Remittances Review
June 2024,
Volume: 9, No: 3, pp.377- 400
ISSN : 2059-6588(Print) | ISSN 2059-6596(Online)

Received : 20 May 2024, Accepted: 15 June 2024
DOI: https://doi.org/10.33282/rr.vx9i2.21

SUSTAINABLE APPROACHES TO THERMAL ENERGY MANAGEMENT

Ibrahim Akhtar[1], Fatima Gulzar[2*], Syeda Azka Sajid[3], Asia Parveen[4], Ayesha Saleem[5], Aisha Ghaffar[6], Zahid Muhammad[7], Muhammad Jamil Khan[8]

[1]A Level Student Researcher, Beaconhouse Margalla Campus, Islamabad Pakistan

[2*]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan

[3]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan

[4]Department of Chemistry, Government College University Faisalabad, Punjab Pakistan

[5]College of Earth and Environmental Sciences, University of the Punjab Lahore Pakistan

[6]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan

[7]Department of Physics, Hazara University, Mansehra Pakistan

[8]Department of Chemistry, Abbottabad University of Science and Technology, Abbottabad, Pakistan

*Corresponding Author: Fatima Gulzar

Abstract

This review paper highlights the significance of sustainable thermal energy in addressing contemporary energy challenges. Exploring energy management concepts, diverse thermal energy sources, and advanced heat generation technologies provides valuable insights into sustainable thermal energy. The incorporation of thermal energy storage and energy-efficient construction is shown to be pivotal in achieving supply-and-demand equilibrium and reducing overall energy consumption. The paper also delves into the support for sustainable practices and the establishment of policy and regulatory frameworks, emphasizing their impact on energy sustainability. Additionally, it sheds light on the anticipated challenges and future resources associated with the widespread adoption of sustainable thermal energy. In conclusion, the paper underscores the critical need for effective thermal management to ensure energy sustainability, thereby contributing to both social and economic welfare. It equips researchers, administrators, and business experts with essential knowledge to navigate the complexities of sustainable thermal energy integration.

1. Introduction

In an era characterized by increasing environmental concerns and an ongoing need to conserve resources, thermal energy management has emerged as a crucial frontier for fostering innovation and establishing transformation [1]. Developing sustainable strategies for thermal energy management is essential to our mutual commitment to decreasing carbon footprints, addressing climate change, and facilitating the transition towards a more environmentally friendly future. Sustainable thermal energy management is the effective and sustainable regulation, production, transmission, and consumption of thermal energy, to mitigate adverse environmental effects and create long-term sustainability [2]. Sustainable thermal energy management refers to the effective and environmentally friendly utilization of heat energy resources. It refers to the energy that is linked to the temperature of a given system. It is often regarded as a form of energy that possesses a lower level of quality and is typically considered as a by-product or waste within the framework of industrial operations. It plays a vital role in a wide range of industrial, residential, and commercial contexts, including applications such as heating, cooling, and process heat [3].

However, there are several challenges associated with thermal energy management including heat loss, temperature variability, thermal resistance, heat generation, dissipation, and most importantly environmental impact [4]. Heat dissipation can happen due to inadequate insulation or the presence of conductive materials that facilitate the escape of heat from a system. This phenomenon can lead to fluctuations in temperature and a decrease in overall efficiency. It can also result in increased energy consumption, which in turn increases the production of greenhouse gasses and contributes to the intensification of global warming [5]. Although, previous years have observed significant advancements in the field of thermal management (TM) due to its considerable significance in various contexts, including energy-efficient cooling and heating, individualized TM, heat depletion in electronic devices, recovery of waste heat, utilization of solar energy, thermotherapy, fire and flame retardancy in batteries, and thermal camouflage, among others [6, 7].

The primary objective of this approach is to enhance the efficiency of processes, systems, and technologies to mitigate energy wastage and reduce overall carbon emissions. In conclusion, it is essential to prioritize sustainable strategies for managing thermal energy in the modern world, considering the increasing energy requirements and pressing environmental issues [8]. Through the use of cutting-edge technologies and the adoption of environmentally friendly strategies, it is possible to effectively reduce our carbon emissions and simultaneously improve energy efficiency. This approach will help to protect and preserve our natural surroundings, ensuring their continued existence for the benefit of future generations., This chapter explores various strategies and technologies available for improving thermal energy management, thereby making a significant contribution towards a more environmentally friendly and sustainable future.

2 Fundamentals of Energy Management:

2.1 Thermal Energy Management Concept:

Thermal energy stands out as a critical source for electricity generation, industrial heating, and daily use. Despite the escalating global demand for energy due to economic expansion and sustainable development, excessive fossil fuel burning leads to pollution and harmful greenhouse gas emissions. Various energy types and conversion methods contribute to addressing these challenges [9]. The medium, which can be solid, liquid, or gaseous, contains thermal energy, or heat, which can be further transmitted to another medium through the process of heat conduction [10]. The energy that an object or system possesses as a result of its temperature is known as thermal energy. Thermal energy moves from a body with a higher temperature to a body with a lower temperature when its temperatures differ. This movement of thermal energy is referred to as heat in thermodynamics [11].There are three main processes. When two things are in close proximity to one another, **conduction** or **diffusion** occurs, causing thermal energy to transfer from the object with the higher temperature to the one with the lower temperature. **Convection** is the process by which heat is transferred from an item to a fluid that flows around the object and either absorbs (if the object has a higher temperature) or increases its heat. Similar to nuclear or radiant energy, **radiation** is the transmission of energy by electromagnetic waves [12].

An **energy management strategy** involves planning, controlling, and monitoring processes to achieve long-term goals, aiming to conserve energy, protect the climate, and reduce costs. These strategies encompass exploitation, supply, consumption, and investment in energy resources, addressing technical, economic, geopolitical, and political aspects. **Sustainability**, defined as meeting present needs without compromising the future, considers ecological health, economic well-being, social empowerment, and cultural creativity. The overexploitation of fossil fuels, with their limited replenishment rate, poses challenges to sustainability. Energy management models have been developed at the macro and micro levels. Governments and international organizations are designing macro-level energy management models to address global concerns. For example, ISO 50001 is an energy management system standard that aims to help organizations across all sectors use energy more efficiently (ISO Standard 2015) [13]. Figure 1 shows the main elements of an energy management system based on ISO 50001.

