**Inorganic Nanoparticles: A New Paradigm in Energy Storage**

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**ABSTRACT**

Today, nanomaterials are considered to be the focal point of modern civilizations. Particularly in the energy sector, nanomaterials contributed substantially. Due to the prevalent use of environmentally hazardous energy sources, the world is witnessing a decline in its strength and resilience. Conversely, clean and alternative energy sources hold the promise of safeguarding our planet. Wind, solar, and biomass are being promoted as feasible substitutes for non-renewable energy sources, advocating for the utilization of renewable energy options. 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 renewable 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.

1. **INTRODUCTION**

Nanotechnology is the science that involves the design, manipulation, production, characterization, and application of materials in the nanometer range [1] (size: 1-100 nm). 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 properties, e.g. very small size, high surface area to volume ratio, high reactivity, biocompatibility, functionalization, biomimetic features and biodegradability. Thus, they have been the focus of research due to their fascinating electronic, optical, and chemical properties and promising biomedical applications [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 flourish of Nanoscience and nanotechnology not only introduces novel concept to understand the nature, but also brings multifunctional nanomaterials and their various applications for modern society. The nanomaterials well render novel functions and properties for advanced applications in the area of electronics. Consequently, the nanomaterials and its related products are potential candidates to be as emerging nano industry originating from the basic scientific research [5]. In the past few years, there has been a significant surge in the demand for fossil fuels, particularly oil and gas, which has had a notable impact on the field of interest for contemporary researchers [6]. Clean and renewable energy-related achievements and issues are highly concerning aspects in the 21st century due to the increasing environmental pollution, depletion of traditional fossil energy, and consequently enhancement in global warming on the Earth. One of the primary factors leading to the presence of greenhouse gases in the atmosphere, air pollution, and climate change is the emission of harmful gases from factories and vehicles, largely stemming from the utilization of finite fossil fuels. Also, due to the increasing population worldwide, the consumption of limited fossil fuels is increasing continuously, and pollution is an unavoidable issue in the foreseeable future, which are the biggest challenges in human society [7]. The urgent demand for innovative, efficient, cost-effective, sustainable, and eco-friendly energy sources has arisen as a result of the growing environmental degradation. As a result, scientists are gradually working towards more sustainable production methods, waste minimization, reduced automobile pollution, distributed energy generation, native forest conservation, and greenhouse gas emission reduction [8]. Solar energy, wind energy, biomass, hydropower, and nuclear power are used as environmentally friendly, renewable and sustainable energy sources. 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. Therefore, how to stop these energy sources is a hot spot of concern. Currently, different kinds of energy storage technologies for stationary applications include mechanical, chemical, electrical and electrochemical energy storage [9]. Energy storage materials should be able to store or generate high amounts of energy in devices that ultimately should be cheap, lightweight and easily produced to maximize efficiency [10]. Among the energy storage devices, supercapacitors and secondary batteries have attracted widespread attention from researchers and are considered potential energy devices due to their good energy or power storage capacity, ultra-long term cycling stability, flexible operating temperature, and environmentally friendly nature. In energy storage devices, the energy density, power density, specific capacity, specific capacitance, and robust cyclability properties are significant indicators to evaluate their performance. To improve these properties in energy storage devices, the performance of supercapacitors and batteries depend highly on the nature of electrode materials. For electrode materials, researchers have developed various high surface area carbon materials and metal oxide/hydroxide-based composites or hybrids. Recently, carbon materials modified with metal oxides or hydroxides using various methods have been utilized as energy storage electrodes in supercapacitors and secondary batteries [7]. Although current energy conversion or storage methods/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 range of applications [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 density and long cycle life, but they come with the trade-off of limited energy density [12]. There are two different ways to store charge in a supercapacitor, *via:* a. non-Faradaic double-layer electrostatic charging process or a Faradaic surface redox process. On the other hand, the lithium-ion battery has also received widespread attention for large-scale power sources and energy storage devices, owing to its high power, high energy density, and long cycle life. There is an increasing demand for key lithium-ion battery materials, especially separators, which serve the crucial functions of physically separating the anode and cathode while allowing the free flow of lithium ions. The battery performance is notably influenced by the microporous structure and thermal dimensional stability of separators, which has been widely acknowledged [13]. In recent years, the utilization 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 address the low thermal conductivity of PCMs, researchers have been incorporating metal and non-metal nanoparticles into the PCM, aiming to enhance the thermal properties of the resulting mixture. Paraffin wax and fatty acids have been employed as thermal storage materials in solar heating and cooling applications. However, their major drawback lies in their low thermal conductivity. It results in decreased heat storage during the melting process and reduced heat retrieval during solidification. 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 reduce the supercooling effect during solidification. Additionally, these additives act as activation energy agents, helping to overcome thermal resistance during the melting process [14]. Over the past decade, nanotechnology has been offering unparalleled solutions to battery research. With various complex nanostructural designs, researchers have come closer to tackling the problems of next-generation battery chemistries. Thus, it is a good time to review the progress made to date and look ahead to what is possible in the near future [15].



