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Comprehensive Review of Sensible Thermal Storage Systems for Cooking Applications

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ABSTRACT

This paper reviewed the sensible thermal storage systems specifically designed for cooking applications. The review focuses on the characteristics of storage materials, their practical applications, and the overall performance of the systems. The review consolidated an array of experimental and numerical research published across various sources such as journals, conferences, books, online resources, and professional reports. A systematic review is used to reach the conclusion of this paper. Significant findings from this study include the wide range of storage capacities attained from small-scale systems that can store ~1–5 MJ of energy for a single meal to bigger systems that can store ~10–50 MJ. Some systems are made for low-temperature cooking ≤ 100 ℃, while others may achieve temperatures of over 300°C for uses like baking or frying. Additionally, the overall efficiency of the systems ranges from 50% to 90% due to charging and discharging losses; this condition emphasizes the importance of optimal designs to reduce heat loss. Materials such as rocks, concrete, and specialized phase change materials exhibit varying thermal conductivities from 0.1 to ~5 W/mK and specific heat capacities from 700 to over 2000 J/kgK, which directly affect the performance of the systems. Furthermore, the research also identified gaps in knowledge concerning the durability of storage mediums and the feasibility of integrating cookers with storage systems. The development and implementation of sensible heat storage systems for cooking applications are in early stages of innovation but have the potential to save energy, especially from intermittent sources.

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INTRODUCTION

The energy demand is expected to increase day to day due to the projected increase in primary energy demand and depletion of fossil fuels. In order to address the growing energy demand, the utilization of sustainable energy sources like solar, wind, and biogas should be given attention. However, it is necessary to emphasize the necessity of effectively storing these energy sources for future usage (Theu & Kimambo, 2023; Bishoge *et al.*, 2018). Solar energy has recently become the most popular renewable energy source for cooking, yet several drawbacks documented concern solar technology. The main issue includes intermittency habit due to a lack of sunlight at night and when there are cloudy skies and rain during the day, but also, many solar systems support only outdoor cooking. Cooking indoors is made feasible by using Thermal Energy Storage (TES) method, which enables cooking activities all the time and avoids the limitation of temperatures when required to cook at all necessary hours of the day (James, 2021; Biadgelegn & Hassen, 2019; Asmelash et al. 2014; Kassem & Youssef, 2011) .

Lentswe et al. (2021) and Saxena & Karakilcik (2017) categorized the temperature extracted from solar energy as low and high. Temperatures greater than 100 °C are considered high, while temperatures less than 100 °C are termed low temperatures. TES enhances appliance efficiency, provides energy security, and enables the extraction of energy from renewable sources such as solar, wind, biomass and grid electricity for heating, cooking or any other application that requires heat. It is a technique of storing thermal energy for later use, and once the objectives of the systems are determined, the design and construction of the selected system may commence (Avghad et al., 2016). TES systems offer efficient use of thermal equipment and economically viable energy substitutes. They rectify energy imbalances by charging the system from an intermittent source or other sources that can enable charging through specified thermal storage materials (Martin, 2014; Stevens et al., 2013).

The scope of this study served as a roadmap for guiding the evaluation process of one type of TES; Sensible Thermal Storage (STS) systems for cooking applications. Its objectives were to analyse the design and optimization of STS systems, to evaluate the performance of different STS materials, to examine the effects of operational factors, to examine how STS integrates with various cooker technologies, user acceptance and socioeconomic characteristics. Additionally, the study determines future directions and research gaps, paying particular attention to uses in cooking through the discussion of both numerical and experimental research.

Methods for Thermal Energy Storage

According to (Diaz, 2016; Socaciu, 2015), TES can be stored by three main methods: sensible, latent, and thermochemical as illustrated in Figure 1. As the systems receive energy and store it for later use, they consist of three main phases: charging, storing, and discharging. Design considerations for TES systems include thermal capacity, technical requirements, environmental factors and cost-benefit analyses. (Dincer & Rosen, 2011; Pachori et al., 2022) emphasizes the importance of storage materials with qualities like complete reversibility, low thermal losses, easy control, good thermal conductivity, mechanical and chemical stability, and chemical compatibility. Cost-related design criteria for storage include the cost of the storage material, heat exchanger cost, container or tank cost, space cost, and other associated costs. TES employs a variety of technologies to store excess thermal energy for hours, days, or months. The scale of the storage varies from small to large, encompassing individual processes, districts, towns, or regions for both storage and consumption. The general overview of TES shows that energy demand and supply in the system can be managed (Cirocco et al., 2022).

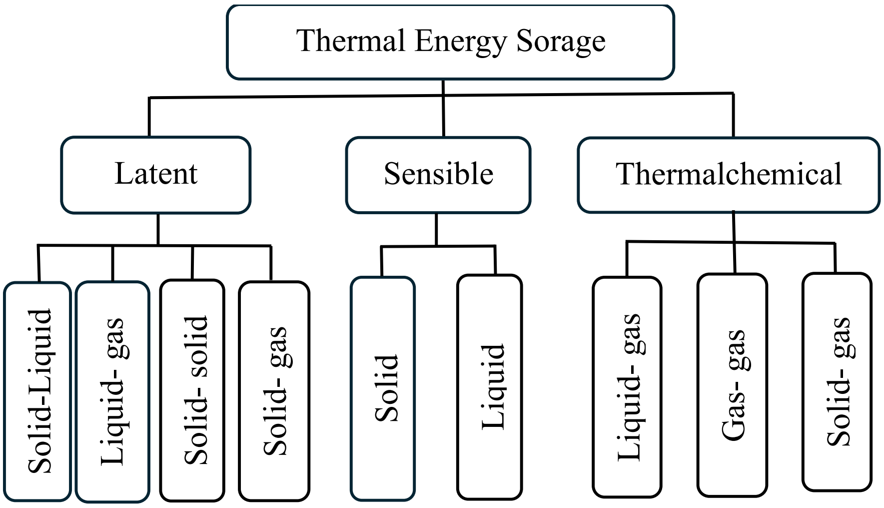

Figure 1: Classification of thermal energy storage methods (Socaciu, 2015).