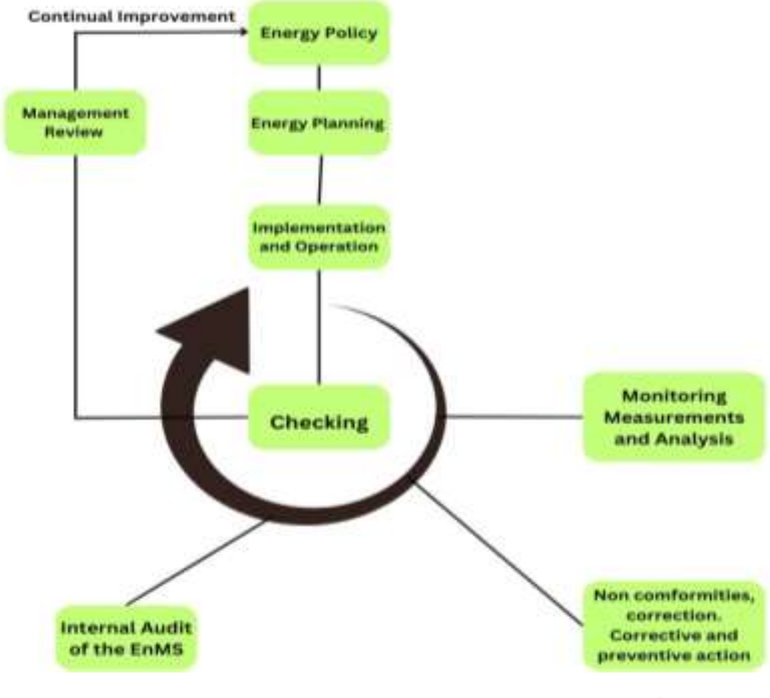

Fig.1 Sustainable Energy Management: ISO 50001 main Elements of Energy Management System [14].

2.2 Principle of Energy Efficiency and Energy Conservation:

Energy analysis predicts a 48% increase in consumption by 2040, with global final energy usage doubling in the past five decades, as per the International Energy Agency. In 2020, a 4.64% decrease occurred due to reduced commercial activities during the Covid-19 crisis. Finite fossil fuel reserves, their emissions, and rising costs underscore the need to transition to renewable sources for a sustainable future. Solar power, ocean waves, wind, and biogas are crucial in restoring environmental balance and meeting the growing energy needs of the population. Today, Thermal Energy Storage (TES) systems are widely adopted and applied integration of renewable energy systems [15].

2.3 Benefits of Sustainable Energy Management:

Energy management practices in smart environments offer cost reduction and enhanced efficiency, benefiting both consumers and utility providers. Controlled energy consumption routines lower energy costs and contribute to environmental sustainability by reducing the carbon footprint. This environmentally responsible approach helps organizations build an eco-friendly image, opening doors to profitable business opportunities. Integrating energy management systems into smart environments also mitigates the risk of catastrophic blackouts and price fluctuations [16].

3. Importance of Transitioning to Renewable and Low-Impact Energy Sources

3.1 Reduce greenhouse gas emissions: Fossil fuels such as coal, oil, and natural gas are the main sources of greenhouse gas emissions, especially carbon dioxide (CO_2). By switching to renewable energy sources such as solar, wind, and hydropower, we can considerably lessen these emissions and reduce the impact of climate change [17].

3.2 Improves air quality: Burning fossil fuels not only releases CO_2 but also harmful pollutants like sulfur dioxide, nitrogen oxides, and particulate matter. These pollutants can cause air pollution, smog formation, and a variety of respiratory and cardiovascular health problems. Switching to cleaner energy sources can improve air quality and human health [18].

3.3 Conserve natural resources: Fossil fuels are finite resources and their exploitation can cause negative impacts on the environment, including habitat destruction and water pollution. Shifting to renewable energy sources reduces the necessity for resource-intensive mining procedures and aids in the preservation of natural habitats and water resources.

3.4 Improved energy efficiency: Renewable energy technologies are more energy efficient than traditional fossil fuel-based electricity generation. As an illustration, solar panels and wind turbines generate electricity with minimal energy input after production and installation.

3.5 Promote sustainable practices: The energy transition encompasses not only a shift in energy sources but also the adoption of more sustainable energy practices. This includes improved energy storage, grid management, and energy efficiency measures, all of which help reduce environmental damage [19].

4. Sustainable Technologies for Heat Generation (Renewable Thermal Technologies)

4.1 Solar Thermal Technologies

Active solar heating systems exploit solar energy to heat a fluid, which can be either a liquid or air, and subsequently convey this solar-derived heat directly to either fulfill an immediate need or store it for later use. Liquid-based systems are predominantly employed when storage is a requirement and excel in applications such as radiant heating systems, boilers equipped with hot water radiators, and even absorption heat pumps and coolers. Both liquid and air-based systems possess the capability to complement forced air heating systems [20]. The essential attributes of solar thermal technologies encompass:

Solar thermal technologies typically cannot fully meet the entire thermal requirements of a building and necessitate supplementary systems to furnish additional heating or cooling. Integrating a solar thermal system with another heat source introduces a heightened level of intricacy. Low and high-concentrating solar thermal systems rely on direct solar radiation for their operation, whereas non-concentrating solar thermal systems can make use of indirect solar radiation and function even under cloudy conditions.

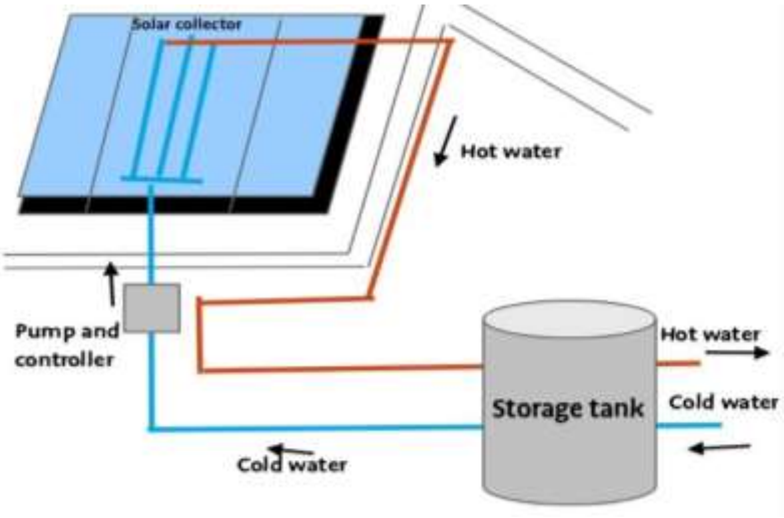

Fig.5 Basic components of solar water heating [21].