Fig 1: A classification of energy storage types

1. **ELECTROCHEMICAL ENERGY STORAGE**
2. Rechargeable batteries

In the realm of small electronic equipment, such as cell 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 same attributes are required for electric vehicles, hybrid electric vehicles, power tool and backup power subsystems. Simplistically, a battery is an electrochemical device that generates DC through a coupled set of reduction–oxidation (‘redox’) reactions. The positive electrode is reduced (‘captures electrons’) and the negative electrode is oxidized (‘releases 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. Intercalation-based batteries using the small lithium (Li+) ion are the most used. These batteries have at least one redox-active electrode with an open crystal structure with ‘holes' capable of intercalating Li+ [16]. The battery safety can be increased, if the graphite electrode in a lithium-battery is replaced with a nanostructured material inert toward 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. For example, the non-toxic magnetite (Fe3O4) has been employed as an active material in a high-capacity Cu nano-architectured electrode [17].

1. Supercapacitors

Supercapacitors, as an alternative means of electricity storage, stand to gain significant advantages through the implementation of nanotechnology. They are needed in those devices that require rapid storage and release of energy, for instance hybrid-electric and fuel-cell powered vehicles. They are constructed by two electrodes immersed in an electrolyte, with an ion permeable separator between them. 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 been on achieving a high surface area while minimizing matrix resistivity. The most remarkable property of a supercapacitor is its high power density, about 10 times that of secondary battery. Carbon, in its diverse forms, presently holds the highest usage as the electrode material in supercapacitors. A typical commercial supercapacitor can produce a power density of about 4 kW/kg. Nanotubes offer a promising avenue to enhance the power density of supercapacitors, as their nanoscale tubular structure provides an exceptional blend of low electrical resistivity and high porosity within an easily accessible configuration [16]. Electrochemical supercapacitors store electrical energy using reversible adsorption of ions from an electrolyte onto two porous electrodes to form an electric double layer at an electrode or electrolyte interface. Electrochemical supercapacitors that only involve physical adsorption of ions in this manner, without any chemical reactions, are called 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. Because there is no physical change in the electrodes on charge or discharge, EDLCs can sustain millions of cycles with an energy density of typically 5 Wh kg-1. The other type of electrochemical supercapacitor is termed a pseudo-capacitor and is fundamentally different from an EDLC in the way in which charge is stored. In principle, pseudo-capacitors can provide a higher energy density than EDLCs, especially in systems where multiple oxidation states can be accessed, but because the electrodes undergo physical changes during charge or discharge they have relatively poor durability compared with EDLCs [18].

1. **THERMAL ENERGY STORAGE (TES)**
2. Sensible heat storage

Sensible heat storage (SHS) is widely recognized as the predominant method for heat storage [19]. It is the simplest and easiest form of heat 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 method of 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 most 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]. Commonly applicable SHS systems include solutions using underground energy storage such as: borehole, aquifer, cavern, ducts in soil, pit hot water storage (hydroaccumulation), and rock filled storage (rock, pebble, gravel) [22].

1. Latent heat storage

Latent heat storage (LHS) involves the transfer of heat through a phase change that takes place within a precise and narrow temperature range in the specific material. The most frequently used for this purpose are: molten salt, paraffin wax and water/ice materials [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].

