© SEP 2025 | IRE Journals | Volume 9 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I3-1710974-8749

Nanomaterials and Their Physicochemical Properties for Energy Storage - A Review

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Abstract- Nanomaterials with sizes ranging from 1 to 100 nm are referred to as nanotechnology. The materials used in the synthesis of nanomaterials determine their size, shape, and other characteristics. Carbon-based nanoparticles, metal-based nanomaterials, ceramic nanomaterials, lipid-based nanomaterials, semiconductor nanomaterials, and polymer nanomaterials are categories of nanomaterials based on the kind of substrate. Inert gas condensation (IGC), physical evaporation, electric arc discharge, sputtering, and laser techniques are some of the several physical processes that are frequently employed to create nanomaterials. These processes allow for precise control over the properties of the nanomaterials, which can be tailored for specific applications in fields such as medicine, electronics, and energy storage. One of today's most critical scientific challenges is achieving highly efficient energy utilization. To meet the growing demand for next-generation energy technologies, sustained research is required to design and optimize advanced inorganic multifunctional nanomaterials. These materials have been widely investigated for applications in energy storage, conservation, transmission, and conversion, where their optical, mechanical, thermal, catalytic, and electrical properties are pivotal. At the nanoscale, triboelectric, piezoelectric, thermoelectric, electrochromic, and photovoltaic systems have significantly advanced energy technologies. Functional inorganic nanomaterials exhibit exceptional thermal and electrical conductivity, chemical stability, and high specific surface area, making them highly competitive for energy-related uses. Recent studies emphasize the development of devices that integrate these diverse functionalities to improve performance and efficiency. This review discusses recent progress and innovations in inorganic multifunctional nanomaterials, highlights their role in energy applications, and outlines key research challenges that must be addressed to enable future breakthroughs.

I. INTRODUCTION

In today's world, access to energy is as essential to society as food and water. The progress of human civilization has always paralleled advances in energy storage and utilization. With the global population approaching eight billion and projected to nearly double by 2050, worldwide energy demand will rise sharply. Under existing and proposed policies, annual CO_2 emissions are expected to climb from 29 Gt to 43 Gt, driven by two critical challenges: an escalating energy deficit and environmental degradation from diminishing fossil fuels and increasing consumption. (Abdelhamid et al., 2023) Achieving sustainable development therefore requires technologies that exploit abundant green energy sources solar, thermal, and mechanical while enabling efficient, long-term energy use.

Clean, reliable, and affordable energy underpins economic growth and human survival. Meeting future demand involves applications such as energy generation, storage, conservation, transmission, and conversion. Energy harvesting transforming light, heat, or mechanical vibrations into electricity offers an alternative to fossil fuels, with the captured energy conditioned and stored in batteries or capacitors for low-power electronics, self-powered sensors, and wireless systems. (Alonzo et al., 2023) Solar and fuel cells have emerged as leading direct energy-conversion technologies. However, renewable sources like geothermal, biomass, tidal, solar, and wind are intermittent, causing supply fluctuations. Advanced energy-storage systems, including supercapacitors and high-performance batteries, are therefore critical for a successful transition from fossil fuels. (Baig et al., 2021)

Another challenge lies in transmitting energy from remote hydro, wind, and solar facilities to dense population centers cost-effectively. Nanomaterials engineered at the nanoscale to integrate multiple properties address these needs by combining electrical, magnetic, optical, and mechanical functions within a single system. Their design requires careful control of chemical and physical interactions to achieve synergistic performance. For example, battery electrodes demand high electrochemical reactivity, stability, and reversibility, while flexible batteries need materials that maintain conductivity and structural integrity under strain. Electrolytes must provide exceptional ionic conductivity, often absent in conventional solids. (Charchi et al., 2020).

