

INORGANIC NANOPARTICLES: A NEW PARADIGM IN ENERGY STORAGE

Abstract

Currently, nanomaterials hold a central position in contemporary societies. Especially within the realm of energy, nanomaterials have made notable contributions. Due to the prevalent use of environmentally hazardous energy sources, the world is witnessing a decline in its strength and resilience. On the other hand, clean and alternative energy sources offer the potential to protect our planet. Biomass, solar and wind are being endorsed as viable replacements for finite energy sources, supporting the adoption of sustainable energy alternatives. Regrettably, these renewable energy sources are solely accessible during specific seasons or periods. Consequently, it is imperative to develop innovative, affordable, and durable energy storage technologies to fully harness the potential of sustainable energy sources. In this chapter, varieties of energy storage techniques are presented, with particular emphasis on batteries, supercapacitors, and phase change materials.

Keywords: Nanoparticles, Energy storage, Supercapacitors, Batteries, Phase change materials.

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I. INTRODUCTION

Nanotechnology encompasses the scientific endeavors related to designing, manipulating, producing, characterizing, and applying materials within the nanometer scale (size: 1-100 nm) [1]. The term "nanotechnology" was introduced by Feynman during his famous lecture "There is plenty of room at the bottom" in 1959[2]. Nanoparticles typically enjoy unique characteristics, e.g. very small size, high surface area to volume ratio, high reactivity, biocompatibility, functionalization, biomimetic features and biodegradability. Consequently, these materials have garnered research attention owing to their intriguing electronic, optical, and chemical characteristics, along with their potential for significant biomedical uses [3]. Nanotechnology is expected to substantially impact science, economy and day to day life in the current century and also to become one of the motivations of the next industrial revolution [4]. The rise of Nanoscience and nanotechnology introduces not only new concepts for understanding nature but also ushers in multifunctional nanomaterials and their diverse applications in modern society. These nanomaterials provide novel features and attributes that are well-matched for advanced purposes in the field of electronics. Consequently, both the nanomaterials themselves and their related products stand as potential candidates for an emerging nano industry stemming from fundamental scientific research [5].

In recent years, there has been a notable surge in the demand for fossil fuels, particularly oil and gas, which has dropped out a notable impact on the field of interest for contemporary researchers [6]. The accomplishments and challenges in the realm of clean and renewable energy are of great concern in the 21st century, driven by escalating environmental pollution, the exhaustion of conventional fossil fuels, and the resulting exacerbation of global warming on our planet.

A major contributor to the existence of greenhouse gases in the atmosphere, as well as air pollution and climate change, is the release of detrimental gases from industrial facilities and vehicles, primarily originating from utilizing finite fossil fuels. Moreover, the ongoing growth of the global population is leading to a continuous rise in the consumption of limited fossil fuels, inevitably resulting in pollution in the foreseeable future. These challenges stand as some of the most significant issues facing human society [7].

The pressing need for inventive, high-performing, affordable, sustainable, and environmentally friendly energy sources has emerged in response to the escalating environmental deterioration. Consequently, researchers are progressively directing their efforts toward methods of production that are more sustainable, minimizing waste, decreasing automobile-related pollution, fostering distributed energy generation, preserving native forests, and curtailing greenhouse gas emissions [8]. Solar energy, hydropower, wind energy, biomass, and nuclear power are harnessed as eco-friendly, renewable, and sustainable energy alternatives. Indeed, the seasonal nature, regional variations, and intermittent supply of clean energy pose significant challenges in utilizing it directly for industrial and daily life purposes. Consequently, the question of how to secure and advance these energy sources remains a focal point of interest. At present, diverse energy storage solutions for stationary use encompass electrical, chemical, electrochemical, and mechanical energy storage methods [9]. Energy storage materials need to possess the capability to efficiently store or generate substantial amounts of energy within devices that are cost-effective, lightweight, and easily manufacturable, in order to optimize their overall efficiency [10].