Solar thermal technologies can be integrated with others. Solar thermal technologies can be readily scaled to small and large systems, ranging from residential buildings to large industrial and district heating applications. Different solar thermal technologies can be used for different temperatures [22].

Advantages of solar thermal technologies in terms of sustainability

Solar energy offers a clean and reliable infrastructure, playing a vital role in achieving long-term climate benefits, clean air, and energy access goals. Integration of solar energy helps decrease peak demand, ensuring system stability, resulting in lower costs and reduced CO_2 emissions, emphasizing environmental advantages. This contributes to the development of clean energy, reinforcing solar energy’s significance for a sustainable future. It stands out as a sustainable and eco-friendly energy source, characterized by low maintenance, durability, and no removable parts [19].

4.2 Biomass Thermal Technologies

Biomass is characterized as any organic material derived from plants or animals, available on a renewable basis. Biomass inherently holds stored energy within it. Plants, through the mechanism of photosynthesis, harness solar energy and transform it into chemical energy. When these plants or other organic materials undergo combustion, this stored energy is subsequently liberated in the form of heat [23]. This versatile biomass feedstock can be harnessed in various forms, including solids, gases, or liquids, serving as a valuable source for generating electricity, transportation fuels, and heat across different temperature ranges. Bioenergy technologies encompass both combustion and pre-treatment methods:

Combustion Technologies: These involve fluidized bed combustion or grate furnaces, designed for a two-phase combustion process.

Pre-treatment Technologies for Feedstock and Fuel Production:

i. **Enhancing Solid Biomass Feedstock**: This includes processes like drying, palletization, briquetting, and Torre faction to improve solid biomass quality.
ii. **Refining Liquid Biomass Feedstock**: Methods such as pyrolysis and hydrothermal treatment are employed to refine liquid biomass materials.
iii. **Processing Gaseous Biomass Feedstock**: Anaerobic digestion, pyrolysis, hydrothermal upgrading, and thermochemical conversion are utilized to process gaseous biomass materials effectively.

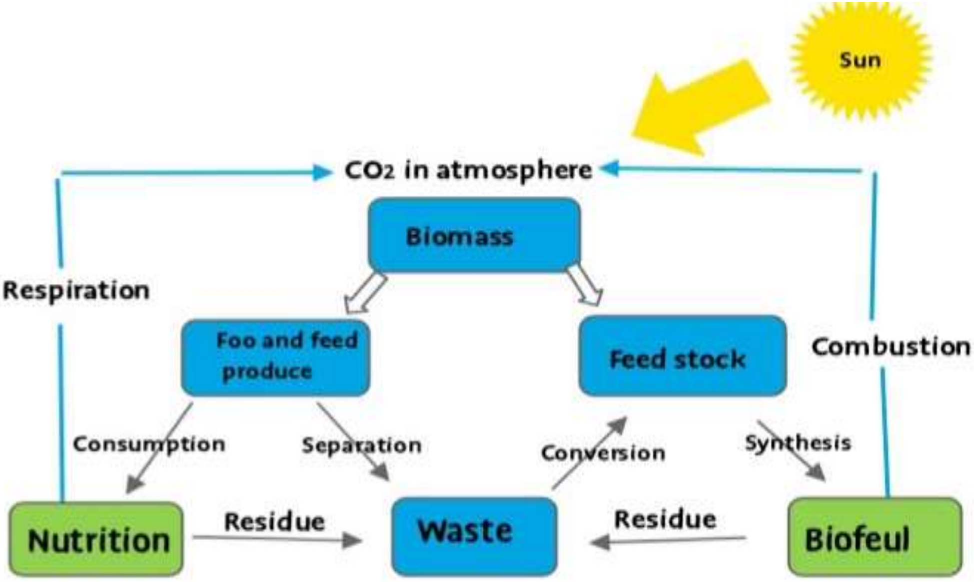

Fig.7 Basic features of biomass energy [24].

The overall efficiency of biomass combined heat and power plants are between 75 and 90 percent, whereas that of biomass heating plants is between 80 and 90 percent, according to Basis Bio energy. The size of the installation, the year of installation, and the energy content of the biomass feedstock all affect efficiency. A wood chip system with a capacity greater than 20 MW is typically five percentage points more efficient than one with a capacity between 1 and 5 MW. To ensure that the total impact of bio energy is preferable to that of fossil fuels, several various environmental, social, and economic challenges must be addressed. Contrary to CO_2 emissions factors for fossil fuels, variables for biomass combustion are not explicitly included in the Intergovernmental Panel on Climate Change (IPCC) energy sector accounting framework [25]. Since the carbon stored in biomass fuel was recently removed from the atmosphere, it is assumed that any carbon released when the fuel is burned will be balanced by carbon absorbed during the growth of new biomass.

Advantages of biomass energy in terms of sustainability

Among renewable energy alternatives, bioelectricity production holds the most significant potential for generating employment opportunities. Enhanced economic development and the alleviation of poverty, particularly in rural regions, can be achieved through the increased utilization of biomass for energy, facilitated by sustainable resource management practices. Diminished indoor air pollution stemming from wood energy combustion in impoverished households, attributed to the favorable attributes of cooking apparatus, resulting in positive effects. Mitigated CO_2 emissions through the adoption of cleaner fuels, such as ethanol and biodiesel [26].

5. Heat Recovery and Cogeneration

5.1 Heat Recovery Systems:

With the growing trend of increases in fuel prices over the past decades as well the rising concern regarding global warming, engineering industries are challenged with the task of reducing greenhouse gas emissions and improving the efficiency of their sites. In this regard, the use of waste heat recovery systems in industrial processes has been key as one of the major areas of research to reduce fuel consumption, lower harmful emissions and improve production efficiency. Industrial waste heat is the energy that is generated in industrial processes that is not put to any practical use and is wasted or dumped into the environment [27]. Waste Heat Recovery (WHR) systems are introduced for each range of waste heat to allow the most optimum efficiency of waste heat recovery to be obtained. High temperature WHR consists of recovering waste heat at temperatures greater than 400 °C, the medium temperature range is 100–400 °C and the low temperature range is for temperatures less than 100 °C.

