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Life Cycle Assessment of Sensible, Latent and Thermochemical Thermal Energy Storage Systems for Climate Change Mitigation – A Systematic Review

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Abstract
Renewable energy sources coupled with thermal energy storage (TES) systems offer a better hope in mitigating climate change. But, in order to integrate TES systems into the grid, it is important to understand their environmental performances. Life cycle assessment (LCA) serves as a leading methodological tool for environmental decision-making processes that allows one to identify the critical areas of improvement in a product life cycle, and hence can be used effectively in climate change mitigation strategies. Due to the scarcity of review articles that provide useful information on the LCAs of TES systems, a total of 23 papers were reviewed in this study. These were reviewed under three categories: sensible heat storage (SHS) systems, latent heat storage (LHS) systems, and thermochemical heat storage (THS) systems. Further, the greenhouse gas (GHG) emissions arising from TES systems were evaluated, giving special attention on the global warming potential impact category. The production stage was found to be the major contributor to GWP in all three TES systems. Following this review study, it can be concluded that the environmental performance can be greatly enhanced through TES systems, due to significant reductions in GHG emissions.

Keywords: LCA, thermal energy storage, sensible heat, latent heat, thermochemical heat, PCMs
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1. Introduction

Climate change is the greatest threat the world has ever experienced, causing extreme weather events such as severe droughts, storms, and heat waves. Greenhouse gas (GHG) emissions associated with the provision of energy services are a major cause of this catastrophic climate change [1]. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), intense mitigation actions are indispensable to limit global warming to 1.5 °C, if we are to achieve an equitable and sustainable world [2]. Back in 2007, the IPCC reported that climate change is likely to be caused by humans, and since then, the evidence has only gotten more conclusive. According to a recent survey by the International Energy Agency (IEA), the overall GHG emissions from the energy sector rose to their highest-ever level in 2021, to 36.3 Gt [3]. This accounted for 46% of the global increase in carbon dioxide (CO_2) emissions, coal being the biggest contributor. Coal-induced CO_2 emissions stood at an all-time high of 15.3 Gt in 2021, as the world economy rebounded strongly from the Covid-19 crisis and had to rely heavily on coal to power that growth. Despite all this, the global electricity generation through renewable sources was at an all-time high, exceeding 8000 TWh in 2021 [3]. Hence, the share of renewable sources in global electricity generation was 29% with solar PV and wind energy contributing to more than two-thirds. If not for these clean energy sources, the rise in global CO_2 emissions would have been 220 Mt higher, in 2021. Thus, conserving energy and switching from fossil fuels to renewable energy (RE) technologies is crucial to mitigate the GHG emissions arising from the energy sector. In order to reach the goal of net zero emissions by 2050, the energy generation through renewable sources has to increase from 29% in 2021 to more than 60% by 2030 [4].

However, RE sources, in particular solar and wind, are intermittent in nature. This impedes the possibility of complete reliance on these energy sources alone, for an electrical grid. Solar panels may be inefficient under rainy weather, wind turbines may be inefficient if the wind is calm, and at times these RE sources may produce surplus energy that cannot be handled by the grid. So, to reduce the impact of inconsistent energy generation from these RE sources, and to maintain a proper balance between demand and energy generation, scientists have developed energy storage systems (ESS) to store excess energy to be used when the demand is high. On the other hand, the demand for electrical energy is increasing rapidly on a daily basis, so there is a need for reliable renewable ESSs that can satisfy future energy needs.

Although various ESSs are available, the importance of thermal energy storage (TES) for RE resources is growing. In such a context, this article focuses on TES systems with a life cycle assessment (LCA) approach. As identified by the two bibliometric studies on TES [5], [6], there is a huge research gap related to LCA studies of TES systems, despite the large number of publications available on TES. To the best of my knowledge, only one article presented a review on LCAs related to TES systems in recent years, but that too wasn't comprehensive. Therefore, this article conducts a systematic review on LCAs of TES systems and their recent advances. LCA is a quantitative method that evaluates the environmental impacts of products and services during their whole life cycle, from cradle-to-grave [7], and it covers a broad range of environmental issues [8]. Furthermore, LCA is a tool that is generally utilized for environmental decision-making processes through the identification of critical areas of improvement, and hence can be used effectively in climate change mitigation strategies [8]. In a study conducted to compare the IPCC methodology versus the LCA methodology, the authors found that the GHG emissions calculated using the LCA method was 20% higher than the IPCC method, when assessing energy-related emissions. Further, the authors concluded that LCA was more effective in achieving GHG reduction goals at a global level [9]. The insightful information presented in this article can serve as an important tool for the researchers interested in TES, and also for the energy companies and governments that are investing in RE sources and TES systems.

