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Specialty grand challenge: Thermal energy storage and conversion

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Introduction

The world is experiencing rapid technological advancement on a multidimensional scale but at the expense of its environmental sustainability. In this ever-developing world, the hunger for energy is increasing day by day. Natural resources for energy production, such as fossil fuels, are on the brink of extinction due to their extensive use to meet this ever-growing demand for energy. Most of the fossil fuel-burned energy in today's world is spent on the continuous production of drinkable water, heating, cooling applications, and power generation (Rupam et al., 2022a). Along with irreversible resource exhaustion, burning fossil fuels causes excessive emissions of greenhouse gases and other pollutants responsible for global warming. Keeping in mind the catastrophic effects of the rising temperature, in recent times, there has been a global urge for the development of energy-saving, eco-friendly systems for water production, HVAC applications, power generation, etc. Although renewables are advancing at a fast pace, it has not yet reached a satisfactory level where all the energy-intensive systems can be operated with that. Apart from that, renewables are overly dependent on environmental constraints. For example, at night time or on gloomy days, solar energy cannot be harvested, or the energy conversion rate of photovoltaics drastically decreases. On the other hand, when there is plenty of sunshine, solar photovoltaics produce more energy than the required amount at that time. Most often, this surplus energy ends up being wasted due to the lack of proper energy storage or conversion systems. In this regard, thermal energy conversion and storage systems can offer reasonably realistic alternatives due to their multifaceted features. Thermal energy storage systems can store surplus energy in favorable conditions and provide clean and affordable energy in adverse situations in various forms such as heating, cooling, drinking water, or even power generation. Contrarily, thermal energy conversion systems can pave the way to further increase the share of renewables in the energy mix and play a significant role in the future decarbonized society.

Globally, there are a variety of thermal energy storage and conversion (TESC) technologies currently being extensively researched. Figure 1 illustrates some of the most prominent technologies associated with the vast research field of TESC. Although the TESC technologies hold enormous potential, their utilization is subjected to various challenges associated with them. Depending on the applications and working conditions, certain obstacles can come forward, and to overcome those, efforts from both science and engineering fields are required. This speciality grand challenge aims to address the major drawbacks and discuss future research directions for overcoming these challenges associated with current TESC technologies.

Prominent TECS technologies

Thermal energy storage systems have the potential to use waste heat from various sources such as solar collectors, geothermal, fossil fuel power plants, nuclear power plants, industrial waste heats, biomasses, and so on. Many materials have befitted thermo-physical properties such as high latent and specific heat, high thermal conductivity, and favorable melting points. Apart from these, the materials should be readily available at an affordable price and should possess some attributes such as thermochemical stability, low volume change, no toxicity, no or minimal flammability, etc. Thermal energy storage systems, when broadly classified, fall into three major categories: sensible, latent, and thermochemical energy storage, depending on the energy storage mechanism (Ren et al., 2020).

Sensible heat storage systems utilize functional materials' specific heat capacity to store the heat without causing any phase change in the material. Water, thermal oils, molten salts, and liquid metals are commonly used materials for such systems depending on the temperature of the heat source. The heat storage capacity of these systems proportionally depends on the volume, density, and heat capacity of the functional material.

Latent heat storage systems, on the other hand, store thermal energy at a constant temperature by utilizing the latent heat of the functional materials by triggering phase change. There can be solid-solid, solid-liquid, or liquid-gas phase changes. In the case of a solid-solid system, a solid material such as paraffin wax or salt hydrates is used to store heat. In liquid-solid systems, a liquid such as water is used to store heat, and the heat is transferred by a solid material such as a metal or ceramic. A liquid-gas system uses a liquid that can be vaporized at relatively low temperatures and pressures, such as propane, ammonia, or water. The heat energy is stored by vaporizing the liquid, and it is released by condensing the vapor back into a liquid. Unlike sensible heat storage systems, latent heat storage systems offer higher energy density and have the potential to be a viable option for large-scale energy storage.

