

Sorption Based Mobile Thermal Energy Storage for Better Sustainability

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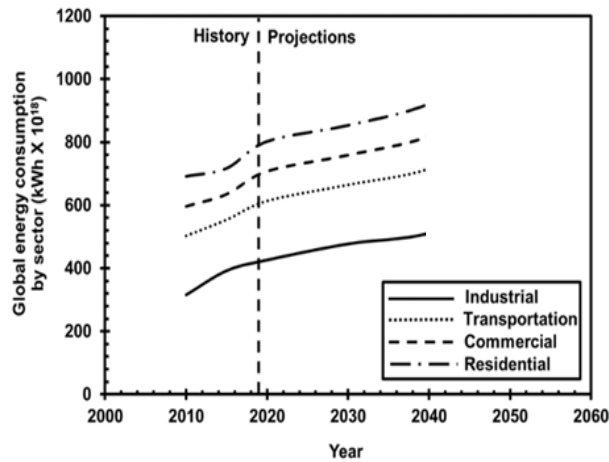
Abstract

Global energy demand is expected to increase significantly due to population expansion, but present energy generation is unable to keep up with it. For the purpose of space heating and cooling, air conditioning is one application where energy demand is anticipated to increase significantly. In order to accomplish sustainable space heating and cooling, it is necessary to investigate alternate/next energy sources for conventional building air conditioning, specifically by utilizing waste heat from industries through mobile thermal energy storage (MTES) devices. The sorption-based storage device, which is one of the many types of thermal energy storage devices, such as latent, sensible, and thermochemical/sorption-based, shows tremendous potential because of its high energy density, low heat losses, and compact design. The development of an MTES system for sustainable space heating and cooling applications in district energy networks is reviewed in-depth in this study. The proposed MTES system offers an effective solution to utilize the waste heat from industry while lowering local heat generation. It does this by utilizing the unused heat created by power plants to provide cooling for buildings. The review digs into a complete examination of sorption materials, including their categorization, selection criteria, assessment criteria, and comparisons. The material comparison primarily focuses on cost analysis, energy storage density, and energy storage capacity. This work also discusses system-level research that includes system analysis, sorption bed design, and process interpretation. Additionally, the research highlights possible areas for research and development of MTES, identifies current shortcomings, and offers a roadmap for next energy sources in this field.

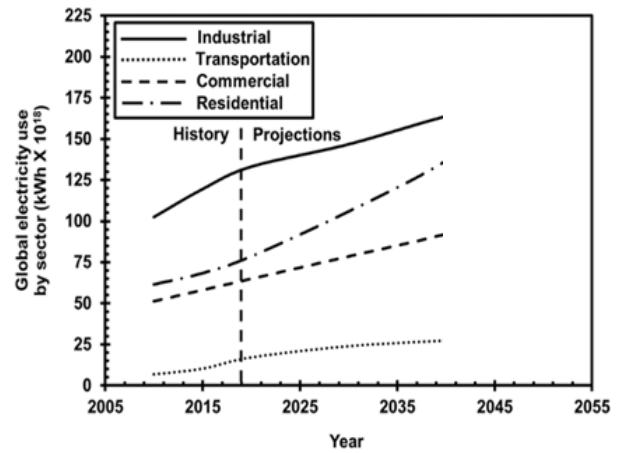
Keywords: MTES, District Energy Network, Waste heat, Sorption energy storage, Space cooling, Material comparison.

1. Introduction

The study of Isaac and Vuuren [1] highlights the escalating energy demand of air conditioners from 2000 to 2100. Recognizing the significance of understanding global energy consumption and demand, it becomes crucial to address this issue. The literature [2, 3] emphasizes the growing concern surrounding waste heat generated by industries, particularly in developing nations. By effectively utilizing this waste heat for space-cooling purposes, there is a substantial opportunity to decrease reliance on fossil fuel energy. An essential aspect of achieving this goal involves the efficient capture and utilization of waste heat through heat recovery methods. Various forms of thermal energy/waste heat storage, such as latent, sensible, and chemical-thermo/sorption-based energy storage, can be employed. Among these forms, sorption-based thermal energy storage stands out due to its exceptional mass and heat exchange capacity, efficient heat conduction, high energy density, and minimal heat losses. Consequently, in the present investigation, the focus is on sorption-based mobile thermal energy storage (MTES) and evaluating its feasibility for transferring waste heat from industries to end users. Thermal energy storage can be implemented on-site or off-site. On-site energy demand can be addressed through thermal energy storage (TES) systems, while for off-site energy requirements, mobile thermal energy storage (MTES) systems have been developed to transport waste heat from industries to the district energy network (DEN). Global energy consumption and electricity usage are surpassing the capacity of global electricity generation. Projections indicate a significant 50% increase in both electricity consumption and energy usage by 2040 (Fig. 1) [3].