This review paper is organized into four sections. Section 2 provides an overview of the TES systems and their recent advances. Section 3 provides an overview of the LCA methodology and goes on to review the LCA studies of TES technologies, categorized as sensible, latent and thermochemical, highlighting their potential to mitigate climate change. Finally, section 4 outlines the research gaps and recommendations for future research.

2. An overview of thermal energy storage systems

TES systems store energy in the form of heat by heating, cooling, condensing, melting, or vaporizing a substance, which is used when the energy demand is high [10], [11]. The importance of TES in future energy systems lies in the fact that half of the total final energy consumption can be attributed to heat. Hence, the application of TES with RE sources can replace the heat generation from fossil fuels, thereby reducing GHG emissions. According to a report on TES by the International Renewable Energy Agency (IRENA), TES has the potential to be an important enabler of increased renewables penetration in energy systems [12]. Key applications of TES in energy systems include demand shifting, seasonal storage, network reinforcement deferral, sector integration, and variable supply integration [12]. When considering seasonal storage, TES systems can store RE for days or even months to help address seasonal variability in supply and demand. It has been estimated that by the extensive use of TES, around 400 Gt of CO_2 emissions could be avoided in the building and industrial sectors in Europe [13].

When considering the overall ESSs, TES has the second-highest installed capacity of 3.21 GW [10]. TES systems are divided into two categories based on its operating temperature: high-temperature energy storage systems and low-temperature energy storage systems. But the most common and frequently used method of categorizing TES systems is by the form of energy stored: sensible heat storage (SHS) systems, latent heat storage (LHS) systems and thermochemical heat storage (THS) systems [10], [11], [14]. Out of these, SHS is considered to be the most developed and widely used technology [14].

2.1. Sensible heat storage (SHS) systems

SHS is based on storing thermal energy by heating or cooling a storage medium, particularly a liquid or solid medium (water, soil, rocks, concrete, or molten salts), without changing its phase [13], [15]. In the comprehensive review conducted by [11], SHS is classified into two types: sensible solid storage and sensible liquid storage. Sensible liquid storage includes hot water TES, aquifer TES, gravel-water TES, molten-salt TES, and cavern TES. Sensible solid storage includes packed-bed TES and borehole TES. Among these, cavern TES, borehole TES and aquifer TES can be classified as underground TES (UTES) systems. UTES systems are mostly used for district heating applications. Hot water TES systems are used for seasonal storage in large-scale applications. Packed-bed TES systems are utilized in buildings and households that usually require only low-grade heat. Molten-salt TES systems are used for the storage of high-grade heat, and are used almost exclusively to help integrate concentrated solar power (CSP), where heat is stored during the day and discharged at night. Molten-salt is commonly used in CSP facilities that use sun-tracking mirrors (heliostats) or parabolic mirrors (troughs). Currently, over 21 GWh of molten-salt storage capacity is installed worldwide. SHS systems offer storage capacities ranging from 10 kWh to 50 kWh per tonne, and the working temperature range generally varies between -160 °C to more than 1000 °C [12]. Compared to other TES systems, SHS offers the simplest and often the cheapest form of storage, mostly due to the usage of water as a storage medium [12], [16]. As a result, SHS is the most commercially widespread today [12].

2.2. Latent heat storage (LHS) systems

In LHS systems the thermal energy is stored or retrieved when the storage material changes from one phase to another, at a constant temperature [11], [17], [18]. LHS systems use phase change materials (PCMs) as the energy storage medium. PCMs are advanced materials that substantially contribute to the efficient use of solar energy and waste heat. LHS systems are broadly classified either based on the type of phase change: solid-liquid, solid-gas, solid-solid, and liquid-gas, or based on the storage material: ice and PCMs. Despite the high latent heat, solid-gas and liquid-gas transformations are generally not employed since gases occupy large volumes. Compared to other transformations, the solid-liquid transition is more efficient, hence, is the most widely used. PCMs integrated with solar collectors in building applications has been found to be effective against the mismatch between supply and demand, and in reducing CO_2 emissions [19].