1. **PHASE CHANGE MATERIALS (PCM)**

Phase change materials are those materials that absorb or release a large amount of thermal energy during their melting or freezing process. Owing to their excellent energy storage property, PCMs have been utilized as one of the most widely implemented materials in the fields of solar energy harvesting, thermal insulation, thermal regulation, and energy conservation in building [24]. PCMs are substances used for latent heat storage, possessing a higher heat of fusion, and they exhibit the ability 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 constant 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 many sensible storage materials. The property of high latent heat in PCMs makes them highly sought-after candidates 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. Due to less than 10% variation in volume during phase change and greater latent heat of fusion, solid-liquid PCMs are most widely used [25]. Furthermore, LHS systems offer cost advantages over SHS systems, as they necessitate smaller weight and volume requirements [26]. Taking into account the environment in which the PCM material is to work, its melting point should be lower than the heat supply temperature and higher than the ambient temperature [27]. Based on the chemical nature and composition, PCMs can be classified into three categories: Organic, Inorganic and Eutectics.



Fig 2: Basic categories of phase change materials

1. Organic material

Among the organic materials known as natural and there are three basic groups of substances: paraffins, fatty acids, and organic mixtures. Organic PCM materials possess both advantages and disadvantages, rendering them competitive with their inorganic counterparts. On the one hand, they are thermally and chemically stable; they are noncorrosive to metals, recyclable and have high latent heat of fusion. On the other hand they are flammable, have lower phase change enthalpy, low thermal conductivity and additionally poor compatibility with polymer containers or encapsulation media [21]. Paraffin, owing to its crucial properties, such as high heat of fusion, varying phase change temperature, substantial phase change enthalpy, absence of supercooling, low vapor pressure, chemical inertness (without corrosion and toxicity), and consistent cyclic stability of conductivity, has found extensive application in energy storage. Fatty acid is categorized as an organic material, specifically a renewable PCM known as non-paraffin, as it is derived from plants and animals. This material exhibits excellent thermal and physical properties, making it a valuable choice for various applications [28].

1. Inorganic PCMs

Inorganic solid PCM (SS-PCM or Solid-Solid PCMs) have the capability to store and release heat energy in the solid phase through various energy storage techniques, including magnetic transformations, crystallographic structure transformations, order-disorder transformations, and transformations between amorphous and crystalline structures. Notably, the first two methods involve significant amounts of latent heat [29]. Indeed, inorganic PCMs are distinguished by their lower cost, higher phase change enthalpy, and relatively superior thermal conductivity. Their disadvantage is their corrosive nature, sub-cooling, segregation and phase separation and potential thermal instability [21]. Therefore, they are best suited for industrial plants to recover heat from high temperature waste heat [29]. One of the forms of inorganic materials is metallic forms. They are characterized by good stability, low density and high ratio coefficient, which increase their thermal conductivity in relation to nanoparticles. However, the size of the pores has very little influence on the thermal conductivity [30]. The appeal of salt hydrates over organic PCMs has surged due to their exceptional high heat of fusion per unit volume, more affordable cost, and non-combustible nature. But at the same time, these inorganic salt hydrates suffer from a high degree of supercooling (due to weak nucleation property), phase segregation, and low thermal conductivity which hinders their performance in practical engineering applications [31].

1. Eutectics

Eutectics are compositions of two or more components such as a combination of organic and organic, inorganic and inorganic, and inorganic and organic. Eutectics have emerged as a promising solution to address the incongruent melting issue encountered with hydrate salts. Mixing two types of hydrate salts, (inorganic and inorganic) as an example, to form a eutectic, helps to prevent incongruent melting and at the same time reduces the melting point and improves the thermal conductivity [32].

1. Encapsulation of PCMs

Encapsulation is an approach that safeguards the active PCM substance from direct contact with the environment, effectively minimizing the risk of leaks. This prolongs its lifetime and reduces problems related to phase separation [30]. There are several ways to improve the performance of PCM systems. The initial method involves augmenting the heat transfer surface area, which can be achieved through PCM encapsulation or the utilization of finned tubes. The second method entails incorporating nano-additives, thereby enhancing the thermal conductivity. The last method is to improve the uniformity of heat transfer and thermodynamic optimization of PCM. The above methods impact both the heat transfer surface and the thermal conductivity [28].

