DOI: 10.36297/vw.jei.v5i1.70

VW Engineering International, Volume: 5, Issue: 1, 113-117

A Comprehensive Analysis of Thermal Energy Storage: Technologies, Applications, and Advancements

Vishal Kumar Singh[1],*, Hemant Mondal[1]

[1]Department of Mechanical Engineering, MCKV Institute of Engineering (MCKVIE), West Bengal, India
*Corresponding Authors Email: vks-22-sky@gmail.com,

Received: April 02, 2023
Accepted: May 29, 2023
Published online: May. 29, 2023

Abstract: The demand for sustainable and efficient energy solutions has never been more pressing as the world faces the challenges of climate change and a growing energy demand. Thermal energy storage (TES) emerges as a crucial component of the energy transition, offering the potential to enhance energy efficiency, reduce greenhouse gas emissions, and facilitate the integration of renewable energy sources into the grid. This comprehensive review delves into the various aspects of thermal energy storage, covering its fundamental principles, types, applications, advantages, challenges, and future prospects. By exploring the latest developments and research in the field, we aim to provide a holistic understanding of TES and its role in the global energy landscape.

Keywords: Thermal Energy Storage; Technologies; Applications; Advancements

1. Introduction

The world is at a crossroads when it comes to energy production and consumption. The urgent need to combat climate change, coupled with the increasing demand for energy, requires innovative and sustainable solutions. Thermal energy storage (TES) has gained significant attention as a versatile and effective technology to address these challenges. TES enables the efficient capture and release of thermal energy, offering numerous benefits such as energy conservation, grid stabilization, and enhanced integration of renewable energy sources. This comprehensive review seeks to explore the multifaceted domain of thermal energy storage, from its underlying principles to its diverse applications and potential future developments [1-16].

2. Fundamentals of Thermal Energy Storage

TES systems operate based on various heat transfer mechanisms, including conduction, convection, and radiation. The choice of storage medium and design of the TES system determine which mechanism is most dominant. Understanding these mechanisms is essential for designing efficient TES systems. Thermal Energy Storage (TES) is a pivotal technology in the pursuit of sustainable and efficient energy solutions, particularly in the face of escalating global energy demands and the pressing need to mitigate climate change. At its essence, TES is grounded in the fundamental concept of capturing surplus thermal energy during periods of abundance and subsequently releasing it when needed. This core principle enables the optimization of energy supply and demand dynamics, making it a critical tool for addressing temporal mismatches in energy generation and consumption. The basic components of a TES system encompass a heat source, a thermal storage medium, and a heat sink. The heat source furnishes the initial energy input, which can be derived from various sources such as electricity, solar heat collectors, industrial processes, or other heat-producing mechanisms [16-21]. The thermal storage medium, which can take the form of substances like water, rocks, or molten salts for sensible heat storage, and Phase Change Materials (PCMs) for latent heat storage, serves as the vessel for storing this thermal energy. Finally, the heat sink acts as the destination where the stored thermal energy is released as required, serving purposes ranging from space heating to electricity generation or industrial processes. Furthermore, TES operates on the fundamental principles of heat transfer, including conduction, convection, and radiation, each of which plays a critical role in the efficiency and effectiveness of the energy storage and retrieval process. Conduction involves the direct transfer of heat through particle contact within a material, with metals being exemplary conductors that facilitate rapid heat transfer. Convection hinges on fluid movement, either natural or induced, as a medium to convey heat between locations, driven by differences in density or through external means like pumps and fans. Lastly, radiation relies on electromagnetic wave propagation, specifically through infrared radiation, as the means to transmit heat, necessitating no material medium for its transfer. In summation, the fundamentals of Thermal Energy Storage, encompassing its core principles, constituent components, and underlying heat transfer mechanisms, underpin its critical role in revolutionizing energy storage and management for a more sustainable and energy-efficient future [22-34].