PCMs can typically be categorized based on the material nature, or based on their operational temperature. Based on the material nature, PCMs are subdivided into organic PCMs, inorganic PCMs or eutectics. Organic PCMs (paraffin wax and fatty acids) have high storage density. Inorganic PCMs include salt hydrates and metallics, and salt hydrates are known to have the highest storage density with minimum heat losses during storage. Apart from these two, eutectics are gaining interest from researchers due to their fixed freezing/melting point. Based on the operational temperature PCMs are subdivided into sub-zero PCMs (0 °C), low-temperature PCMs (0-120 °C) and high-temperature PCMs (above 120 °C). Compared to SHS materials, PCMs have a higher energy density, and can store 5-14 times more energy per unit volume.

Despite several advantages, one major limitation of PCMs is their lower thermal conductivity [19]. Novel research on PCMs is focused on identifying better materials with low cost, improved thermal conductivities, better thermal stability and long-term storage capacities. Venkateswarlu and Ramakrishna [20] reviewed the recent advances in PCMs for TES and found micro PCMs, metal-organic PCMs, bio-based PCMs, metal-organic framework (MOF) PCMs and nano encapsulated PCMs are the recent trends in PCM studies. The authors provide insight into how the thermal conductivity of PCMs can be enhanced significantly by the use of composite PCMs, MOFs, PCM slurries, and exfoliated graphite nanoplates.

2.3. Thermochemical heat storage (THS) systems

The storage density per unit volume of THS materials is 8-10 times higher than the SHS systems, while it’s 2 times higher than the LHS materials [21]. THS systems are generally divided into reversible thermochemical reaction-based storage and sorption-based energy storage. In the review by [21], the authors have conducted an extensive study on sorption and reversible reaction-based storage materials. In a reversible reaction, a thermochemical material is converted into two components with the addition of heat. By recombining these two components, the original material is reproduced, releasing the same amount of heat that was previously stored (exothermic synthesis reaction) [22]. In a sorption process, heat is stored by breaking the binding energy between the sorbent and the sorbate. Reversible thermochemical reaction-based storage consists of technologies such as chemical looping, redox reactions and metal hydrides. Chemical looping is a promising technology that is explored as a potential carbon capture technology as well. For example, in a calcium looping (CaL) process, the reversible reaction between CaO and CO_2 producing $CaCO_3$ is used to store and release energy as required. In more recent studies, CaL technology’s potential for storing energy in CSP facilities is being explored. Sorption-based storage consists of hydration/dehydration, liquid-based sorption and porous solid sorption. In recent years, THS is widely researched as potential seasonal energy storage systems and is amongst the most promising options to increase the integration of RE sources. A recent study by Farulla et al. [23] features a state-of-the-art comprehensive review on THS systems, both at a system and material level and discusses the advantages and also challenges faced by THS systems.

Table 1. features the recent trends and research gaps in TES systems which were identified through bibliographic studies conducted by [5], [6], in 2021. PCMs related to TES show the highest number of research studies, while thermochemical TES is the most recent technology studied.

Table 1. Recent trends and research gaps in TES systems [5], [6]

TES system	Most studied areas	Recent trends	Main category of study	Research gaps
TES systems (overall)	Numerical studies on TES systems with particular relevance to solar energy; PCMs.	Thermochemical TES	TES applied to buildings	Environmental impacts of TES systems; LCA; GHG emissions; & techno-economic analysis
Sensible heat storage (SHS)	Solar applications in CSP plants; optimization, demand side management, cogeneration; waste heat recovery; distributed energy systems	Distributed energy systems based on demand-side management	TES applied to districts	LCA; economic analysis; pumped thermal energy storage
Latent heat storage (LHS)	Material development related to PCMs; heat transfer enhancement through the use of PCMs coupled with nanomaterials or nanofluids; enhancement of thermal properties through microencapsulation & shape-stabilized PCMs	Bio-based PCMs, nano-enhanced PCMs, Solar applications	TES applied to buildings	LCA; GHG emissions; techno-economic analysis; use of nanomaterials, nanofluids, & bio-based PCMs
Thermochemical heat storage (THS)	Developing new composites to achieve the required energy density (In this regard, zeolites, silica gel, & MOFs are studied as host materials); high-temperature applications in CSP plants	Sorption TES, solar thermochemical hybrid system, solar fuel	TES storage applied to buildings (seasonal storage)	LCA studies on materials & systems; application of sorption technologies; optimization techniques; environmental & economic analysis of sorption systems