1. Nanomaterials PCMs

For the production of nanomaterials, the methodology uses either a top-down or a bottom-up technique [33]:

Top-Down Technique: This approach employs specific methods to decrease the size and shape the required nanomaterial for various applications. The techniques utilized under this method include emulsification and emulsification solvent evaporation.

Bottom-Up Technique: In this method, materials are created through the self-assembly of molecules, influenced by factors such as concentration, ion properties, temperature, and pH. Techniques used in this category encompass coacervation and nanoprecipitation.

1. Shape stabilization

Shape stabilization is an important technique to avoid leakage and improve the energy storage ability of PCM materials. Form-stabilized phase change material or in short SSPCM consists of a working material and a supporting component. The working material absorbs or removes latent heat during the melting or solidifying cycle, while the supporting substance stops the melting process from leaking of material so that the entire system stays in solid state [34].

1. Temperature range

PCM are developed in accordance to the working temperature of the material used. The working temperature of PCMs are mainly categorised into 4 different ranges mainly as:

* High temperature (+80 °C to +200 °C or above);
* Medium temperature (+40 °C to +80 °C);
* Low temperature (+5 °C to +40 °C).

The high temperature application includes the use of PCM for waste heat recovery and absorption cooling, whereas, the medium range PCMs are used for solar and electronic thermal management systems. On the other hand, the low range temperature PCMs are utilized for thermal cooling and heating applications and use in buildings [21].

1. **NANOMATERIALS**

Nanomaterials can be classified into organics and inorganics, which has been concluded from. Organic nanomaterials consist of fullerenes, carbon nanotubes (CNT), single-walled carbon nanotubes (SWCNT), multi-walled carbon nanotubes (MWCNT), graphite and nanofibers. Most of the organic nanomaterials are carbon-based nanomaterials. While, metal and metal oxide-based nanomaterials such as aluminium, zinc, copper, iron, aluminium oxide, iron oxide, titanium oxide are categorized as inorganic nanomaterials. Metalloid nanomaterials like CdSe, ZnS, ZnO, and others, known as quantum dots, are also classified as inorganic nanomaterials. Hybrid nanomaterials are a new class included. Hybrid nanomaterials are formed by combining various nanomaterials, including organic-organic, organic-inorganic, and inorganic-inorganic, through synthesis methods such as chemical vapor deposition (CVD), electrospinning, and atom transfer radical polymerization (ARTP). Although, nanomaterials possess many advantages, there are risks and they having a toxic effect on humans and the environment [32].

1. **APPLICATIONS OF NANOCOMPOSITES IN THERMAL ENERGY STORAGE**
2. Heating and Cooling of Buildings

Space cooling in industrial areas is an enormous scientific challenge, which also applies to many other diverse production areas, including transportation, manufacturing, microelectronics, sporting arenas etc. Traditionally, the heating and cooling of a building or space has been in practice for many decades. The construction of buildings amidst trees to aid for cooling in hot weather, or the use of bricks in the building of walls to aids cooling in hot weather. 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. PCMs have a high latent heat storage capacity and as such have been considered for thermal storage in building applications [35]. The utilization of PCM-enhanced nanocomposites in buildings or spaces primarily revolves around harnessing solar radiation as a natural heat source for heating during cold weather and utilizing man-made heat or cold sources for cooling during hot weather conditions. In any case, storage of thermal energy is important to match availability and demand with respect to time and also with respect to power [32].

1. Heating and Cooling of Electrical and Electronic Components

As technological advancements progress in the development of smart materials and components, the demand for efficient heat dissipation mechanisms has intensified, particularly for microelectronic devices operating at high speeds, higher power engines, and brighter optical devices. This need arises from the ongoing efforts to reduce the weight and size of electromechanical devices. This has driven increased thermal loads that require advances in cooling [36]. Thermal management challenges pose significant barriers to achieving high-density electronic packaging and miniaturization. Within the electronic industry, enhancing the thermal performance of cooling systems while simultaneously reducing their required surface area has consistently presented a formidable technical challenge. The continually increasing power of microprocessors and other electronic components requires a search for a more efficient heat dissipating system [32].