5.1.1 Heat Recovery Ventilation System:

The heat recovery ventilation (HRV) principle is to recover heat from the exhaust air and to transfer it to the supply air through a heat exchanger. With the growing share of ventilation heating loads, heat recovery over mechanical ventilation systems appears as one of the key solutions to reduce heat losses and generate consequent energy savings. The benefit of HRV systems must always be balanced against the electrical power requirements consumption needed to power the fans [28]. HRV units, equipped with air-to-air heat exchangers, continuously supply clean, fresh, and filtered outdoor air to indoor living spaces while expelling stale air from high-moisture areas like kitchens, laundries, and bathrooms. Up to 95% of the heat from exhaust air can be recovered and transferred to the incoming air, depending on the HRV model and brand. Smart sensors monitor relative humidity and adjust indoor air quality automatically, minimizing heat loss. Depending on factors such as window quality, architectural air permeability, and climate zone, HRVs can save up to 30% in heating energy [29]. HRVs, also known as heat recovery air exchangers, feature two fans in constant operation. One expels indoor stale air laden with odors, smoke, and pollutants, while the other introduces fresh, filtered outdoor air. Crucially, these two air streams never mix, ensuring that air is not recirculated. Instead, the technology captures and recycles heat during winter or provides cooling during summer, transferring it between the expelled stale air and the incoming filtered air. There are two main types of HRVs: **Centralized** HRVs require ducting for air distribution and ventilate the entire house. **Decentralized** HRVs are designed for installation directly in walls or windows, catering to a single room or space [30].

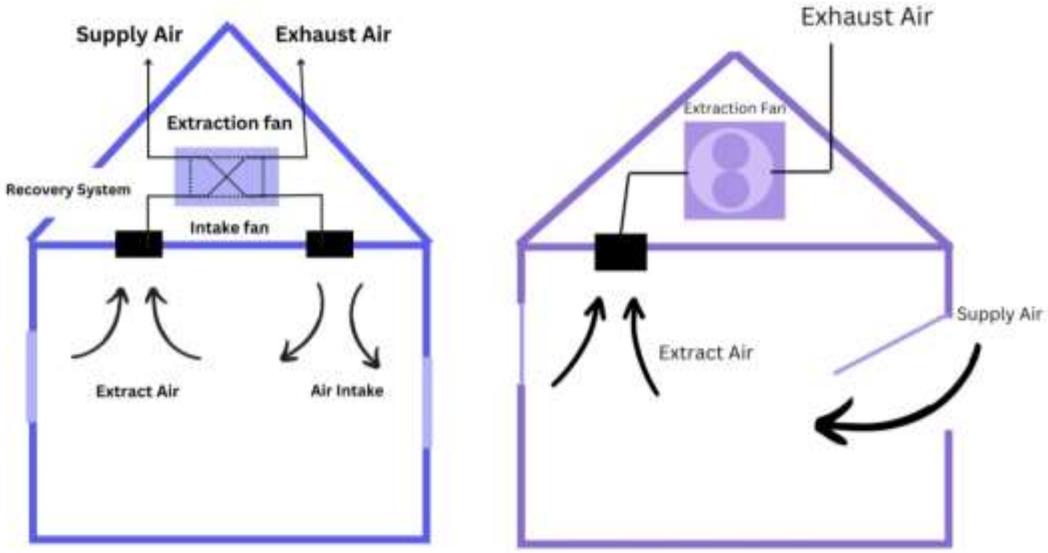

Fig.10 Ventilation of Buildings with heat recovery system [31].

5.1.2 Combined Heat and Power (Cogeneration):

Cogeneration, also known as combined heat and power (CHP), involves the simultaneous generation of electrical or mechanical energy and valuable thermal energy from a single energy source. This source can range from oil, coal, natural or liquefied gas, biomass, to solar energy. The shift from steam-driven systems to electric power marked the adoption of cogeneration. In the early 20th century, electricity generation heavily relied on coal-fired boilers and steam turbine generators, utilizing exhaust steam for industrial heating. By the early 1900s, approximately 58% of on-site industrial power plants in the United States were estimated to be co-generating power [32]. Combined heat and power (CHP) systems have been utilized across a range of heat and power applications for an extended period. The micro combined heat and power (mCHP) system represents a cutting-edge, compact iteration of CHP technology and is poised to play a pivotal role in reducing CO_2 emissions and enhancing primary energy conservation in the imminent future [33]. Cogeneration systems exhibit significantly higher energy conversion efficiency compared to conventional fossil fuel-fired electricity generation systems. While conventional methods typically achieve around 58% efficiency, cogeneration systems elevate this to over 85% [34].

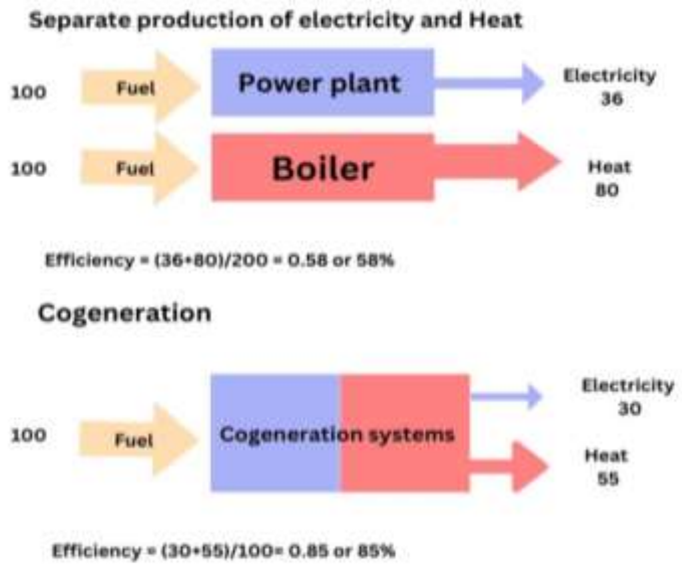

Fig.11 Efficiency of Cogeneration [35].

5.2 Advantages of Recycling Waste Heat:

Installing the best available ventilation system in your new or existing home ensures a constant supply of fresh, healthy, and filtered air without the need for trickle vents or bathroom extractor fans. This advanced system not only eliminates issues like mould, mildew, and condensation but also recovers up to 95% of heat from wet rooms, contributing to energy efficiency. Notably, it has been clinically proven to assist allergy and asthma sufferers, and it offers full control via manual or remote controls. By reducing heating costs by up to 25%, this system enhances both your comfort and the overall well-being of your home [36].

6. Energy-Efficient Building Design

Energy-efficient and resource-conscious designs are oriented toward the diminishment of resource depletion, pollution reduction, and the establishment of a secure and productive environment for both residents and occupants. Green structures, characterized by their minimal environmental footprint and utilization of natural resources, not only promote community and environmental well-being but also demonstrate social responsibility, garnering widespread acceptance.