Working Principles of Sensible Thermal Storage

This type of the storage relies on the heat capacity of a storage substance to hold thermal energy. It stores energy by altering the temperature of the storage medium. The commonly used storage mediums include liquids and solids. Liquid medium storage encompasses molten salts, thermal oils, and water, while solid mediums consist of rocks, concrete blocks, sand-like particles, and pebbles. However, the solid and liquid storage medium can be mixed to enhance the cooking performance (Li, 2016; Suresh & Saini, 2020). The storage captures and stores thermal energy by changing the temperature of the storage materials without experiencing their phase changes. Menghare & Jibhakate (2013 describes the thermal energy stored or released as being directly proportional to the density (ρ) of the storage material, its volume (V), specific heat (cp), and the temperature variation, as shown in Equation 1.

$$Q_s = m_m c_m \Delta T \quad = \rho v c_m \left(T_i - T_f\right) \qquad (1)$$

where Q_s is the sensible thermal retained in J, m_m is the mass of the storage medium, c_m is the specific heat capacity of the storage medium, ΔT is the temperature gradient in K, ρ is the density of the storage medium, v is the volume of the storage medium, Ti is the initial temperature, and T_f is final temperature of the storage medium during the storage process. Fundamentally, the primary thermal characteristics of sensible heat storage materials are specific heat capacity, density and thermal conductivity of the specific material.

Classification of Sensible Thermal Storage Materials

(Boulevard & Miranda, 2018) provided an overview of the STS system classification based on the states of storage materials used. The two primary states are solid and liquid storage materials, and the thermophysical properties for some of them have been summarized by Bauer *et al.* (2012) through Table 1.

Table 1: **Thermophysical Properties of Commonly Used Mediums for Sensible Thermal Storage** (Bauer et al., 2012)

No	SHS Material	Heat capacity (J · kg -1 · K⁻ 1)	Density (kg · m - 3)	Thermal conductivity (W · m -1 · K -1)	Energy density (kJ m -3)
1	Water	4200	998.3	0.609	4175
2	Molten salt (Nitrate based)	1542.3	2240	0.5	1.28 × 10 6
3	Engine oil	1880	888	0.152	36 × 10 6
4	Iron	465	7850	59.3	3650
5	Alluminium	945	2700	238.4	2551.5
6	Copper	419	8300	372	3477.7
7	Sand	710	1631	1.8	1562
8	Concrete	879	2400	1.28	1933.8
9	Graphite	609	2260	155	13,339.8
10	Granite	892	2750	2.9	2453
11	Limestone	741	2500	2.2	1852.5
12	Brick	840	1800	0.5	1512
13	Lead	131	11,340	35.25	1485.5
14	Sodium Chloride	860	2165	6.5	-

Solid Storage Materials

This category of material has been used in numerous STS systems because of its dependability, affordability, simplicity of use, and suitability in a wide range of real-world scenarios (Lugolole et al., 2019; Shaikh et al., 2022). Thermal storage in solid state have been investigated in various research and describes that thermal storage can be conducted in concrete, rocks pebbles and other solid depends on the availability due to location. The stated materials can be utilized for low and high temperature applications which does not require a phase change. Furthermore, thermal storage in liquid form can be accompanied by several challenges such as leakages and high vapour pressure however thermal storage in solid state does not contain such challenges (John et al., 2013; Soprani et al., 2019). Solid heat storage requires other medium in fluid form for heat exchange in order to be useful. To enhance the heat transfer efficiency in the system, it is recommended that solid materials should be in contact with the used fluid. The storage with solid materials stated by various researches that are suitable for low temperature applications like space heating and industrial waste heat recovery (Johar et al., 2022). Storage materials are many but this study described the following types:

Rocks

In order to enhance the heat transfer in rocks Hänchen et al.(2011) recommends that rocks be packed loosely in the thermal storage bed to facilitate the flow of heat transfer fluids (HTF). Thermal storage in rocks is made possible through the circulation of captured and stored heat, which is circulated using HTF. Since rocks exist in various sizes, it is recommended to use rock sizes ranging from 1 to 5 cm, which is advantageous due to the increased contact area between the HTF and thermal storage rocks.

The availability of rocks and non-flammable nature, makes this thermal storage possible and reliable for low temperature applications (Prasad et al. 2019;Soprani et al., 2019; Cirocco et al., 2022).

Concrete

According to Martins et al. (2015), concrete has high mechanical strength, does not require a container and is easy to use as a solid material for STS. An HTF can be circulated through pipes placed inside a concrete block to facilitate heat exchange between the HTF and the concrete. In high-temperature applications, its tendency to fracture under repeated cycles of thermal expansion and contraction may be a drawback; nevertheless, efforts are underway to determine the best mixing technique to improve chemical-physical characteristics and durability at elevated temperatures. A volume of 20 m^3 of concrete can store 400 kWh of energy.

Sand

Schlipf et al. (2015) demonstrated that materials with fine grains like gravel and silica sand are good for storing thermal energy. Typically, air would be used as an HTF in beds of sand grains with a diameter of 0.2 – 0.5 mm. It has been displayed that these beds have up to 550 °C of storage potential. The packing density increases with sand fineness, and larger grains of about 0.4 mm in diameter are found in gravel. It is possible to utilize the grain particles of basalt gravel directly to harvest solar thermal energy from the receiver. Sand falls from a reception tower, absorbing heat from concentrated solar radiation.

Liquid Storage Materials

The primary reason that liquid storage media is seen as a potential is its ability to circulate heat more readily than solid media. In addition to its buoyancy-producing properties, the density difference between warm and cool liquids also generates a temperature gradient throughout the storage system; separation results from hot fluid rising and cold fluid falling (Bauer et al., 2012). Three selected storage materials can be described as follows:

Water

Because of its high specific heat capacity, non-toxicity, affordability and ease of availability, water is often used as a fluid storage material for STS, as explained by Furbo (2015). However, because of its high vapour pressure, it needs expensive insulation with abilities to withstand high pressure for areas requiring temperature applications from 100 °C to 700 °C. Water is frequently employed in space pre-heating and for heat storage below 100 °C (Simonetti & Gentile, 2019). The buoyancy force causes the water to stratify because of the density difference brought on by heating the liquid, creating a temperature gradient throughout the storage. Water can enhance the system to release energy efficiently in high-temperature technologies like Concentrated Solar Power (CSP) plants and refrigeration systems. However, water is a liquid material which is mostly available and cheap but has disadvantages like high vapour pressure and corrosive to containers over boiling point (Bott et al., 2019).

Thermal Oils

Thermal oils function as HTF in numerous power and energy systems and are often an organic fluid. They have substantially higher liquid phase temperatures than liquid water when used as a thermal storage medium, with stable thermal characteristics reaching temperatures of 400 °C (Prasad et al., 2019). The larger temperature operating range indicates that thermal oils have a greater capacity to store thermal energy. Additionally, compared to water, the oils have a lower vapour pressure, which is advantageous for the mechanical design of associated pipelines and containers.

