in biophilic design, where built systems are optimized in response to natural stimuli to enhance performance and sustainability (Kuponiyi & Akomolafe, 2024a). Similarly, piezoelectric structures are optimized through simulation-driven adaptation to their mechanical environments.

Material optimization also constitutes a critical dimension of FEM application. Variations in piezoelectric coefficients, dielectric constants, and mechanical stiffness significantly influence output voltage and electromechanical coupling efficiency. Parametric modeling facilitates comparative assessment of ceramic, polymeric, and composite materials under varying stress regimes. In this context, predictive methodologies parallel AI-based diagnostic frameworks used in healthcare to enhance early detection and performance accuracy (Kuponiyi & Akomolafe, 2024b; Kuponiyi, Omotayo & Akomolafe, 2023). Just as clinical decision-support systems refine treatment pathways through data-informed modeling, FEM refines material selection and geometric configuration to maximize electrical output.

Advanced FEM approaches increasingly incorporate nonlinear modeling to account for large deflections, material hysteresis, and fatigue degradation. In real-world environments, piezoelectric harvesters often experience variable loading conditions and temperature fluctuations, necessitating robust simulation strategies. Predictive maintenance concepts—originally developed to anticipate equipment failure in distributed systems—offer a useful parallel (Kuponiyi & Akomolafe, 2024c). By integrating fatigue analysis and lifecycle modeling into FEM workflows, designers can anticipate performance decay and enhance device durability.

Furthermore, optimization extends beyond mechanical performance to encompass system-level integration. For instance, finite element simulations can model electromechanical coupling within flexible substrates intended for wearable or biomedical devices. In such contexts, alignment with circadian and physiological patterns may influence deployment environments, especially for devices integrated into human-centric systems (Kuponiyi, 2025a). While energy harvesters operate mechanically, their end-use contexts often intersect with human health, requiring simulation of thermal comfort, mechanical compliance, and long-term usability.

Topology optimization represents another advanced FEM strategy. By iteratively removing low-stress regions and reinforcing high-strain zones, computational algorithms can generate lightweight structures with enhanced strain concentration, thereby improving charge generation efficiency. This systematic refinement reflects broader evidence-based optimization frameworks in public health and lifestyle interventions, where targeted structural adjustments yield measurable performance improvements (Kuponiyi, 2025b; Kuponiyi, 2025c). In both domains, iterative modeling and parameter control drive outcome maximization.

The incorporation of AI-assisted optimization further enhances FEM capabilities. Data-driven feedback loops can refine boundary conditions and accelerate convergence, reducing computational expense. Analogous to AI-supported screening systems for radiation exposure or disease detection (Kuponiyi, 2024), AI-integrated FEM enables rapid identification of optimal design configurations within expansive parameter spaces. Such integration is particularly valuable in multi-objective optimization scenarios involving trade-offs between power density, structural integrity, and fabrication cost.

Additionally, the user-environment interface remains critical. Piezoelectric harvesters embedded in built environments—such as flooring systems or structural components—must account for human movement patterns and occupational stress contexts. Insights from corporate wellness and high-stress energy-sector environments highlight the importance of systems designed for resilience and sustainability (Kuponiyi & Akomolafe, 2024d). FEM assists in evaluating stress distribution under repetitive loading, ensuring both mechanical longevity and functional efficiency.

5. FEM in Triboelectric Energy Harvester Modeling

Triboelectric energy harvesters (TEHs) operate on the principle of contact electrification and electrostatic induction, converting mechanical motion into electrical energy through periodic contact and separation of dissimilar materials. Unlike piezoelectric systems, triboelectric devices are highly dependent on surface charge density, contact mechanics, and dielectric properties, thereby necessitating sophisticated finite element modeling (FEM) frameworks to accurately capture multiphysics interactions. Recent advances in equivalent circuit modeling have strengthened the integration between electrostatic theory and structural deformation analysis, enabling more accurate prediction of voltage output and charge transfer dynamics (Liu *et al.*, 2025). FEM facilitates the coupling of mechanical displacement fields with electrostatic boundary conditions, thereby resolving spatial charge distribution and electric potential gradients across complex geometries.