1. In power generation

It is discovered that approximately 47% of existing concentrating solar power plants use molten salt storage to produce electricity [37]. The key issue related with molten salt system are the requirement of high-volume storage, costly and very expensive heat exchangers, and the need for heavy installation facilities. The advancements of molten salt integrated PCMs can provide promising results for concentrated solar plants that operate in the medium to high temperature of between 200 °C and 1000 °C range [28].

1. In district heating

The integration of district heating systems with thermal storage offers numerous economical, environmental, and technical advantages. Regarding this matter, both short- and long-term system storage approaches were explored, showcasing how these technologies can be effectively combined with district energy supply. In this context, investigations were carried out concerning chemical, sensible, and latent heat storage systems. These studies aimed to assess the potential advancements of state-of-the-art technologies for next-generation district heating and network-based energy delivery systems [28].

1. Automobile applications

Radiant energy that falls on the vehicle through the windows of the car is another storage source for automobiles during daytime especially at times of high solar intensity. Numerous methods for storing this type of energy and subsequently utilizing it when required have been attempted and implemented thus far. Effective TES of this waste heat can be used in the preheating of the engine, preheating the catalytic converter, heating and cooling the passenger compartment and defrosting the car windows. A huge amount of energy is lost due to incomplete combustion in automobile engines; as such considerable amounts of gasoline are consumed thereby adding to environmental pollution. Also, a significant amount of thermal energy generated by automobile engines is wasted to the environment especially in the case of diesel engines. Hence, various heat recovery and reuse systems are under investigation for probable use of nanomaterials as thermal energy storage. Engine cylinders (liners) are being envisaged to be coated with nanocrystalline ceramics, such as zirconia and alumina, for purposes of heat retention and a more efficient combustion system [38].

1. Solar thermal heating

Water heating is a major source of energy consumption in domestic and commercial buildings where low temperatures are mostly required. The primary energy sources used to generate hot water are non-renewable. Regrettably, this condition remains despite efforts to develop and promote the use of renewable, solar thermal water heaters for over a century [39]. Solar thermal collector systems are by far the most reversed means of harvesting solar radiation to be used for the heating of water [40].

1. **CONCLUSION**

This chapter presents a study on different kinds of energy storage systems. It is explained that supercapacitors and rechargeable batteries are the growing demand of high energy and power densities of electronic devices of the present era, as a result of the rapid development in this field. Also, different kinds of PCMs according to their chemical nature as organic, inorganic and Eutectics is a subject of growing interest as they are the sought out materials nowadays in heat storage systems. It is discussed that encapsulation is a method of enhancing the performance of PCM materials and shape-stabilization is a technique applied to improve the energy storage ability and stability of PCM materials. Their applications span many areas such as heating and cooling of buildings, electrical and electronic components, solar thermal heating, power generation and in automobile applications.

