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Frontiers in Advanced Materials for Energy Harvesting and Storage in Sustainable Technologies

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ABSTRACT

The global pursuit of sustainable energy has spurred transformative innovations in materials designed for energy harvesting and storage, enabling efficient utilization of renewable resources. This manuscript examines recent progress in energy harvesting technologies, including piezoelectric, thermoelectric, and photovoltaic systems, which convert ambient energy sources like vibrations, heat, and sunlight into electrical power. Simultaneously, advancements in storage solutions, such as solid-state batteries, supercapacitors, and novel electrode materials, enhance energy retention and delivery. The integration of nanostructured composites, two-dimensional materials like graphene, and bio-inspired designs has significantly improved energy conversion efficiency, storage capacity, and cycle stability. These developments address critical challenges, including scalability, cost-effectiveness, and environmental sustainability, through initiatives like battery recycling and the use of non-toxic materials. The abstract explores diverse applications, from wearable electronics and autonomous devices to grid-scale energy storage, and underscores the importance of interdisciplinary research to drive the transition toward a clean energy future.

Keywords: Energy harvesting; Nanostructured materials; Solid-state batteries; Bio-inspired materials; Sustainable technologies.

Introduction

Sustainable energy generation and efficient storage have emerged as the twin pillars of efforts to address escalating environmental concerns, such as climate change and air pollution, while reducing global reliance on finite fossil fuel resources. The ongoing rise in global energy demand, coupled with the urgent need to curtail greenhouse gas emissions, has elevated the significance of innovative renewable energy technologies in modernization of energy systems [1-3]. Governments and industries around the world are increasingly committed to integrating renewable sources into energy portfolios, fostering accelerated research and development in advanced energy harvesting and storage materials. Traditional energy harvesting methods—primarily based on fossil and thermal plants—are being surpassed by cutting-edge technologies that tap into natural, ambient energy streams such as sunlight, kinetic movement, and thermal gradients. Photovoltaic (PV) systems harness solar radiation, thermoelectric devices exploit temperature differentials, and piezoelectric materials convert mechanical deformation into electrical charge [5-7]. These approaches offer decentralized, modular, and scalable solutions suitable for urban infrastructure, off-grid rural communities, and increasingly, for applications requiring miniaturized form factors such as wearable and implantable devices. The progress in harvesting technologies is closely intertwined with advances in materials science, which directly impacts efficiency, energy density, and device longevity. The challenge, however, does not terminate at harvesting energy—efficient, safe, and reliable storage remains crucial for establishing robust and resilient renewable energy systems. The irregular and intermittent nature of renewable sources necessitates effective storage technologies to distribute energy temporally and spatially, ensuring consistent delivery to end-users. Innovations in battery chemistries, including lithium-ion (Li-ion), sodium-ion, lithium-sulphur, and solid-state batteries, as well as emerging supercapacitor architectures, provide the means to store harvested energy and support demanding applications from electric vehicles to grid-level energy balancing [10-14]. The performance, safety, and sustainability of these storage systems are profoundly determined by the choice of electrode and electrolyte materials, which are subject to ongoing optimization. Recent advances in nanotechnology and materials engineering have catalysed the development of next-generation energy harvesting and storage solutions. The integration of nanostructured materials, such as graphene, transition metal dichalcogenides, and metal-organic frameworks, has enabled notable improvements in energy conversion efficiency, storage capacity, and cyclic stability [17-19]. Multifunctional, flexible, and biodegradable materials are finding increasing utility in autonomous sensors, wearable electronics, and multifunctional smart textiles, broadening the landscape of possible applications. Simultaneously, sustainability considerations—driven by environmental regulation and economic imperatives—are pushing the field towards eco-friendly, non-toxic, and recyclable materials, as well as life cycle management through recycling and reuse. This review synthesizes recent progress in harvesting and storage materials, tracing their historical evolution, highlighting seminal breakthroughs, and critically assessing the challenges that remain in translating laboratory research into real-world technologies. By providing an overview of contemporary advances and their practical implications, we emphasize the need for interdisciplinary approaches to achieve global energy sustainability—bridging materials science, chemistry, engineering, environmental science, and policy. Ultimately, a holistic strategy to energy technology development is expected to pave the way toward a low-carbon, resource-efficient, and technologically sophisticated energy future.