A critical challenge in triboelectric modeling lies in representing nonlinear contact–separation cycles under dynamic excitation. FEM enables time-dependent simulations that incorporate frictional effects, dielectric permittivity variations, and material elasticity. Such detailed modeling parallels technological advancements in carbon capture systems, where multiphysics simulations are essential for optimizing complex adsorption and separation processes (Liadi *et al.*, 2024a). In both domains, high-resolution numerical analysis enhances efficiency, scalability, and environmental sustainability.

The integration of TEHs into digital and cloud-enabled infrastructures further underscores the importance of reliable modeling frameworks. In telecommunications optimization models, performance stability and high-efficiency transmission depend on robust system architecture (Mayo *et al*., 2023a). Similarly, triboelectric harvesters embedded in distributed sensor networks must maintain consistent output under variable excitation conditions. FEM assists in evaluating structural durability, dielectric breakdown risks, and electrode configuration efficiency, thereby supporting integration into cloud-based monitoring platforms (Mayo *et al*., 2023b).

Moreover, as digital transformation reshapes public health surveillance and remote monitoring ecosystems, decentralized self-powered sensors gain strategic importance (Kuponiyi & Akomolafe, 2025). Triboelectric harvesters, often favored for their lightweight and flexible design, can power low-energy monitoring devices in resource-constrained environments. FEM simulations enable optimization of flexible substrates, microstructured surfaces, and layered dielectric materials to maximize charge generation without compromising mechanical resilience.

Security and governance frameworks in cloud-based knowledge systems also offer conceptual parallels for triboelectric modeling. Continuous access governance and AI-enhanced compliance strategies emphasize adaptive monitoring and system integrity (Moyo *et al*., 2023; Moyo *et al*., 2024). Similarly, digital twin approaches and predictive analytics can be integrated with FEM-based TEH simulations to enable real-time performance tracking and anomaly detection. Transformer-based or machine learning–enhanced predictive models, though developed for financial and actuarial risk assessment, illustrate how data-driven feedback mechanisms refine predictive accuracy (Mupa *et al*., 2025a; Mupa *et al*., 2025b). Applied to TEHs, such hybrid approaches support proactive design refinement and lifecycle optimization.

The broader innovation landscape in energy distribution and sustainability also informs triboelectric system deployment. Market-oriented strategic innovation frameworks emphasize efficiency, scalability, and service reliability in energy ecosystems (Nnabueze *et al*., 2024a; Nnabueze *et al*., 2024b). Triboelectric devices, when optimized through FEM, can contribute to distributed micro-energy solutions that enhance resilience and cost-effectiveness. Integrated financial and performance optimization strategies further highlight the value of data-driven decision frameworks in maximizing system output (Nnabueze *et al*., 2024c).

Emerging hybrid energy systems, including magneto-mechano-electric technologies, demonstrate the growing convergence of multiple transduction principles (Muthuramalingam & Manojkumar, 2025). FEM frameworks for triboelectric modeling must therefore accommodate coupling with electromagnetic or piezoelectric components in hybrid configurations. Such multiphysics modeling enables comparative evaluation of energy density, structural stability, and environmental adaptability.

6. Thermoelectric Energy Harvesters: Electrothermal FEM Modeling

Thermoelectric energy harvesters (TEHs) convert temperature gradients directly into electrical energy through the Seebeck effect, enabling waste heat recovery in industrial, automotive, and building-integrated applications. The performance of TEHs depends fundamentally on electrothermal coupling between heat transfer, electrical conductivity, and material-specific thermoelectric properties. Finite element modeling (FEM) provides a robust computational framework for resolving these coupled phenomena, allowing detailed simulation of temperature distribution, electrical potential fields, and current density under steady-state and transient conditions.