**REFERENCES**

1. K. A. Youssif, A. M. Elshamy, M. A. Rabeh, N. Gabr, W. M. Afifi, M. A. Salem, A. Albohy, U. R. Abdelmohsen, E. G. Haggag; “Cytotoxic Potential of Green Synthesized Silver Nanoparticles of Lampranthus coccineus Extracts, Metabolic Profiling and Molecular Docking Study”; Chemistry Select, 5 (2020) 12278-12286.
2. Ijaz, E. Gilani, A. Nazir, A. Bukhari; “Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles”; Green Chemistry Letters and Reviews, 13 (2020), 223-245.
3. Z. Aghili, S. Taheri, HA Zeinabad, L Pishkar, AA Saboury, A Rahimi, M. Falahati; “Investigating the Interaction of Fe Nanoparticles with Lysozyme by Biophysical and Molecular Docking Studies”; PLoS ONE 11(10), (2016), e0164878.
4. N. Krumov, I.P. Nochta, S. Oder, V. Gotcheva, A. Angelov, C. Posten, “Production of Inorganic Nanoparticles by Microorganisms”, Chem. Eng. Technol, (2009), 32, No.7, 1026.
5. Q. Zhang, J. Huang, W. Qian, Y. Zang and F.Wei, “The Road for Nanomaterial Industry: A Review of Carbon Nanotube Production, Post-Treatment, and Bulk Applications for Composites and Energy Storage”, small (2023), No. 8, 123.
6. R. Singh, A Altaee, S, Gautam, “Nanomaterials in the advancement of hydrogen energy storage”, Heliyon 6 (2020), e04487.
7. N. Devi, S. Sahoo, R. Kumar, and R.K. Singh, “A review of the microwave assisted synthesis of the carbon nanomaterials, metal oxides/hydroxides and their composites for energy storage appications”, Nanoscale, (2021), 13, 11679.
8. P.C. Ani, P.U. Nzereogu, A.C. Agbogu, F.I. Ezema, A.C. Nwanya, “Cellulose from waste materials for electrochemical energy storage application: A review”, Applied Surface Science Advances, 11, (2022), 100298.
9. K.Yu, X. Pan, G. Zhang, X. Liao, X. Zhou, M. Yan, L. Xu, and L. Mai, “Nanowires in Energy Storage Devices: Structures, Synthesis, and Applications”, Adv. Energy Mater, (2018), 1802369.
10. M.E. Abdelhamid, A.P.O’Mullane and G.A. Snook, “Storage Energy in Plastics: A review on Conducting Polimers and thei role in Electochemical Energy Storage”, RSC Advances, 5(15), pp.11611-11626.
11. B. Jun, S. Kim, J. Heo, C.M. Park, N. Her, M. Jang, Y. Huang, J. Han, and Y. Yoon, “Review of MXenes as new nanomaterials for energy storage/delivery and selected environmental applications”, NanoResearch, (2018), 12(3).
12. Y. Shi, L. Peng, Y. Ding, Y. Zhao and G. Yu, “Nanostructured conductive polymers for advanced energy storage”, Chem. Soc. Rev., (2015), 44, 6684.
13. S. Dutta, J. Kim, Y. Ide, J.H. Kim, Md. S.A. Hossain, Y. Bando, Y. Yamauchi and K.C.W. Wu, “3D network of cellulose-based energy storage devices and related emerging applications”, Mater. Horiz., (2017), 4,522.
14. S.C. Lin, H.H. Al-Kayiem, “Evaluation of copper nanoparticles- Paraffin wax compositions for solar thermal energy storage”, Solar Energy, 132 (216), 267-278.
15. Y. Liu, G. Zhou, K. Liu, and Y. Cui, “Design of Complex Nanomaterials for Energy Storage: Past Success and Future Opportunity”, Acc. Chem. Res. (2017), 50, 2895-2905.
16. Z. Abdin, M.A. Alim, R. Saidur, M.R. Islam, W. Rashmi, S. Mekhilef, A. Wadi, “Solar energy harvesting with the application of nanotechnology”, Renewable and Sustainable Energy Reviews, 26, (2013), 837-852.
17. Taberna PL, Mitra S, Poizot P, Simon P, Tarascon JM. “High rate capabilities Fe3O4-based Cu nano-architectured electrodes for lithium-ion battery applications.” Nature Materials (2006), 5:567–73.
18. X. Zhao, B. M. Sanchez, P.J. Dobson, and P.S. Grant, “The role of nanomaterials in redox-based supercapacitors for next generation energy storage devices”, Nanoscale, (2011), 3, 839-855.
19. H. Mehling, L.F. Cabeza, “Heat and Cold Storage with PCM”, Springer Berlin Heidelberg, Berlin, Heidelberg, (2008).
20. P.K.S. Rathore, S.K. Shukla, N.K. Gupta, “Potential of microencapsulated PCM for energy savings in buildings: a critical review”, Sustain. Cities Soc. 53 (August 2019) (2020) 101884