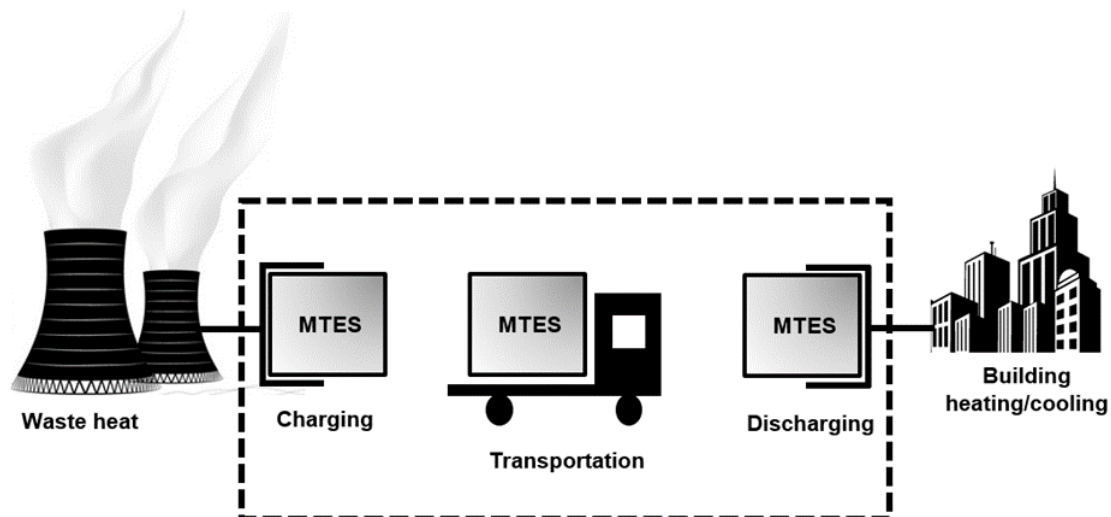
(a) Global energy consumption



(b) Global energy usage

Fig. 1: Global electricity demand and energy consumption scenario.

In order to reduce greenhouse gas emissions and meet the increasing energy demand, an effective approach is to implement an energy-efficient, environmentally friendly, and sustainable district energy system (DES). This system encompasses three key components: air drying to remove moisture from humid air, centralized air conditioning for cooling buildings, and water extraction from humid air for desalination purposes. The DES concept revolves around the efficient utilization of waste heat generated by thermal power plants and industrial facilities. This waste heat is transported to centralized air dryers and air conditioning units, where it is converted into valuable and usable heat, thereby maximizing its potential and minimizing waste. By adopting this pathway, the DES plays a crucial role in simultaneously addressing greenhouse gas emissions, energy efficiency, and the extraction of valuable resources from the environment. Consequently, the concept of MTES (Multi-Technology Energy Systems) for District Energy Networks (DEN) has emerged as a crucial solution for space heating and cooling applications (Fig. 2).

**Fig. 2:** Schematic of mobile thermal energy storage.

This manuscript's major goal is to present a thorough and critical analysis of the developments in Multi-Technology Energy Systems (MTES) for environmentally friendly space heating and cooling applications. To provide a comprehensive grasp of the subject, the study includes examinations at the material-, system-, and numerical-levels. This review's objectives are to pinpoint research voids and suggest new lines of inquiry. With reference to earlier publication [4], the review begins by going through the key criteria for choosing sorption-based MTES for DEN in sustainable space heating and cooling applications. The classification of sorption materials is covered next, along with selection criteria, metrics for evaluating materials, and a case study that suggests the best

material among the ones that have been chosen [5]. The paper also addresses the concepts and operating principles of MTES systems. It gives an overview of the experimental settings utilized for absorption- and adsorption-based closed and open MTES systems that have been applied to space heating and cooling applications thus far. It defines system selection criteria and contrasts open and closed absorption and adsorption systems. The review also looks at several thermal models and numerical methods used in sorption energy storage prototypes, and it suggests the most accurate models with the fewest assumptions and the shortest computation times. The review also briefly examines the benefits and drawbacks of the current sorption systems, materials, and computational methods. As a result of considering the heat of absorption/adsorption and including the idea of minimum sorption material density, it also presents new definitions for energy storage density (ESD) and energy storage capacity (ESC).