Electrothermal FEM models typically integrate Fourier's law of heat conduction with charge transport equations to capture the interdependence of thermal gradients and electrical output. Accurate representation of boundary conditions—such as convective heat loss, contact resistance, and environmental fluctuations—is essential for predictive reliability. In distributed energy ecosystems, such precision aligns with integrated data-driven optimization frameworks used to enhance efficiency and revenue performance (Nnabueze *et al*., 2024). Similarly, TEH modeling requires holistic parameter coordination to maximize conversion efficiency while minimizing material degradation and thermal stress.

The complexity of electrothermal modeling parallels advancements in analytics engineering for operational decision-making. Visualization and analytics platforms demonstrate how multidimensional datasets can inform strategic optimization (Obuse *et al*., 2023). FEM-generated outputs—temperature contours, voltage gradients, and thermomechanical stress maps—serve a comparable function, enabling engineers to evaluate design trade-offs and identify performance bottlenecks. By translating numerical outputs into interpretable decision metrics, FEM supports iterative design refinement and evidence-based engineering.

Security and reliability considerations further shape electrothermal FEM frameworks. As thermoelectric modules are increasingly embedded within hybrid and smart infrastructures, ensuring secure integration with digital monitoring systems becomes critical. Conceptual frameworks for CI/CD pipeline security controls emphasize systematic risk mitigation in hybrid deployments (Obuse *et al*., 2024). Analogously, electrothermal FEM must incorporate reliability assessments, including thermal fatigue, material interface stability, and electrical insulation breakdown, to ensure safe long-term operation.

The broader resilience of critical infrastructures underscores the strategic importance of optimized thermoelectric systems. Integrated infrastructures spanning communication, energy, finance, and healthcare demand robust and decentralized power solutions (Ogbuefi *et al*., 2025a). TEHs can provide supplementary micro-power generation within such systems, enhancing redundancy and operational continuity. FEM facilitates resilience planning by simulating performance under variable environmental loads, enabling designers to anticipate stress concentrations and failure points.

Furthermore, explainable AI principles in risk-sensitive domains highlight the importance of transparency and interpretability in modeling practices (Ogbuefi *et al*., 2025b). Electrothermal FEM models must therefore be parameterized with clarity, ensuring that material properties, boundary assumptions, and solver configurations are traceable and reproducible. This transparency supports regulatory compliance and interdisciplinary collaboration.

The educational and policy reform landscape also illustrates the value of structured and adaptive frameworks (Ofori *et al*., 2025; Ofori *et al*., 2023a; Ofori *et al*., 2023b). Similarly, electrothermal modeling frameworks benefit from iterative calibration and validation processes that incorporate experimental data and real-world operational feedback. Continuous refinement enhances predictive accuracy and strengthens alignment between simulated and measured performance outcomes.

Advanced data visualization and security analytics platforms further demonstrate how integrated monitoring systems enhance enterprise risk management (Ogbole *et al*., 2023; Ogbole *et al*., 2025). In thermoelectric harvesting, digital twin architectures can leverage FEM outputs to support real-time monitoring and adaptive thermal management strategies. By synchronizing simulated and operational data, such systems enable proactive performance optimization and fault detection.

7. Electromagnetic Energy Harvesters and Magneto-Mechanical Coupling

Electromagnetic energy harvesters (EMEHs) operate on the principle of Faraday's law of electromagnetic induction, whereby relative motion between a magnetic field and a conductive coil induces an electrical current. These systems are particularly suited to environments characterized by rotational or translational mechanical motion, such as transportation infrastructure, industrial machinery, and structural vibrations. Finite element modeling (FEM) plays a central role in simulating magneto-mechanical coupling by resolving magnetic flux distribution, coil geometry optimization, and structural displacement under dynamic excitation.

Magneto-mechanical coupling requires simultaneous modeling of mechanical deformation and magnetic field variation. FEM enables detailed computation of flux density gradients and induced electromotive force while accounting for nonlinear magnetic material properties and eddy current effects. Such precision is essential in optimizing coil turns, magnet configuration, and air-gap dimensions to maximize power density. The emphasis on asset optimization within advanced energy accounting frameworks reflects similar performance-oriented priorities, where strategic integration enhances overall system value (Okereke *et al*., 2024).