6.1 Passive Heating Techniques

Passive heating encompasses the natural process of warming initiated by the absorption of solar radiation, leveraging solar energy to facilitate the transfer of heat from the exposed Surface to the indoor atmosphere, while concurrently encouraging Heat retention within the building's structure. Passive heating encompasses the natural process of warming initiated by the absorption of solar radiation, leveraging solar energy to facilitate the transfer of heat from the exposed Surface to the indoor atmosphere.

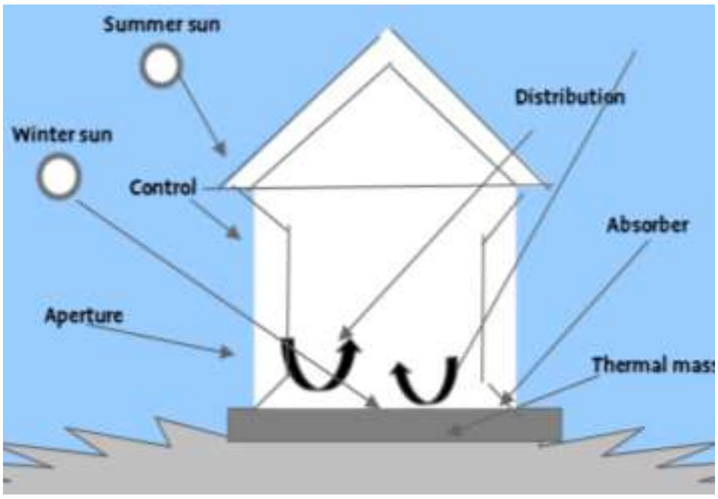

Fig.12 Passive heating design [37].

6.1.1 Basic Passive Solar Design

1. Aperture: The expansive glass region through which light enters the structure is known as an aperture or collector. During the heating season, the aperture(s) should face within 30 degrees of true south and not be blocked by any other structures or trees from 9 a.m. to 3 p.m.

2. Absorber: The storage element's hard, drab surface. The area is directly in the path of the sun and maybe a stone wall, a floor, or a water container. Heat is created when sunlight hits a surface.

3. Thermal mass: Materials with a high thermal mass can hold or store solar heat. The thermal mass is the substance beneath and behind the absorber, which is an exposed surface.

4. Distribution: The process by which solar heat is distributed throughout the house from the places of collection and storage. Conduction, convection, and radiation are the only three natural heat transport modes that are used in a strictly passive design.

5. Control: During the summer, roof overhangs can be used to shade the aperture area. Electronic sensing systems, such as a differential thermostat that instructs a fan to switch on, movable vents and dampers that permit or restrict heat flow, low-emissivity shutters, and awnings are further components that control under and/or overheating [38-40].

6.2 Passive Cooling Techniques

Passive cooling is valuable in hot and humid or hot and dry climates, using natural heat sinks to remove excess heat without electricity. These systems harness evaporation, convection, and radiation, capitalizing on diurnal temperature and humidity changes. Their effectiveness depends on local climate conditions and optimizing heat exchange with the surrounding air, requiring a significant temperature difference of at least 7°C for noticeable heat transfer.

6.2.1 Passive Cooling Design Principles

Building envelopes are created to decrease daytime heat gain, maximize nighttime heat loss, and promote access to cool breezes when they are present to achieve thermal comfort in cooling applications. Among the factors to be taken into account are:

- Developing the floor plan and building shape to respond to the site and local climate.
- placing windows and openings to enhance air movement and cross ventilation,
- shading windows, solar exposed walls and roofs where possible,
- installing and correctly positioning appropriate combinations of both reflective and bulk insulation, and

They may be simulated in any design for 69 distinct Australian climate zones [41].

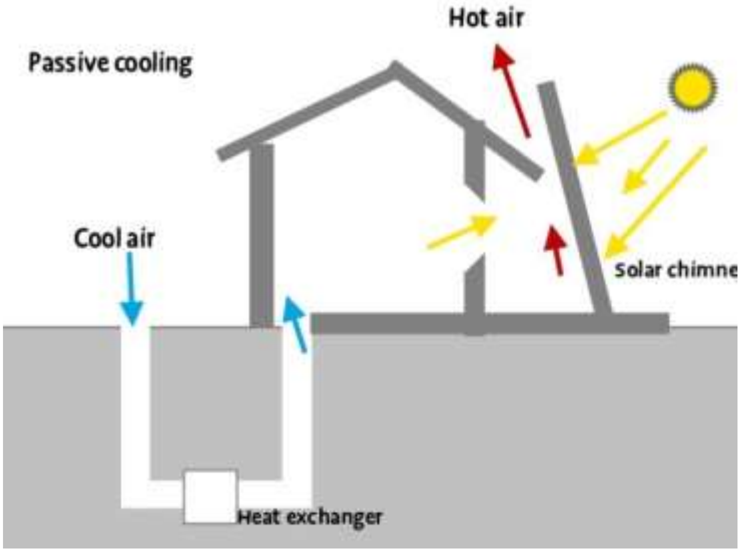

Fig.13 Passive cooling design [42].

6.2.2 Technique

1. Solar shading

Due to their low cost and simplicity of implementation, solar shading is among the numerous sun passive cooling strategies that is relevant to the thermal cooling of buildings, especially in poor nations. House roofs made of RCC. Nevertheless, the availability of electricity in the communities, particularly during the summer is brief. The inside temperature is frequently very high under these RCC roofs, reaching 41°C: This is brought on by hot, dry locations with rooftop temperatures of about 65 °C. Solar awnings with regional Terracotta tiles, hay, inverted earthen pots, date palm branches, and other readily available materials can lessen a considerable temperature difference. The ambient temperature near the outer wall is lowered by 2 to 2.5°C when a tree provides shade. When solar shading techniques are used, the room temperature is often lowered by six degrees centigrade [43].

2. Insulation

Insulation has the effect of lowering heat gain and heat loss. The less heat is transmitted into or out of a structure as a result of temperature differences between the interior and exterior, the more insulation there is in the outer envelope of the building. By shielding the interior surfaces from the effects of the outside environment, insulation also regulates the internal mean radiant temperature (MRT) and lessens draughts Created by a differential in air and wall temperatures. When a building needs mechanical heating or cooling, insulation is very important since it lowers the space-conditioning loads. The best Insulation location and thickness are crucial. Utilizing 40 mm thick Vermiculite concrete insulation on the roof and expanded polystyrene insulation on the walls have brought The RETREAT building in Gurgaon’s space-conditioning loads by around 15%. Air pockets reduce the amount of solar heat gain inside walls or attic space in the roof-ceiling combination [44].

