

Nanotechnology for Energy Storage and Conversion Applications

Priti Goyal

Department of Physics, Acharya Narendra Dev College, University of Delhi, India
Email: prutigoyal@andc.du.ac.in

Abstract

The high performance, sustainable, and effective energy storage devices are developed to meet the ever-growing energy demand of the world. Nanotechnology, with its distinguishing characteristics such as conductivity and surface area, has the capability to revolutionize the performance of energy storage devices by manipulating the materials at the nanoscale. This article, with a focus on capacitors and batteries, aims to identify the importance of nanotechnology in the development of energy storage devices such as sodium sulfur, redox flow, and lithium-ion batteries. We examine the use of nanomaterials in batteries, including separators, electrolytes, and electrode materials (such as metal oxides and carbon nanotubes). By modifying materials at the molecular level to improve the capacity, charging rates and efficiency, nanotechnology has transformed energy storage and conservation. Important uses include supercapacitors for quick energy release, graphene and carbon nanotubes in lithium-ion batteries to increase energy density, and nano coatings to improve solar cell efficiency and lower heat loss. The development of improved nanostructured materials is being undertaken to tackle issues such as interfacial side reactions. Solid-state batteries and the integration of nanomaterials with artificial intelligence for improved energy storage are two recent advancements that are encouraging for nanotechnology in energy storage, despite ongoing concerns about cost-effectiveness and environmental impact.

Keywords: Nanomaterials; Energy storage; Batteries; Supercapacitors, energy conversion

Introduction

In view of environmental impact and non-renewable nature, traditional fossil fuels have received attention in the current phase of the energy sector's reform (Choe et al., 2024). There has been a focus on the search for a sustainable source of energy (He et al., 2024). The production of electrode materials has become vital to the growth of the industry, with electrochemical performance of battery technology emerging as a competitive option in the field (Xu et al., 2023). In an effort to move the industry forward, the production of electrode materials has been achieved through the application of various building methods (Xiong et

al., 2025). Among these, the management of the dispersal and transformation of nanomaterials on composite materials for specific purposes has become popular. The degradability and renewability of biomass materials make them excellent candidates for the development of potentially new electrode materials (Zhang et al., 2019). However, there are several serious issues concerning biomass-based electrode materials that need to be studied in comparison to conventional electrode materials.

Nanoparticles have transformed the field of energy storage and conservation technology with their tremendous capability to improve the functionality and efficiency of various forms of energy systems. The application of nanostructured particles has become an indispensable catalyst and electrode material in battery technology, energy density, and charge/discharge rates in batteries. By modifying the structure of nanoparticles, tremendous advancements have been achieved in overcoming the conventional limitations of batteries, thus leading to the development of new forms of batteries with high capacities and long lifetimes. The application of particles in supercapacitors has led to significant improvements in the transfer and storage of energy.

The nanoparticle-based electrodes have shown better porosity, surface area, and conductivity, thus enhancing the energy density and power density of supercapacitors. The application of nanomaterials and the use of new electrolytes have not only increased the life of supercapacitors, but have also reduced the worries about the loss of energy during the cycles. The role of nanoparticles has been found to be crucial in the conversion of solar energy. Nanoparticles with specific optoelectronic properties have been found to improve the efficiency of charge separation, electron transportation, and light absorption. The use of nanoparticles as photocatalysts for the production of solar fuel has accelerated the production of clean energy carriers. Although the transformative potential of nanoparticles is extremely high, there are certain issues to be addressed methodically to ensure the smooth incorporation of nanoparticles into real-world applications. Nanoparticles have the potential to revolutionize the field of energy conversion and accelerate the process of achieving an efficient and sustainable energy future with the continued exploration of new nano architectures and revolutionary fabrication techniques.

The main aim of the paper is to systematically explore how nanotechnology can be utilized to develop energy storage and conversion devices, such as lithium-ion batteries, supercapacitors, phase-change materials, solar cell technology, fuel cell technology, and thermoelectric devices. In addition to improving performance, key challenges such as

scalability, costs, and environmental and life-cycle sustainability are also discussed in this paper. The integration of material science and engineering application is expected to offer a comprehensive perspective on the revolutionary capability of nanotechnology in the development of future energy systems.

Nanotechnology Application in Batteries Technologies

However, the technology associated with the battery has been revolutionized through the introduction of nanoparticles, which have greatly improved the performance and the energy storage capabilities of the batteries. This has been attributed to the increased surface area and the ability of the particles, made up of materials such as titanium dioxide or lithium iron phosphate, for increased electron mobility that has resulted in the batteries having more rapidly charge and discharge as well as increased capacity (Chen et al., 2014). They are improving the efficiency of the system, the life span of the batteries, and making it possible for space-efficient and lightweight batteries for various needs such as electric cars and electronic gadgets as the nanoparticles integrate into the electrodes of the batteries. The ability to control the characteristics of nanoparticles has the potential for further advancements in the design of batteries and the achievement of the need for the development of sustainable and efficient sources of energy (Tian et al., 2021).

