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Specialty grand challenge in thermal science and energy systems

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Introduction

Energy is crucial to a country's economic progress and development. Domestic, industrial, and commercial sectors have seen tremendous growth in recent years, resulting in increased energy demand. Despite increased energy production, the growing demand for energy has outstripped supply. Energy scarcity and variable power availability stymie societal progress. The rise in energy demand and peak shortages has harmed a variety of industries. Because of increased energy demand, price volatility of fossil fuels, climate mitigation, and an impending energy crisis due to the depletion of fossil fuels, renewable energy has emerged as a key option. The unpredictability of the output of renewable energy conversion systems, on the other hand, necessitates the use of robust, reliable, and efficient technologies. Such systems can generate savings by reducing energy consumption and replacing fossil fuel expenses.

Renewable energy storage is important for achieving a zero-carbon future because it allows us to build a reserve of storage options that can be used anytime needed to fulfill user demand and control the energy supply during peak usage periods. By figuring out ways to store energy in this way, we can address some of the problems that arise frequently when employing renewable energy sources. Since the last 3 decades, there has been an augmented demand for space heating. Energy policies in many countries prioritize the development of renewable energy sources. Among various renewable energy techniques, thermal energy storage is an effective peak demand reduction technique. Thermal energy storage systems link the gap between the supply and demand for energy. Improvements in thermal energy storage decrease the need for infrastructure and lower the price of heating and cooling systems. Thermal energy storage makes it possible to store and use energy at a different period. The heat energy produced during the day can be used at night, and the cool nighttime breeze can be used to chill indoor rooms during the day. Thermal energy storage systems, such as heat pumps, solar energy, waste heat from power plants, and engine waste heat, offer resilience against varying energy sources. Thermal energy storage systems can aid in the daily, weekly, and even seasonal balance of energy demand and supply. Besides, thermal energy storage can improve overall energy system efficiency by lowering peak demand, reduction in energy consumption, abatement of CO_2 emissions, and reduction in costs. Thermal energy storage is gaining attention towards energy storage, particularly in conjunction with concentrating solar power plants. The global thermal energy storage industry was valued $20.8 billion in 2020 and is expected to be worth $51.3 billion by 2030, growing at an 8.5 percent compound annual growth rate from 2021 to 2030 (Saurabh Dixit, 2022).

In the United States, thermal energy usage accounts for roughly half of total building energy demand and are expected to increase in the coming years. Thermal energy storage is an important enabler of large-scale renewable energy deployment as well as the transition to a decarbonized building stock and energy system by 2050 in the United States (energy.gov).

The production of heat and cold from fossil fuels can be replaced with thermal energy storage, reducing CO_2 emissions and the requirement for expensive peak power and heat production capacity. By using heat and cold storage more extensively, it has been calculated that Europe could save about 1.4 million GWh annually and avoid 400 million tonnes of CO_2 emissions in the building and industrial sectors (IRENA, 2013). Energy storage technology does, however, confront some market entry challenges. Cost is typically a big concern. In Phase change material (PCM)-based storage systems, it is also necessary to improve the stability of storage performance, which is linked to material qualities. The size of the PCMs market was estimated to be approximately USD 1.9 billion in 2019 and it is expected to increase at a rate of more than 17.4% from 2020 to 2026 (GMI, 2020). The demand for PCM in the packaging sector will increase due to the expansion of the e-commerce sector and rising investments in cutting-edge packaging trends, notably for food materials.

In this specialty grand challenge we present the importance of thermal energy storage and major challenges faced in thermal energy storage systems. The role of waste heat recovery and the need to advance the waste heat recovery systems is presented.

Importance of thermal energy storage

Thermal energy is stored as heat and cold in the media called thermal energy storage materials. In thermal energy storage, two mechanics such as thermophysical or thermochemical mechanisms are involved (either or both are involved based on the type of storage). Thermophysical mechanism is based on the internal energy difference of energy storage materials at different states, whereas reversible chemical reactions drive the thermochemical mechanisms which depend on reaction enthalpy. Depending on the type of energy employed, thermal efficiency of energy storage systems can reach up to 90%. The usage of thermal energy storage has the potential to increase process energy efficiency, a function that is difficult for other energy storage technologies to fulfill. Another interesting role of thermal energy storage is its potential to significantly increase the efficiency and range of electrical vehicles, which currently have a range of less than 200 km. When air conditioning is used, the range is reduced by 30%–40%. Lastly, integration of thermal energy storage with power plants could greatly improve their ability to peak-shave and dramatically lower the price of carbon capture.