7. Thermal Energy Storage

7.1 Role of Thermal Energy in Sustainable Energy Management:

There is a notable demand for a substantial amount of thermal energy, yet available thermal energy is abundant. However, disparities exist between the demand for thermal energy and its supply which can be enumerated as follows:

1. **Time Discrepancy**: There is a temporal mismatch between the generation of thermal energy and its consumption.

2. **Cost Differential**: There is a variance in the cost of thermal energy between peak and off-peak hours of the day.

3. **Geographical Separation**: The distance between the source of thermal energy and the location where it is needed can be significant.

It is important to note that excess thermal energy, if not utilized, is dissipated into the environment, resulting in wastage. To bridge the demand-supply gaps, fuels are often burned to generate thermal energy as required. However, this practice carries certain implications:

I. **Environmental Degradation:** The burning of fuels leads to increased environmental pollution. This contributes to the release of harmful gases like CO_2 into the atmosphere, which causes the greenhouse effect. Additionally, it results in the release of unused heat into the environment, both of which are contributing factors to global warming [45].
II. **Economic Implications:** The increased cost incurred due to the heightened consumption of fossil fuels is noteworthy. This situation not only leads to financial burdens but also represents a missed occasion to utilize openly accessible thermal energy obtained from renewable sources, such as solar radiation.

The fundamental objective of TES systems is to prevent the loss of thermal energy by storing surplus heat until it is required. Across various human activities, heat is consistently generated. There is a promising scope for cost-effectively implementing TES systems for substantial heat sources like solar thermal energy, geothermal energy, fossil fuel power plants, nuclear power plants, and industrial waste heat [46].

7.2 Thermal Energy Storage Systems:

A diverse array of materials is utilized in thermal energy storage (TES), requiring specific thermo-physical properties for suitability in intended thermal applications. These properties include an ideal melting point, high latent heat capacity, high specific heat capacity, and excellent thermal conductivity. Thermal energy storage (TES) systems can be broadly categorized into three classes based on the chosen type of TES material for heat or cold storage.

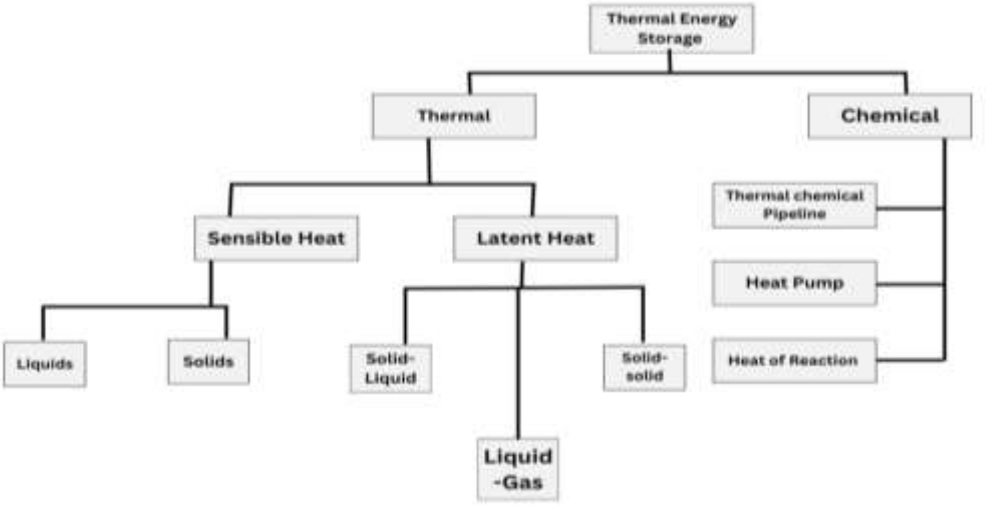

Fig.14 Types of Thermal Energy Storage Systems [47].

7.2.1 SENSIBLE HEAT STORAGE:

Sensible heat thermal energy storage materials store heat energy through their specific heat capacity (Cp). The thermal energy stored through sensible heat can be mathematically expressed as follows:

$$Q = m * Cp * \Delta T \qquad (1)$$

In this equation, 'Q' represents the stored heat energy, 'm' is the mass of the material in kilograms, 'Cp' stands for the specific heat capacity in **kJ/kg· K**, and **ΔT** represents the temperature increase during the charging process. In the process of absorbing heat energy, there is no change in phase, and the materials undergo a temperature rise. The quantity of heat stored is directly proportional to the density, volume, specific heat capacity, and the change in temperature of the storage material [48].

- **Materials for Sensible Heat Storage:**

1. Water: Water is a highly versatile substance with several advantages for thermal energy storage (TES) applications. It can serve as both a heat transfer fluid (HTF) and a TES material in active systems. Water's key benefits include its high specific heat capacity (4.184 kJ/kg·K), non-toxic nature, affordability, and widespread availability. Water can be utilized in different phases, including ice, liquid, and steam. Ice is employed for cold storage purposes, while the liquid phase is suitable for low-temperature heat energy storage below 100°C. Its non-toxic and non-flammable properties make it safe for various applications, including home space heating, cold storage of food products, and hot water supply. However, water does have drawbacks, including high vapor pressure and corrosiveness [49].

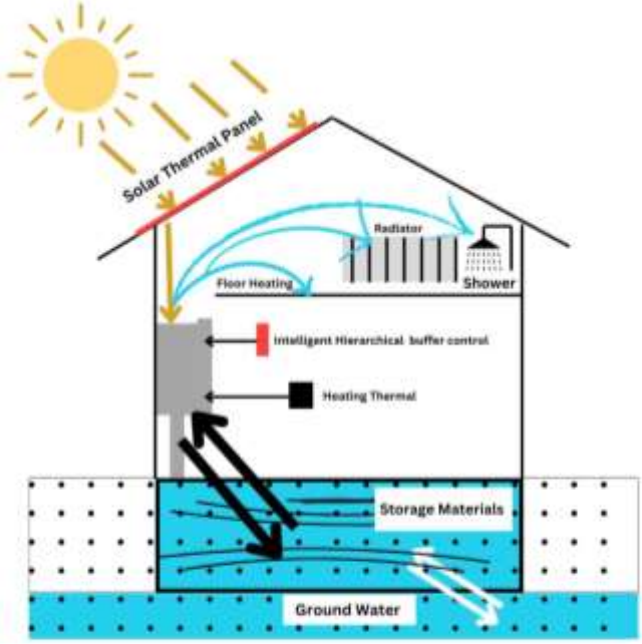

Fig.15 Sensible Heat Storage System [50].