Nanoscale materials exhibiting triboelectric, piezoelectric, thermoelectric, photovoltaic, and catalytic properties have already advanced numerous energy applications. Inorganic nanomaterials, with their chemical stability, high surface area, and excellent thermal and electrical conductivities, are particularly promising. Nano structuring further enhances catalytic activity and energy-conversion efficiency. Current research explores how structure influences fabrication, design, and performance of multifunctional nanomaterials. Remaining obstacles include discovering new structural systems, revealing hidden properties of known materials, and optimizing size- and shape-dependent electrical, physical, and chemical characteristics to fully realize their potential in next-generation energy technologies. (Chen et al., 2017)

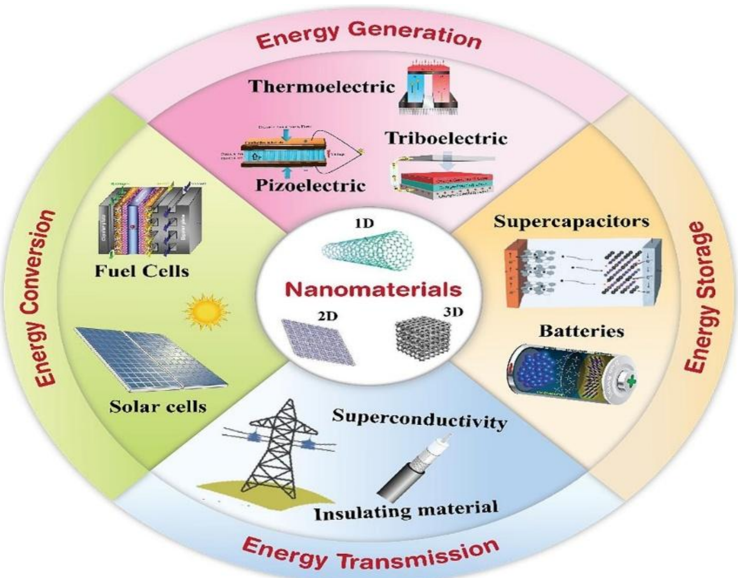

Figure 1. Schematic demonstration of various nanomaterial applications in different areas. © Elsevier, 2024.

The electrical characteristics of nanoparticles are a crucial factor that sets them apart in electrochemical applications. Based on their capacity to conduct electricity, nanomaterials can be roughly categorized as conductive, semiconductive, or insulating. Because of their high electrical conductivity, conductive nanomaterials like graphene and carbon nanotubes are widely used as electrodes, catalysts, and current collectors (Serrano-Garcia et al., 2023). Metal oxides and sulfides are examples of semi-conductive nanomaterials that have moderate electrical conductivity and can be used as active materials for energy conversion and storage. Metal organic frameworks (MOFs) and covalent organic frameworks (COFs) are examples of insulating nanomaterials that have poor electrical conductivity but high surface area and large pore volumes, which makes them appropriate support materials for electrochemical devices (Wang et al., 2022).

Furthermore, the electrical characteristics of nanomaterials are also influenced by their composition. Novel nanomaterials such as MOFs, COFs, and MXenes have drawn a lot of interest because of their high surface areas and adjustable electrical characteristics, which make them attractive options for use in electrochemical devices (Wang et al., 2022).

All things considered, nanomaterials' special qualities make them desirable for use in electrochemical devices, and their potential for cost-effectiveness only heightens this attractiveness.

Researchers can continue to create new and improved electrochemical devices with increased performance and cost-effectiveness by comprehending the many kinds of nanomaterials and their characteristics. As a result, this review will focus on energy storage, electrochemical methods, and nanotechnology-based electrochemical sensors. Additionally, in economically significant applications, nanostructures are integrated with the electrochemical system. It will provide insight into the difficulties associated with environmental sustainability as well as the future of these applications. Cellulosic waste in treatment (Dawoud et al., 2022 and Abdelhamid et al., 2023), cement mixed with plant waste (Sale et al., 2020), natural clay (Bayoumi et al.,2013 and Saleh et al., 2014), bitumen (Reda and Saleh 2021 & Saleh et al., 2021) or with asphaltene and polymer (Saleh et al., 2022), cement waste (El-Sayed et al., 2022), and glass (Ehab et al., 2022 & Eid et al., 2022) for waste stabilization and radiation shielding are examples of innovative sustainable materials that have also been used in nuclear applications.