Thermochemical thermal energy storage (TES) systems involve storing and releasing heat by means of chemical reactions, typically exothermic and endothermic reactions. Systems for thermochemical heat storage have the capacity to store a lot of energy in a relatively small space, which may be advantageous in some circumstances. These systems' capacity to store energy for long periods of time makes them valuable for tasks like load balancing and peak shaving. The systems may also be made to have as little impact on the environment as possible by employing non-toxic, non-corrosive, and non-flammable materials and not releasing greenhouse gases.

When it comes to thermal energy conversion systems, the first things that come into mind are thermoelectric generators, organic Rankine cycles, or steam-assisted power production units, which convert thermal energy into electrical energy. Although these systems are well-known and are already utilized in many applications, when the temperature of the heat source becomes less than 100°C, the efficiency usually drastically decreases. In those scenarios, low-grade heat collected from industry or even heat from solar thermals can be utilized in many applications, such as thermal management (Vodianitskaia et al., 2017), air conditioning (Rupam et al., 2022b), desalination (Saha et al., 2016), gas storage and purifications (Li et al., 2022), and so on. These low-grade thermal energy conversion technologies have the potential to recover a significant amount of useful energy that would otherwise be wasted and can be integrated with renewable energy sources such

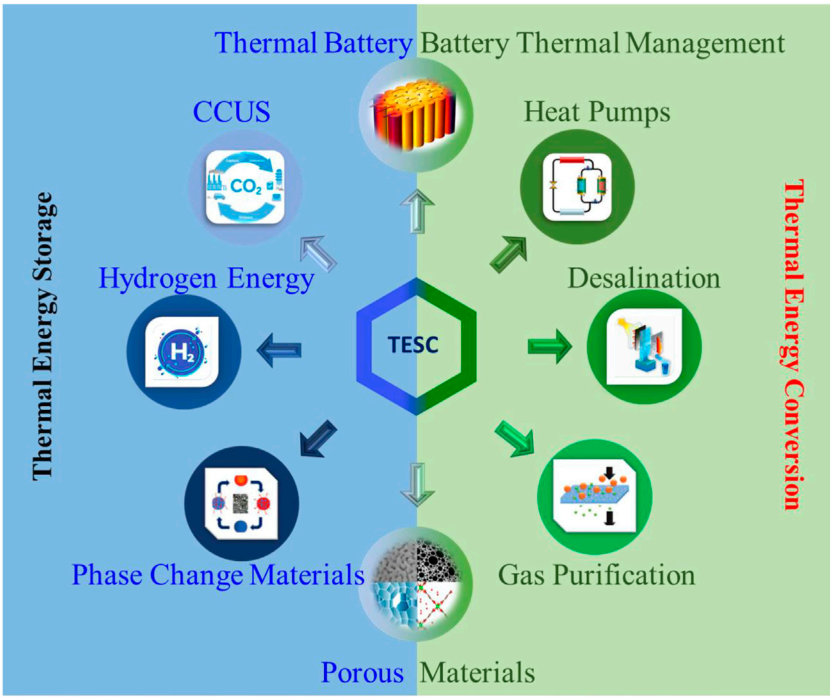

FIGURE 1
Promising research topics in thermal energy conversion and storage field.

as solar and geothermal to make a more reliable and consistent source of energy (Kumar and Shukla, 2015). However, these technologies are still in the development stage and require more research to improve their efficiency and reduce costs.