Concentrated solar power – CSP

3. Life cycle assessment of thermal energy storage systems

LCA is a method that has been standardized by the International Organization for Standardization (ISO), specified by ISO 14040:2006 [24] & ISO 14044:2006 [25]. ISO 14040 describes the principles and framework for LCA studies, but it does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA. ISO 14044 on the other hand, specifies requirements and provides guidelines for LCA. In general, both these standards comprise four main stages: (i) definition of goal and scope, (ii) inventory analysis (iii) impact assessment, and (iv) interpretation. An excellent introduction to LCA can be obtained through [8]. Generally, there are two distinctive forms of LCA: attributional LCA (ALCA) and consequential LCA (CLCA), which guide the methodological decisions in the LCA [26]. ALCA answers the specific question, what part of the global environmental burdens belongs to the studied product, while CLCA answers the specific question, what is the impact of the studied product on the global environmental burdens [27]. Generally, most LCA studies related to TES follow the CLCA form, while some follow the ALCA form.

3.1. Overview of the LCA methodology

3.1.1. Goal and scope definition

The goal defines the main purpose of conducting the LCA study and its intended applications, the method used, its target audience, methodological limitations and type of analysis. The scope determines what product systems are to be assessed and includes the functional unit, the system boundary, allocations, and relevant perspectives to apply, i.e., ALCA or CLCA. When the life cycle of a product is considered, it consists of five phases: raw material extraction, manufacturing & processing, transportation, use phase, and finally waste disposal & recycling. When all five steps are included in the LCA, it is regarded as cradle-to-grave. However, if the product is assessed only up to the use phase, or even a step before, that scenario is considered cradle-to-gate. Out of the 23 publications considered in this review study, 14 studies used the cradle-to-grave approach, while the other 9 used the cradle-to-gate approach.

Another important aspect of the goal and scope phase is the definition of the functional unit. Especially when comparing the environmental performance of a product, this is used as a reference unit in quantifying energy use and the resulting emissions. If a study does not use a functional unit, it makes it difficult to compare the results from various energy storage types. kWh, MJ, and MWh of electricity are some of the common functional units considered in energy-related LCAs.

The other critical area to be considered in LCA-related studies is the modelling approach. In most process-based LCA, commercially available software and databases are used. For example, Karasu & Dincer [28] used SimaPro, Roux et al. [29] used OpenLCA, and De Falco et al. [30] used GaBi.

3.1.2. Inventory analysis

Life cycle inventory (LCI) analysis involves the most laborious stage of all, which involves the collection of data and modelling them into input-output flows. This also includes energy and flow balances for each unit process considered in the system boundary. When plant-specific primary data are lacking, researchers often rely on databases such as Ecoinvent, and ELCD, while others use literature inventories. The LCI is essential during LCAs since it directly affects the impact assessment phase. Furthermore, a clear and concise LCI is vital to ensure the reproducibility of a study, and should clearly describe the primary and secondary data and their sources [8].