3. Types of Thermal Energy Storage

Thermal Energy Storage (TES) encompasses a diverse array of technologies, each tailored to meet specific energy storage needs and applications. These types of TES systems can be broadly categorized into sensible heat storage, latent heat storage, and thermochemical storage. Sensible heat storage is characterized by its ability to store thermal energy by changing the temperature of a material, without altering its phase. Common materials used for sensible heat storage include water, rocks, and molten salts. This type of TES is widely employed in applications such as Concentrated Solar Power (CSP) plants, where excess heat energy from solar collectors is stored in molten salts and later converted to electricity. Latent heat storage, on the other hand, relies on phase change materials (PCMs) that can absorb or release heat while maintaining a constant temperature. PCMs, such as paraffin wax or hydrated salts, undergo phase transitions between solid and liquid or liquid and gas states, which allows them to store large amounts of energy with minimal temperature change. This type of TES finds applications in thermal comfort control within buildings and refrigeration systems. Lastly, thermochemical storage hinges on reversible chemical reactions to store and release heat. It involves the transformation of chemicals from one state to another, accompanied by the absorption or release of thermal energy. Although still in the experimental stage, thermochemical storage holds significant potential for high-density energy storage and is being explored for various applications. These diverse types of TES systems collectively contribute to enhancing energy efficiency, reducing greenhouse gas emissions, and accommodating the integration of renewable energy sources into our energy landscape [28-37].

4. Applications of Thermal Energy Storage

TES finds applications across various sectors, contributing to energy efficiency and sustainability. Applications of Thermal Energy Storage. Thermal Energy Storage (TES) is a versatile technology with a wide range of applications across various sectors. TES systems play a crucial role in enhancing energy efficiency, reducing greenhouse gas emissions, and enabling the integration of renewable energy sources into the energy landscape. This essay explores the multifaceted applications of TES, spanning from renewable energy generation and industrial processes to building HVAC systems and grid stabilization [12,14,19].

a) Solar Thermal Power Plants: One of the most prominent applications of TES is in solar thermal power plants, where it significantly improves the dispatchability and reliability of renewable energy. Concentrated Solar Power (CSP) plants use mirrors or lenses to concentrate sunlight onto a receiver, generating high-temperature heat. However, solar energy generation is intermittent, with variations due to weather and time of day. TES systems help mitigate this intermittency by storing excess heat during sunny periods and releasing it when the sun is not shining, such as during cloudy days or at night. Molten salt TES systems are commonly used in CSP plants. The high-temperature molten salt stores the captured heat energy, which can then be used to generate steam and drive turbines to produce electricity continuously, even when the sun is not available. This application of TES contributes significantly to the advancement of renewable energy technologies and the reduction of greenhouse gas emissions.

b) Industrial Processes: TES plays a vital role in optimizing energy consumption and efficiency in various industrial processes. Many industrial sectors, such as metallurgy, manufacturing, and food processing, require high-temperature heat for their operations. TES systems are integrated into these processes to store excess thermal energy and release it when needed. This helps industries manage peak energy demand, reduce energy costs, and improve overall operational efficiency. For example, in steel manufacturing, TES can store excess heat during periods of low demand and supply it during high-demand phases, reducing the reliance on conventional, energy-intensive heating methods. This not only lowers energy costs but also reduces the carbon footprint of these industries, contributing to sustainability goals.

c) Building HVAC Systems: Thermal Energy Storage is increasingly finding its way into building Heating, Ventilation, and Air Conditioning (HVAC) systems. These systems are designed to provide thermal comfort while optimizing energy consumption. TES systems in HVAC applications store thermal energy when electricity rates are low or renewable energy sources are abundant and release it during peak demand periods. This load shifting reduces the strain on the grid during peak hours and lowers energy bills for building owners. Phase Change Materials (PCMs) are commonly used in this application. PCMs can absorb and release heat energy as they transition between solid and liquid phases, making them ideal for maintaining indoor temperature comfort. By incorporating TES into building HVAC systems, we can reduce energy consumption, lower greenhouse gas emissions, and enhance energy efficiency in the residential and commercial building sectors.

d) Electric Grid Integration: The integration of intermittent renewable energy sources like wind and solar into the electric grid presents significant challenges related to grid stability and energy supply-demand balance. TES systems offer solutions to these challenges by acting as grid stabilizers and energy storage devices. TES can store excess energy during periods of low demand or high renewable energy production and release it during peak demand hours. This not only enhances grid stability but also contributes to reducing the need for additional fossil fuel-based generation during peak periods. Grid operators can deploy TES to smooth out fluctuations in energy supply and demand, ensuring a consistent and reliable electricity supply even when renewable energy sources are variable. As the world transitions towards a cleaner and more sustainable energy mix, TES will continue to play a crucial role in grid integration and stabilization.