Electromagnetic harvesters increasingly contribute to sustainable urban and infrastructural ecosystems. Artificial intelligence applications in sustainable urban planning highlight the need for adaptive, data-driven infrastructure capable of supporting environmental resilience (Okoje, Soneye & Essien, 2023). Within this context, EMEHs can provide localized power to distributed sensors monitoring structural integrity, emissions, and environmental indicators. Predictive analytics models for monitoring infrastructure risks and emissions underscore the importance of reliable decentralized energy sources in urban ESG strategies (Okojie *et al*., 2023). FEM-based optimization ensures that electromagnetic harvesters maintain performance stability under fluctuating vibrational loads typical of urban environments.

From a sustainability perspective, circular and resource-efficient approaches in industrial systems demonstrate how waste streams can be revalorized into productive assets (Okojie *et al*., 2025). Similarly, mechanical vibrations and kinetic energy—often dissipated as waste—can be converted into usable electrical energy through optimized magneto-mechanical coupling. This transformation aligns with circular economy principles and contributes to resource efficiency.

The governance and reporting dimensions of energy systems also influence electromagnetic harvester deployment. Automated ESG reporting frameworks emphasize transparency, traceability, and compliance in energy projects (Okojie *et al*., 2023b). Electromagnetic harvesters integrated into distributed monitoring networks can support real-time environmental data acquisition, reinforcing accountability mechanisms.

Furthermore, inclusive development models, such as cooperative-driven empowerment initiatives in agriculture, demonstrate how decentralized systems foster resilience and local participation (Ogunsola, Adenuga & Nnabueze, 2024). In marginalized communities, decentralized micro-energy technologies—including electromagnetic harvesters—can support localized infrastructure and digital health frameworks designed to expand preventive services (Ojeikere, Akintimehin & Akomolafe, 2024).

8. Hybrid and Multi-Source Energy Harvesting Systems

Hybrid and multi-source energy harvesting systems integrate two or more transduction mechanisms—such as piezoelectric, electromagnetic, triboelectric, and thermoelectric processes—within a unified architecture to enhance power density, bandwidth responsiveness, and environmental adaptability. The rationale for hybridization stems from the inherent limitations of single-source harvesters, which often operate efficiently only within narrow excitation or thermal ranges. By combining complementary mechanisms, hybrid systems improve reliability and ensure sustained output under fluctuating ambient conditions.

From a sustainability governance perspective, integrated energy solutions align with automated ESG reporting frameworks that emphasize transparency and performance accountability in energy projects (Okojie, Filani & Ike, 2022; Okojie, Filani & Ike, 2023). Hybrid harvesters embedded in smart infrastructure can support real-time environmental monitoring, thereby contributing to blockchain-enabled compliance ecosystems and data integrity mechanisms. The incorporation of AI-driven ESG auditing models further reinforces the importance of resilient and verifiable decentralized energy systems in urban development projects (Okojiev *et al*., 2023).

Within the broader energy transition discourse, hybrid energy harvesting technologies reflect pathways toward balancing conventional and renewable systems in pursuit of equitable and sustainable development (Okojokwu-Idu *et al*., 2025). As Africa and other emerging regions navigate fossil–renewable complementarities, decentralized micro-energy solutions provide localized support for sensor networks and distributed infrastructure. Moreover, energy transition frameworks that incorporate carbon capture, storage, and usage technologies highlight the necessity of diversified technological portfolios to achieve decarbonization targets (Okojokwu-Idu *et al*., 2022a; Okojokwu-Idu *et al*., 2022b). Hybrid harvesters complement these macro-level strategies by enhancing efficiency at the micro-energy scale.