2. Thermal Oils: Thermal oils are organic fluids recognized for their efficient heat transfer properties. Additionally, non-edible vegetable oils have been explored as potential thermal oil alternatives. Thermal oils typically appear as colorless and clear liquids. One significant advantage they offer over water is their ability to stay in a liquid state at elevated temperatures, even up to 250°C at air pressure. This broader temperature range, spanning from -12°C to 400°C, results in a higher Delta T (as mentioned in Equation (1)) and greater heat storage capacity. Furthermore, when compared to water, thermal oils exhibit lower vapor pressure [49].

3. Molten Salts: When a system's temperature surpasses the thermal oil's limit of 400°C, molten salts becomes the preferred choice for both heat transfer and storage in various concentrated solar power (CSP) plants, such as solar power towers (SPT) and parabolic dish collector (PDC) setups. Molten salts are already widely used as a thermal energy storage (TES) medium in CSP plants due to their favorable thermophysical properties [49, 51].

8. Emerging Sustainable Thermal Technologies

There are two types of energy technologies: mainstream and emerging. These can be used for renewable energy. Hydropower, wind, solar, biomass, biofuels, and geothermal energy are examples of mainstream renewable energy sources. On the other hand, emerging renewable energy sources encompass marine energy, concentrated solar photovoltaics, enhanced geothermal energy, cellulosic ethanol, and artificial photosynthesis. In addition to the mainstream energy technologies, some novel and sustainable energy technologies have surfaced in the past ten years, drawing interest from the scientific community [52]. These renewable technologies have not yet gained widespread acceptance or reached a high enough degree of commercialization. While many are still in the future, some offer greater promise than others in terms of renewable energy.

Conclusion

In summary, this review paper highlights the crucial role that sustainable thermal energy plays in addressing today's energy challenges. By delving into energy management concepts, various thermal energy sources, and cutting-edge heat generation technologies, valuable insights into sustainable thermal energy have been gained. The findings emphasize the importance of integrating thermal energy storage and energy-efficient construction to balance supply and demand while significantly cutting overall energy consumption. Additionally, the paper stresses the need for strong policy and regulatory frameworks to support sustainable practices, which are essential for promoting energy sustainability. Acknowledging the anticipated challenges and future resources needed for the widespread adoption of sustainable thermal energy provides a comprehensive outlook on what lies ahead. Ultimately, this paper underscores the critical need for effective thermal management to ensure energy sustainability, which is vital for both social and economic well-being. By equipping researchers, administrators, and business experts with key knowledge, it aims to help navigate the complexities of integrating sustainable thermal energy and contribute to a more sustainable future.

Reference

1. Koçak, B., A.I. Fernandez, and H. Paksoy, *Review on sensible thermal energy storage for industrial solar applications and sustainability aspects.* Solar Energy, 2020. **209**: p. 135-169.

2. Khare, V., P. Chaturvedi, and M. Mishra, *Solar energy system concept change from trending technology: A comprehensive review.* e-Prime-Advances in Electrical Engineering, Electronics and Energy, 2023. **4**: p. 100183.

3. Akram, M.W. and M. Hasanuzzaman, *Fundamentals of thermal energy and solar system integration*, in *Technologies for Solar Thermal Energy*. 2022, Elsevier. p. 1-24.

4. Rashidi, S., et al., *Progress and challenges on the thermal management of electrochemical energy conversion and storage technologies: Fuel cells, electrolysers, and supercapacitors.* Progress in Energy and Combustion Science, 2022. **88**: p. 100966.

5. Fraleoni-Morgera, A. and M. Chhikara, *Polymer-based nano-composites for thermal insulation.* Advanced engineering materials, 2019. **21**(7): p. 1801162.

6. Khudhair, A.M. and M. Farid, *A review on energy conservation in building applications with thermal storage by latent heat using phase change materials.* Thermal energy storage with phase change materials, 2021: p. 162-175.

7. Saleh, H.M. and A.I. Hassan, *Synthesis and characterization of nanomaterials for application in cost-effective electrochemical devices.* Sustainability, 2023. **15**(14): p. 10891.

8. Hasanbeigi, A., L. Price, and E. Lin, *Emerging energy-efficiency and CO2 emission-reduction technologies for cement and concrete production: A technical review.* Renewable and Sustainable Energy Reviews, 2012. **16**(8): p. 6220-6238.

9. Arshad, K., et al., *Air pollution and climate change as grand challenges to sustainability.* Science of The Total Environment, 2024: p. 172370.

10. Xu, H.J., et al., *Review on heat conduction, heat convection, thermal radiation and phase change heat transfer of nanofluids in porous media: Fundamentals and applications.* Chemical Engineering Science, 2019. **195**: p. 462-483.

11. Schneider, E.D. and D. Sagan, *Into the cool: Energy flow, thermodynamics, and life*. 2005: University of Chicago Press.

12. Balaji, C., *Essentials of radiation heat transfer*. 2014: Springer.

13. Jovanović, B. and J. Filipović, *ISO 50001 standard-based energy management maturity model–proposal and validation in industry.* Journal of cleaner production, 2016. **112**: p. 2744-2755.

14. Valencia, G., et al., *Implementation of the ISO 50001 standard to sustainable energy and economic saving the industrial sector.* Scientia et Technica, 2020. **25**(2 (2020)): p. 261-268.

15. Erdemir, D. and I. Dincer, *Potential use of thermal energy storage for shifting cooling and heating load to off-peak load: A case study for residential building in Canada.* Energy Storage, 2020. **2**(2): p. e125.

16. Rosman, M.A., N.A.I. Janipha, and N.A.M. Sabli. *The Benefits of Energy Management System (EMS) in Building Sustainability Components*. in *IOP Conference Series: Earth and Environmental Science*. 2022. IOP Publishing.

17. Perkins, D.M., et al., *Global change and food webs in running waters.* Hydrobiologia, 2010. **657**: p. 181-198.

18. Sharma, S.B., et al., *The effects of air pollution on the environment and human health.* Indian Journal of Research in Pharmacy and Biotechnology, 2013. **1**(3): p. 391-396.