3.1.3. Impact assessment

Life cycle impact assessment (LCIA) is both a qualitative and quantitative assessment of the environmental impacts, where the emissions and resource extractions are translated into a limited number of environmental impact scores [31]. Steps in LCIA involve the selection of impact categories, classification, characterization, normalization, and weighting. Of these five elements, normalization and weighting are considered optional according to the ISO standards [24], [25]. Among energy-related LCA studies, global warming potential (GWP) is the most common and frequently assessed impact category. Acidification potential (AP), eutrophication potential (EP), cumulative energy demand (CED), resource consumption, and toxicity effects are also often considered [32]. There are many commercially available LCIA analysis methods included in LCA software, such as ReCiPe, CML, TRACI, EDIP, IMPACT 2002+, which is chosen by the researcher depending on the requirements and specifications of the study. When considering the ReCiPe method it contains 18 impact categories at the midpoint level, while the endpoint level contains three impact categories: human health, resources and ecosystem quality. The last phase of an LCA analysis is the interpretation stage, where environmentally significant issues are identified and the obtained LCA results are assessed with respect to completeness, sensitivity and consistency. In addition, conclusions and recommendations are also a part of this stage [33].

3.2. LCA studies related to thermal energy storage & the potential to mitigate climate change

This study used databases such as “ScienceDirect”, “Google scholar”, “Scopus” and “Web of science” to access publications related to LCAs on TES systems. After searching the databases, 23 relevant studies were selected and reviewed. These were regrouped and categorized as LCAs on SHS, LHS, THS, and TES. The TES group includes the publications that assessed several TES systems in one paper, which is summarized in Table. 2.

Table 2. A detailed summary of comparative LCA studies on thermal energy storage systems

Ref.	Year	TES system	Goal	FU & System boundary	LCIA method, software & database	ICs	Emissions	Comment
Oró et al. [34]	2012 Spain	SHS in high-temperature concrete media	Compare the environmental impact of 3 different TES systems for CSP using LCA	Global impact per kWh stored Cradle-to-grave	EI99 Endpoint Ecoinvent 2009	HH EQ RE	Total impacts per kWh. Solid media: (50˚C) 0.80 (250˚C) 0.16	Solid media is by far the most environmentally friendly, mainly due to the construction simplicity
		SHS in molten salt media, based on a mixture of $NaNO_3$ & KNO_3					Molten salts (50˚C) 29.47 (250˚C) 5.89	Two tank molten salts storage poses the highest environmental impact
		LHS using a PCM made of KNO_3 & $NaNO_3$ eutectic mixture					PCM (50˚C) 12.59 (250˚C) 4.68	Since the PCM uses latent heat, its impact per kWh is reduced

Ref.	Year	TES system	Goal	FU & System boundary	LCIA method, software & database	ICs	Emissions	Comment
Thaker et al. [35]	2019 Canada	SHS: two-tank indirect (S1)	Evaluating the GHG emission footprints of 5 different TES systems for CSP applications	1 kWh of energy delivered from stored heat Cradle-to-grave	Excel-based model	GWP NER	30 gCO_2eq/kWh	The largest share of GHG emissions in all five systems is from production, attributed mainly to electricity & fossil fuel consumption by production facilities. S1 shows the highest GHG emission with a contribution of 80% to GWP
		SHS: two-tank direct (S2)					15 gCO_2eq/kWh	Since S2 uses two tanks the GHG emissions are higher than that of S3
		SHS: one-tank direct (S3)					11 gCO_2eq/kWh	Lowest GHG emissions when considering all five systems. This is attributed to its tank volume requirement. S3 uses only one tank
		LHS: uses encapsulated PCM & molten salt (S4)					21 gCO_2eq/kWh	In S4, GHG emissions are caused mainly by the production of PCMs (75%) and molten salts (25%)
		THS: uses ammonia (S5)					19 gCO_2eq/kWh	In S5, GHG emissions are a result of the operating conditions of ammonia, which makes up nearly 70% of production emissions

Functional unit – FU, impact categories – ICs, Human health – HH, ecosystem quality – EQ, Resources – RE, eco-indicator 99 – EI99, concentrated solar power – CSP