The energy storage sector is one area where nanoparticles are likely to have a major impact, especially if used in the development of lithium-ion batteries, where lithium iron phosphate nanoparticles are used to enhance thermal stability, minimize toxicity, and extend the lifespan of the batteries (Mohammed et al., 2025; Nitta et al., 2015). Silicon nanoparticles, when used in lithium-ion batteries, have the advantage of enhancing the energy density of the batteries, whereas the use of sulfur nanoparticles enhances the energy density of lithium-sulfur batteries by stabilizing the electrode structure (Ting et al., 2022). Vanadium oxide nanoparticles have the advantage of enhancing the efficiency of vanadium redox flow batteries (VRFBs) (Chakrabarti et al., 2020). In lithium-ion batteries, nano-engineered nickel-cobalt-manganese oxide materials have the ability to accelerate charging and discharging processes. Additionally, carbon-coated nanomaterials have been proven to have the ability to prevent structural deterioration, thereby enhancing thermal stability.

Another important aspect of nanotechnology, with regards to lithium-ion batteries, is the concept of interfacial engineering. In lithium-ion batteries, surface coatings such as Al_2O_3 ,

ZrO₂, and LiPON have the ability to create a protective interface, thereby preventing the decomposition of the liquid electrolyte. This has the effect of improving the stability of the lithium-ion battery, especially during fast charging. Collectively, these nanoscale particles offer a safe, durable, and effective form of energy storage, which could have a significant impact on various technological fields/sectors (Mohammed et al., 2025; Lakshmanan et al., 2025).

Nanotechnology Application in Super capacitors

Super capacitors (SCs) are considered to become one of the most promising solutions to offer robust, reliable, and sustainable energy storage systems because of their high power density, reversibility, long lifetime, and safe state. Super capacitors have been a focus of interest because of their fast charging rate, extraordinary cycle count, and high power density. These characteristics make super capacitors a better choice compared to lithium-ion batteries and potassium batteries (Chmiola et al., 2008; Hussain et al., 2022; Zhang et al., 2023). Super capacitors are a new type of device designed to achieve energy storage. There is interaction of various forces, including Coulomb forces, intermolecular forces, and interatomic forces which results in the formation of a steady interface between the combination of the solid and liquid with an opposite double charge, denoted as the "interface double charge" (Deng et al., 2017; Kothandam et al., 2023). However, low energy density is a drawback for super capacitors. The double-layer super capacitors are composed of two passive porous plates placed in an electrolyte solution which leads to the large surface area of electric double-layer capacitors (EDLCs). The capacitors have the capability to store energy through reversible adsorption/desorption of ions of the electrolyte at the interface of the material and electrolyte. There is no transfer of charge between the two media (Singh & Tripathi, 2018).

Pseudo capacitors make use of reversible Faraday reactions on the electrodes to store energy. This type of device has a higher energy density compared to EDLCs. There are various substances that are used in the electrodes. These substances include compounds such as metal oxides and organic polymers, in addition to carbon compounds. The rapid reactions of ion intercalation result in the creation of pseudo capacitors (Zhang & Nicolosi, 2019). The electrodes are normally composed of compounds that are composed of metals and polymers. The rapid Faraday reactions with the electrolyte solution enable rapid charge storage. The nanoparticles have a great potential to be used as electrodes because of their large surface

area (Yadav and Devi, 2020). The unique electrical properties of nanoparticles have a great potential to enhance the transfer of charge, which is likely to optimize electrochemical reactions in various applications, such as fuel cells, batteries, and super capacitors (Conte, 2010). They have the ability to enhance energy conversion and storage using nanoparticle electrode and leads to the development of more efficient and ecofriendly electrochemical devices. The unique electrical properties of nanoparticles have a great potential to enhance energy conversion and storage. The development of efficient energy storage devices is necessary to support renewable energy sources like solar energy, tidal energy, wind energy, etc., to overcome issues like environmental pollution and carbon emissions.

Zero Intervening State Capacitors have the potential to overcome the low energy density drawback of super capacitors. In fact, it is a balanced approach to improve the energy storage capability of super capacitors through the combination of high energy densities of batteries and high power densities of capacitors. This technology is significant in light of the increasing need to store energy in the dynamic energy scenario.

Electrical double layer capacitors, hybrid super capacitors, and pseudo capacitors are all heavily influenced by nano sizing. The mechanism of charge storage in active carbons, which are vital to the operation of EDLCs, is heavily influenced by their size and shape. It is possible to decrease the size of the particles/electrode, as well as the shape and size of active carbons, through the production of porous structures. The size of active materials used in pseudo capacitors is also a factor. In a surprising turn of events, materials with reversible redox activity, which are characteristics of batteries, can also become pseudo capacitors when nanosized. Additionally, it is possible to obtain materials with high energy and power densities on a device level by using a hybrid device with capacitive and faradaic-type electrodes (Dsoke et al., 2021).