2. Materials

This section presents in detail the classification of adsorption and absorption materials, material selection criteria, material assessment parameters, and a case study on the most appropriate sorption material for MTES based DEN.

2.1 Classification

Adsorption, absorption, and composites are the three main types of materials utilized to store sorption energy [6]. Materials that typically experience gas/solid reactions and are predominately affected by absorption mechanisms fall within the absorption category [7]. The adsorption category, on the other hand, includes elements that only go through adsorption processes. As their name implies, composites are made up of several different processes and frequently a few inert materials are included. The classification of the sorption energy storage materials is shown in Fig. 2.

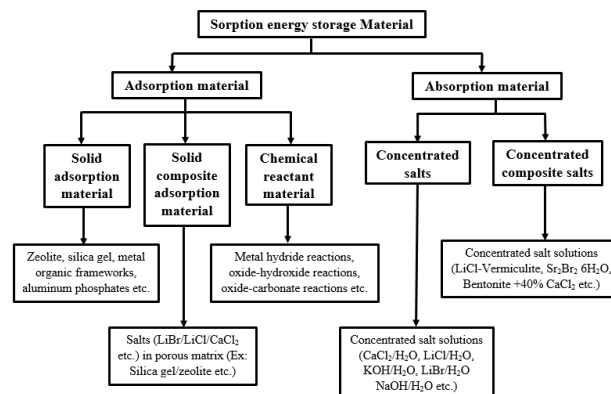


Fig. 2: Sorption energy storage materials classification [7].

The following are the standards for selecting an energy storage system based on sorption for DEN applications.

- Non-corrosive, non-hazardous.
- Elevated energy density per unit volume.
- Sorbate uptake should be high.
- Material energy capacity per kg should be high.
- Exchange capability of mass and heat should be high.
- Low cost.
- Sorption charging temperature/material regeneration and time should be low.
- Material thermal conductivity should be high.
- Eco-friendly material.
- Chemical and thermal stability of the material should be high.

2.2 Evaluation parameters

The evaluation parameters for analyzing the suitability of sorption materials for MTES based on Direct Energy Network (DEN) can be outlined as follows,

2.2.1 Energy storage capacity (ESC)

Energy Storage Capacity (ESC) refers to the maximum amount of energy that a material can store under specific nominal conditions [8]. The estimation of ESC for a material is done as follows,

$$ESC = ESD \frac{M_{sorp}}{\rho_m} \quad (1)$$

where M_{sorp} is the mass of sorption material after absorption/adsorption (kg_{mat}).

2.2.2 Energy storage density (ESD)

In the present study, the definition for ESD developed by [8] has been modified by considering the heat of adsorption/absorption during crystallization and by implementing the concept of minimum density of the salt hydrate [9, 10]. It is formulated as follows,

$$ESD = \delta_m \Delta X \psi \rho_m \quad (2)$$

where ΔX is the change in mass of water per unit mass of sorption material ($kg_w/kg_{sorp.}$), δ_m is the dilution enthalpy (kJ/kg), ρ_m is the minimum density of the sorption material (kg/m^3), ψ is the mass fraction of sorption material (kg_{sorp}/kg_{mat}).

2.2.3 Temperature lift

The difference between the temperature of the material before and after absorption/adsorption gives the temperature lift. It is defined as follows,

$$\Delta T_L = T_b - T_a \quad (3)$$

where T_b and T_a are the temperature (K) after and before adsorption/absorption.