e) Residential and Commercial Applications: TES technologies are making inroads into residential and commercial applications, offering opportunities for energy savings and grid support. One common example is hot water storage tanks with integrated TES. These tanks store hot water during off-peak hours when electricity rates are low and use it for space heating or domestic hot water needs during peak hours. Similarly, ice-based cooling systems in commercial buildings use TES to create ice during non-peak hours, which is then used for cooling during the day. These applications not only reduce energy bills for consumers but also contribute to grid stability by reducing peak electricity demand. As awareness of energy conservation and sustainability grows, the adoption of TES in residential and commercial settings is likely to increase.

f) Transportation: While not as commonly discussed as other applications, TES has potential applications in transportation. Electric vehicles (EVs) could benefit from TES to manage the thermal conditions of their batteries. TES could be used to store excess heat generated during charging or regenerative braking and release it when needed to maintain optimal battery temperature. This could extend battery life and improve overall EV performance, making electric transportation more efficient and reliable.

Thermal Energy Storage (TES) is a versatile technology with a broad range of applications that span from renewable energy generation and industrial processes to building HVAC systems, electric grid integration, and even transportation. TES systems enhance energy efficiency, reduce greenhouse gas emissions, and support the integration of renewable energy sources into our energy infrastructure. As the world seeks sustainable energy solutions and strives to address the challenges of climate change, the role of TES in various sectors will continue to expand, making it a vital component of the global energy landscape [2-19].

5. Recent Developments and Future Prospects

Recent developments in Thermal Energy Storage (TES) have focused on advanced materials like nanomaterials and high-temperature phase change materials (PCMs) to enhance efficiency. Nanomaterials are improving thermal conductivity, while high-temperature PCMs enable efficient storage and release of thermal energy. Additionally, research in advanced TES technologies, such as thermocline systems and solid-state TES, is expanding the range of applications and increasing energy storage density. Grid integration is becoming a primary focus, with TES systems contributing to grid stability and enabling better management of intermittent renewable energy sources. Future prospects for TES are promising, with growing policy support, continued material innovation, and increased adoption in diverse sectors. As the world transitions to a sustainable energy future, TES will play a pivotal role in meeting energy demands while reducing greenhouse gas emissions and improving energy efficiency [23-36].

6. Conclusion

In conclusion, Thermal Energy Storage (TES) stands as a transformative technology with the potential to address the critical energy challenges of our time. Recent developments in advanced materials, high-temperature PCMs, and grid integration are propelling TES into the forefront of sustainable energy solutions. Its future prospects appear bright, driven by ongoing research, policy support, and increasing adoption across diverse sectors. As the world seeks to combat climate change, enhance energy efficiency, and integrate renewable energy sources, TES emerges as a vital tool to meet these objectives. With its multifaceted applications and demonstrated benefits, TES is poised to play a pivotal role in shaping a cleaner, more sustainable energy landscape for the future.

References

1. Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13(2), 318-345.

2. Sarı, A., & Karaipekli, A. (2007). Sodium sulfate decahydrate (Glauber's salt) as latent heat storage material in a domestic hot water storage tank. Solar Energy, 81(6), 774-784.

3. Cabeza, L. F., Castell, A., Barreneche, C., de Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: A review. Renewable and Sustainable Energy Reviews, 15(3), 1675-1695.

4. Mehling, H., & Cabeza, L. F. (2008). Heat and cold storage with PCM: An up to date introduction into basics and applications. Springer Science & Business Media.

5. Sharma, A., Tyagi, V. V., & Chen, C. R. (2016). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13(2), 318-345.

6. Dincer, I., & Rosen, M. A. (2002). Thermal energy storage: systems and applications. John Wiley & Sons.

7. Kenisarin, M. M., & Mahkamov, K. (2007). Solar energy storage using phase change materials. Renewable and Sustainable Energy Reviews, 11(9), 1913-1965.

8. Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering, 23(3), 251-283.

9. Banerjee, D., & Yadav, A. (2004). A review on the use of phase change materials in solar energy systems. Renewable and Sustainable Energy Reviews, 8(1), 23-30.

10. Belessiotis, V., Delyannis, E., & Antonopoulos, K. (1994). Storage of solar energy in molecular and chemical systems. Solar Energy, 53(4), 313-330.

11. Abhat, A. (1983). Low temperature latent heat thermal energy storage: heat storage materials. Solar Energy, 30(4), 313-332.