There are various types of supercapacitor (SC) electrode materials, including battery-type material, pseudocapacitor material, and EDLC material, which have different operating principles. Due to their superior electrochemical properties and multiple valency, transition metal-based nanomaterials, particularly metal chalcogenides, have gained significant interest in recent times. According to a recent study, binary metal sulfide-based nanomaterials, including copper zinc sulfide (CuZnS), have been observed to have superior performance with regard to energy storage due to superior conductivity. In response to the dynamic

demand for energy storage materials, copper-doped zinc introduces new possibilities for the development of superior supercapacitor electrodes (Abbas et al., 2022).

Significant progress in the field of hybrid supercapacitors and nano-engineered asymmetric supercapacitors is oriented towards achieving battery-type and capacitor-type behavior within a single supercapacitor device architecture. There is a growing trend in the research field to develop techniques for synthesis and flexible device fabrication along with environmentally friendly materials for electrodes to facilitate large-scale practical applications.

Nano enhanced phase change materials for thermal energy storage

While electrochemical storage systems dominate portable and grid-scale applications, thermal energy storage provides an efficient solution for managing waste heat and improving overall energy system efficiency through phase change materials (PCM).

Energy can be conserved in a number of ways, but two common ones are changes in the physical as well as chemical properties of the storage material, such as a change in temperature or the media's phase, and change in the chemical energy (Fallahi et al., 2017). In a variety of heat storage systems, the absorption and release of heat energy is governed by the material. Latent heat thermal energy storage (TES) is a highly favorable technique among these basic thermal energy storage techniques because of its better energy storage capacity and the ability to maintain a constant temperature. The latent heat of phase transitions, such as liquid to solid or vice versa, makes thermal energy storage devices utilizing phase change material particularly attractive. According to the research, it is stated that the devices are renowned for having large storage capacity, small volumetric changes, wide temperature ranges, and reusability. Hence, the use of the PCM-based TES system is regarded as an essential candidate for various applications, such as the use of the system in the solar heating/cooling system (Mofijur et al., 2019), building cooling/heating system (Souayfane et al., 2016), air heating system (Ghritlahre, P.K. Sahu, 2020), solar energy conservation system (Lin and Al-Kayiem, 2016), optimization of the energy usage of the electronic devices, HVAC systems, etc. (Lin et al., 2018).

Thermal energy storage with PCMs is the most promising methods for energy storage. However, during the periodic phase change processes, PCMs' poor conductive heat transmission slows down the pace of thermal energy transfer. Numerous techniques have been reported in the literature to get around this restriction. The efficiency of PCMs has been

shown to increase with the addition of thermally conductive nanoparticles, such as graphene, carbon nanotubes, metal oxides, and metallic nanoparticles. They create conductive pathways within the PCM matrix. These nano-additives reduce thermal resistance, accelerate phase transition kinetics, and improve heat storage–release efficiency through enhanced phonon transport mechanisms. Accordingly, nano-enhanced phase-change media (NePCMs) with special qualities have been created using nano-metals oxides, nano-carbons, and nano-metal (Xiong et al., 2020). Heat transfer capabilities and nano-sized fillers composed of carbonic, metals, hybrid materials, and ceramic are only a few of the numerous materials, structures, and uses of NePCMs that are demonstrated in the following sections.

The term "Nano-PCMs composites" refers to the dispersion of materials with high thermal conductivity and nanosize into pure PCMs. In addition to their thermal conductivity, the type of nanomaterials and their properties (thermal, chemical, physical, etc.) and the amount of nanomaterials that must be added—typically in volume or mass fraction (%)—have a significant impact on a number of other aspects of Nano-PCM composites, including their density, viscosity, heat capacity, morphological, and rheological characteristics.

Emerging research focuses on hybrid nano-enhanced PCMs that combine metallic, carbon-based, and oxide nanoparticles to achieve synergistic thermal performance. Future challenges include optimizing filler concentration to balance latent heat retention with conductivity enhancement, as well as developing scalable and cost-effective synthesis methods for large-scale thermal energy storage applications.

Application of Nanoparticles in Energy Conversion

Nanoparticles in Solar Energy Conversion

The use of nanoparticles has gained much attention in the transformation of solar energy into useful energy due to the excellent properties associated with nanoparticles (Samdhyan et al., 2022). Nanoparticles, at the nanoscale, have the advantage of creating an increase in the production of charge carriers, an increase in the efficiency of light absorption, and the ability to skillfully manage photons. The revolution in the field of photovoltaic and solar thermal systems is possible with the adaptable properties of nanostructured particles, such as the sizes, shapes, and composition of the particles (Pasupathi et al., 2020). The combination of the properties of solar energy with nanotechnology is a ground-breaking method of achieving

the potential of creating efficient results with cost-effective renewable energy solutions, with various applications ranging from the production of fuel to the generation of power.