2.3 Material comparison

After conducting a literature review, a selection of materials belonging to absorption, adsorption, and composite categories have been identified for comparison. The absorption materials include NaOH/H₂O, LiBr/H₂O, CaCl₂/H₂O, KOH/H₂O, and LiCl/H₂O. The adsorption materials consist of zeolite MgNaX, zeolite 13X, zeolite NaCa 5A, silica gel, MgCl₂, and Na₂S. The composite materials include CaCl₂-silica gel, CaCl₂-PTHS, FAM-ZO₂, SrBr₂.6H₂O, APO-LTA, CaCl₂-vermiculite, LiCl-vermiculite, LiCl-MCNWT, SAPO-34, Bentonite+40%CaCl₂, Zeolite13X+15%MgSO₄, Al₂SiO₅+30%CaCl₂, Zeolite4A+10%MgSO₄, and Silicagel+33%CaCl₂. Fig. 3 illustrates the variation of energy storage capacity (ESC) with regeneration temperature for these absorption, adsorption, and composite materials. In MTES, materials with a high energy storage capacity are preferred. By determining the material with the highest energy storage density, we can identify the sorption material that offers the best performance. From the analysis of energy storage density and the comparison in Fig. 3, it can be observed that composite materials generally exhibit lower energy storage capacity compared to absorption and adsorption materials. Therefore, composite materials with very low energy storage capacity may not be suitable for MTES applications. After examining the variations presented in Fig. 3, the materials exhibiting high energy storage capacity are subjected to further analysis. Among them, NaOH/H₂O, LiBr/H₂O, CaCl₂/H₂O, KOH/H₂O, and LiCl/H₂O in the absorption category, as well as zeolite MgNaX, zeolite 13X, zeolite NaCa 5A, silica gel, MgCl₂, Na₂S, SrBr₂.6H₂O, Bentonite+40%CaCl₂, Zeolite13X+15%MgSO₄, Al₂SiO₅+30%CaCl₂, Zeolite4A+10%MgSO₄, and Silicagel+33%CaCl₂ in the adsorption and composite categories, exhibit acceptable energy storage capacity. To further assess their suitability for MTES, the variation of energy storage density with regeneration temperature is illustrated in Fig. 4, for these selected absorption, adsorption, and composite materials. The materials with higher energy storage density values are considered preferable for MTES applications. After analyzing the variations in energy storage density with regeneration temperature, as depicted in Fig. 4, the selected materials include NaOH/H₂O, LiBr/H₂O, CaCl₂/H₂O, KOH/H₂O, and LiCl/H₂O in the absorption category, as well as zeolite, silica gel, MgCl₂, SrBr₂.6H₂O, and Bentonite+40%CaCl₂ in the adsorption and composite categories.

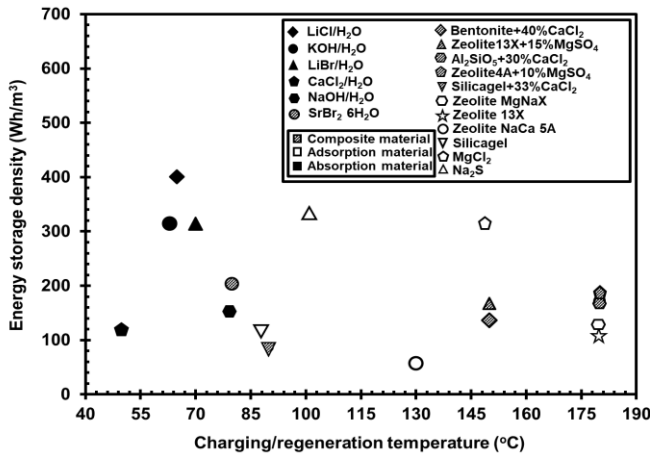


Fig. 3: Adsorption, absorption, and composite material's energy storage capacity for corresponding charging/regeneration temperature.

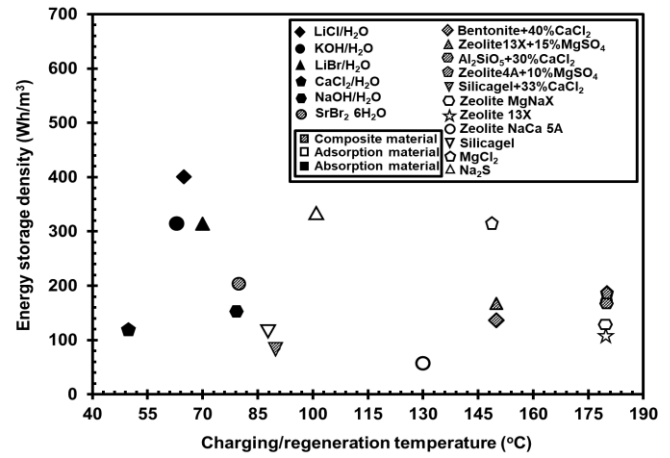


Fig. 4: Adsorption, absorption, and composite material's energy storage density for corresponding charging/regeneration temperature.

To further assess the economic feasibility of these materials for MTES applications, the variation in the cost of energy sorption material per kilogram with regeneration temperature is illustrated in Fig. 5 [11]. Materials with affordable costs, while also possessing large energy storage capacity and energy storage density, are considered preferable choices.