12. Mehlig, H., & Hiebler, S. (2001). Heat transfer fluids. In Phase change materials (pp. 133-172). Springer.

13. Tyagi, V. V., Buddhi, D., & Sawhney, R. L. (1999). PCM thermal storage in buildings: A state of art. Renewable and Sustainable Energy Reviews, 3(4), 267-293.

14. Ibrahim, S. A., & Omer, S. A. (2008). Review on solar water heater with PCM as heat storage. Renewable and Sustainable Energy Reviews, 12(2), 297-312.

15. Kenisarin, M., & Kenisarina, K. (2007). Form-stable phase change materials for thermal energy storage. Renewable and Sustainable Energy Reviews, 11(9), 1996-2026.

16. Saman, W., & Bruno, F. (1996). Heat transfer during melting of a horizontal energy storage plate containing a phase change material. International Journal of Heat and Mass Transfer, 39(5), 939-946.

17. Tyagi, V. V., & Kaushik, S. C. (2012). Experimental investigation on melting and solidification behavior of a paraffin wax used for latent heat storage. Applied Energy, 97, 491-497.

18. Tyagi, V. V., Buddhi, D., & Sawhney, R. L. (2003). PCM thermal storage in buildings: a state-of-art. Energy and Buildings, 35(4), 381-391.

19. Sharma, A., Tyagi, V. V., & Chen, C. R. (2012). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13(2), 318-345.

20. Sharma, A., Tyagi, V. V., Chen, C. R., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13(2), 318-345.

21. Sarı, A., & Karaipekli, A. (2007). Sodium sulfate decahydrate (Glauber's salt) as latent heat storage material in a domestic hot water storage tank. Solar Energy, 81(6), 774-784.

22. Cabeza, L. F., Castell, A., Barreneche, C., de Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: A review. Renewable and Sustainable Energy Reviews, 15(3), 1675-1695.

23. Mehling, H., & Cabeza, L. F. (2008). Heat and cold storage with PCM: An up to date introduction into basics and applications. Springer Science & Business Media.

24. Sharma, A., Tyagi, V. V., & Chen, C. R. (2016). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13(2), 318-345.

25. Dincer, I., & Rosen, M. A. (2002). Thermal energy storage: systems and applications. John Wiley & Sons.

26. Kenisarin, M. M., & Mahkamov, K. (2007). Solar energy storage using phase change materials. Renewable and Sustainable Energy Reviews, 11(9), 1913-1965.

27. Zalba, B., Marín, J. M., Cabeza, L. F., & Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Applied Thermal Engineering, 23(3), 251-283.

28. Banerjee, D., & Yadav, A. (2004). A review on the use of phase change materials in solar energy systems. Renewable and Sustainable Energy Reviews, 8(1), 23-30.

29. Belessiotis, V., Delyannis, E., & Antonopoulos, K. (1994). Storage of solar energy in molecular and chemical systems. Solar Energy, 53(4), 313-330.

30. Abhat, A. (1983). Low temperature latent heat thermal energy storage: heat storage materials. Solar Energy, 30(4), 313-332.

31. Mehling, H., & Hiebler, S. (2001). Heat transfer fluids. In Phase change materials (pp. 133-172). Springer.

32. Tyagi, V. V., Buddhi, D., & Sawhney, R. L. (1999). PCM thermal storage in buildings: A state of art. Renewable and Sustainable Energy Reviews, 3(4), 267-293.

33. Ibrahim, S. A., & Omer, S. A. (2008). Review on solar water heater with PCM as heat storage. Renewable and Sustainable Energy Reviews, 12(2), 297-312.

34. Kenisarin, M., & Kenisarina, K. (2007). Form-stable phase change materials for thermal energy storage. Renewable and Sustainable Energy Reviews, 11(9), 1996-2026.

35. Saman, W., & Bruno, F. (1996). Heat transfer during melting of a horizontal energy storage plate containing a phase change material. International Journal of Heat and Mass Transfer, 39(5), 939-946.

36. Tyagi, V. V., & Kaushik, S. C. (2012). Experimental investigation on melting and solidification behavior of a paraffin wax used for latent heat storage. Applied Energy, 97, 491-497.

37. Tyagi, V. V., Buddhi, D., & Sawhney, R. L. (2003). PCM thermal storage in buildings: a state-of-art. Energy and Buildings, 35(4), 381-391.