Historical Background

The evolution of energy harvesting and storage technologies dates back to the 19th and 20th centuries. The discovery of the photovoltaic effect by Edmond Becquerel in 1839 established the groundwork for converting sunlight into electrical energy, forming the basis of modern solar power technologies. Shortly thereafter, the 19th-century discoveries of Thomas Seebeck, Jean Peltier, and William Thomson (Lord Kelvin) elucidated thermoelectric phenomena, allowing the direct conversion of thermal gradients into electrical voltage, thus opening new horizons for waste heat recovery and thermal-to-electricity conversion. In 1880, the Curie brothers, Pierre and Jacques, demonstrated the piezoelectric effect, which became the foundation for harnessing mechanical vibrations and stress as alternative energy sources, particularly useful in low-power electronics and sensors. Advances in energy storage technologies paralleled these discoveries. The commercial introduction of the lead-acid battery by Gaston Planté in 1859 marked the inception of rechargeable energy storage that continues to play a pivotal role in automotive and backup power applications. Subsequent innovations led to the development of nickel-cadmium, nickel-metal hydride, and ultimately, the lithium-ion battery, first commercialized by Sony in 1991 based on the pioneering work of John B. Goodenough and colleagues. Lithium-ion technology revolutionized portable electronics and set the stage for the electrification of vehicles and renewable energy integration, owing to its superior energy density, cycle life, and efficiency. The latter part of the 20th century and the early 21st century have witnessed a rapid acceleration in materials science advances, profoundly impacting both energy harvesting and storage fields. The emergence of nanomaterials—such as graphene, carbon nanotubes, and other low-dimensional structures—along with advanced ceramic composites and solid-state electrolytes, has drastically enhanced device efficiencies and safety. These developments have enabled not only the miniaturization and flexibility of energy devices but also the integration of multifunctional capabilities, tailored for IoT, biomedical, and smart grid applications. This continuous trajectory underscores how historical breakthroughs in fundamental physics and materials chemistry have driven the evolution of contemporary sustainable energy solutions.

Review of Literature

Recent literature elucidates significant progress across various energy harvesting paradigms.

Photovoltaic Systems

Silicon-based solar cells remain the industry standard, offering high efficiencies exceeding 26% and excellent operational stability for both residential and utility-scale applications. However, the relatively high energy cost of silicon purification and wafer processing has motivated interest in emerging materials. Perovskite solar cells (PSCs) have demonstrated power conversion efficiencies surpassing 25% in laboratory settings, owing to their tunable bandgaps and facile processing. Yet, concerns regarding their long-term environmental stability—particularly moisture sensitivity and the use of lead—remain hurdles to commercialization. Organic photovoltaics (OPVs), constructed from conjugated polymers and small molecules, are valued for their mechanical flexibility and potential for large-area, roll-to-roll processing, but their efficiencies (currently ~18%) and device durability still lag significantly behind inorganic counterparts.

Thermoelectric Materials

Bulk thermoelectric materials such as bismuth telluride (Bi$_2$Te$_3$) and lead telluride (PbTe) have set early benchmarks for thermoelectric performance, with figures of merit (ZT) up to 1.5 at room temperature. These materials are widely used in niche refrigeration and waste heat recovery, but toxicity (lead, tellurium) and intrinsic brittleness restrict their scalability and broader applicability. Recent breakthroughs in nanostructured and composite thermoelectric, such as nanowire arrays, quantum dot superlattices, and organic-inorganic hybrids, have enabled enhanced ZT values (>2 in some systems) by decoupling thermal and electronic transport.

Piezoelectric Energy Harvesting

Lead zirconate titanate (PZT) remains the benchmark for piezoelectric energy harvesters due to its high electromechanical coupling and energy output. However, owing to the toxicity associated with lead, research has surged into lead-free alternatives such as barium titanate ($BaTiO_3$), potassium sodium niobate (KNN), and polyvinylidene fluoride (PVDF) . These materials have shown promise for flexible and biocompatible applications, including wearables and biomedical devices, but often face trade-offs between power output and mechanical robustness.

Beyond Conventional Harvesting: Hybrid and Multifunctional Systems

To extend device operation under varied environmental conditions, researchers are increasingly investigating hybrid energy harvesters that integrate multiple mechanisms—for example, combining photovoltaic, thermoelectric, and piezoelectric modules within a single framework. Such hybrid systems can maximize energy capture from sunlight, ambient heat, and mechanical vibrations, making them particularly attractive for autonomous wireless sensor networks, smart buildings, and self-powered IoT applications.