Major challenges

There are many promising aspects of the current TESC technologies; however, there are major challenges to overcome before their comprehensive utilization. Among the thermal energy storage systems, sensible heat storage systems suffer from low energy density, and during discharge, the output temperature decreases with time. Sensible heat storage systems can require a large volume and footprint, making them impractical for certain applications or locations. Additionally, storage materials may degrade over time, reducing their thermal storage capacity or rendering them unusable. On the other hand, latent heat storage has the potential for high energy density, but the technology is still in the development stage and requires more research to improve its efficiency and reduce costs. Some latent heat storage materials, such as molten salt, can be corrosive or toxic, which can pose safety risks. Additionally, latent heat storage systems can experience thermal losses due to conduction, convection, and radiation, which can reduce the overall efficiency of the system. Perhaps, the most promising thermal energy storage system currently in the developing stage is based on thermochemical reactions. However, it also comes with its own daunting challenges. Finding suitable materials that can withstand high temperatures, pressures, and thermal cycling can be a challenge. The system efficiency can be affected by various factors such as the heat of the reaction, the reaction kinetics, the heat transfer rate between the storage material and the heat exchanger, and so on.

There are certain challenges when it comes to thermal energy conversion systems (Chen et al., 2021). Low conversion efficiencies could make them less economical and ecologically beneficial. Scaling thermal energy conversion systems to satisfy the needs of large-scale energy generation can be challenging. These systems can be pricey, especially for cutting-edge or innovative technologies. Some systems, like coal-fired power stations, may significantly harm the environment by emitting greenhouse gases and causing air pollution. Systems for converting thermal energy frequently need routine maintenance and are prone to failure, which raises costs and lowers total system effectiveness. It can be challenging to guarantee a steady supply of thermal energy since some sources, like solar, are intermittent and difficult to anticipate due to their dependence on the weather and time of day. Addressing such challenges of thermal energy storage and conversion requires the development of advanced technologies and strategies for improving the efficiency of energy conversion processes and transitioning towards a sustainable future.

Future research direction

Future research in thermal energy storage and conversion is likely to focus on several key areas. Advanced functional materials are expected to make a significant improvement in the currently available technologies. Research on developing new materials that can store and release heat more efficiently and at higher temperatures, such as high-temperature phase change materials and thermochemical storage materials, would be required. On the other hand, extensive research will be carried out to develop new thermal energy storage technologies, such as latent heat storage systems, thermal batteries, and thermoelectric generators, to improve the efficiency and cost-effectiveness of thermal energy storage systems. Researchers are working to improve the efficiency and cost-effectiveness of thermal energy conversion systems, which simultaneously generate electricity and useful heat. Advanced heat exchangers having innovative designs that can transfer heat more efficiently between fluids at different temperatures will play a significant role in the rapid commercialization of the TECs technologies. Artificial intelligence and machine learning will be integrated to optimize the control and management of futuristic thermal energy storage and conversion systems, making them more efficient and cost-effective.

Conclusion

Thermal energy storage and conversion are essential for a sustainable energy system, as they provide opportunities for the efficient and cost-effective storage and use of heat energy. However, achieving their full potential requires a number of obstacles to be addressed. The effectiveness of thermal energy storage and conversion devices is a major hindrance. Many of the systems in use today have low conversion efficiencies, which can reduce their cost-effectiveness and environmental impact. Furthermore, it might be challenging to scale thermal energy storage and conversion systems to satisfy the needs of large-scale energy production. The price of designing and installing thermal energy storage and conversion systems is another hurdle. Many cutting-edge technologies are pricey, and maintaining and running these systems may be expensive as well. Some thermal energy conversion systems are concerned about their potential negative environmental effects. Extensive research is going on in the development of advanced materials, thermal energy storage technologies, concentrated solar power, and combined heat and power (CHP) systems. New heat exchanger designs, AI and machine learning algorithms, and hybrid systems that combine various thermal energy storage and conversion technologies are also being developed by researchers. These advancements can aid in enhancing the effectiveness and affordability of thermal energy storage and conversion systems and overcoming the obstacles preventing their mainstream adoption. A combined effort from academia and industry, along with worldwide policy adoption of sustainable energy usage, would lead these systems to thrive in the near future.

Author contributions

BS: Concept, Manuscript write-up and review, supervision. TR: Manuscript write-up. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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