Unlike molten salts, thermal oils do not necessitate an antifreeze system, as they do not freeze in pipes overnight. However, the shortcoming of thermal oils is their greater cost compared to molten salts and water (Ali et al., 2021).

Molten Salts

Molten salt is one of the most often used storage materials in CSP reactors. Compared to other liquid thermal storage mediums, they are reasonably priced, have low viscosities, good thermal stabilities, high energy storage densities, and are non-flammable (Zhao & Wu, 2011). High-temperature CSP plants can benefit greatly from the use of molten salts in their liquid state, which can operate at temperatures as high as several hundred degrees Celsius with a vapour pressure far lower than that of water. Pure molten salt typically melts at temperatures higher than 200°C, making it difficult to use at lower temperatures (Gunasekara et al., 2021). It is better to utilize molten salt that has a lower melting point in order to preserve its liquid condition while storing thermal energy. Low heat conductivity, volumetric changes throughout the melting stage, and corrosiveness to the storage container are some of the constraints of molten salt that limit its use. The lowest melting temperature of a mixture of salt is recommended to those which melts at 80, 78 and 76 °C. These salts has a potential to prevent solidification at low temperatures to enable a broader range of TES applications (Turchi et al., 2015).

Energy and Temperature Required for Cooking

Thermal energy is required for cooking various types of food, but at specified temperatures. Kajumba *et al.* (2022) determined the energy requirements for local food items through laboratory tests and surveys. Results showed that high moisture content food items require more energy to boil than to simmer, while dry food items require more energy after boiling. According to the findings, a household of five people can have enough cooking energy each day for 14 litres of hot oil at a temperature of roughly 200 °C when using an oil-based thermal energy storage system that supplies hot oil to a dedicated burner. It also reported that, approximately 2.6 kilograms of firewood are used to cook 1 Kg of dry beans and 1 Kg of maize flour. Depending on the particular technique and the intended result, different cooking methods have been tested through this study with variable energy and temperature needs, and Table 2 shows the findings.

Performance Parameters of Sensible Thermal Storage

González-Roubaud et al. (2017) state that, the performance of a sensible thermal storage system can be evaluated by considering some of parameters. The main parameters include storage capacity, power, efficiency, cost, charging and discharging time.

Suresh & Saini, (2020) carried out the investigation to evaluate the effectiveness of latent and sensible thermal energy storage devices for solar thermal applications. Air was employed as the heat transmission fluid in concrete spheres and metal capsules encased in paraffin. The findings indicates that, sensible storage outperforms latent storage in terms of charging time and energy storage capacity. While sensible storage could be a suitable choice for improved charging and medium storage capacities, the study suggests latent storage for larger energy storage capacity.

Table 2: Cooking and Food Requirements with Relation to Cooking Techniques

Cooking Category	Cooking Method	Temperature Required	Energy Required and Transfer Mode	Recommended Food
Moist Heat Cooking	Boiling	100°C	Moderate, primarily used to heat water	Pasta, vegetables, eggs, and some meats
	Simmering	85-95°C	Moderate, lower than boiling	Soups, stews, and slow-cooked meats

Cooking Category	Cooking Method	Temperature Required	Energy Required and Transfer Mode	Recommended Food
	Poaching	65-85°C	Low, gentle heat	Delicate foods like fish, eggs, and fruits
	Steaming	100°C	Moderate, similar to boiling	Vegetables, dumplings, and seafood
Dry Heat Cooking	Baking	150-250°C	High, used to heat the oven	Breads, pastries, cakes, and roasted meats
	Roasting	150-250°C	High, similar to baking	Meats, vegetables, and nuts
	Grilling	200-300°C	High, direct heat source	Meats, fish, and vegetables
	Broiling	200-300°C	High, direct heat source from above	Meats, fish, and vegetables
Other Cooking Methods	Sautéing	175-200°C	Moderate, quick cooking method	Vegetables, meats, and seafood
	Frying	175-200°C	High, uses oil to transfer heat	Potatoes, chicken, and other breaded foods
	Braising	130-150°C	Moderate, slow cooking method	Tough cuts of meat

Technologies of Sensible Thermal Storage System

The technologies of STS system can be classified into mainly four categories and according to Koçak et al. (2020), these are as follows:

i. Underground thermal energy storage (aquifer thermal energy storage, Borehole thermal energy storage, Tank thermal energy storage, Pit thermal energy storage).
ii. Thermal energy storage in tanks (Vertical-thermocline and Horizontal).
iii. Thermal energy storage in packed beds (Stationary beds and Fluidised beds).
iv. Thermal energy storage in building structures.

Evaluation of Benefits and Drawbacks of STS for Use in Cooking Applications

Sensible thermal storage is an economical and straightforward method of thermal energy storage, which uses rocks, water or ceramics and can be used in sustainable cooking. It also improves energy security by reducing the reliance on fossil fuels when combined with other sources such as solar thermal collectors and biomass cookstoves. Nevertheless, STS has some drawbacks including lower energy density, heat escaping to the surroundings that lead to insulation requirements. The selection of appropriate storage materials is crucial as they must exhibit high specific heat capacity, thermal stability and food safety. Additionally, efficient heat transfer from storage to cooking appliances is essential for optimal performance. Addressing these limitations, material innovation, system design optimization and rigorous testing is crucial for widespread adoption of STS (Nydal, 2023; Okello et al., 2022).

STS systems have a number of significant benefits which attract the users to adopt for specific applications like cooking. STS systems are simple to install and maintainable because of their comparatively basic design and operation. The system construction and material costs are lower than those of other thermal storage technologies like latent. STS systems can function well for extended periods with minimal maintenance and have proven track records of reliability. The systems are appropriate for a variety of applications because they can be made to function over a wide range of temperatures.

The technology allows the characteristic that small home systems, big industrial systems, and utility-scale applications can all be easily scaled to suit varying energy storage requirements (Koçak et al., 2020; Sarbu & Sebarchievici, 2018).

Sensible heat storage technologies have certain drawbacks in addition to their benefits, and some are described by Cabeza et al. (2015). When considering alternative thermal storage methods, like latent heat storage or thermochemical storage, STS systems often have lower energy densities. Even with insulation, there always be some thermal energy loss, especially over extended storage times. This can lower the overall efficiency of the system. A significant amount of area is needed for storage tanks or containers in STS systems, particularly those that use water or solid materials. The specific heat capacity and temperature range of the storage media may be factors limiting the efficiency of STS systems. The installation and maintenance of sizable STS systems may have an effect on the environment in terms of resource and land use.