Within the realm of energy storage systems, supercapacitors and secondary batteries have garnered significant research interest and are regarded as promising energy solutions owing to their impressive energy and power storage capabilities, exceptional extended cycling durability, adaptable temperature range, and environmentally friendly attributes. When evaluating the efficiency of energy storage devices, key indicators including energy density, power density, specific capacity, specific capacitance, and robust cycling properties play crucial roles. Enhancing these attributes in energy storage devices hinges largely on the attributes of electrode materials. In the context of electrode materials, the efficacy of supercapacitors and batteries is heavily influenced by factors such as high surface area carbon materials and the composition of metal oxide or hydroxide-based composites or hybrids. In recent times, researchers have employed diverse methods to modify carbon materials with metal oxides or hydroxides, employing them as electrodes for energy storage in both supercapacitors and secondary batteries[7]. Although present energy conversion or storage techniques/devices, such as batteries and supercapacitors, have undergone significant development, there is still a need for further advancements because: (i) achieving simultaneous high energy conversion and power density levels remains a challenging task and (ii) rechargeable devices pose limitations due to their high cost and restricted scope of utilization [11].

Lithium-ion batteries and supercapacitors exhibit similarities in design and energy-transformation processes, both occurring at the phase boundary of the electrode/electrolyte interface. Nonetheless, these two energy storage systems also boast distinct characteristics. Lithium-ion batteries excel in high energy density but face limitations in cycle life and charge-discharge rates. On the other hand, supercapacitors are renowned for their high power output and extended lifespan, but they come with the trade-off of limited energy density [12].

Charge storage in a supercapacitor can occur through two distinct mechanisms: a) non-Faradaic double-layer electrostatic charging, or b) a Faradaic surface redox process. Conversely, the lithium-ion battery has gained considerable prominence as a viable option for substantial power generation and energy storage, thanks to its notable attributes like high power and energy density, along with an extended cycle life. A growing need exists for essential lithium-ion battery components, with separators being of particular significance. These separators play a critical role by physically isolating the anode and cathode while enabling the unimpeded movement of lithium ions. The performance of the battery is notably impacted by the nanoporous architecture and thermal dimensional integrity of these separators, a factor widely recognized in the field [13].

In recent years, the application of phase change materials (PCMs) for thermal energy storage has seen a significant surge in various applications, including harnessing waste heat, space heating, cooling, and more. To mitigate the low thermal conductivity of PCMs, researchers have been incorporating metal and non-metal nanoparticles into the PCM, aiming to improve the thermal properties of the resulting mixture. Paraffin wax and fatty acids have found utility as thermal storage materials in applications related to solar heating and cooling. Nonetheless, a significant limitation they present is their low thermal conductivity. This characteristic results in diminished heat storage capacity during the melting phase and decreased heat release during the solidification process. This effect is attributed to the occurrence of supercooling (or subcooling) during both the melting and solidification processes. Both organic and inorganic PCMs exhibit a small supercooling effect, which is a natural characteristic of these materials. The supercooling effect refers to the PCM's

resistance to melting during the melting process, necessitating higher heat absorption to transition from a solid to a liquid phase. While, during the solidification process, the PCM initiates crystallization at temperatures below its phase change point. By augmenting the thermal conductivity of the PCM, the supercooling effect can be minimized, leading to enhanced heat diffusivity within the material and facilitating better heat flow. One of the approaches involves incorporating nanoadditives that function as nucleation agents to diminish the supercooling effect during solidification. Furthermore, these additives function as agents that facilitate activation energy, aiding in overcoming thermal resistance throughout the melting phase [14]. In the last ten years, nanotechnology has presented unmatched solutions to battery research. Through intricate nanostructural designs, researchers have made significant strides in addressing the challenges posed by next-generation battery chemistries. Consequently, this is an opportune moment to assess the advancements achieved thus far and anticipate the potential developments in the immediate future [15].