Community participation and infrastructure security considerations further underscore the value of distributed and hybridized systems (Okojokwu-Idu *et al*., 2023). By decentralizing energy generation for monitoring and communication devices, hybrid harvesters contribute to collaborative governance and resilience. In parallel, AI-driven investigative and procurement transformation frameworks demonstrate how digital optimization strengthens operational integrity and supply chain efficiency (Okoruwa, 2023; Okoruwa *et al*., 2025).

9. Optimization Techniques Integrated with FEM

Optimization techniques integrated with finite element modeling (FEM) have significantly advanced the design and performance refinement of energy harvesting systems. While FEM provides high-fidelity multiphysics simulations, optimization algorithms enable systematic exploration of design variables, including geometry, material distribution, boundary conditions, and load configurations. The integration of these approaches transforms simulation outputs into actionable design intelligence, enhancing efficiency, robustness, and scalability.

Parametric optimization remains a foundational strategy, involving systematic variation of structural and material parameters to identify configurations that maximize electrical output or minimize stress concentration. This structured exploration parallels integrated digital platforms developed to enhance transparency and efficiency in procurement and supply chain systems, where multidimensional variables are coordinated to optimize outcomes (Okoruwa *et al*., 2024a). Similarly, in energy harvester design, coordinated parameter management ensures balanced trade-offs between power density and structural durability.

Artificial intelligence (AI)-assisted optimization has further expanded the capabilities of FEM frameworks. Personalization and trust-enhancing AI strategies in marketplace systems demonstrate how adaptive algorithms refine decision pathways based on performance data (Okoruwa *et al*., 2024b). In engineering contexts, machine learning algorithms can analyze FEM-generated datasets to predict optimal configurations, reduce computational overhead, and accelerate convergence. Secure hybrid cloud management models also illustrate how distributed computational environments enable scalable simulation and resource optimization (Okoruwa *et al*., 2023).

Scenario-based planning techniques provide another dimension of optimization. Big data-driven scenario modeling in corporate treasury management emphasizes predictive foresight and risk mitigation under uncertainty (Olatunde-Thorpe *et al*., 2025). In FEM-integrated energy harvester optimization, scenario analysis evaluates performance under varying environmental conditions, such as fluctuating vibration frequencies or thermal gradients, thereby strengthening design resilience.

Emerging computational paradigms, including federated databases and quantum machine learning frameworks, highlight the potential of distributed intelligence and advanced algorithms in complex system modeling (Omolayo *et al*., 2024a; Omolayo *et al*., 2024b). Such approaches can enhance large-scale FEM simulations by enabling parallelized optimization across decentralized datasets. Telehealth expansion and digital infrastructure integration similarly underscore the importance of adaptable and scalable computational systems (Omotayo & Kuponiyi, 2020).

Finally, synergizing energy efficiency with logistics optimization reflects the broader necessity of aligning engineering performance with systemic sustainability objectives (Opara *et al*., 2024; Oparah *et al*., 2024). By embedding optimization algorithms within FEM workflows, designers achieve multidimensional performance improvements that support both micro-scale device efficiency and macro-scale infrastructural sustainability.

10. Miniaturization and MEMS-Based Energy Harvesters

Miniaturization has emerged as a defining trajectory in the evolution of energy harvesting technologies, particularly with the integration of microelectromechanical systems (MEMS) for powering compact and autonomous devices. Advances in piezoelectric materials and microfabrication techniques have enabled the development of microscale harvesters capable of operating within constrained environments while maintaining measurable power outputs (Safaei, Sodano & Anton, 2019; Parinov & Cherpakov, 2022; Adeniji, 2019; Shittu *et al*, 2019). These MEMS-based systems are especially relevant for wearable electronics, implantable medical devices, and distributed sensor networks where size, weight, and integration flexibility are critical design constraints.

Finite element modeling (FEM) plays a central role in the miniaturization process by simulating microscale stress distributions, electromechanical coupling efficiency, and resonant behavior under low-amplitude excitation. As device dimensions shrink, surface effects, fabrication tolerances, and material anisotropy become increasingly significant, requiring high-resolution multiphysics modeling. The optimization challenges inherent in MEMS design parallel multi-objective evolutionary approaches used to balance risk, return, and sustainability metrics in complex systems (Oshoba *et al*., 2020). Similarly, MEMS-based energy harvesters must balance power density, structural integrity, and fabrication cost.