Adoption of Cooking Systems Integrated with Thermal Storage

AfricaLive (2022) reported on the development of thermal energy storage systems using solar energy for cooking applications. The article highlighted the use of locally available food-grade materials such as sunflower oil and erythritol to reduce storage costs and ensure food safety. This system made to store energy for future use specifically for cooking later. Additionally, a solar food dryer was presented, allowing for night-time operation with thermal energy storage. However, consumers have been slow to adopt domestic solar thermal food processing devices due to a lack of research on socio-economic aspects, including cultural aspects, cost, and the lifespan of the cookers. Recent research in STS for cooking applications is focusing on enhancing efficiency and material versatility. Researchers are exploring high-specific-heat capacity materials from sustainable sources, such as ceramics and industrial byproducts. The integration of STS with smart control systems and technologies is also being explored. Advanced insulation techniques and computational modelling are being used to optimize storage system designs. The integration of STS with biomass cookstoves is particularly relevant for resource-constrained communities (Patel & Patel, 2024) .

User Acceptance of Sensible Thermal Storage for Cooking and Socioeconomic Factors

(Johar et al., 2022; Nkhonjera et al., 2017; Nydal, 2023; Patel & Patel, 2024) reported on the characteristics of such systems for the acceptance determination. Despite being simply technically efficient, STS systems for cooking applications must be implemented successfully. This largely depends on understanding and addressing socioeconomic issues and ensuring consumer acceptability. Affordability, cultural practices, availability and accessibility, education and awareness, gender roles, and environmental awareness are some of the most important socioeconomic aspects.

One major obstacle to STS system integration with cooking systems is their initial cost, particularly in low-income areas. The economic viability of such systems in terms of material costs, production and maintenance should be considered in early stages. When manufacturing such systems, the cost factor is considered while choosing the materials regarding the size, location and application. Awareness of the environmental benefits and the ease of use of the storage system for cooking are among the parameters that influence user acceptability. Maintenance and use of the system should not be complex. The dependability and functionality of the system are essential to create a habit for users to rely on. The cooking result when the system is applied in terms of time and flavour of the food is to be consistent and reliable, which can maintain the satisfaction of customers.

To summarize, technical and socioeconomic factors are the crucial approaches that lead the STS system to be adapted for cooking applications. The acceptance of the system regarding the inclusion of many factors inspires the researchers and inventors to design the appropriate solutions for cooking.

Identified Gap

The optimization of operational elements that influence the heat transfer in the STS systems is still a gap. However, the thermal storage materials, which are mostly used, have been investigated; extracting enough required energy is still a problem unless the storage technology provides it. Other investigations are essential to determine the best way to construct STS configurations by considering compatibility with different styles of cooker attachments. Studies that examine means of avoiding or reducing heat loss from the storage systems are required.

There is also the challenge of material degradation when applied for long time under high temperature conditions with repeated cycles. The materials to be utilized in the STS system for cooking applications require a combination of factors. In the real-world working environments, evaluation of the materials for long-term performance, specific heat capacity, lifespan, and thermal stability are among the crucial factors. To reach an efficient STS system that fulfils cooking requirements, the selected materials should be affordable, available and eco-friendly along with the site. Social and cultural behaviour may interrupt socioeconomic factors and the adoption of cooking systems in some societies, so the studies under this scenario are still relevant. Research is required to evaluate the economic feasibility, cultural appropriateness, and user acceptability of these systems within diverse communities. Enhancing the user-friendliness of the systems is essential.

Solar as a heat source is common for producing energy cooking systems, but little research have been completed on hybrid systems consisting of photovoltaic power and other storage systems like oil or rock STS systems. More research is still needed on how STS technologies can be combined with other renewable sources while ensuring the required reliability and flexibility.

Because of the lack of universalized testing protocols and performance criteria, it is difficult to compare different STS systems. Standard methods of testing the reliability and performance of the STS solar cookers need to be established.

In summary, although the basic ideas of STS are well-established, further investigation is required to bridge the gap between laboratory studies and practical applications. To guarantee that sustainable solar cooking solutions are widely adopted, this entails resolving socioeconomic issues, enhancing material performance, and optimizing system design. This review was conducted to address some of the issues concerning the STS for the cooking application.

METHODS AND MATERIALS

A systematic review of sensible thermal storage systems for cooking applications was conducted using a comprehensive literature search. The review focused on fundamental principles, materials, designs, performance, advantages, limitations, current research, integration, socio-economic factors and applications. Relevant studies were selected and critically analyzed, identifying gaps and proposing future research directions. The Dimension, Springer databases and VOSviewer tools were used to find references and a total of 25,102 relevant sources were identified. After applying screening criteria for review and journal papers published between 2009 and 2024, 2750 sources were left. Further screening to identify papers related to STS for cooking applications resulted in 58 potentially relevant papers, and the selected papers are mapped out and shown in Figure 2. The findings were organized into categories, highlighting advancements and challenges in STS cooking applications. Thermal storage systems are investigated using two main paths: experimental and numerical.

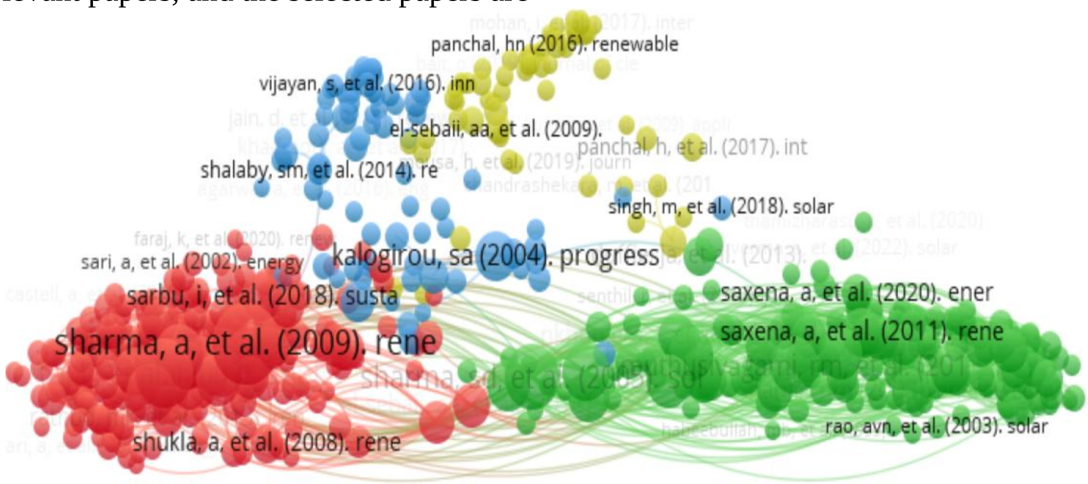

Figure 2: Mapping of storage systems for cooking applications.