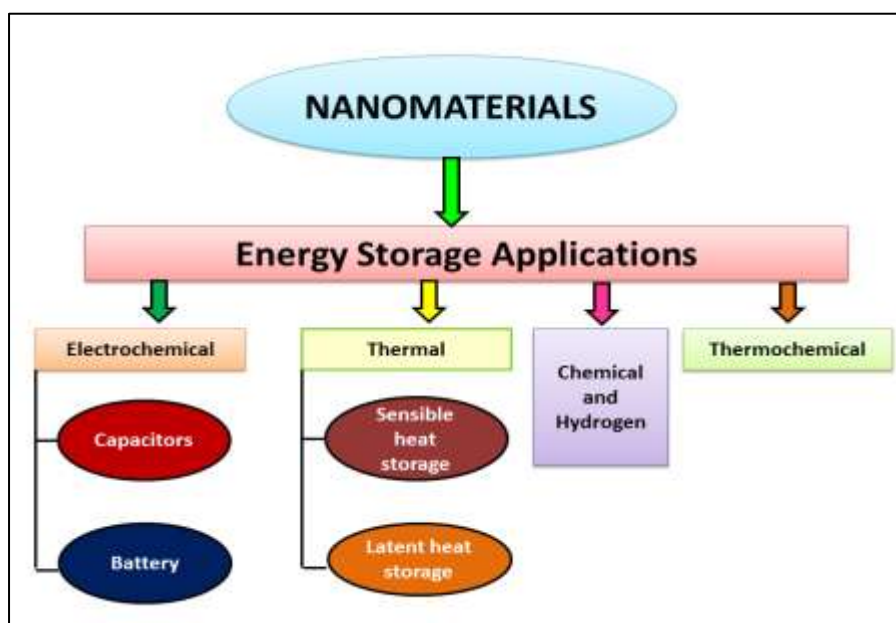


Figure 1: Categorization of Energy Storage Methods

II. ELECTROCHEMICAL ENERGY STORAGE

1. Rechargeable Batteries: In the realm of compact electronic devices, such as mobile phones and personal computers, rechargeable batteries play a crucial role as energy storage devices, valued for their ability to provide high power output and maintain a lightweight profile. These very characteristics are essential not only for electric vehicles, hybrid electric vehicles, and power tools but also for backup power subsystems. In basic terms, a battery functions as an electrochemical device that produces direct current (DC) through a linked series of reduction-oxidation (redox) reactions. In this process, the positive electrode undergoes reduction (collecting electrons), while the negative electrode experiences oxidation (releasing electrons). The battery configuration comprises a positive electrode and a negative electrode, separated by a porous separator to prevent direct contact between them. The ionic electrolyte, acting as a conductive medium, facilitates the movement of ions between the electrodes. The predominant type of batteries relies on intercalation, a process utilizing the small lithium (Li^+) ion. These

batteries feature at least one electrode that undergoes redox reactions and possesses a porous crystal structure with spaces capable of intercalating Li^+ ions [16]. Enhanced battery safety can be achieved by substituting the graphite electrode in a lithium battery with a nanostructured material that remains unreactive towards the electrolyte. Nanotechnology offers the opportunity to explore alternative active materials that are more cost-effective and environmentally benign, providing additional avenues for technological advancement. As an illustration, non-toxic magnetite (Fe_3O_4) has been utilized as an active component within a high-capacity copper nano-architected electrode [17].

- 2. Supercapacitors:** Supercapacitors, as a substitute means of electricity storage, stand to gain significant advantages through the implementation of nanotechnology. They find application in devices necessitating quick energy storage and discharge, like hybrid-electric and fuel-cell-driven vehicles. These devices are comprised of two electrodes submerged in an electrolyte, separated by an ion-permeable barrier. Considering each electrode-electrolyte interface as a capacitor, the complete cell can be visualized as two capacitors connected in series. The emphasis in the advancement of these devices has focused on attaining a high surface area while minimizing matrix resistivity. The most striking characteristic of a supercapacitor is its exceptional power density, approximately tenfold higher than that of a secondary battery. Carbon, in its diverse forms, presently holds the highest usage as the electrode material in supercapacitors. An average commercial supercapacitor is capable of delivering a power density of approximately 4 kW/kg. Nanotubes offer a promising avenue to increase the power density of supercapacitors, as their nanoscale tubular structure provides an exceptional blend of low electrical resistivity and high porosity within an easily available configuration [16].

Electrochemical supercapacitors achieve energy storage through the reversible adsorption of ions from an electrolyte onto two porous electrodes, leading to the creation of an electric double layer at the interface between the electrode and electrolyte. Electrochemical supercapacitors that exclusively rely on this physical adsorption process, devoid of any chemical reactions, are termed electric double-layer capacitors (EDLCs). Unlike batteries, in supercapacitors, both the anode and cathode can be composed of the same high specific surface area material. This is because supercapacitors do not require different reversible chemical reactions at the electrodes. Due to the absence of any physical alteration in the electrodes during the charging or discharging process, EDLCs can endure millions of cycles, typically achieving an energy density of 5 Wh kg^{-1} . Another category of electrochemical supercapacitor is referred to as a pseudo-capacitor, which differs fundamentally from an EDLC in terms of charge storage mechanisms. In theory, pseudo-capacitors can offer greater energy density than EDLCs, particularly in scenarios where various oxidation states can be reached. However, due to the fact that the electrodes undergo physical changes during charge or discharge, pseudo-capacitors tend to have inferior longevity compared to EDLCs [18].