Challenges of thermal energy storage

Latent Heat Storage systems have recently demonstrated that they have intentional advantages. The use of PCMs in latent heat storage systems has proved to be an efficient means of utilizing the heat from solar energy and industrial waste, but also shows promising developments in the field of thermal regulation. PCMs are materials that fluctuate between the liquid and solid states while storing, releasing, and absorbing heat. They may store substantial amounts of thermal energy as latent heat during phase transition. The main advantages of these products are that they store/release energy. Despite the fact that many disadvantages remain, research is being conducted to overcome the barriers that are impeding the adoption of PCMs. A few benefits of PCMs are variable phase change temperature, high heat of fusion, chemical inertness, high storage capacity, no phase segregation, self-nucleating, and decreased vapor pressure during melting. Additionally, these materials have a variety of uses, including solar energy storage, smart fabrics, biomedical, and electrical cooling. PCM's main drawback is lower thermal conductivity, which increases thermal resistance during the phase shift process. The majority of PCMs have their own set of drawbacks, including low phase change enthalpies, weak specific heats, poor thermal conductivities, supercooling, volume changes, phase segregation, *etc.* Consequently, enhancing PCMs' thermophysical characteristics is necessary for effective thermal energy storage. The low thermal conductivity of the PCM would force the heating systems to operate longer in order to supply the heat energy, consuming more energy and raising the unit's electricity bill. Therefore, it is essential to increase the thermal conductivity of the PCMs in order to create energy-efficient thermal energy storage systems. Considering the technological challenges with thermal energy storage materials, the energy densities of materials need to be improved. Also, the durability and thermal property of the materials should be improved to extend to large scale applications. It is necessary to develop advanced manufacturing technologies to create thermal energy storage devices with controllable charging and discharging rates along with reduced interfacial thermal resistance. Thermal energy storage devices must be integrated into energy networks to further improve system dependability, system level performance, and the capacity to satisfy system dynamics.

The economic performance of a thermal energy storage system is heavily influenced by a number of factors, including the number/frequency of storage cycles. In general, PCM and thermochemical storage systems are more expensive than sensible heat systems. The low construction rate of new buildings in mature economies is a major constraint for

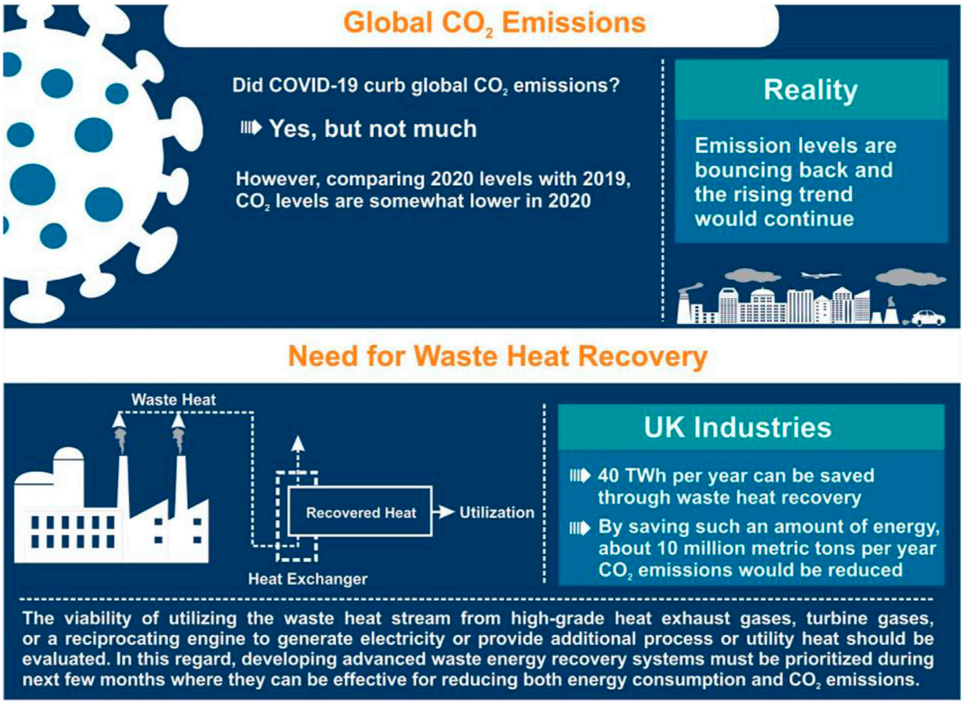

FIGURE 1
A challenging waste energy recovery for CO_2 emission reduction for post-COVID-19 era.

thermal energy storage deployment, whereas thermal energy storage systems have a greater deployment potential in emerging economies.