FINDINGS AND DISCUSSION

Experimental Investigation of Sensible Thermal Storage

The experimental method investigation was based on the developed and tested prototype for cooking applications. The findings through such method are described as follows:

Nydal et al. (2019) developed a passive solar heat storage system for cooking, converting extra electricity into high-temperature heat. The system uses photovoltaic (PV) electricity and direct power from PV panels. Heat storage can replace dump loads for wind or hydroelectric generators. The system is scalable and designed for small workshops, with a mechanical thermostat valve and gravity driving the flow. The prototype system primarily aims to switch from firewood to solar energy for cooking in remote, off-grid areas especially for schools and other communities. The cooking tests and a prototype system are displayed to evaluate the performance of the system.

The behaviour of thermocline in a STS was studied by Bruch et al.(2017) Focusing on the impact of solid storage materials on the performance of the system. The investigation results demonstrated that the known performance of operating variables such as tank initial conditions, temperature range and fluid velocity have no major impact on the thermocline of the system. It noted that, the performance of the storage lowered by partial charging. The thermocline of the system is reliable and suitable for applications using solar thermal power.

When investigating the thermal extraction in the rock bed stratification thermoelectric storage systems by Mulane *et al.* (2017), it noted that well-stratified rock beds allow quick release of stored energy, and this rate decreases over time. Forced fluid convections boost the discharge rate, and a controlled flow of discharge fluid is best when using STS systems for cooking applications. Furthermore, the study showed that destratification happens more quickly in high-temperature areas and harms the function of the thermal storage system. For this reason, it is advised to prevent large temperature differences inside the storage tank.

For high-temperature applications, Okello et al. (2016) conducted an experimental study on thermal energy extraction using airflow under various conditions from a rock thermal storage system. The research findings indicated that, consistently maintaining a specific airflow rate in a bed containing rocks initially resulted on heightened energy output; nevertheless, over time, the energy yield diminishes. Additionally, it was shown that controlling the discharge to provide the necessary heat while using a system with adjustable airflow for cooking purposes is advantageous.

Lwiwa & Nydal (2023) demonstrated a basic small-scale solution for cooking beans. Heating was applied to an insulated iron cylinder using photovoltaic heating components or a solar concentrator. The amount of heat that is stored can then be adjusted to cook a specific amount of beans. The pot can be put on top of the cylinder until it has attained the calibrated temperature during the charging process. An iron cylinder that has been heated to 220 °C has been used to establish a small-scale method of cooking beans after sundown. After three hours, one kilogram of dried beans was cooked in the cylinder. After cooking, the residual heat decreases to 100 °C in twelve hours. It noted that the insulation can lengthen the boiling time and shorten the decay time, where the system can also be heated using either grid power or photovoltaic electricity.

Tusiime et al.(2022) demonstrated a three-tanks STS system consisting of a residual drainage tank, heat storage tank, and cold oil reservoir. The system achieves 51.3% charging efficiency and a 15.3–34.7% overall discharge efficiency. The heating unit's thermal transfer efficiency ranges from 34.7–57.6%. The study suggests a procedure for sizing oil-based STS systems based on the discharge collected data.

Experimental results highlight the promise of STS systems for environmentally friendly cooking while also pointing up issues with material performance, design, and practicality. To encourage the broad adoption of this technology, ongoing research and development efforts have been focused on addressing these issues.

Numerical Investigation of STS

Numerical studies provide a valuable way to understand, enhance, and validate STS systems designed for food preparation. Researchers use it to create more dependable and efficient cooking systems by allowing them to test a variety of design possibilities, assess material performance, and predict system behaviour in diverse operating conditions. This numerical investigation is grounded in the prototypes developed and tested for cooking applications. The results obtained through this approach are described as follows:

Andreozzi et al. (2009) modelled the STS for a temperature greater than 800 ^{0}C for thermal power plants through a commercial Computational Fluid Dynamics (CFD) Fluent package. The research analyzed the relationship between HTF flows and rock porosity indicates that to achieve energy storage in the shortest possible time, the packed bed porosity should be 0.40, coupled with an HTF flow rate of approximately 0.2 kg/s.

A 7.2 GWh heat storage system was simulated and the results showed that, the STS system should be charged in order to improve performance prior to cyclic operation. The tank diameter to height ratio has a quite large effect on the performance of the system. When this ratio is reduced, the temperature drop when the storage is discharged reduced, as a result, the efficiency is improved. Furthermore, the study noted that using smaller rocks resulted in a higher pressure drop, which increased the required pumping work, but this also helped to maintain the final exit temperature of the system. The findings suggest no one size that fits all guidelines for STS design. Each design must be customized due to its specific applications to optimize cost and thermal efficiency (Zanganeh et al., 2015).

To investigate the transient properties and performance of the STS between 250 °C and 400 °C, Bataineh & Gharaibeh (2018) used a numerical technique. Storage beds containing concrete, rocks and sea salt with silica sand were analyzed using a numerical model. The outcomes were compared with additional information found in the literature. The results demonstrated that, in order to improve the designs of all reasonable heat storage systems, a balance between energy stored and charging efficiency must be taken into account. Basalt rock and Dead Sea salt, both with adequate thermal performance, were suggested as viable substitutes for molten salts in thermal storage materials for application in solar plants. Furthermore, it was mentioned that natural stones, as opposed to concrete, can be used more successfully for applications requiring higher temperatures for storage.

Elouali et al. (2019) studied the dynamic behaviour of efficient STS systems using four distinct numerical models, and for numerical results, they were supported with some successful experimental data in the literature. Findings revealed that bed void, solid particle diameter, and the mass flow rates of the working fluid were influential in the thermal performance of the systems. It was also noted that well-packed bed STS systems are likely run more efficiently due to optimum solid state particle sizes and allowable flow rates.