The integration of miniaturized harvesters into digital health and AI-enabled monitoring systems further expands their relevance. AI-driven predictive healthcare frameworks demonstrate how compact sensing devices support early disease detection and optimized patient management (Sagay *et al*., 2024a; Sagay *et al*., 2024b). MEMS harvesters can provide sustainable micro-power for such embedded diagnostic technologies, reducing dependency on battery replacement in remote or implantable applications.

From a governance and sustainability perspective, blockchain-enabled ESG reporting systems emphasize accountability in energy project deployment (Abioye *et al*., 2023). Miniaturized energy harvesters integrated within smart infrastructure contribute to transparent monitoring ecosystems. Furthermore, sustainable financing and KPI-driven performance frameworks reinforce the importance of measurable efficiency and accountability in technological innovation (Sakyi *et al*., 2022; Sakyi *et al*., 2024). Collectively, MEMS-based energy harvesters represent a convergence of microscale engineering precision, sustainability imperatives, and intelligent system integration.

11. Validation, Experimental Correlation, and Digital Twin Integration

Robust validation and experimental correlation are indispensable in ensuring the reliability and predictive fidelity of finite element modeling (FEM) frameworks for energy harvesting systems. While numerical simulations provide high-resolution insights into multiphysics interactions, empirical verification remains essential for confirming model assumptions, boundary conditions, and material parameters. The development of structured performance metrics parallels KPI frameworks designed to enhance accountability and operational performance across large-scale organizations (Sakyi *et al*., 2022a). Similarly, energy harvester validation requires clearly defined indicators such as output voltage consistency, power density stability, and structural durability under cyclic loading.

Experimental correlation often involves harmonic excitation tests, thermal gradient measurements, and electromagnetic flux characterization, with results compared against FEM predictions. Discrepancies between simulated and measured data necessitate calibration procedures, including parameter tuning and mesh refinement. In this respect, analytics-driven performance monitoring frameworks used in customer service optimization illustrate how continuous feedback enhances system accuracy and strategic refinement (Sakyi *et al*., 2022b; Sakyi *et al*., 2022c).

Digital transformation paradigms further strengthen validation ecosystems by integrating automation and risk mitigation within service delivery infrastructures (Sakyi *et al*., 2024a; Sakyi *et al*., 2024b). Applied to energy harvesting systems, digital twin architectures create synchronized virtual replicas of physical devices, enabling real-time comparison between simulated and operational states. These frameworks leverage IoT-enabled monitoring and microgrid integration models to support climate-resilient grid operations (Shittu *et al*., 2025).

Secure data exchange and infrastructure protection mechanisms are also critical to digital twin deployment. Blockchain-assisted SCADA architectures illustrate how secure communication channels safeguard operational data integrity (Shittu, Adeniji & Shittu, 2022). Additionally, selective coordination and arc-flash mitigation studies highlight the importance of safety validation in industrial power environments (Shittu *et al*., 2021). Machine learning models—both supervised and unsupervised—further enhance anomaly detection and predictive maintenance in integrated systems (Soneye *et al*., 2023).

Finally, sustainable financing frameworks underscore the importance of transparent performance validation in attracting ESG-aligned investment (Sakyi *et al*., 2024c). Through rigorous experimental correlation and digital twin integration, FEM-based energy harvesting systems achieve enhanced credibility, operational resilience, and long-term sustainability within interconnected energy infrastructures.

12. Emerging Research Directions

Emerging research directions in finite element modeling (FEM) for energy harvesting systems increasingly converge with advances in artificial intelligence (AI), predictive analytics, and digital twin ecosystems. The integration of explainable AI into predictive modeling frameworks demonstrates how transparency and interpretability enhance trust in computational decision-making (Tafirenyika, 2023). Applied to energy harvesting, explainable AI can augment FEM outputs by clarifying parameter sensitivity, identifying dominant physical mechanisms, and guiding adaptive optimization strategies.