Paraffin, a phase change material, contains nanoparticles that offer an opportunity to enhance the efficiency of the utilization of solar energy. Its thermal conductivity is substantially enhanced by the incorporation of various kinds of additives. The incorporation of various kinds of nanoparticles in PCMs substantially enhances their thermal conductivity, which can be several times higher compared to pure PCMs. A wide range of compounds can be used to enhance the thermal conductivity making it appropriate for various applications (Katekar and Deshmukh, 2020).

The small particles, which can also be made up of chemicals such as carbon or metals, have the ability to absorb a significant amount of solar energy which has the effect of enhancing the storage and release of thermal energy via a smooth transition of the paraffin matrix from a solid to a liquid state. This integration has the effect of enhancing the heat capacity and conductivity of the composite material. Therefore, the effectiveness of the composite material is boosted in terms of absorption, transfer, and storage of heat. The integration of the paraffin matrix with the particles is exceptional when it comes to solar thermal systems. In this solar energy collection method, the innovative composites have a significant impact on enhancing the process of heat collection, preservation, and dispersion. The innovative composites are essential to enhancing the effectiveness of the solar energy collection and utilization technology. The overall performance of the solar energy system may be enhanced by the innovation.

Nanoparticles in Fuel Cell Technology

The fuel cell has the advantage of high efficiency, chemical reactions, low emissions, and direct chemical energy conversion to electrical energy. Despite the advantages, the reaction kinetics, especially the oxygen reduction reaction at the cathode, are a major challenge. Being a vital part of the hydrogen energy system, which can serve as a renewable energy source if used with sporadic energy sources like solar and wind energy, is a fuel cell used to produce electrical energy through the electrochemical oxidation of hydrogen and many other organic molecules (Kumar and Gupta, 2025). Molten carbonate and solid oxide fuel cells (SOFC) are the current technology leaders in power generation, while polymer electrolyte membrane fuel cells (PEMFC) and their derivatives known as direct methanol fuel cells are current

technology leaders in shipment volume for small power and high-temperature fuel cells (Verma et al., 2024). The major barriers to the adoption of fuel cells include their costs and durability, and hydrogen availability, and nanotechnology is a promising technology to address such barriers. The last ten years have witnessed developments in synthetic methods which have led to the production of nanomaterials of various dimensions, shapes, and properties, even though the development of nanosized catalysts supported on high surface area carbons of various shapes has greatly enhanced their performance. The development of innovative electrolytes for fuel cells has been greatly enhanced by nanotechnology (Bandara et al., 2022).

Nanoparticles in Thermoelectrics

Although thermoelectrics can directly convert heat into electricity and create affordable, pollution-free energy conversion methods, the area has long been seen as a potentially revolutionary power production technology and is now expanding steadily. The special advantages of thermoelectric materials draw a lot of interest. The direct conversion of heat to electricity is one of those advantages that makes this material promising. Wearable thermoelectric materials have the ability to convert the heat generated by the human body into useful power. In order to retain good electrical conductivity and minimize thermal conductivity, nanotechnology-based materials enhance thermoelectric characteristics and heat absorption capabilities for nanostructures (Wang et al., 2024). PEDOT, or poly (3, 4-ethylenedioxythiophene), is being studied in great detail because of its high conductivity, flexibility, and good transparency, among other qualities (Chen et al., 2012).

Nanostructured thermoelectric materials have a promising potential for waste heat recovery in vehicles, industrial processes, and electronic devices. Despite the promising potential, the mechanical instability, toxicity of telluride compounds, and large-scale fabrication are the major challenges associated with their practical application.

Challenges and Perspectives

Although there have been tremendous advancements in the field of nanotechnology-enabled energy storage and conversion systems, there are a number of scientific, engineering, economic, and environmental hurdles to be cleared to ensure the large-scale commercialization of such systems.

Technical and Materials Challenges

One of the major technical hurdles associated with nanomaterials-based energy storage systems is the issue of structural and chemical stability. In spite of the enhanced ionic conductivity of nanoscale architectures, their high surface energy may trigger undesirable side reactions, electrolyte degradation, and interfacial instability. For instance, in lithium-ion batteries, large surface area nanomaterials may induce uncontrolled solid electrolyte interphase (SEI) layer formation, whereas in supercapacitors and fuel cells, nanostructured architectures may face the problem of agglomeration or mechanical instability during repeated cycling.