Vannerem et al. (2021) employed an experimental approach with temperature data ranging from 293 to 393 °C to validate the simulation results about the thermocline performance of the storage system. The study showed maximum heat storage capacity is achieved when heat is added at a fluid velocity of 4 m/s. It was also revealed that changes in temperature and fluid velocity resulted in a decrease in storage capacity. In conclusion, the authors stated that while further experimental investigations at temperatures relevant to industrial conditions are necessary, the results indicate that thermocline is a reasonable candidate for high thermal efficiency in the storage system.

According to Li (2016), various operational scenarios were analyzed with respect to the methods used for sensible heat storage. This evaluation examined several factors related to the performance of the system such as fluid properties, storage tank geometry, fluid velocity, and fluid temperature at the point of entry. It was illustrated that low HTF velocity might increase the outlet temperature; however, the mass flow rate could be hindered by thermal diffusion and mixing effects. It was also observed that a larger tank aspect ratio could enhance thermal stratification. Additionally, it was noted that the properties of the solid storage material and HTF affected the performance of the STS systems. Therefore, these criteria must be considered in sensible TES designs. The analysis suggested that the primary focus should be on the thermal behaviour of the storage system, and subsequently, the charging and discharging processes in the systems should be examined.

Nkhonjera et al. (2017) analyzed different solar cooker designs and their corresponding heat storage materials. Their studies show that the diffusivity of thermal storage material greatly influences solar cookers' efficiency. The authors pointed out the gaps in the literature regarding the design of heat storage systems for high temperatures and urged to improve system configurations and study the heat transfer processes in these systems.

Synthesis of the Findings from the Study

Numerical and experimental approaches are used to assess STS systems for cooking applications. Numerical simulations provide in-depth understanding of heat transfer phenomena, while experimental investigations verified theoretical ideas and numerical predictions. These means demonstrated the practicality of STS systems and emphasize how system design, material choice, and integration of cookers affect cooking efficiency. Nonetheless, issues like user acceptability and material deterioration are carried to light. Computational fluid dynamics simulations and other numerical studies offer a more reflective comprehension of heat transfer pathway and directing design advancements. The findings discussed and noted that, it is possible to comprehend the complicated relationships between design, materials, and operating circumstances in greater detail, which lead to cooking solutions that are more dependable, effective, and easy to use.

CONCLUSIONS AND RECOMMENDATIONS

Concluding Remarks

The sensible thermal storage system has the potential to save energy from intermittent sources for cooking applications. Numerical and experimental research have thoroughly explored design concerns and performance evaluation of STS systems. The findings from this paper demonstrate that cooking from sensible thermal storage systems can significantly help to address clean cooking possibilities. The system can utilize different solid and liquid materials to enhance performance. The selection of storage materials depends on the projected temperature, either low or high, and the cooking method to be used. The characteristics of storage materials, considering solid and liquid, can possess several appealing qualities of the system, including affordability, accessibility, and environmental safety. The materials like concrete, fire bricks, oils and industrial waste have good heat storage properties. They can be obtained locally, making cooking through sensible thermal storage systems viable and performing well. The study reveals diverse storage capacities, ranging from small-scale to large systems, suitable for low-temperature cooking to high temperatures, and overall efficiency between 50% and 90% due to charging and discharging losses. There is, however, a lack of research on the performance of the sensible thermal storage systems under final implementations to society. Several experimental rigs in laboratories perform well due to reported results, but are missing minor improvements and upscale stages.

Recommendation

Further research on the effects of developing hybrid sensible-latent TES systems for cooking is essential. It is suggested to improve the performance of the existing sensible thermal storage systems and stabilize the functionality for cooking applications. The review also recommends making the development of advanced STS materials a top priority, optimizing integration and system design. Creation of standardized procedures for performance evaluation while encouraging user involvement is also recommended. Promoting investment and policy support, and expanding long-term evaluations of the STS systems for cooking applications is vital.

Implications of the Review Findings

A review of STS systems for cooking applications suggests a shift towards optimized system design, improved insulation techniques, and continuous integration with cooker designs. The review recommends a focus on women's empowerment, standardised performance evaluation, and improved material selection. Additionally, it highlights how STS systems can alleviate energy poverty in different areas, and it recommends that governments and non-governmental organisations encourage their implementation through focused initiatives and financial rewards. The review also emphasises the advantages of STS technologies for the environment and human health, highlighting the necessity of educational and public health campaigns. The importance of sustainable supply chains and local entrepreneurship for long-term viability and accessibility is also emphasised in the review's conclusion.

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REFERENCES

AfricaLive. (2022). *Night-time cooking with solar is possible with thermal energy storage* Energy. https://africalive.net/article/night-time-cooking-with-solar-is-possible-with-thermal-energy-storage/

Ali, D., Kaya, M. F., & Şendoğdular, L. (2021). Today, Tomorrow, and the Future of Energy Storage Materials for Solar Energy. *Mühendis ve Makina*, *62*(702), 70–90. doi:10.46399/muhendismakina.797433

Andreozzi, A., Bianco, N., Manca, O., Nardini, S., & Naso, V. (2009). Numerical investigation of sensible thermal energy storage in high temperature solar systems. *WIT Transactions on Modelling and Simulation*, *48*, 461–472. doi:10.2495/CMEM090421

Asmelash, H., Bayray, M., Kimambo, C., Gebray, P., & Sebbit, A. (2014). Performance test of Parabolic Trough Solar Cooker for indoor cooking. *Momona Ethiopian Journal of Science*, *6*(2), 39. doi:10.4314/mejs.v6i2.109621

Avghad, S. ., Keche, A. ., & Kousal, A. (2016). Thermal Energy Storage: A Review. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE*, *13*(3), 72–77. doi:10.9790/1684-1303027277

Bataineh, K., & Gharaibeh, A. (2018). Optimal design for sensible thermal energy storage tank using natural solid materials for a parabolic trough power plant. *Solar Energy*, *171*(January 2017), 519–525. doi:10.1016/j.solener.2018.06.108

Bauer, T., Steinmann, W.-D., Laing, D., & Tamme, R. (2012). Thermal Energy Storage Materials and Systems. *Annual Review of Heat Transfer*, *15*(15), 131–177. doi:10.1615/annualrevheattransfer.2012004651

Biadgelegn, M., & Hassen, A. A. (2019). *Design and experimental investigation of solar cooker with thermal energy storage*. *December*. doi:10.3934/energy.2019.6.957

Bishoge, O. K., Zhang, L., & Mushi, W. G. (2018). The Potential Renewable Energy for Sustainable Development in Tanzania : A Review. *Clean Technology*, 70–88. doi: 10.3390/cleantechnol1010006