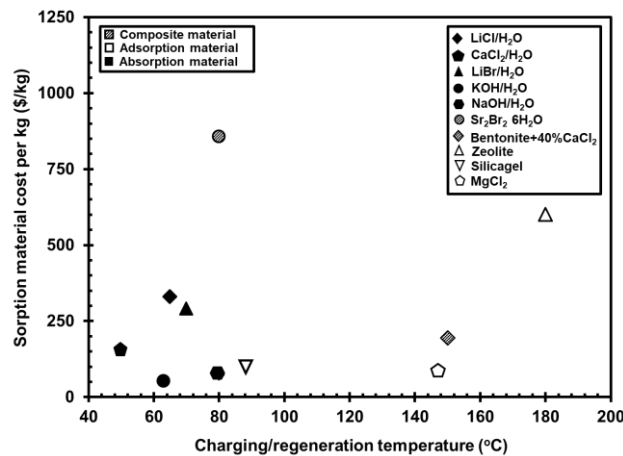


Fig. 5: Adsorption, absorption, and composite material's cost per kg for corresponding charging/regeneration temperature.

2.3 Case study

Fig. 6 presents a Venn diagram that categorizes these materials according to their theoretical, experimental, and economic potential. It also considers their potential for being used as MTES materials for DEN applications [12, 13]. The literature has revealed that LiBr/H₂O, CaCl₂/H₂O, KOH/H₂O, and LiCl/H₂O exhibit significant potential as MTES materials for DEN applications after analysing the theoretical, experimental, and financial aspects of the various materials shown in Fig. 6. These materials have advantageous qualities like affordability, low regeneration temperature, high energy capacity, high energy storage density, and low discharge temperature. The literature has highlighted their potential for MTES-DEN applications, making them interesting options for efficient and effective thermal energy storage inside district energy networks. Table 1 is a pictorial representation depicting the suitability of LiBr/H₂O, CaCl₂/H₂O, KOH/H₂O, and LiCl/H₂O for DEN application. This table takes into account a number of factors, such as storage capacity, storage capacity per unit volume, material safety, low-temperature regeneration ability, temperature lift, cost, flammability, chemical reactivity, and stainless-steel corrosion resistance. A color-coding system is used to show each parameter's appropriateness. Red denotes poor conditions, orange partial poor, blue partial favorability, and green partial favorability.

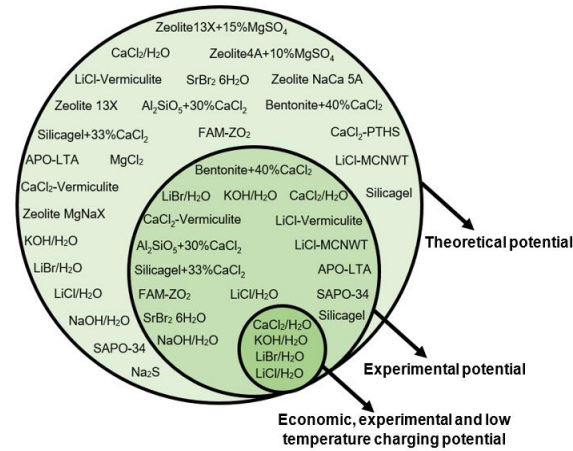
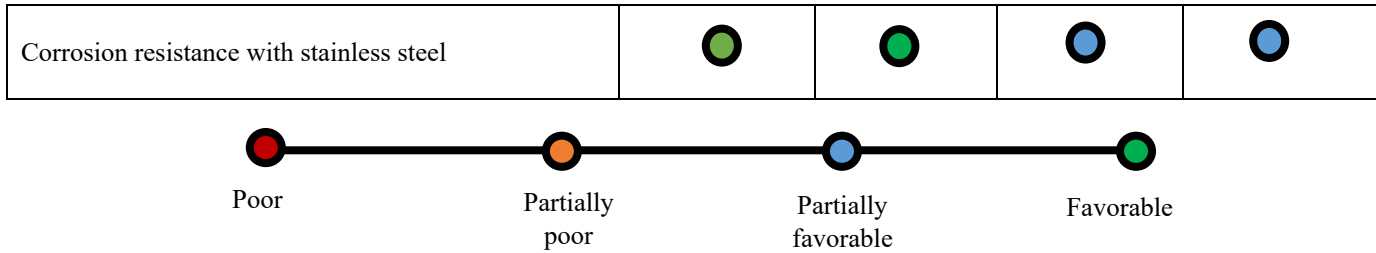


Fig. 6: Types of sorption materials grouped depending upon theoretical, experimental, and low-temperature charging potentials (Scapino, 2019; Garimella et al., 2020; Liu et al., 2013).