Another important challenge is the balance between conductivity and stability. For example, the smaller the particles, the better the diffusion kinetics, but the smaller the particles, the lower the structural stability. Similarly, in thermoelectric materials, nanostructuring decreases thermal conductivity by scattering phonons, but it can simultaneously affect charge carrier mobility. This balance between competing material properties is another challenge in the design of materials.

Scalability and Manufacturing Constraints

However, most of the nanomaterials that have exhibited remarkable performance at the laboratory-scale have been produced using methods such as chemical vapor deposition, hydrothermal synthesis, sol-gel processing, and template synthesis. These methods have been associated with issues such as high energy demands, processing complexities, and low yields. Scaling up these methods for industrial-scale processing while ensuring uniformity, reproducibility, and cost-effectiveness remains a major engineering challenge.

In addition, size control, distribution and morphology of the nanoparticles as well as the dispersion of the nanoparticles in the device has been crucial in ensuring the quality and reproducibility of the device performance. The unpredictability of the electrochemical or thermal behavior of the nanoparticles has been a major quality control challenge in the processing of these materials at the industrial-scale.

Economic and Cost Considerations

The economic viability of nanotechnology-based energy solutions is not just a function of the enhancement of performance, but it is also a function of the availability of the material, the cost of synthesizing the material, and the material's durability over time. For example, the use of noble metals like platinum, used in fuel cells, increases the overall cost of the fuel cell.

The assessment of the cost of the material over the lifespan must take into consideration the material's lifespan, so if the material's lifespan is low, the replacement costs will far outweigh the benefits of the material's performance. The optimization of the cost/performance relationship is critical for the viability of the material.

Environmental and Safety Concerns

The environmental impact of nanomaterials is another area of research that is in development. Due to their small size and reactivity, nanoparticles have demonstrated distinct toxicological properties. The hazards of nanoparticles include bioaccumulation, ecotoxicity, and uncontrolled release in the soil or water system during the manufacturing process. As such, an in-depth lifecycle assessment study is required to evaluate the environmental impact, commencing with the raw material extraction process and ending with the recycling process. The importance of green nanotechnologies, which are environmentally friendly in synthesis, precursors, and recycling, is also gaining momentum. Sustainable material design should not be an afterthought but rather integrated in the early stages.

Regulatory and Standardization Issues

Regulatory guidelines on nanomaterials are still in the developmental stage. In the absence of universally accepted standards on the characterization of nanomaterials, safety assessment, and performance benchmarking, the commercialization of nanotechnology may face a roadblock. Development of standardized test protocols on toxicity, stability, and device integration is vital to the commercialization of nanotechnology.

Future Perspectives

Despite these challenges, the outlook for nanotechnology in energy systems is extremely promising. The integration of artificial intelligence, machine learning, and computational materials science is anticipated to enhance the rate of discovery and optimization of

nanomaterials. This is because data-driven modeling has the potential to predict material properties, optimize nanostructures, and eliminate experimental trial and error. This would allow for the rational design of multifunctional nanocomposites with specific electrochemical and thermal properties.

The advent of novel energy architectures, including solid-state batteries, hybrid supercapacitor-battery systems, and nano-engineered thermoelectric generators, is revolutionizing design principles. Nano-engineered solid electrolytes and three-dimensional electrode architectures are particularly exciting areas for enhancing energy density, safety, and fast-charging capabilities.

Future energy systems might be designed to include integrated functionalities such as storage, conversion, and thermal management using a single nanostructured system. For instance, hybrid nanocomposites that integrate electrochemical storage and thermal regulation might be used to boost system efficiency in electric vehicles and grid-scale applications.

The success of energy storage in the future will depend on the development of recyclable materials and the adoption of a sustainable concept such as the circular economy. In particular, the development of materials that can be recovered and reused at the end of the life span of the material, such as lithium, cobalt, rare earths, and noble metals, is critical to the sustainability of the material.

The potential of nanotechnology to revolutionize the field of energy storage and conversion is undeniable. Nevertheless, to achieve future breakthroughs, there is a need to achieve a balance between material science, engineering, economic viability, environmental concerns, and the law. The synergy between material scientists, engineers, lawmakers, and industry players is critical to transform the potential of nanotechnology into reality.

Economic Analysis

Significant improvements in the efficiency of energy storage and conversion using nanotechnology have been realized; however, economic viability is a major factor in the large-scale commercialization of such technologies. Although improvements in the efficiency of energy storage and conversion using nanotechnology have been realized, economic viability is a major factor in the large-scale commercialization of such technologies.

The economic viability of nanomaterials is greatly affected by the cost of the precursor material. For instance, platinum nanocatalysts used in fuel cell technology drive up the cost of fuel cell technology owing to the precious nature of the material. Although the nanostructuring of the material minimizes the amount of platinum required to achieve the desired efficiency, the cost of the material is still high. In the same vein, the use of Lithium, Cobalt, and Rare Earth elements in battery technology is affected by supply chain volatilities. To reduce such problems, research is shifting focus to Earth-abundant alternatives like transition metal oxides, carbon-based nanomaterials, and metal-nitrogen-carbon composites. For economic sustainability, it is important to find replacements without compromising performance.