Advancements in Energy Storage Materials

Solid-state batteries, notably those utilizing ceramic or sulphide-based solid electrolytes (e.g., garnet-type $Li_7La_3Zr_2O_{12}$), address key safety concerns such as leakage and flammability found in conventional liquid-electrolyte systems. The move toward all-solid-state designs is also expected to enable the use of high-capacity lithium metal anodes. Supercapacitors employing graphene, carbon nanotubes, and metal-organic frameworks (MOFs) have shown rapid charge/discharge capabilities, high power density, and superior cycling stability, though their energy storage (kg) remains lower than next-generation batteries. Beyond lithium-ion, lithium-sulphur (Li-S), sodium-ion (Na-ion), and potassium-ion batteries are being intensively explored for grid applications due to the abundance and low cost of their constituent materials, though technical obstacles like the polysulfide shuttle effect (in Li-S) and electrode stability are ongoing areas of research [53-55]. In addition to material innovations, significant research has turned to eco-friendly and sustainable material choices, with the aim of mitigating the environmental impact across the device lifecycle. Recent studies highlight the use of biodegradable polymers for battery separators, bio-derived electrodes, and water-based electrolytes to minimize environmental footprint [20,56-58]. Life cycle assessments and recycling technologies are gaining traction, especially as the deployment of large-scale batteries increases and electronic waste becomes a pressing issue. Furthermore, the advent of machine learning and computational materials science has accelerated the discovery and screening of candidate materials for both energy harvesting and storage by enabling high-throughput predictions of structures and properties before costly physical synthesis. Equally important, device miniaturization and the growing demand for flexible, stretchable, and wearable electronics have necessitated the development of conformal energy systems. The integration of flexible perovskite solar cells, stretchable piezoelectric nanogenerators, and ultrathin supercapacitors is at the frontier of personalized energy solutions. These advancements are poised to drive the proliferation of self-powered devices for health monitoring, smart textiles, and untethered environmental sensing, matching the evolving needs of society for sustainable, ubiquitous energy access.

Recent Advances in Materials and Technologies

Nanostructured and Two-Dimensional Materials

The introduction of two-dimensional (2D) materials such as graphene and molybdenum disulfide (MoS_2) has revolutionized the design of both energy harvesting and storage devices. Graphene, known for its exceptional electrical conductivity and mechanical strength, has facilitated the development of supercapacitors with specific capacitances exceeding 300 F/g and enabled superior electrode kinetics in lithium-ion and sodium-ion batteries by promoting rapid ion transport and large surface-to-volume ratios. Similarly, nanostructured

MoS_2 and other transition metal dichalcogenides have been integrated into novel electrode architectures, boosting the energy density and cycling stability of batteries and capacitors. The application of nanostructured materials in thermoelectric devices has also enabled the engineering of quantum size effects and phonon scattering, significantly enhancing the thermoelectric figure-of-merit (ZT) beyond what has been achievable with bulk materials.

Bio-Inspired and Sustainable Designs

Bio-inspired approaches are leading to the development of energy materials with unprecedented architectural control and functionalities. Templating from natural structures such as nacre (mother-of-pearl) or plant vascular tissues yields hierarchical, porous architectures that optimize both mechanical stability and ion/electron transport within batteries and supercapacitors. These strategies not only improve the efficiency and mechanical robustness of energy devices but also enhance their environmental compatibility; for example, biocompatible and biodegradable templates help address end-of-life disposal concerns. Efforts have also been directed toward synthesizing electrode and separator materials from renewable sources, such as cellulose-based polymers, lignin, and chitosan, further reducing the environmental footprint of next-generation energy technologies.