Cost is a major barrier to market penetration of thermal energy storage technology. Other obstacles have to do with the stability and material qualities, particularly with regard to thermochemical storage. For each storage application's unique boundary conditions and requirements, a unique thermal energy storage design is needed.

The role of waste heat recovery systems

The process of recovering heat energy from exhaust and using it in other operations is known as waste heat recovery. It is estimated that up to 50% of the energy used in industry is eventually dissipated as waste heat. The global Oil and Gas Waste Heat Recovery market is expected to grow at a compound annual growth rate of 5.2% between 2021 and 2027, from US$ 8972.9 million in 2020 to US$ 13,190 million by 2027 (QYResearch, 2021).

There is a significant quantity of heat that is lost to the environment in the majority of fossil fuel-based energy systems. Alternatively, this energy might be captured and used to turn on heating systems. Since one of the main elements affecting how much of an influence emissions have on the environment is their temperature, this will indeed reduce emissions and the consequences they have on the environment. Various industrial processes use different energy and generate waste heat. Therefore, it is crucial to analyze the industrial processes to fully realize the potential of industrial waste heat. It is also important to look into what suitable waste heat recovery methods can be applied to the systems of each sector. Besides, examining the source and the value of the waste heat produced will help to choose which waste heat recovery method is best for industrial operations.

It is recommended to move towards advanced waste energy recovery systems in this post-COVID-19 era. Figure 1 depicts the pressing need of advanced waste energy recovery for CO_2 emission reduction for post-COVID-19 era. Enhancing the performance of thermal systems can significantly reduce global emissions (Henry et al., 2020). For instance, it is predicted that waste heat recovery in UK companies can save roughly 40 TW h of energy yearly (Jouhara et al., 2018). Additionally, by saving this much energy, CO_2 emissions would be lowered by nearly 10 million metric tonnes annually (https://bulb.co.uk/carbon-tracker/). Therefore, it is essential to give top priority to creating advanced waste energy recovery systems, which will aid in lowering energy use and CO_2 emissions.

Concluding remarks

Thermal energy storage is critical to reducing our reliance on fossil fuels. Thermal energy storage is important at both the utility and building ends of the energy supply chain. At present, wide scale thermal energy storage implementation is hampered by the high initial capital costs. Continued research is required to reduce costs by utilizing alternative low-cost energy storage materials. Furthermore, future energy storage systems should offer higher energy storage. To promote adoption of thermal energy storage, funding for research and development of new storage materials is crucial, as are legislative changes and investment incentives for thermal energy storage integration in buildings, commercial and industrial applications, and variable renewable energy generation. The various thermal storage technologies (sensible, latent, and thermochemical) are at various stages of development. For large scale energy storage, a sensible heat storage method is preferred to a latent heat method. However, the use of latent heat energy storage in building cooling systems is gaining popularity in recent days. With reference to PCM and thermochemical storage systems, research and development are extremely crucial. For industrial processes with fluctuating heat demands, the uses of high temperature PCMs are now being explored. It is crucial for various stakeholders to create an effective strategy and workable methods for thermal energy storage *via* conventional and renewable energy sources in order to improve the role and market share of this technology. Determining the possible effects of thermal energy storage on the existing and future mix of sustainable energy sources is extremely important. Furthermore, it is essential to investigate the main forces behind the regulations and policies at different levels that will enable the implementation of thermal energy storage while boosting process and industrial applications.

Effective distributed heat storage may play an important role in reducing the number of generators with low capacity factor and utilization, as well as the need for electrical network strengthening. Besides, the use of thermal energy storage systems may have an economic impact due to the requirements for initial installation and ongoing maintenance. These will necessitate the development of new skills, including specialist knowledge, particularly in the effective and efficient maintenance of the system.

The section on *thermal science and energy systems* concentrates on innovative concepts, measurement methods, and results in the fields of heat and mass transfer and/or fluid flow, as well as technologies in the field of thermal engineering, such as, but not limited to, new energy materials, waste to energy, thermal energy storage technologies, energy measurement and management technologies, sustainability of energy systems, *etc.* This section primarily supports low-carbon environmental protection, climate change mitigation, and sustainable development goals, as well as multidisciplinary research. It pays special attention to the newest technical discoveries and material innovation in the field of energy science. As we lead the development of this new and fascinating section in Frontiers in Thermal Engineering we now invite you to contribute publications that address the challenges mentioned in this article and in the journal's scope. We encourage authors to submit research that is accessible and applicable to a cross-disciplinary and multidisciplinary audience energy.gov, 2021.

Author contributions

AA—Orginal draft preparation and OM—Review, editing and supervision.

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.

Publisher's note

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