III. THERMAL ENERGY STORAGE (TES)

- 1. Sensible Heat Storage:** Sensible heat storage (SHS) is widely recognized as the predominant approach for thermal storage [19]. It represents the most straightforward and uncomplicated variant of thermal energy storage technology [20]. Sensible heat refers to the heat transferred by a system that does not cause a change in the phase of the storage

medium but rather leads to a change in its temperature. Despite its prevalence, this approach to energy storage has its drawbacks, such as low energy density and thermal energy loss at any given temperature. Ceramics, along with water and oil, are the foremost commonly employed materials for sensible heat storage (SHS). Indeed; these materials find versatile applications in both industrial and residential settings. They can be utilized for various purposes, such as hot water storage in district-heating networks and as building materials with the ability to store energy for extended periods due to their high thermal capacity [21]. Frequently utilized Sensible Heat Storage (SHS) systems encompass solutions that make use of subsurface energy storage techniques, including: boreholes, aquifers, caverns, soil ducts, hydro-accumulation through pit hot water storage, and retaining configurations involving rock-filled materials like rock, pebbles, and gravel [22].

- 2. Latent Heat Storage:** Latent heat storage (LHS) involves the transfer of heat through a phase change that takes place within a precise and limited temperature range within the specific material. The most commonly employed for this intention are: molten salt, paraffin wax, and water or ice substances [21]. Two systems of latent heat storage, differing in terms of heat transfer, are commonly employed: direct and indirect. In the context of heat transfer, a direct system refers to a setup where the heat transfer fluid (HTF) and the LHS material come into direct contact, whereas an indirect system involves a solid heat transfer boundary between the HTF and LHS material [23].

IV. PHASE CHANGE MATERIALS (PCM)

Phase change materials (PCMs) are substances with the capacity to absorb or release substantial thermal energy as they transition between their solid and liquid states. Because of their exceptional heat storage characteristics, PCMs have found extensive application in various domains including solar energy capture, thermal insulation, temperature control, and energy preservation within building environments [24]. PCMs are substances used for latent heat storage, possessing a higher heat of fusion, and they exhibit the capability to store and release energy at a consistent temperature. The heat storage occurs when the PCMs transition from a solid to a liquid phase, while the heat retrieval takes place when they shift from a liquid to a solid phase. Initially, as heat is absorbed, the temperature of PCMs continues to rise. Unlike sensible storage materials, PCMs maintain a nearly consistent temperature during the absorption and release of heat while undergoing phase change. In a Thermal Energy Storage (TES) system, PCMs function similarly to a battery. Therefore, the storage of heat and the melting of PCM is referred to as the charging process, while the release of heat and the solidification of PCM is termed the discharging process. The heat storage capacity of PCMs per unit volume is significantly higher, ranging from 4 to 15 times greater than that of numerous sensible storage materials. The attribute of high latent heat in PCMs renders them highly sought-after contenders for thermal energy storage applications. The phase change process presents diverse modes, such as solid-solid, solid-liquid, and liquid-gas transformations. Solid-solid heat storage occurs through a phase transition, wherein the material changes from one crystalline form to another. The liquid-gas system exhibits a significantly high latent heat, but the substantial volume variations during the phase change present challenges in terms of storage control. Solid-liquid PCMs are extensively preferred due to their volume change during phase transition being less than 10% and their higher latent heat of fusion [25]. Furthermore, LHS systems offer cost advantages over SHS systems, as they necessitate smaller weight and volume requirements [26]. Considering the operational

environment of the PCM material, its melting point should ideally be lower than the heat supply temperature while being higher than the ambient temperature [27]. PCMs can be classified into three main categories according to their chemical composition and nature: Organic, Inorganic, and Eutectic.