Table 1 provides a simple visual evaluation of the various sorption materials based on their performance across the chosen parameters by employing this color-coded methodology. This chart aids in the decision-making process for material selection by providing a thorough comparison of the appropriateness of LiBr/H₂O, CaCl₂/H₂O, KOH/H₂O, and LiCl/H₂O for DEN applications. Upon reviewing the data, it becomes evident that LiCl/H₂O exhibits the most favorable conditions for MTES as compared to other materials, except for cost. Although KOH/H₂O may possess better properties and lower cost than LiBr/H₂O, it falls short in terms of material safety. Therefore, LiBr/H₂O is preferred over KOH/H₂O. Among the materials considered, CaCl₂/H₂O is found to have the least favorable conditions for MTES applications.

Table 1: Evaluation and comparison LiBr/H₂O, CaCl₂/H₂O, KOH/H₂O, and LiCl/H₂O based absorption materials.

	CaCl ₂ H ₂ O	KOH H ₂ O	LiBr H ₂ O	LiCl H ₂ O
Storage capacity (Wh/kg)	●	●	●	●
Storage capability per unit volume (Wh/m ³)	●	●	●	●
Material safety/Health hazard	●	●	●	●
Low temperature regeneration ability (°C)	●	●	●	●
Temperature lift (K)	●	●	●	●
Cost (\$/kg)	●	●	●	●
Inflammability	●	●	●	●
Chemical reactivity	●	●	●	●



3. Sorption MTES system for sustainable space cooling application

Fig. 7 illustrates the schematic of a district energy system designed for sustainable space cooling. The system consists of various components, including a thermal energy storage platform/charging station, a regenerator cum desalination system, an MTES (Material Thermal Energy Storage) unit for transportation purposes, an absorber, an expansion valve, and an evaporator. These components work together to achieve the desired cooling effect while maintaining sustainability [14, 15].

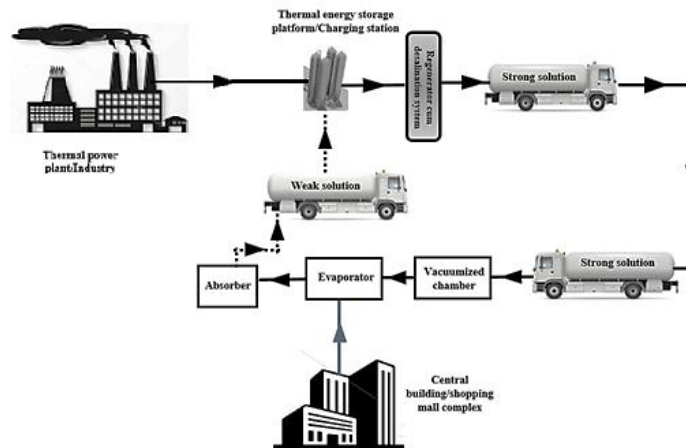


Fig. 7: Schematic of a centralized vapor absorption system for sustainable space cooling.

3.1 System comparison and analysis

The objective of this study is to evaluate the performance of thermal energy storage (TES) systems for sorption-based applications, focusing on energy storage capacity and costs. The sorption systems can be categorized into two types based on their interaction with the ambient air: open systems and closed systems. The choice of mass and heat exchangers, as well as the overall system design, depends on the specific sorbent material used. Closed systems are considered for sorbent materials that react with carbon dioxide and are hazardous when in contact with the air. On the other hand, open systems are used for nonhazardous sorbent materials due to their simpler operation. Fig. 8 [16] provides an overview of various sorption systems that have been installed for space cooling and heating applications. In an open sorption system, energy and mass exchange occur with the surrounding environment, and the system operates at ambient pressure. The sorbate, or the substance being sorbed, is both released to and sourced back from the atmosphere. Unlike closed systems, open systems do not include sorbate storage, condenser, and evaporator units, and they do not require pressure or vacuum conditions. As a result, the volume and complexity of the system are reduced. The temperature lifts that are obtained from the open and closed systems for different types of materials can be observed from the literature review. Based on these observations, the temperature lifts obtained in other closed and open systems implementing absorption or adsorption methods for different materials are tabulated in Table 2.

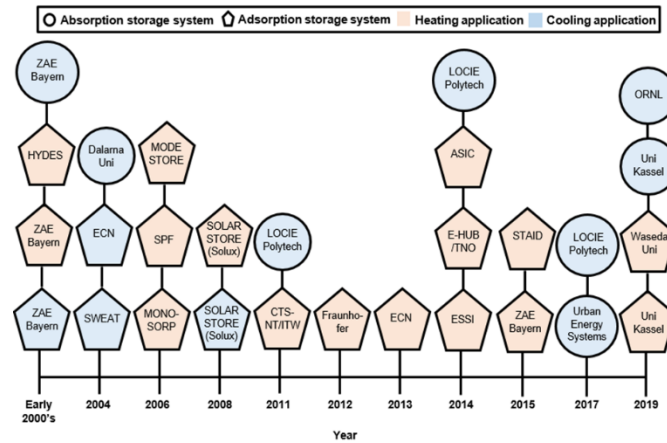


Fig. 8: Adsorption and absorption systems installed till date for space heating and cooling application.