Nanomaterial fabrication methods like chemical vapor deposition, hydrothermal methods, sol-gel methods, template methods, etc., are associated with complicated processes, high energy requirements, or the need for sophisticated equipment. These factors contribute to increased fabrication costs compared to their bulk counterparts. Additionally, the reproducibility of uniform particle size distribution and morphology at the industrial scale is another financial constraint. Inconsistency of the batch may affect the performance of the device. Hence, the need for large-scale, low-temperature, and solution-phase methods is being explored to reduce the cost of production.

One of the most important aspects in the assessment of the implementation of nanotechnology is the performance-cost ratio as opposed to performance outcomes. To exemplify this, consider the implementation of silicon-based anodes in the form of nanostructures that have been observed to increase the capacity of the batteries while in operation. However, the increased volume of the silicon might reduce the lifespan of the batteries, thus negating the positive techno-economic outcomes associated with the implementation of the technology.

The scaling up of laboratory-scale nanomaterials to gigawatt hours of battery technology or hydrogen production poses challenges. Scaling up also poses challenges in terms of reproducibility and supply chain management. Industrialization also poses a challenge in terms of compatibility with existing manufacturing infrastructure. The retrofitting of manufacturing plants to include nanomaterials may also involve a capital investment. This will be justified in terms of enhanced efficiency and product life.

Aside from the cost of production, another important consideration is the lifecycle assessment. The degradation rate, the frequency of maintenance, recyclability, and the process of waste disposal are important considerations. For instance, if the nanostructured electrodes have better cycle stability, the cost of production may be compensated by the longer lifespan of the material. The recyclability of the material, especially the lithium, cobalt, and the precious metals, is becoming an important consideration to improve the economic sustainability of the nanomaterials. The recyclability of the nanomaterials may reduce future dependency on resources and the cost of compliance with environmental regulations.

The adoption of nanotechnology-based energy systems also depends on policy incentives, carbon pricing, and renewable energy subsidies. The support of various governments for clean energy systems can further increase the commercialization rate of nanotechnology-based energy systems. On the contrary, regulatory risks associated with nanomaterials can also impact the commercialization rate.

Although nanotechnology has increased the performance of energy conversion and energy storage systems, the commercialization rate of nanotechnology-based energy systems depends on developing cost-effective, scalable, and sustainable energy systems. Therefore, future research should focus on developing low-cost material alternatives, energy-efficient synthesis techniques, and lifecycle optimization. The techno-economic framework is essential for developing nanotechnology-based energy systems. The techno-economic framework should focus on integrating material science with industrial engineering principles for translating nanoscale innovations into economically viable energy solutions.

Conclusions

The potential of nanotechnology to revolutionize the development of energy storage as well as energy conversion systems is becoming increasingly clear, especially with the growing global energy demand and the pace of renewable energy integration into the global energy mix. The present study aims to demonstrate the potential of nanotechnology to improve the performance of critical energy storage solutions like capacitors, as well as other energy storage solutions like lithium-ion, sodium-sulfur, and redox flow batteries. In addition, the capability of nanotechnology to improve the performance of energy conversion solutions like fuel cells, PV systems, thermoelectric devices, and photocatalytic systems is also discussed.

With the ability to regulate materials on a nanoscale, it is possible to engineer materials with electric conductivity, strength, and catalytic activity to an unprecedented level compared to traditional materials science. The high efficiency of nanomaterials is mainly due to their high surface volume ratio, good electrode/electrolyte interfaces, optimized band structure, short ion transport paths, and high charge transfer rates. In energy storage devices, the advantages of nanomaterials result in high energy density, good power output, and long lifespan. In energy conversion devices, the advantages of nanomaterials result in high rates of photon absorption, catalytic reactions, and heat-to-electric energy conversion.

As the importance of the use of renewable sources such as solar and wind energy increases, it is vital to have storage systems to ensure a sustainable future. Further research into nanotechnology-based energy systems is therefore important not only to overcome the challenges associated with the technology, but to do it in a sustainable manner. It is therefore vital to ensure the sustainability of the technology by addressing the associated challenges to ensure the technology is available on a larger scale.

Ultimately, the scope for continued innovation in the improvement of nanomaterials, along with the collaboration of various fields and the use of technology in an appropriate manner, is going to be crucial in the development of a robust and efficient energy infrastructure on a global scale that is also sustainable in the future. Nanotechnology is seen as the foundation pillar for the development of the next generation of energy storage and conversion technologies that are going to be crucial in the development of a clean and secure energy future.