Bott, C., Dressel, I., & Bayer, P. (2019). State-of-technology review of water-based closed seasonal thermal energy storage systems. *Renewable and Sustainable Energy Reviews*, *113*(January), 109241. doi:10.1016/j.rser.2019.06.048

Boulevard, S., & Miranda, A. M. (2018). *Overview of the existing heat storage technologies: sensible heat*. *28*, 82–113. https://www.proakademia.eu/gfx/baza_wiedzy/481/nr_28_82-113_2.pdf

Bruch, A., Molina, S., Esence, T., Fourmigué, J. F., & Couturier, R. (2017). Experimental investigation of cycling behaviour of pilot-scale thermal oil packed-bed thermal storage system. *Renewable Energy*, *103*, 277–285. doi:10.1016/j.renene.2016.11.029

Cabeza, L. F., Martorell, I., Miró, L., Fernández, A. I., & Barreneche, C. (2015). Introduction to thermal energy storage (TES) systems. In *Advances in Thermal Energy Storage Systems: Methods and Applications*. Woodhead Publishing Limited. doi:10.1533/9781782420965.1

Cirocco, L., Pudney, P., Riahi, S., Liddle, R., Semsarilar, H., Hudson, J., & Bruno, F. (2022). Thermal energy storage for industrial thermal loads and electricity demand side management. *Energy Conversion and Management*, *270*(August), 116190. doi:10.1016/j.enconman.2022.116190

Diaz, P. . (2016). Analysis and Comparison of different types of Thermal Energy Storage Systems: A Review. *Journal of Advances in Mechanical Engineering and Science*, *2*(1), 33–46. doi:10.18831/james.in/2016011004

Dincer, I., & Rosen, A. M. (2011). *Thermal Energy Storage Systems And*

Applications, Second Edition (second). John Wiley & Sons, Ltd.

Elouali, A., Kousksou, T., El Rhafiki, T., Hamdaoui, S., Mahdaoui, M., Allouhi, A., & Zeraouli, Y. (2019). Physical models for packed bed: Sensible heat storage systems. *Journal of Energy Storage*, *23*(February), 69–78. doi:10.1016/j.est.2019.03.004

Furbo, S. (2015). Using water for heat storage in thermal energy storage (TES) systems. In *Advances in Thermal Energy Storage Systems: Methods and Applications*. Woodhead Publishing Limited. doi:10.1533/9781782420965.1.31

González-Roubaud, E., Pérez-Osorio, D., & Prieto, C. (2017). Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts. *Renewable and Sustainable Energy Reviews*, *80*(February), 133–148. doi:10.1016/j.rser.2017.05.084

Gunasekara, S. N., Barreneche, C., Inés Fernández, A., Calderón, A., Ravotti, R., Ristić, A., Weinberger, P., Ömur Paksoy, H., Koçak, B., Rathgeber, C., Chiu, J. N., & Stamatiou, A. (2021). Thermal energy storage materials (Tesms)—what does it take to make them fly? *Crystals*, *11*(11). doi:10.3390/cryst11111276

Hänchen, M., Brückner, S., & Steinfeld, A. (2011). High-temperature thermal storage using a packed bed of rocks - Heat transfer analysis and experimental validation. *Applied Thermal Engineering*, *31*(10), 1798–1806. doi:10.1016/j.applthermaleng.2010.10.034

James, A. (2021). Solar Photovaltaic Energy: Advantages and Disadvantages. *Global Science Research Journals*, *2*(3), 1–2. https://doi.org/https://www.globalscienceresearchjournals.org/articles/solar-photovoltaic-energy-advantages-and-disadvantages.pdf

Johar, D. kishor, Sharma, D., Yadav, H., & Patel, S. (2022). Energy and Exergy Analysis of Pebble Bed Thermal Energy Storage System for Diesel Engine Exhaust. *Thermal Science*, *26*(6), 4969–4980. doi:10.2298/TSCI210628072J

John, E., Hale, M., & Selvam, P. (2013). Concrete as a thermal energy storage medium for thermocline solar energy storage systems. *Solar Energy*, *96*, 194–204. doi:10.1016/j.solener.2013.06.033

Kajumba, P. K., Okello, D., Nyeinga, K., & Nydal, O. J. (2022). Assessment of the energy needs for cooking local food in Uganda: A strategy for sizing thermal energy storage with cooker system. *Energy for Sustainable Development*, *67*, 67–80. doi:10.1016/j.esd.2022.01.005

Kassem, T. K., & Youssef, M. S. (2011). Solar Cookers and Its Application for Food Cooking in Remote Areas: Review. *JES. Journal of Engineering Sciences*, *39*(5), 1033–1042. doi:10.21608/jesaun.2011.129391

Koçak, B., Fernandez, A. I., & Paksoy, H. (2020). *Review on Sensible Thermal Energy Storage for Industrial Solar Applications and Sustainability Aspects*. https://diposit.ub.edu/dspace/bitstream/2445/174646/1/707743.pdf

Lentswe, K. ., Mawire, A., Owusu, P., & Shobo, A. . (2021). An experimental study of solar thermal system with storage for domestic applications. *Journal of Mechanical Engineering and Sciences*, *12*, 4098–4116. doi:10.15282/jmes.12.4.2018.09.0355

Li, G. (2016). Sensible heat thermal storage energy and exergy performance evaluations. *Renewable and Sustainable Energy Reviews*, *53*, 897–923. doi:10.1016/j.rser.2015.09.006

Lugolole, R., Mawire, A., Okello, D., Lentswe, K. A., Nyeinga, K., & Shobo, A. B. (2019). *Experimental analyses of sensible heat thermal energy storage systems during discharging*. *35*(February), 117–130.

Lwiwa, C., & Nydal, O. (2023). Sensible Heat Bean Cooker. *Tanzania Journal of Engineering and Technology*, *42*(1), 79–84. doi:10.52339/tjet.v42i1.890

Martin, V. (2014). Introduction to thermal energy storage. *Dept of Energy Technology, KTH Royal Institute of Technology*, 1–32. %5C%5CKwi-server%5Cliteratur%5Cedo%5Carticles%5CDSH%5CDSH_0458.pdf%5Cn%5C%5CKwi-server%5Cliteratur%5Cedo%5Carticles_ocrtxt%5CDSH%5CDSH_0458.txt

Martins, M., Villalobos, U., Delclos, T., Armstrong, P., Bergan, P. G., & Calvet, N. (2015). New Concentrating Solar Power Facility for Testing High

Temperature Concrete Thermal Energy Storage. *Energy Procedia*, *75*, 2144–2149. doi:10.1016/j.egypro.2015.07.350

Menghare, Y. M., & Jibhakate, Y. M. (2013). *Review On Sensible Heat Storage System Principle, Performance And Analysis*. *2*(6), 3432–3435.