21. C.N. Elias, V.N. Stathopoulos, “A comprehensive review of recent advances in materials aspects of phase change materials in thermal energy storage”, Energy Procedia 161 (2019) 385–394.
22. S. Koohi-Fayegh, M.A. Rosen, “A review of energy storage types, applications and recent developments”, J. Energy Storage 27 (July 2019) (2020) 101047.
23. EASE-EERA, Joint EASE/EERA Recommendations For a European Energy Storage Technology Development Roadmap 2017 Update, EASE/EERA, (2017).
24. N. Gupta, A. Kumar, H. Dashmana, V. Kumar, A. Kumar, P. Shukla, A. Verma, G.V. Nutan, S.K. Dhawan, V.K. Jain, “Enhanced thermophysical properties of Metal oxide nanoparticles embedded magnesium nitrate hexahydrate based nanocomposite for thermal energy storage applications”, Journal of Energy Storage, Volume 32, (2020), 101773.
25. A. Yadav, A. Verma, A. Kumar, H. Dhashmana, A. Kumar, P.K. Bhatnagar, V.K. Jain, “Recent Advances on Enhanced Thermal Conduction in Phase Change Materials using Carbon Nanomaterials”, Journal of Energy Storage**,** Volume 43, (2021), 103173.
26. S. Wu, T. Yan, Z. Kuai, W. Pan, Thermal conductivity enhancement on phase change materials for thermal energy storage: a review, Energy Storage Mater. 12 (1) (2019).
27. A. Reyes, L. Henríquez-Vargas, J. Vasquez, N. Pailahueque, G. Aguilar, Analysis of a laboratory scale thermal energy accumulator using two-phases heterogeneous 22 H. Jouhara et al. / International Journal of Thermofluids 56 (2020) 100039 paraffin wax-water mixtures, Renew. Energy 145 (2020) 41–51.
28. H. Jouhara, A.Z. Gora, N. Khordehgah, D. Ahmad, T. Lipinski, “Latent thermal energy storage technologies and applications: A review”, International Journal of Thermofluids, 5–6, (2020), 100039.
29. A. Fallahi, G. Guldentops, M. Tao, S. Granados-Focil, S. Van Dessel, “Review on solid-solid phase change materials for thermal energy storage: molecular structure and thermal properties”, Appl. Therm. Eng. 127 (2017) 1427–1441.
30. Z.A. Qureshi, H.M. Ali, S. Khushnood, “Recent advances on thermal conductivity enhancement of phase change materials for energy storage system: a review”, Int. J. Heat Mass Transf. 127 (2018) 838–856.
31. N. Gupta, A. Kumar, H. Dhasmana, A. Kuma, A. Verma, P. Shukla, V.K. Jain, “Effect of shape and size of carbon materials on the thermophysical properties of magnesium nitrate hexahydrate for solar thermal energy storage applications”, Journal of Energy Storage, Volume 41, (2021), 102899.
32. H. Hussain, Al-Kayiem, S.C. Lin, and A. Lukmon, “Review on Nanomaterials for Thermal Energy Storage Technologies”, Nanoscience & Nanotechnology-Asia, (2013), 3, 60-71.
33. S.S. Magendran, et al., Synthesis of organic phase change materials (PCM) for energy storage applications: a review, Nano Struct. Nano Obj. 20 (2019) 100399.
34. M.M. Umair, Y. Zhang, K. Iqbal, S. Zhang, B. Tang, Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storagea review, Appl. Energy 235 (October 2018) (2019) 846–873.
35. Khudhair, A.M; Farid, M.M., “A review on energy conservation in building applications with thermal storage by latent heat using phase change materials.”, Energ. Convers. Manage., (2004), 45, 263- 275.
36. Zhou, D.; Zhao, C.Y.; Tian, Y., “Review on thermal energy storage with phase change materials (PCMs) in building applications.” Appl. Energ., (2009), 12, 76-81.
37. J. Sunku Prasad, P. Muthukumar, F. Desai, D.N. Basu, M.M. Rahman, A critical review of high-temperature reversible thermochemical energy storage systems, Appl. Energy 254 (October 2018) (2019) 113733.
38. Wang, X.; Mujumdar, A.S. “A review on nanofluids - part II: experiments and applications.” Braz. J. Chem. Eng., (2008), 25(4), 631-648.
39. Singh, D.; Toutbort, J.; Chen, G. Heavy vehicle systems optimization merit: review and peer evaluation. Annual Report, Argonne National Laboratory, (2006), 23, 405 – 411.
40. Tian, Y.; Zhao, C.Y. “A review of solar collectors and thermal energy storage in solar thermal applications.” Appl. Energ., (2013), 104, 538-553.