Acknowledgements

The author would like to thank the principal, Acharya Narendra Dev College, University of Delhi, for the infrastructural assistance and direction.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Funding sources

The author declares that no funds, grants, or other support were received during the preparation of this manuscript.

References

Abbas N., Shaheen I., Hussain I. et al., (2022) Glycerol-mediated synthesis of copper-doped zinc sulfide with ultrathin nanoflakes for flexible energy electrode materials,” *Journal of Alloys and Compounds*, vol. 919, Article ID 165701.

Bandara K. M. G. C., Herath H. M. R. S., Adassooriya N.M., (2022) Nanomaterials for Energy Storage Applications, *Sustainable and Clean Energy Production Technologies*, 10.1007/978-981-16-9135-5_4, 67-91.

Chakrabarti, B., Rubio-Garcia, J., Kalamaras, E., Yufit, V., Tariq, F., Low, C. T. J., Kucernak, A., & Brandon, N. (2020). Evaluation of a Non-Aqueous Vanadium Redox Flow Battery Using a Deep Eutectic Solvent and Graphene-Modified Carbon Electrodes via Electrophoretic Deposition. *Batteries*, 6(3), 38.

Chen Z., Xu M., Du B., Zhu H., Xie T., and Wang W., (2014) Morphology control of lithium iron phosphate nanoparticles by soluble starch-assisted hydrothermal synthesis, *Journal of Power Sources*, vol. 272, 837–844.

Chen Z. G., Han G., Yang L., Cheng L., Zou J., (2012) Nanostructured thermoelectric materials: Current research and future challenge, *Progress in Natural Science: Materials International*, 22, 6, 535-549.

Chmiola, J.; Gogotsi, P.; Weerasooriya, R.; Gogotsi, Y. (2008) Low-Cost Supercapacitors for Household Electrical Energy Storage and Harvesting. *ECS Meet. Abstr*, MA2008-02, 46.

Choe, G.; Kim, H.; Kwon, J.; Jung, W.; Park, K.Y.; Kim, Y.T. (2024) Re-evaluation of battery-grade lithium purity toward sustainable batteries. *Nat. Commun.*, 15, 1734.

Conte M., (2010) Supercapacitors technical requirements for new applications,” *Fuel Cells*, vol. 10, no. 5, 806–818.

Deng Y., Li, Li T., Zhang J., Yang F., and Yuan C., (2017) Life cycle assessment of high capacity molybdenum disulfide lithium-ion battery for electric vehicles,” *Energy*, 123, 77–88,.

Dsoke S., Pfeifer K., and Zhao Z., (2021) The role of nanomaterials for supercapacitors and hybrid devices,” in *Nanomaterials for Electrochemical Energy Storage*, 19 of *Frontiers of Nanoscience*, 99–136.

Fallahi A., Guldentops G., Tao M., Granados-Focil S., Dessel S.V., (2017) Review on solid-solid phase change materials for thermal energy storage: Molecular structure and thermal properties, *Applied Thermal Engineering*, 127, 1427-1441.

Ghritlahre H.K., Sahu P.K., (2020) A comprehensive review on energy and energy analysis of solar air heaters, *Arch. Thermodyn.* 41 183–222.

He, J.Y.; Cao, L.Q.; Cui, J.J.; Fu, G.W.; Jiang, R.Y.; Xu, X.; Guan, C. (2024) Flexible Energy Storage Devices to Power the Future. *Adv. Mater.*, 36, 202306090.

Hussain I., Ahmad M., Chen X. et al., (2022) Glycol-assisted Cudoped ZnS polyhedron-like structure as binder-free novel electrode materials,” *Journal of Saudi Chemical Society*, vol. 26, no. 4, Article ID 101510.

Katekar V. P. and Deshmukh S. S., (2020) A review of the use of phase change materials on performance of solar stills,” *Journal of Energy Storage*, vol. 30, Article ID 101398.

Kothandam, G.; Singh, G.; Guan, X.; Lee, J.M.; Ramadass, K.; Joseph, S.; Benzigar, M.; Karakoti, A.; Yi, J.; Kumar, P.; (2023) Recent Advances in Carbon-Based Electrodes for Energy Storage and Conversion. *Adv. Sci.*, 10, 2301045.

Kumar A., Gupta P., (2025) Nanotechnology for Energy Applications: Harnessing Nano and AI for Sustainable Energy, *NanoMind: Exploring Synergies in Nanotechnology and Machine Learning*, 10.1007/978-3-031-77296-2_7, 129-150.

Lakshmanan P, Huang CH, Rengapillai SD, Chen YS, Liu WR, Hsu CL, Marimuthu S. (2025) Graphite Felt Decorated with Metal-Organic Framework-Derived Nanocomposite as Cathode for Vanadium Redox Flow Battery. *Nanomaterials (Basel)* 1;15 (7):535.