Nanotechnology and Nanomaterials

Nanotechnology manipulating matter at dimensions below 100 nm has revolutionized materials science and energy research. At this scale, quantum confinement, surface-to-volume ratio, and tunable defect chemistry create physicochemical properties not observed in bulk materials. Current studies highlight nanomaterials as key enablers of high-performance energy storage and conversion devices. (Charchi et al., 2020)

Recent work explores carbon-based nanostructures (graphene, carbon nanotubes) for supercapacitors and next-generation lithium-sulfur or sodium-ion batteries, where their exceptional conductivity and mechanical strength enhance charge transport and cycling stability. Metal oxide and sulfide nanostructures (e.g., MnO_2, MoS_2) are being engineered with hierarchical porosity to boost ion diffusion and catalytic activity in batteries and electrochemical capacitors. 2D materials such as MXenes and transition-metal dichalcogenides offer tunable surface terminations and redox-active sites for rapid energy storage. (Chen et al., 2017)

Nanotechnology also drives solid-state electrolytes, nanostructured perovskite photovoltaics, and thermoelectric materials, enabling flexible, lightweight devices. Ongoing research focuses on scalable synthesis, interface engineering, and lifecycle sustainability to translate these nanoscale advances into commercially viable, environmentally responsible energy technologies.

Types of Energy Storage Technology

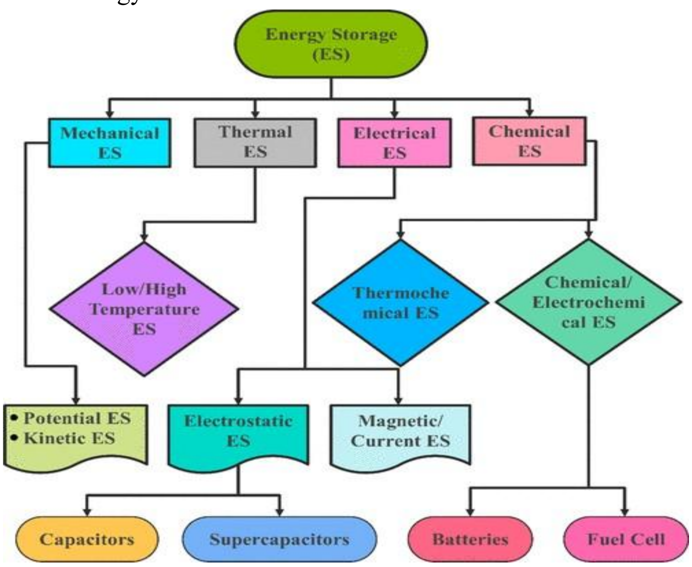

Figure 2. Credit: Energy Fuels 2023, 37, 24, 19433–19460

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DOI: https://doi.org/10.64388/IREV9I3-1710974-8749

The classification of key energy-storage technologies highlights their diverse capabilities.
Batteries remain the most common electrical-energy storage systems because they can pack large amounts of energy into small, lightweight units while supplying stable output for many applications.

Despite their high energy density, conventional batteries often suffer from limited power delivery, making them less suitable when rapid charge discharge and high instantaneous power are required.

To overcome these limitations, electrochemical capacitors (ECs) widely known as supercapacitors or ultracapacitors have gained significant attention. (Dawoud et al., 2022)

These devices offer exceptional specific power, long cycle life, and rapid energy storage and release, positioning them as valuable complements or alternatives to traditional batteries in advanced energy-storage applications.
Electrochemical capacitors (ECs) exhibit exceptionally rapid charge discharge behavior, completing these processes within seconds.

Although their energy density is notably lower than that of conventional batteries, their ability to deliver very high power output makes them indispensable in modern energy-storage systems.

ECs serve either as secondary devices or, in specific cases, as stand-alone battery alternatives. For instance, they provide reliable backup power to prevent system failures and help stabilize electrical loads by regulating sudden demand fluctuations. (Deng, 2015)

Progress in functional materials for energy-storage systems
Developing advanced energy-storage technologies for renewable sources remains one of the most promising strategies to address the global energy crisis and environmental challenges. A key focus is the discovery of suitable active materials that enable highly stable, efficient, eco-friendly, and cost-effective storage systems. Nanomaterials with exceptionally high specific surface areas are particularly attractive, as they can narrow the gap between experimental and theoretical capacitance without increasing electrode mass. Electrochemical energy-storage devices—primarily batteries and supercapacitors are vital for managing intermittent renewable inputs such as solar and wind. Supercapacitors achieve remarkable power density because charge is confined to surface layers, avoiding diffusion-limited bulk processes, and their charge discharge cycles are highly reversible since no bulk phase transformations occur. In contrast, batteries store charge within the bulk of electrode materials via redox reactions, yielding higher energy density but lower power output. Growing demand for efficient, high-performance batteries underscores their critical role in future energy systems. (El-Sayed et al., 2022)