Integrated and Wearable Energy Devices

Flexible and wearable energy devices mark a significant leap towards personalized, on-demand energy solutions. The integration of energy harvesters with storage units enables self-powered systems that directly serve wearable electronics, biomedical sensors, and smart textiles. For instance, stretchable PVDF-based piezoelectric nanogenerators seamlessly embedded in clothing can power health monitoring sensors, while flexible perovskite solar panels offer lightweight alternatives for wearable or portable charging applications. The development of hybrid devices—combining photovoltaic, thermoelectric, and triboelectric modules—further increases the adaptability and reliability of energy supply in dynamic, real-world environments. In addition to flexible form factors, recent research is focused on the miniaturization and multifunctionality of energy systems. Micro-supercapacitors and thin-film batteries are being patterned onto flexible substrates, enabling seamless integration into compact electronic circuits and wearable platforms. Advanced encapsulation strategies using elastomers, hydrogels, and self-healing polymers further enhance the mechanical durability and environmental tolerance of these devices, ensuring sustained performance under bending, stretching, or exposure to sweat and humidity. Moreover, advancements in crumple- and fold-tolerant materials are opening possibilities for origami-inspired and shape-programmable energy devices, aligning with the future of adaptive and reconfigurable electronics. Recent advances also encompass environmentally responsible innovations, such as closed-loop manufacturing and recycling processes for battery electrodes and separators. Researchers are increasingly applying green chemistry principles to the synthesis and processing of nanomaterials, minimizing hazardous byproducts and reducing energy consumption across the device lifecycle. Additionally, the introduction of machine learning for materials discovery and device optimization is poised to accelerate the identification of new candidates for both harvesting and storage, shortening the path from laboratory research to commercial deployment.

Challenges

Despite significant progress in the development of advanced materials for energy harvesting and storage, several critical challenges remain that hinder large-scale commercialization and long-term sustainability.

Material Lifecycle and Toxicity: Many state-of-the-art materials demonstrate exceptional electrochemical or energy conversion properties but pose substantial environmental and health risks. For example, lead-based perovskite solar cells and lead zirconate titanate (PZT) in piezoelectric devices offer high efficiencies and output but introduce toxicity concerns due to lead leaching and disposal issues. Similarly, cobalt, commonly used in lithium-ion battery cathodes, not only raises toxicity concerns but is also linked to unethical mining practices and resource scarcity. Addressing these issues requires either the replacement of toxic elements with environmentally benign alternatives—such as lead-free piezoelectrics or cobalt-free cathodes—or the development of effective recycling and waste management strategies to mitigate lifecycle impacts.

Cost and Scalability: Economic considerations significantly impact the feasibility of deploying advanced energy materials on a global scale. Many promising nanomaterials, including graphene, transition metal dichalcogenides, and certain engineered composites, involve costly synthesis procedures, low yield, or difficulty in achieving uniform, defect-free production at scale. Scalability concerns are further complicated by the purity and quality control required for high-performance devices. To address this, innovations in low-cost synthesis, green chemistry, and manufacturing processes such as solution processing or roll-to-roll fabrication are under active investigation.

Long-Term Stability: The operational and environmental stability of next-generation materials remains a significant barrier to practical deployment. For instance, perovskite solar cells, despite their rapid rise in laboratory efficiency, are susceptible to degradation by moisture, heat, and ultraviolet radiation, resulting in poor long-term reliability. Organic and polymer-based materials in supercapacitors and batteries may also experience rapid capacity fading, electrode dissolution, or mechanical breakdown after repeated cycling. Developing robust encapsulation, protective coatings, and inherently more stable material chemistries is therefore essential to extend device lifespan and ensure dependable field operation.

Integration and Compatibility: Creating multifunctional, hybrid, or integrated energy systems involves combining diverse materials with different mechanical, thermal, and electrochemical properties. Compatibility issues—such as thermal expansion mismatch, interfacial reactivity, and differences in mechanical flexibility—can compromise device performance or reliability. Furthermore, interfacing harvesting and storage units in flexible or wearable applications necessitates advanced packaging, effective encapsulation, and seamless system-level integration to protect against environmental exposure and mechanical stress. Addressing these engineering complexities will require interdisciplinary solutions spanning materials science, mechanical engineering, and device architecture.