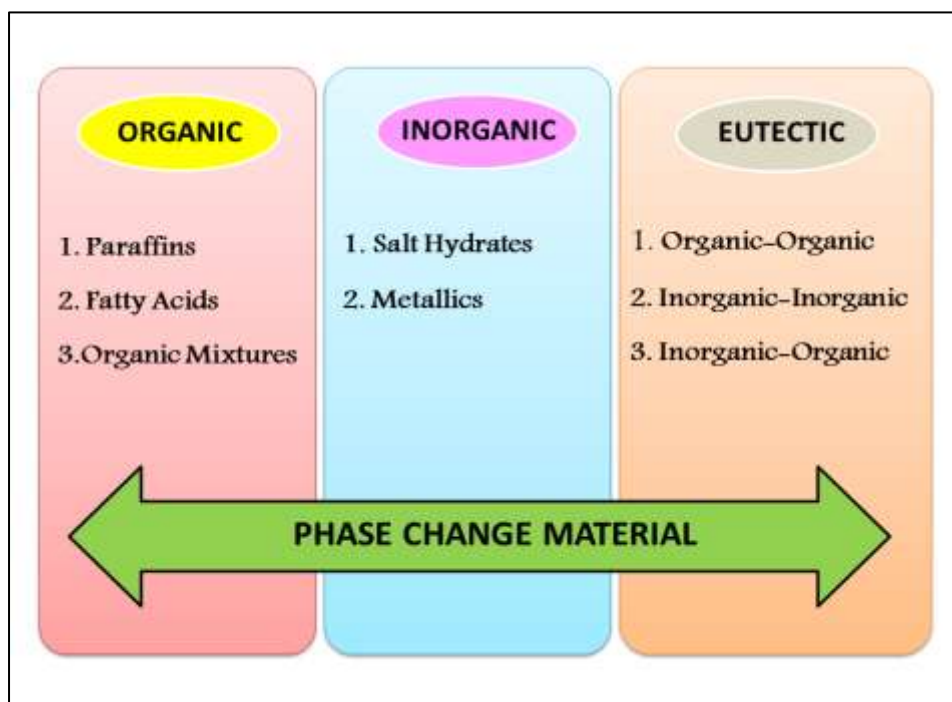


Figure 2: Basic Categories of Phase Change Materials

- 1. Organic Material:** Within the organic materials category, three primary groups exist: paraffins, fatty acids, and organic mixtures. Organic PCM materials exhibit both pros and cons, making them comparable to inorganic alternatives. On the positive side, they offer thermal and chemical stability, non-corrosiveness to metals, recyclability, and a substantial latent heat of fusion. Conversely, they are susceptible to flammability, possess a lower phase change enthalpy, limited thermal conductivity, and may have suitability issues with polymer containers or encapsulation media [21]. Paraffin stands out owing to its significant attributes: a notable heat of fusion, adjustable phase change temperature, substantial phase change enthalpy, absence of supercooling, low vapor pressure, chemical inertness (lacking corrosion and toxicity), and reliable cyclic stability of conductivity. Consequently, paraffin has been widely employed in energy storage applications. On the other hand; fatty acids belong to the category of organic materials and are identified as a renewable PCM, distinct from paraffin, as they originate from plant and animal sources. This material boasts exceptional thermal and physical characteristics, rendering it a valuable selection for diverse applications [28].
- 2. Inorganic PCMs:** Inorganic solid PCM, often referred to as SS-PCM (Solid-Solid PCMs), possess the capacity to store and release heat energy while in the solid state. This is achieved through diverse energy storage mechanisms, including magnetic transformations, changes in crystallographic structure, shifts between ordered and disordered configurations, and transformations between amorphous and crystalline states.

Importantly, the initial two methods involve substantial amounts of latent heat [29]. Indeed, inorganic PCMs are distinguished by their cost-effectiveness, elevated phase change enthalpy, and comparatively enhanced thermal conductivity. However, these materials are hindered by their corrosive tendencies, potential for subcooling, susceptibility to segregation and phase separation, and the possibility of thermal instability [21].

Hence, these materials are most suitable for applications in industrial plants where they can efficiently capture and utilize heat from high-temperature waste heat sources [29]. Among the categories of inorganic materials, metallic forms are noteworthy. They exhibit robust stability, low density, and a high ratio coefficient, leading to enhanced thermal conductivity compared to nanoparticles. Interestingly, the size of the pores has minimal impact on the overall thermal conductivity [30].

Salthydrates have garnered increased focus compared to organic PCMs owing to their remarkable high heat of fusion per unit volume, cost-effectiveness, and non-combustible characteristics. Nevertheless, these inorganic salt hydrates are challenged by notable supercooling (attributed to weak nucleation properties), phase segregation, and inadequate thermal conductivity. These limitations impede their effectiveness in real-world engineering applications [31].