Advancements in lithium-sulfur batteries
Lithium–sulfur (Li–S) batteries have gained wide attention because sulfur is abundant, inexpensive, environmentally benign, and offers a high theoretical capacity of 1675 mAh g^{-1}. Nevertheless, Li–S cells face major obstacles, including polysulfide "shuttle" effects, sluggish redox kinetics, and the intrinsic insulating nature of sulfur. To overcome these issues, a porous carbon nanofiber host decorated with nickel and carbonyl groups (Ni/PCNFO) has been developed. The spacious porous carbon network accommodates sulfur loading and volume expansion, while nickel species improve electrical conductivity and accelerate sulfur redox reactions. Carbonyl groups further suppress polysulfide migration through strong chemical adsorption. Ni/PCNFO–S cathodes therefore deliver long cycle life, a high specific capacity of ~1320 mAh g^{-1}, and a rate capability of ~780 mA h g^{-1}. (Eid et al., 2022)

Other innovations include freestanding electrodes combining three-dimensional nitrogen-doped graphene with titanium nitride (TiN) nanowires, which provide efficient electron/ion pathways and strong polysulfide anchoring, enhancing electrochemical performance. Flexible Li–S batteries have also advanced through reduced graphene oxide/graphene-crumple/sulfur (rGrO/GrCs/S) hybrid cathodes, maintaining ~524 mAh g^{-1} after 100 cycles at 0.2 C and stable discharge during repeated bending.

Zhang et al. reported a sulfur host of Fe_3C–N/C hollow "frogspawn" structures derived from Prussian blue templates. The N-doped carbon shell and polar Fe_3C core supply excellent conductivity, rapid Li^+ transport, and catalytic polysulfide conversion. This architecture accommodates sulfur's volume change and traps intermediates, achieving ~1351 mAh g^{-1} at

0.1 C and retaining ~792 mAh g^{-1} after 400 cycles with only 0.08 % capacity loss per cycle, highlighting the promise of tailored nanostructured hosts for next-generation Li–S batteries. (Gohar et al., 2024)

Advancements in zinc-air batteries
Zinc–air batteries are considered a highly promising option for large-scale energy storage because of their exceptional theoretical energy density, cost-effectiveness, inherent safety, and long operational lifespan. Nevertheless, their relatively low power density has limited practical deployment. To overcome this limitation, nickel-doped cobalt oxide (Ni–CoO) nanosheets (NSs) with multiscale structural engineering have been developed, delivering enhanced durability and markedly higher power and energy densities in zinc–air systems. (Jeerapan & Ma, 2019)

On the nanoscale, the robust two-dimensional morphology and abundant nanopores of these Ni–CoO NSs provide an extensive electrocatalytically active surface area while enabling efficient oxygen (O_2) transport. At the atomic level, Ni doping significantly boosts the intrinsic oxygen-reduction-reaction (ORR) activity at each active site. Incorporating these engineered nanosheets into zinc–air batteries has produced striking performance: a discharge peak power density of 377 mW cm^{-2} and operational stability exceeding 400 h at 5 mA cm^{-2}.(Joan Lowy, 2013
Moreover, rechargeable zinc–air cells utilizing Ni–CoO NS electrodes achieve exceptionally low charge–discharge voltage gaps of around 0.63 V, outperforming conventional Pt/C catalyst systems.