Table 1. State-of-the-art Energy Harvesting and Storage Materials

Technology	Leading Materials	Efficiency/Performance	Key Challenges
Photovoltaic	Silicon, Perovskite, Organic	20-26% PCE (Si, PSC)	Lifetime, Toxicity (Pb), Cost
Thermoelectric	Bi$_2$Te$_3$, Nanostructures	ZT up to 2.6 (lab)	Material Toxicity, Brittleness
Piezoelectric	PZT, BaTiO$_3$, PVDF	Output up to mW/cm^2	Lead toxicity, Durability
Solid-state Battery	LLZO, Sulfide solid electrolytes	>400 Wh/kg (theoretical)	Dendrites, Interface Stability
Supercapacitor	Graphene, MOFs	>300 F/g (capacitance)	Voltage window, Energy Density
Advanced Battery	Li-S, Na-ion	>350 Wh/kg (Li-S theoretical)	Cyclability, Shuttle Effect

In summary, overcoming toxicity, cost, stability, and integration barriers is essential for translating laboratory advances into mature, market-ready energy technologies. Meeting these challenges will require not only innovations in material design and processing but also holistic strategies spanning supply chain management, lifecycle analysis, policy, and infrastructure development.

Discussion

The convergence of emerging materials, device architectures, and integrated systems is redefining the landscape of energy harvesting and storage. One of the central trends is the shift toward resource-abundant, non-toxic materials that can be manufactured and recycled with minimal environmental impact, in response to both regulatory pressures and consumer demand for greener technology. For example, the adoption of lead-free piezoceramics and the exploration of sodium- and potassium-ion batteries as alternatives to lithium-ion technology demonstrate a clear trajectory toward safer, more sustainable chemistries. This materials innovation is being complemented by new device engineering approaches, such as the use of solid-state electrolytes, which offer improved safety and permit the pairing of high-energy-density anodes previously considered too hazardous for conventional batteries. Hybrid energy systems are rapidly gaining prominence, as they offer the ability to collect and manage multiple types of ambient energy within a unified platform. Integrating photovoltaic, piezoelectric, and thermoelectric modules can help overcome the intermittency and variability inherent in renewables, enabling more reliable and resilient power solutions for critical applications such as distributed sensor networks and medical implants. Multifunctionality is also becoming a design paradigm, with power-textiles and smart materials capable of simultaneously harvesting, storing, and delivering energy, as well as monitoring physiological signals or environmental conditions. Achieving seamless integration without sacrificing performance, mechanical flexibility, or biocompatibility remains a topic of intense interdisciplinary research. Despite these encouraging advances, several technical and practical bottlenecks persist. Interface engineering, especially in hybrid or layered architectures, presents significant challenges in terms of charge transport efficiency and long-term reliability. Device miniaturization for wearables, ingestible, and implantable requires not only new form factors but also the development of stretchable, self-healing, and environmentally stable encapsulation materials. Furthermore, scaling up laboratory-scale innovations to industrial processes demands cost reductions, high-yield manufacturing, and robust quality control. Addressing these issues is a collective responsibility spanning materials science, device engineering, manufacturing, and supply chain management. Collaboration with policymakers and industry stakeholders will be vital for setting sustainability standards and accelerating the transition toward widespread adoption of advanced, eco-friendly energy harvesting and storage technologies.

Conclusion

Advancements in energy harvesting and storage materials offer a sustainable pathway toward carbon-neutral technologies and resilient energy infrastructures. The deployment of nanostructured materials, two-dimensional conductors such as graphene and MoS$_2$, and bio-inspired composites has dramatically improved the performance, flexibility, and integration potential of next-generation devices. These breakthroughs are already enabling the design of smart, self-powered solutions for wearable electronics, grid-scale storage, and autonomous sensing systems, and foreshadow the development of entirely new technology paradigms, such as energy-autonomous IoT devices. Nonetheless, to fully realize the promise of these transformative materials, it is imperative to address outstanding challenges. Lifecycle sustainability must remain at the forefront, necessitating innovations in green synthesis routes, device recycling, and the use of benign, abundant feedstocks. Long-term stability, reliability under real-world ambient conditions, and compatibility with flexible or stretchable substrates will be crucial for expanding the scope of applications. Additionally, efforts to standardize testing, characterize device lifetimes, and evaluate full environmental impacts through comprehensive life cycle analysis should be prioritized to avoid unintended environmental or health consequences. The future of sustainable energy technologies will hinge on a holistic approach that integrates material innovation with advances in device engineering, manufacturing, and circular economy principles. Increased interdisciplinary collaboration among researchers, industry, regulators, and end-users will accelerate the pace of discovery and deployment. If these multifaceted goals are met, advanced energy harvesting and storage systems will not only support the world's transition to renewable energy but also catalyze the emergence of a more self-sufficient, environmentally responsible, and technologically empowered society.

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