Li G., (2016) Title of document: review of thermal energy storage technologies and experimental investigation of adsorption thermal energy storage for residential application, *Appl. Ther. Eng.* 100 (5) 434–452.

Lin S.C., Al-Kayiem H.H., (2016) Evaluation of copper nanoparticles - paraffin wax compositions for solar thermal energy storage, *Sol. Energy* 132 267–278.

Lin W., Ma Z., Ren H., Liu J., Li K., (2018) Solar thermal energy storage using paraffins as phase change materials for air conditioning in the built environment, *Ther. Ener. Storage*.

Mofijur M., Mahlia T.M.I., Silitonga A.S., Ong H.C., Silakhori M., Hasan M.H., Putra N., Ashrafur Rahman S.M., (2019) Phase change materials (PCM) for solar energy usages and storage: an overview, *Energies* 12 3167.

Mohammed, H.; Mia, M.F.; Wiggins, J.; Desai, S. (2025) Nanomaterials for Energy Storage Systems—A Review. *Molecules*, 30, 883.

Nitta, N.; Wu, F.; Lee, J.T.; Yushin, G. (2015) Li-Ion Battery Materials: Present and Future. *Mater. Today*, 18, 252–264.

Pasupathi M. K., Alagar K., and Aritra G., (2020) Characterization of hybrid-nano/paraffin organic phase change material for thermal energy storage applications in solar thermal systems,” *Energies*, vol. 13, no. 19, Article ID 5079.

Samdhyan K., Chand P., Anand H., and Saini S., (2022) Development of carbon-based copper sulfide nanocomposites for high energy supercapacitor applications: a comprehensive review,” *Journal of Energy Storage*, vol. 46, Article ID 103886.

Singh R. and Tripathi C. C., (2018) Electrochemical exfoliation of graphite into graphene for flexible supercapacitor application, *Materials Today: Proceedings*, 5, 1125–1130.

Souayfane F., Fardoun F., P. Biwole H., (2016) Phase change materials (PCM) for cooling applications in buildings: a review, *Energy Build.* 129 396–431.

Tian, J., Xing, F., & Gao, Q. (2021). Graphene-Based Nanomaterials as the Cathode for Lithium-Sulfur Batteries. *Molecules*, 26(9), 2507.

Ting L. K. J., Gao Y, Wang H, Wang T, Sun J, Wang J. (2022) Lithium Sulfide Batteries: Addressing the Kinetic Barriers and High First Charge Overpotential. ACS Omega. 7(45):40682-40700. doi: 10.1021/acsomega.2c05477.

Verma K., Chaturvedi A., Paliwal S., Dwivedi J., Sharma S., (2024) Polymeric Nanocarriers for the Delivery of Phytoconstituents, Nanotechnology Based Delivery of Phytoconstituents and Cosmeceuticals, 10.1007/978-981-99-5314-1_4, (89-123).

Wang Y, Dai W, Wu T, Qi H, Tao J, Wang C, Li J, Cao X, Liu L, Fang L, Wang C, Gong N, Liu Y, Chen X, Jiang W, Wang X. (2024) Advancements in Nanotechnology-Based PEDOT and Its Composites for Wearable Thermoelectric Applications. Small Sci. 7;4 (11):2400149.

Xiong T., Zheng L., Shah K.W., Nano-enhanced phase change materials (NePCMs): a review of numerical simulations, Pergamon, 2020.

Xiong, C.Y.; Zheng, C.M.; Zhang, Z.; Xiong, Q.; Zhou, Q.S.; Li, D.P.; Shen, M.X.; Ni, Y.H. (2025) Polyaniline@cellulose nanofibers multifunctional composite material for supercapacitors, electromagnetic interference shielding and sensing. J. Materiomics, 11, 100841.

Xu, Z.Q.; Hu, X.; Fu, B.W.; Khan, K.; Wu, J.T.; Li, T.; Zhou, H.P.; Fang, Z.X.; Wu, M.Q. (2023) Co-doping strategy enhanced the ionic conductivity and excellent lithium stability of garnet-type $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ electrolyte in all solid-state lithium batteries. J. Materiomics, 9, 651–660.

Yadav S. and Devi A., (2020) Recent advancements of metal oxides/ nitrogen-doped graphene nanocomposites for supercapacitor electrode materials,” Journal of Energy Storage, vol. 30, Article ID 101486.

Zhang C. and Nicolosi V., (2019) Graphene and MXene-based transparent conductive electrodes and supercapacitors, Energy Storage Materials, vol. 16, pp. 102–125.

Zhang X., Javed M. S., Shah S. S. A. et al., (2023) N-functionalization and defect engineering in ZnCo_2O_4 nanosheets boosted the performance of Zn-ion hybrid supercapacitor,” Electrochimica Acta, 461, Article ID 142654.