3. **Eutectics:** Eutectics refer to compositions comprising two or more components, which could entail a fusion of organic with organic, inorganic with inorganic, or inorganic with organic components. Eutectic formulations have arisen as a promising remedy for tackling the incongruent melting predicament associated with hydrate salts. By combining two different types of hydrate salts, such as inorganic and organic variants, to create a eutectic mixture, it becomes possible to prevent incongruent melting while concurrently lowering the melting point and enhancing thermal conductivity [32].
4. **Encapsulation of PCMs:** Encapsulation is a strategy employed to shield the active PCM substance from direct exposure to the surrounding environment, effectively mitigating the potential for leaks. This method extends the substance's lifespan and mitigates challenges associated with phase separation [30]. Enhancing the performance of PCM systems can be accomplished through various approaches. The first method entails increasing the heat transfer surface area, achievable through PCM encapsulation or the utilization of finned tubes. The second approach involves the incorporation of nano-additives, which enhances thermal conductivity. The final method revolves around enhancing heat transfer uniformity and optimizing the thermodynamics of PCM. These techniques collectively influence both the heat transfer surface and the overall thermal conductivity [28].
5. **Nanomaterials PCMs:** Nanomaterial production involves two main methodologies: top-down and bottom-up techniques [33]:
 - **Top-Down Technique:** This method utilizes specific methods to minimize the dimensions and form of nanomaterials to suit diverse applications. Techniques within this category include emulsification and emulsification solvent evaporation.

- **Bottom-Up Technique:** In this approach, materials are synthesized via the self-organization of molecules, influenced by factors like concentration, ion properties, temperature, and pH. Methods falling under this approach comprise coacervation and nanoprecipitation.
6. **Shape Stabilization:** Shape stabilization is a vital approach employed to prevent leakage and enhance the energy storage capacity of PCM materials. Form-stabilized phase change material, abbreviated as SSPCM, comprises a working material and a supportive component. The working material assimilates or releases latent heat during the melting or solidification cycle, while the supportive substance prevents the material from leaking during the melting process, sustaining the entire system in a solid state [34].
7. **Temperature Range:** PCMs are developed based on the specific working temperature requirements of the material. The working temperature ranges of PCMs are broadly classified into four distinct categories:
- High temperature (+80 °C to +200 °C or higher)
 - Medium temperature (+40 °C to +80 °C)
 - Low temperature (+5 °C to +40 °C)

High-temperature applications encompass the use of PCMs for waste heat recovery and absorption cooling, while medium-temperature PCMs find utility in solar and electronic thermal management systems. In contrast, low-temperature PCMs are applied for thermal cooling and heating purposes, along with their utilization in building-related applications [21].

V. NANOMATERIALS

Nanomaterials are grouped into two categories: organics and inorganics, as deduced from research findings. Organics encompass materials like fullerenes, carbon nanotubes (CNTs), single-walled carbon nanotubes (SWCNTs), multi-walled carbon nanotubes (MWCNTs), graphite, and nanofibers. A significant portion of organic nanomaterials is composed of carbon-based variants. Conversely, inorganic nanomaterials include metal and metal oxide-based substances like aluminum, zinc, copper, iron, aluminum oxide, iron oxide, and titanium oxide. Metalloid nanomaterials like CdSe, ZnS, ZnO, and others, known as quantum dots, are also classified as inorganic nanomaterials. Hybrid nanomaterials are a novel category included. Hybrid nanomaterials result from the fusion of diverse nanomaterials, encompassing combinations like organic-organic, organic-inorganic, and inorganic-inorganic, achieved through synthesis techniques like chemical vapor deposition (CVD), electro spinning, and atom transfer radical polymerization (ARTP). Despite the manifold advantages of nanomaterials, it's important to acknowledge the potential risks they pose, including the possibility of exerting hazardous impact on both people and the ecosystem [32].

VI. APPLICATIONS OF NANOCOMPOSITES IN THERMAL ENERGY STORAGE

1. **Heating and Cooling of Buildings:** Space cooling in industrial settings represents a formidable scientific undertaking, applicable across a wide spectrum of production

domains such as transportation, manufacturing, microelectronics, and sports arenas. The conventional practice of heating and cooling structures has prevailed for several decades. Architectural techniques like constructing buildings amidst trees to facilitate cooling during hot weather or employing specific materials like bricks in wall construction for enhanced cooling effects have been practiced over time. The necessity for efficient Thermal Energy Storage (TES) has driven the integration of PCM into diverse building technologies, facilitating both cooling and heating solutions to achieve the desired comfort levels. With their substantial latent heat storage capacity, PCMs have garnered attention as potential candidates for thermal storage in building-related utilizations [35]. Incorporating PCM-enhanced nanocomposites within buildings or spaces primarily revolves around capitalizing on solar radiation as a natural heat source for warming during colder periods and leveraging artificial heat or cooling sources for temperature regulation during hot weather. In either scenario, the storage of thermal energy is crucial to align the supply and need over a period as well as in terms of intensity [32].