Mulane, S. A., & Havaldar, S. N. (2017). A Review on Rock Bed Thermal Energy Storage System for Thermal Stratification and Heat Extraction. *International Journal of Current Engineering and Technology*, *7*(7), 335–337. https://www.researchgate.net/publication/317740585_A_Review_on_Rock_Bed_Thermal_Energy_Storage_System_for_Thermal_Stratification_and_Heat_Extraction

Nkhonjera, L., Bello-Ochende, T., John, G., & King'ondu, C. K. (2017). A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews*, *75*(August 2015), 157–167. doi:10.1016/j.rser.2016.10.059

Nydal, O. J. (2023). Heat Storage for Cooking: A Discussion on Requirements and Concepts. *Energies*, *16*(18). doi:10.3390/en16186623

Nydal, O. J., Thaule, S., Kolderup, M., Gustafson, K., & Bjerre, P. (2019). Passive solar system to store heat for cooking. *Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019*, 1681–1688. doi:10.18086/swc.2019.33.02

Okello, D., Nydal, O. J., Nyeinga, K., & Banda, E. J. K. (2016). Experimental investigation on heat extraction from a rock bed heat storage system for high temperature applications. *Journal of Energy in Southern Africa*, *27*(2), 30–37. doi:10.17159/2413-3051/2016/v27i2a1339

Okello, D., Omony, R., Nyeinga, K., & Chaciga, J. (2022). Performance Analysis of Thermal Energy Storage System Integrated with a Cooking Unit. *Energies*, *15*(23), 1–19. doi:10.3390/en15239092

Pachori, H., Choudhary, T., & Sheorey, T. (2022). Significance of thermal energy storage material in solar air heaters. *Materials Today: Proceedings*, *56*, 126–134. doi:10.1016/j.matpr.2021.12.516

Patel, R., & Patel, V. (2024). Experimental Analysis of Scheffler Reflector-Based Solar Cooking System: An Application of Sensible and Latent Heat Storage Materials. *Jurnal Kejuruteraan*, *36*(4), 1505–1518. doi:10.17576/jkukm-2024-36(4)-16

Prasad, D. M. R., Senthilkumar, R., & Lakshmanarao, G. (2019). *A critical review on thermal energy storage materials and systems for solar applications*. *7*(July), 507–526. doi:10.3934/energy.2019.4.507

Sarbu, I., & Sebarchievici, C. (2018). A comprehensive review of thermal energy storage. *Sustainability (Switzerland)*, *10*(1). doi:10.3390/su10010191

Saxena, A., & Karakilcik, M. (2017). Performance Evaluation of a Solar Cooker with Low Cost Heat Storage Material. *International Journal of Sustainable and Green Energy*, *6*(4), 57. doi:10.11648/j.ijrse.20170604.12

Schlipf, D., Schicktanz, P., Maier, H., & Schneider, G. (2015). Using Sand and other Small Grained Materials as Heat Storage Medium in a Packed Bed HTTESS. *Energy Procedia*, *69*(May), 1029–1038. doi:10.1016/j.egypro.2015.03.202

Shaikh, M., Uzair, M., & Ahmad Raza, S. (2022). Optimization of thermal storage using different materials for cooking with solar power. *Transactions of the Canadian Society for Mechanical Engineering*, *46*(2), 490–502. doi:10.1139/tcsme-2021-0160

Simonetti, M., & Gentile, V. M. (2019). CFD optimization of large water storages for efficient cooling of high power intermittent thermal loads. *Case Studies in Thermal Engineering*, *14*(August), 100466. doi:10.1016/j.csite.2019.100466

Socaciu, L. (2015). An Overview of Thermal Energy Storage. *Applied Mathematics and Mechanics*, *55*(February).

Soprani, S., Marongiu, F., Christensen, L., Alm, O., Petersen, K. D., Ulrich, T., & Engelbrecht, K. (2019). Design and testing of a horizontal rock bed for high temperature thermal energy storage. *Applied Energy*, *251*. doi:10.1016/j.apenergy.2019.113345

Stevens, V., Craven, C., & Grunau, B. (2013). Thermal Storage Technology Assessment. *Rapport CCHRC*, *Volume 1*(February), 1–54. MECHANICAL/Downloads/Thermal_Storage assesment.pdf

Suresh, C., & Saini, R. P. (2020). Thermal performance of sensible and latent heat thermal energy storage systems. *International Journal of Energy Research*, *44*(6), 4743–4758. doi:10.1002/er.5255

Theu, A. P., & Kimambo, C. Z. M. (2023). Performance analysis of parabolic dish solar cooking system with improved receiver designs. *Renewable Energy and Environmental Sustainability*, *8*, 1. doi:10.1051/rees/2022015

Turchi, C., Kurup, P., Akar, S., Flores, F., Turchi, C., Kurup, P., & Akar, S. (2015). *Domestic Material Content in Molten-Salt Concentrating Solar Power Plants Domestic Material Content in Molten-Salt Concentrating Solar Power Plants*. *August*.

Tusiime, S., Nyeinga, K., Okello, D., & Nydal, O. J. (2022). Performance Investigations of the Charging and Discharging Processes in a 3-Tank Thermal Energy Storage System. *Tanzania Journal of Science*, *48*(4), 727–740. doi:10.4314/tjs.v48i4.1

Vannerem, S., Neveu, P., & Falcoz, Q. (2021). Experimental and numerical investigation of the impact of operating conditions on thermocline storage performance. *Renewable Energy*, *168*, 234–246. doi:10.1016/j.renene.2020.12.061

Zanganeh, G., Pedretti, A., Haselbacher, A., & Steinfeld, A. (2015). Design of packed bed thermal energy storage systems for high-temperature industrial process heat. *Applied Energy*, *137*, 812–822. doi:10.1016/j.apenergy.2014.07.110

Zhao, C. Y., & Wu, Z. G. (2011). Thermal property characterization of a low melting-temperature ternary nitrate salt mixture for thermal energy storage systems. *Solar Energy Materials and Solar Cells*, *95*(12), 3341–3346. doi:10.1016/j.solmat.2011.07.029