The rapid progress in inorganic multifunctional nanomaterials continues to drive significant improvements in both commercial and laboratory-scale battery technologies. Looking ahead, the discovery and optimization of novel nanostructured materials supported by artificial-intelligence based material screening and design are expected to further elevate the performance and commercial viability of next-generation energy-storage devices. (Levine, 2010)

Basics of Li- Ion Batteries
A typical Li-ion cell comprises a cathode (positive electrode) and an anode (negative electrode) separated by a microporous separator and contacted via an electrolyte that conducts Li^+ ions. Electrons flow through the external circuit while Li^+ ions move internally through the electrolyte between electrodes during charge/discharge. Cells are combined in parallel to raise current and in series to raise voltage; cells → modules → packs (e.g., an 85 kWh Tesla pack contains thousands of cylindrical cells arranged in modules). Commercial cells are usually assembled in the discharged state because common cathode and anode materials (e.g., $LiCoO_2$ or $LiFePO_4$ cathodes and carbon anodes) are air-stable in that state. Electrolytes can be liquid (organic carbonate mixtures), gels, polymers, or ceramics; separator membranes (microporous polymers) prevent electronic contact while permitting ion exchange. The basic operating principle Li^+ intercalation/de-intercalation driven by an external supply during charge remains the foundation of modern LIBs. (Reda & Saleh, 2021)

Why innovation is needed
The commercial cell design pioneered decades ago is still fundamentally the same, but demands for higher energy density, faster charging, lower cost, improved safety, and longer cycle life have driven intense materials research across electrodes, electrolytes, interfaces, and pack engineering.

Major recent advances

1. Solid-state electrolytes (SSEs) and solid-state Li batteries

Solid electrolytes ceramics, sulfides, oxidic glass-ceramics, and polymer/ceramic composites aim to eliminate flammable organic liquids and enable Li metal anodes for much higher energy density and safety. Work in 2024–2025 has improved ionic conductivities of composite SSEs and focused on interfacial engineering to reduce contact resistance and dendrite growth. While SSEs promise higher energy and improved safety, challenges remain in mechanical/chemical stability at interfaces and scalable processing. Recent comprehensive reviews summarize material designs and interfacial strategies that are bringing solid-state cells closer to commercialization. (Saleh et al., 2020)

2. Silicon-dominant and silicon-composite anodes
Silicon anodes provide ≈10× the gravimetric capacity of graphite (theoretical ~3579 mAh g^{-1} for Si vs ~372 mAh g^{-1} for graphite), making them a leading route to >30% increase in cell energy. The main problem is >300% volume expansion during lithiation, leading

to particle fracture, SEI (solid electrolyte interphase) instability, and rapid capacity fade. Recent 2024–2025 work emphasizes nanoscale engineering (nanoparticles, yolk–shell architectures, conductive carbon matrices), binders that accommodate strain, artificial stable SEIs, and prelithiation techniques. Progress toward scalable silicon-composite electrodes (limited Si loadings in commercial cells today) is accelerating, with several companies moving to pilot production. (Shi et al., 2023)