19. Cantarero, M.M.V., *Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries.* Energy Research & Social Science, 2020. **70**: p. 101716.

20. Thirugnanasambandam, M., S. Iniyan, and R. Goic, *A review of solar thermal technologies.* Renewable and sustainable energy reviews, 2010. **14**(1): p. 312-322.

21. Jamar, A., et al., *A review of water heating system for solar energy applications.* International Communications in Heat and Mass Transfer, 2016. **76**: p. 178-187.

22. Kamel, R.S., A.S. Fung, and P.R. Dash, *Solar systems and their integration with heat pumps: A review.* Energy and buildings, 2015. **87**: p. 395-412.

23. Sánchez, J., et al., *Biomass resources*, in *The role of bioenergy in the bioeconomy*. 2019, Elsevier. p. 25-111.

24. Usman, I.M.T., et al., *A comprehensive review on the advances of bioproducts from biomass towards meeting net zero carbon emissions (NZCE).* Bioresource Technology, 2022. **366**: p. 128167.

25. Quadrelli, R. and S. Peterson, *The energy–climate challenge: Recent trends in CO2 emissions from fuel combustion.* Energy policy, 2007. **35**(11): p. 5938-5952.

26. Ladanai, S. and J. Vinterbäck, *Global potential of sustainable biomass for energy.* Rapport (Institutionen för energi och teknik, SLU), 2009(013).

27. Cuce, P.M. and S. Riffat, *A comprehensive review of heat recovery systems for building applications.* Renewable and Sustainable Energy Reviews, 2015. **47**: p. 665-682.

28. El Fouih, Y., et al., *Adequacy of air-to-air heat recovery ventilation system applied in low energy buildings.* Energy and Buildings, 2012. **54**: p. 29-39.

29. Pekdogan, T., et al., *Experimental investigation of a decentralized heat recovery ventilation system.* Journal of Building Engineering, 2021. **35**: p. 102009.

30. O'Connor, D., J.K.S. Calautit, and B.R. Hughes, *A review of heat recovery technology for passive ventilation applications.* Renewable and Sustainable Energy Reviews, 2016. **54**: p. 1481-1493.

31. Picallo-Perez, A., et al., *Ventilation of buildings with heat recovery systems: Thorough energy and exergy analysis for indoor thermal wellness.* Journal of Building Engineering, 2021. **39**: p. 102255.

32. Thorin, E., J. Sandberg, and J. Yan, *Combined heat and power.* 2015.

33. Maghanki, M.M., et al., *Micro combined heat and power (MCHP) technologies and applications.* Renewable and Sustainable Energy Reviews, 2013. **28**: p. 510-524.

34. Isa, N.M., C.W. Tan, and A. Yatim, *A comprehensive review of cogeneration system in a microgrid: A perspective from architecture and operating system.* Renewable and Sustainable Energy Reviews, 2018. **81**: p. 2236-2263.

35. NAVA, A., *Energy audit of a steel mill and feasibility analysis of a cogeneration system.* 2018.

36. Hooshmand Zaferani, S., et al., *Thermal management systems and waste heat recycling by thermoelectric generators—an overview.* Energies, 2021. **14**(18): p. 5646.

37. Sharma, D. and G. Purohit, *Improving the liveability of cities: The role of solar energy in urban and peri-urban areas.* The security of water, food, energy and liveability of cities: Challenges and opportunities for peri-urban futures, 2014: p. 151-162.

38. Nikolic, D., et al., *Basic principles of passive solar heating.* 2018.

39. Oliveira, A. and E. de Oliveira Fernandes, *A new simplified method for evaluating the thermal behaviour of direct gain passive solar buildings.* Solar energy, 1992. **48**(4): p. 227-233.

40. Bakos, G., *Electrical energy saving in a passive-solar-heated residence using a direct gain attached sunspace.* Energy and buildings, 2003. **35**(2): p. 147-151.

41. Xiong, J., et al., *A hierarchical climatic zoning method for energy efficient building design applied in the region with diverse climate characteristics.* Energy and Buildings, 2019. **186**: p. 355-367.

42. Altamirano, A., B. Stutz, and N. Le Pierrès. *Selection of High-Performance Working Fluid for a Solar-Geothermal Absorption Cooling System and Techno-Economic Study in the Northern Mexican Conditions*. in *12th International Conference on Solar Energy for Buildings and Industry, September*. 2018.

43. Ullah, Q., et al., *EXPLORING THE INFLUENCE OF NANOPARTICLES AND PGPRS ON THE PHYSICO-CHEMICAL CHARACTERISTICS OF WHEAT PLANTS: A REVIEW.* EPH-International Journal of Agriculture and Environmental Research, 2024. **10**(1): p. 1-9.

44. Waseem, M., et al., *PHYTO-REMEDIES FOR SOIL RESTORATION: A DEEP DIVE INTO BRASSICA'S PLANT CAPABILITIES IN CADMIUM REMOVAL.* EPH-International Journal of Biological & Pharmaceutical Science, 2023. **9**(1): p. 23-44.

45. Appannagari, R.R., *Environmental pollution causes and consequences: a study.* North Asian International Research Journal of Social Science & Humanities, 2017. **3**(8): p. 151-161.

46. Dincer, I. and M.A. Rosen, *Energetic, environmental and economic aspects of thermal energy storage systems for cooling capacity.* Applied Thermal Engineering, 2001. **21**(11): p. 1105-1117.

47. Romdhane, S.B., et al., *A review on thermal energy storage using phase change materials in passive building applications.* Journal of Building Engineering, 2020. **32**: p. 101563.

48. Seyitini, L., B. Belgasim, and C.C. Enweremadu, *Solid state sensible heat storage technology for industrial applications–a review.* Journal of Energy Storage, 2023. **62**: p. 106919.

49. Olivkar, P.R., et al., *Effect of sensible heat storage materials on the thermal performance of solar air heaters: State-of-the-art review.* Renewable and Sustainable Energy Reviews, 2022. **157**: p. 112085.

50. Hailemariam, H. and F. Wuttke, *Temperature dependency of the thermal conductivity of porous heat storage media.* Heat and Mass Transfer, 2018. **54**: p. 1031-1051.

51. Bespalko, S., *Overview of the existing heat storage technologies: sensible heat.* Acta Innovations, 2018(28): p. 82-113.

52. Hussain, A., S.M. Arif, and M. Aslam, *Emerging renewable and sustainable energy technologies: State of the art.* Renewable and sustainable energy reviews, 2017. **71**: p. 12-28.