- 2. Heating and Cooling of Electrical and Electronic Components:** As technical advancements progress in the evolution of smart materials and components, the demand for efficient heat dissipation mechanisms has intensified, particularly for microelectronic components functioning at high velocities, more powerful engines, and more brilliant optical devices. This need arises from the ongoing efforts to reduce the weight and size of electromechanical instruments. This has led to higher thermal loads; necessitating advancements in cooling techniques [36]. Thermal management challenges pose significant obstacles to achieving high-density electronic packaging and miniaturization. In the realm of electronics, the endeavor to bolster the thermal efficacy of cooling systems while concurrently minimizing their surface area demand has persistently posed a significant technical hurdle. The escalating power of microprocessors and other electronic elements continually mandates the quest for a more streamlined heat dissipation system [32].
- 3. In Power Generation:** Research has unveiled that around 47% of current concentrating solar power facilities employ molten salt storage to generate electricity [37]. The primary challenge linked to molten salt systems involves the demand for substantial storage volume, costly heat exchangers, and the necessity for robust implementation infrastructure. Progress in the integration of molten salt with PCM technology holds the potential to yield promising outcomes for concentrated solar plants operating within the medium to high temperature range of 200 °C to 1000 °C [28].
- 4. In District Heating:** The amalgamation of district heating systems with thermal storage presents a host of economic, environmental, and technical advantages. This entails the exploration of both short- and long-term storage strategies, illustrating how these methods can be synergistically integrated into district energy supply. In this context, research endeavors delved into various aspects of chemical, sensible, and latent heat storage systems. The objective of these investigations was to evaluate the potential advancements of cutting-edge technologies for the future evolution of district heating and network-based energy delivery systems [28].
- 5. Automobile Applications:** The radiant energy that enters a vehicle through its windows during the daytime, particularly during periods of intense solar exposure, serves as an additional energy reservoir for automobiles. Diverse approaches have been explored and

put into practice to store this energy and subsequently harness it as required. Proficient Thermal Energy Storage (TES) of this surplus heat can find application in multiple areas, including preheating the engine, warming the catalytic converter, regulating the temperature of the passenger compartment, and thawing the car windows. It's noteworthy that a substantial quantity of energy is dissipated because of inadequate combustion within automobile engines, leading to significant gasoline consumption and consequently contributing to environmental pollution. Furthermore, a considerable portion of the thermal energy produced by automobile engines is dissipated into the environment, particularly evident in diesel engines. Therefore, diverse systems for heat recovery and reuse are being explored, with the potential utilization of nanomaterials in thermal energy storage. An emerging avenue involves the consideration of engine cylinders (liners) coated with nanocrystalline ceramics like zirconia and alumina. This strategic coating aims to improve heat retention and facilitate a more effective combustion process [38].

- 6. Solar Thermal Heating:** Water heating constitutes a significant proportion of energy usage in both residential and business buildings, particularly in cases where lower temperatures are in demand. The main energy resources employed for hot water production predominantly rely on non-renewable sources. Unfortunately, despite endeavors spanning over a century to pioneer and encourage the adoption of renewable solar thermal water heating systems, the status quo persists [39]. Solar thermal collector systems stand out as the preeminent approach for harnessing solar radiation to facilitate water heating [40].

VII. CONCLUSION

This chapter delves into an exploration of diverse energy storage systems. The rise in demand for supercapacitors and rechargeable batteries with heightened energy and power densities for contemporary electronic devices is elucidated, driven by the swift advancements in this domain. Similarly, the escalating interest revolves around different categories of Phase Change Materials (PCMs) categorized by their chemical attributes organic, inorganic and Eutectics given their current prominence in heat storage systems. The discourse extends to encapsulation, a technique enhancing PCM material efficacy, and shape-stabilization, an approach bolstering the energy storage capacity and stability of PCM materials. These technologies find multifaceted applications encompassing building heating and cooling, electrical and electronic components, solar thermal heating, power generation, and automotive implementations.

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