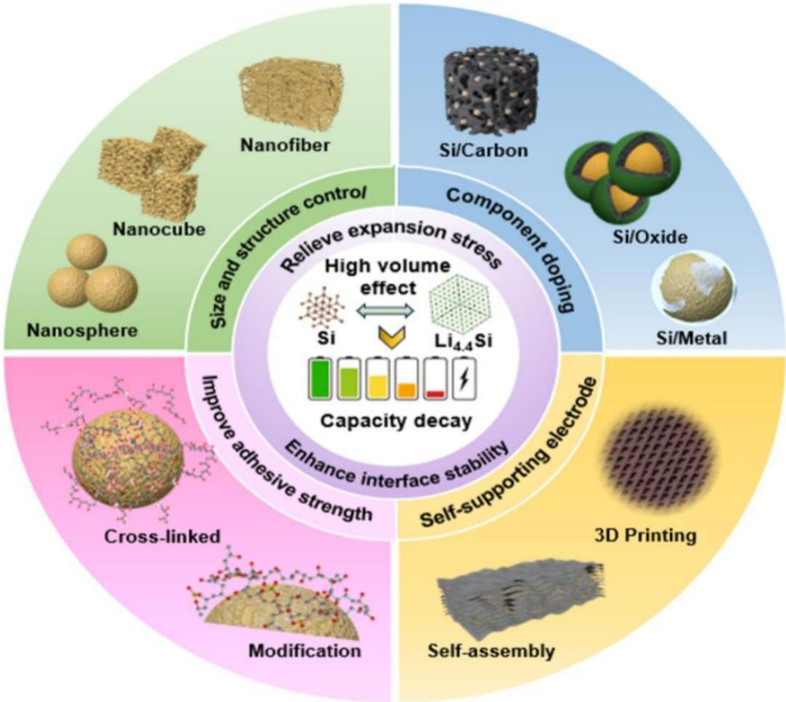

Figure 3: Schematic demonstration of the Silicon Materials

3. High-Ni and concentration-gradient layered cathodes (NMC-based)

Nickel-rich layered oxides (e.g., NMC811, NMC9xx) raise cathode capacity but introduce structural instability, oxygen release, and electrolyte oxidation especially at high voltage. Recent studies (2023–2025) focus on concentration-gradient particles (Ni-rich core, Ni-lean shell), surface coatings (oxides, phosphates), dopants, and electrolyte additives to stabilize the surface and suppress high-voltage degradation. These approaches improve cycle life and thermal stability while retaining high capacity, but managing parasitic reactions at high state-of-charge remains critical. (Sun et al., 2021)

4. Fast-charging strategies

Fast charging presents kinetic (Li^+ transport), thermodynamic, and safety challenges (lithium plating on anodes). Recent research (2024–2025) combines electrode materials with fast Li^+ diffusion pathways (e.g., Ti-based anodes), nanoscale architectures to shorten ion diffusion lengths, SEI chemistry control to avoid plating, and thermal/pack-level management strategies. Standardizing test protocols for "extreme fast charge" (XFC) and reporting (charge rate, capacity retention, cycle life) is an active community effort. Promising approaches now demonstrate substantially faster charging with acceptable cycle life in lab and prototype cells. (Tondan & Singh, 2024)

5. Electrode hosts, electrocatalysts, and hybrid chemistries (Li-S, Li–air)

Beyond conventional Li-ion, Li–S and Li–air promise higher theoretical energy densities. For Li–S, tailored carbon hosts, polar metal sites (Fe_3C, Ni, etc.), and electrocatalysts mitigate polysulfide shuttling and speed redox kinetics, delivering impressive lab capacities and cycle stability when combined with conductive, porous hosts. Engineered cathode architectures (3D graphene networks, hollow N-doped carbons) are central to recent successes. Nonetheless, translation to commercial cells requires further breakthroughs in electrolyte design and cathode/electrolyte stability. (See recent Li–S nanoscale host reports and rate/capacity improvements.)

6. Pack- and system-level engineering

Cell chemistry advances must be paired with intelligent module/pack design (thermal management, cell balancing, safety electronics). EV pack examples (e.g., Tesla 85 kWh packs with thousands of cylindrical cells) illustrate the scale and complexity of integration (cells → modules → pack), and how small improvements at the cell level scale into large energy/density gains at pack level. Accurate modeling, BMS improvements, and manufacturing control remain essential to deploy new chemistries safely and economically.

Remaining challenges & outlook

- Interface stability: solid/liquid and solid/solid interfaces remain the Achilles' heel SEI control, interfacial mechanics, and chemical compatibility need further materials and engineering solutions.
- Scalability and cost: many promising architectures (e.g., advanced SSEs, silicon yolk–shells) require cost-effective, high-throughput synthesis to reach commercial volumes.
- Standardized testing: harmonized protocols for fast-charge, calendar life, abuse tests, and real-world cycling are still evolving.
- Sustainability and recycling: end-of-life recovery and low-CO_2 supply chains for Li, Ni, Co, etc., are essential for large-scale deployment. (Xu et al., 2019)

II. CONCLUSION

Inorganic multifunctional nanomaterials, with exceptional thermal, electrical, and chemical properties, are driving advances in next-generation energy storage, conversion, and transmission. Their high surface area, stability, and low cost make them ideal for batteries and other energy devices, yet large-scale implementation is limited by incomplete understanding of structure property relationships and the vast range of possible compositions. Cutting edge characterization and AI-driven materials screening now enable rapid exploration of complex element combinations, reducing human bias and accelerating discovery. Future progress will focus on composite and core shell architectures that synergistically combine multiple functions, achieving higher performance and multifunctionality for advanced energy applications.

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