Table 2: Temperature lift for various sorption MTES systems reported in the literature [13, 17].

Sl. No.	Type of system	Type of material	System temperature lift range (K)
1.	Open adsorption system	SG+CaCl ₂ (43 wt.%)	12.1–16.8
2.	Closed adsorption system	SG+MgCl ₂ ·2H ₂ O (44 wt.%)	7.5–10.0
3.	Closed adsorption system	SG+SrBr ₂ (58 wt.%)	5.2–8.0
4.	Open adsorption system	Zeolite 13X /Zeolite 4A	15–25
5.	Open adsorption system	SG+CaCl ₂ (43 wt.%)	6–15
6.	Closed absorption system	NaOH	35
7.	Closed absorption system	LiBr-H ₂ O	7–30
8.	Closed absorption system	KOH	3–7
9.	Closed absorption system	NaOH	3–15

4. Numerical analysis

Numerical analysis employs models to enhance the comprehension of the behavior of various sorption materials concerning system design, analysis, and process interpretation. These simulations utilize approaches such as the finite difference method (FDM), finite element method (FEM), or finite volume method (FVM) [6, 18]. The choice of simulation method depends on the model's nature, whether it is three-dimensional (3D), two-dimensional (2D), or one-dimensional (1D). Further details regarding the chosen simulations are elaborated (Fig. 9).

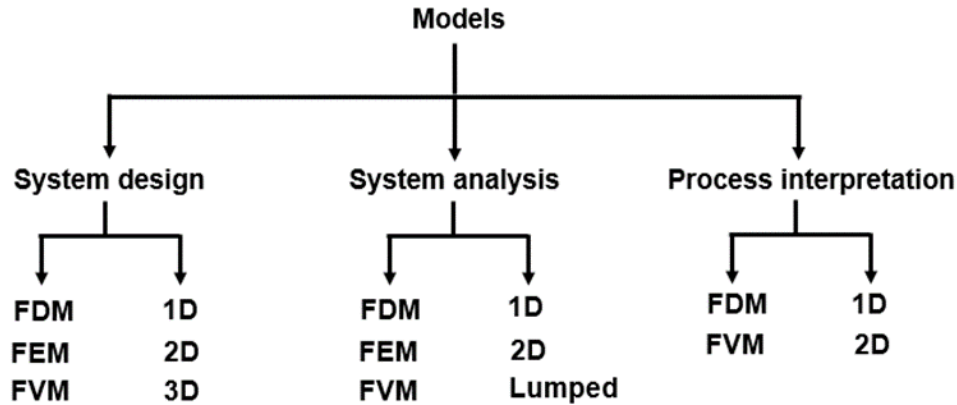


Fig. 9. Model classification based on the system design, analysis, and interpretation.

Fig. 10a provides graphical representations of the computational time and accuracy of results observed for the different numerical simulation methods: FDM, FEM, and FVM. Accuracy is measured based on the number of assumptions made by each method. FEM exhibits the highest accuracy as it makes the fewest assumptions, but it comes with a significant computational time requirement. On the other hand, FVM involves numerous assumptions, resulting in lower accuracy, but it offers faster computational time. FDM falls between FEM and FVM in terms of accuracy, number of assumptions, and computational time. These graphical representations visually illustrate the trade-offs between accuracy and computational efficiency associated with each simulation method. Based on the accuracy, number of assumptions, and processing time, several types of models are graphically shown (Fig. 10b). The models can be divided into lumped systems, 1D, 2D, and 3D categories. The shortest computational times are seen in 1D models because of their less complicated structures and simpler discretization settings. However, because of their simplification, they make more assumptions, which reduces their accuracy. On the other hand, 3D models provide more accuracy since they can record more system parameters. However, their higher complexity results in longer computational times, primarily due to the time-consuming process of discretization and simulation. Comparatively, 2D and lumped systems have similar numbers of assumptions, with 2D models providing slightly higher accuracy than lumped systems. However, lumped systems offer slightly lower computational times.