Reinforcement learning approaches, originally developed for infrastructure maintenance optimization, present promising avenues for adaptive harvester tuning under variable environmental conditions (Tafirenyika, Moyo & Fasasi, 2022). Similarly, deep learning models for predicting pavement deterioration under changing climate conditions highlight the value of data-driven forecasting in dynamic systems (Tafirenyika, Moyo & Lawoyin, 2022). These methodologies can be translated into adaptive energy harvesting systems capable of modifying operational parameters in response to fluctuating mechanical or thermal stimuli.

AI-driven business intelligence tools further illustrate how large-scale data integration enhances strategic decision-making in complex environments (Tafirenyika *et al*., 2023a; Tafirenyika *et al*., 2023b). In energy harvesting research, coupling FEM simulations with real-time data streams enables intelligent performance monitoring and optimization within distributed infrastructures. Digital twin frameworks for multiscale physiological modeling provide an instructive parallel, demonstrating how real-time data assimilation enhances predictive accuracy and system responsiveness (Taiwo *et al*., 2022).

At the material and nanoscale levels, innovative biomedical strategies targeting metabolic pathways underscore the importance of multiphysics modeling in complex systems (Taiwo *et al*., 2024a; Taiwo *et al*., 2024b; Taiwo *et al*., 2024c). Analogously, next-generation energy harvesters increasingly require nanoscale material modeling to capture nonlinear electromechanical or magneto-thermal interactions.

Environmental compliance and sustainability considerations will also shape future research. Geological big data analytics exemplify how advanced data processing strengthens regulatory adherence and environmental oversight (Usiagu *et al*., 2023). Preventive maintenance frameworks for renewable energy systems further emphasize proactive lifecycle optimization (Yeboah *et al*., 2024). Finally, generative AI-driven cybersecurity models highlight the necessity of secure and adaptive digital ecosystems supporting energy technologies (Zhuwankinyu, Moyo & Mupa, 2024).

13. Conclusion

This study set out to critically examine finite element modeling (FEM) approaches as strategic instruments for optimizing emerging energy harvesting systems across diverse transduction mechanisms. The review achieved its aim by systematically synthesizing multiphysics modeling frameworks applied to piezoelectric, triboelectric, thermoelectric, electromagnetic, and hybrid architectures, demonstrating how FEM has evolved from a verification tool into a predictive and optimization-driven design engine. Through detailed analysis, the study highlighted the centrality of coupled-field simulations in capturing electromechanical, electrothermal, and magneto-mechanical interactions under realistic boundary conditions.

Key findings reveal that FEM-based optimization significantly enhances resonance tuning, structural durability, material parameterization, and power density performance. The integration of parametric modeling, topology optimization, and AI-assisted algorithms has expanded the analytical capacity of simulation environments, enabling adaptive and data-informed design refinement. Moreover, the incorporation of digital twin architectures and real-time validation frameworks has strengthened the alignment between numerical prediction and experimental performance, thereby improving system reliability and lifecycle management. The review also underscored the growing relevance of hybrid and multi-source harvesting systems in addressing fluctuating environmental conditions and supporting decentralized energy ecosystems.

Importantly, the study demonstrated that optimization in this domain extends beyond technical performance to encompass sustainability governance, resilience, and secure digital integration. As energy systems become increasingly interconnected, FEM-supported energy harvesters play a vital role in advancing efficiency, transparency, and environmental accountability.

Based on these insights, it is recommended that future research prioritize AI-integrated multiphysics modeling, nanoscale material characterization, and standardized validation protocols to enhance reproducibility and scalability. Greater emphasis should also be placed on digital twin deployment and cybersecurity integration to support resilient smart infrastructure. Collectively, these directions will consolidate simulation-driven innovation as a cornerstone of next-generation self-powered energy systems.

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