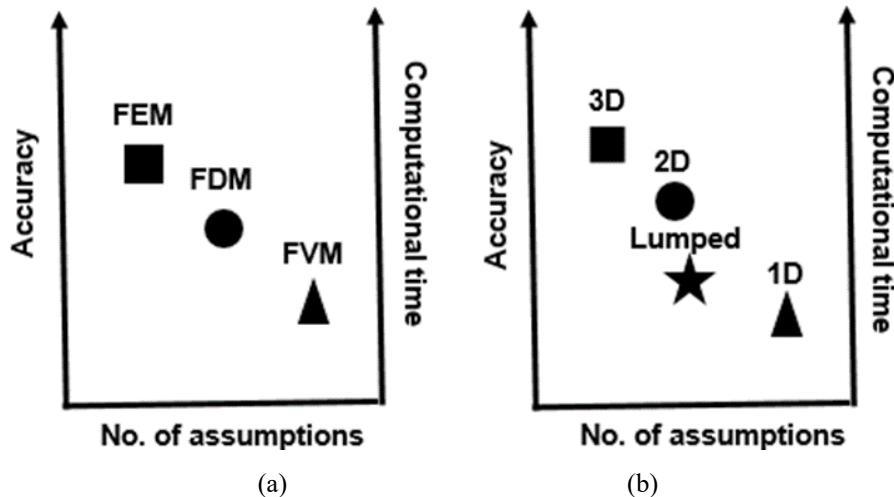


Fig. 10: Variation of accuracy and computational time.

5. Conclusions

The sorption-based thermal energy storage (TES) concept, specifically using desiccant-based energy storage, is widely regarded as the most effective method for sustainable building cooling and heating applications. It enables the storage of energy at low

temperatures for extended periods while offering high energy storage capacity and density, along with economic viability. The review of sorption TES technologies created expressly for desiccant-based energy storage in sustainable building applications is the main goal of the current work. The examination covers materials, system configurations, numerical models, and resources employed for optimizing and predicting the performance of these systems. We pay special attention to the usage of sorption-based multi-bed TES (MTES) systems, which have shown promise in sustainable building cooling and heating applications. The following points must be taken into consideration from the review on sorption-based MTES for DEN-based sustainable building cooling and heating applications:

- From the material viewpoint, it is found that LiBr/H₂O, KOH/H₂O, CaCl₂/H₂O, and LiCl/H₂O have small charging/regeneration temperature, less sorption material cost per ton, and elevated energy storage density/capacity.
- Depending on the system performance comparison case study for selected materials (LiBr/H₂O, KOH/H₂O, CaCl₂/H₂O, and LiCl/H₂O), it is observed that LiCl/H₂O found to be the suitable material for MTES system application due to high-temperature lift, low charging/ regeneration temperature, low required volume per 1000 kWh of capacity and high system efficiency. But LiCl/H₂O is highly corrosive, expensive, and toxic in nature compared to CaCl₂/H₂O and KOH/H₂O materials.
- From the system point of view, for building heating/cooling applications, it is understood that an absorption-based closed system has a high-temperature lift, energy storage density is high, and low regeneration/charging temperature.
- Based on the literature, it has been noticed that most of the established models were emphasized on the system design and analysis, and very little emphasis is given to process interpretation. Further, the majority of the numerical models were developed for adsorption-based MTES systems, and very limited research was carried out on theoretical investigations of absorption-based MTES system.
- Based on 1D, 2D, 3D and lumped thermal models for MTES, it is observed that 3D thermal models have fewer assumptions, high accuracy, and more computational time. Further, based on FVM, FDM, FEM, and hybrid (combination of FDM and FEM or FEM and FVM) models for MTES device, it is found that hybrid models can be used for design control, simulation, optimization, and geometric aspects but the computational time and required number of iterations are high.

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Nomenclature

M_{sorp}	mass of sorption material after absorption/adsorption	(kg _{mat})	ESD	energy storage density	(GJ/m ³)
T	Temperature	(kg _{mat})	FDM	finite difference method	--
K	Kelvin	K	FEM	finite element method	--
ρ_m	minimum density of the sorption material	(kg/m ³)	FVM	finite volume method	--
δ_m	dilution enthalpy	(kJ/kg)	$MTES$	mobile thermal energy storage	--
ψ	mass fraction of sorption material	(kg _{sorp} /kg _{mat})	TES	thermal energy storage	--

ΔX	change in mass of water per unit mass of sorption material ($\text{kg}_w/\text{kg}_{\text{sorp}}$)	($\text{kg}_w/\text{kg}_{\text{sorp}}$)			
DEN	district energy network	--			
ESC	energy storage capacity	($\text{GJ}/\text{kg}_{\text{dryzeolite}}$)			

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