The potential of reducing the negative environmental impact of the manufacturing process of three types of TES systems for a solar power plant was evaluated by [34] using an LCA analysis. The three systems considered were: SHS in solid media (high-temperature concrete), SHS in liquid media (molten salt based on a mixture of $NaNO_3$ & KNO_3), and LHS using a PCM (eutectic salt made of KNO_3 & $NaNO_3$). It was discovered that the manufacturing of the heat-storing material caused the greatest negative environmental impact; in the case of concrete this was 23.46%, and in the case of molten salt and PCM, this accounted for 94.2% and 95.66%, respectively. But on a positive note, the solid media and PCM do not cause any negative impact during the operation phase, as opposed to molten salts which causes negative environmental impacts in their operational phase as well. It is of vital importance that the positive impacts obtained during the operation phase exceed the negative impacts of the manufacturing stage if we are to achieve carbon neutrality by 2050. Thaker et al. [35], in the LCA study, evaluated the GHG emission footprints of five TES systems to be used in CSP applications. Three SHS systems (S1- indirect two-tank, S2 – direct two-tank, S3 – direct one-tank), one LHS system (S4) and one THS system (S5) were evaluated. The production stage was the major contributor to GHG emissions in all five systems, with a share of 63% from S1, 47% from S2, 36% from S3, 70% from S4, and 67% from S5, out of the total life cycle emissions. Thus, considering a system that requires the least amount of material during its production stage would significantly reduce GHG emissions, thereby aiding in climate change mitigation.

3.3. LCA studies of sensible heat storage systems & the potential to mitigate climate change

Table 3. summarizes 8 recent publications related to LCA studies on SHS systems. While TES systems are increasingly becoming key enablers in the integration of RE sources into the grid and enhancing the stability of the grid, SHS systems continue to dominate the market. Multiple forms of SHS systems are already available commercially and are being used, while new ones are being investigated actively. But it is crucial that LCAs of those new technologies be performed at earlier stages of their development in order to have a better understanding of the potential in real-life applications.

Table 3. A detailed summary of LCA studies on sensible heat systems

Ref.	Year	SHS system description	Goal	FU & System boundary	LCIA method, software & databases	ICs	Emissions (GWP)	Comments
Fiaschi et al. [36]	2020 Italy	The storage system uses sensible heat liquid reservoirs, for cold and hot	Estimate the environmental impacts of a solar integrated thermo-electric	1 MWh of output electricity Cradle-to-grave	ReCiPe 2016 Midpoint OpenLCA Ecoinvent	GWP AP HTP PMF POF	June-August 855.56 kg-CO_2/MWh May-September 517.15 kg-CO_2/MWh	PV and solar thermal panels contribute most to the overall environmental burden

		storage.	ESS		v3.4	HH EQ RE	Jan-December 266.72 kg-CO_2/MWh	
Gasa et al. [31]	2021 Spain	Molten-salt tower, which is heated from 290 °C to 565 °C using heat from a CSP field with heliostats	Comparison of the LCA of a CSP plant with and without TES	1 kWh of net electricity fed to the grid Cradle-to-grave	ReCiPe 2016 Midpoint & Endpoint, IPCC2013 GWP Ecoinvent v3.6	GWP	Without TES 31 g-CO_2eq/kWh With TES 9.8 g-CO_2eq/kWh	Both the LCIA methods show that major impacts are caused by the solar field & the HTF. Nitrate molten-salts contributes up to 90% within this system
Nahhas et al. [37]	2018 Spain	Thermocline tank with a basalt packed bed, using air as the HTF	Evaluating environmental impacts from an air-basalt packed storage system in a CSP plant	Ratio of kWh produced Cradle-to-grave	CML 2001 Midpoint GaBi Ecoinvent	CED GWP WC	Basalt production 0.01-0.03 kgCO_2eq/kg Basalt storage system 1.5 gCO_2eq/kWh	Impact on GWP is about 86% lower for basalt than for molten salts. Mining & manufacturing stages of basalt show the highest impact on GWP
AlShafi & Bicer [38]	2021 Qatar	Two tank (hot & cold) molten salt TES	Estimating GHG emissions associated with the ES systems: molten salt TES, CAES & VRFB	1 kWh of energy Cradle-to-gate	CML 2001 GaBi v6.0	GWP ODP MAETP AP HTP	Molten salt TES 0.0306 kg-CO_2eq/kWh CAES 0.117 kg-CO_2eq/kWh VRFB 0.121 kg-CO_2eq/kWh	Production stage for the ES systems accounted for the highest share of carbon footprint
Welsch et al. [39]	2018 Germany	The storage system is a medium deep borehole heat exchanger (MD-BTES)	Environmental and economic implication due to the construction and integration of BD-BTES to the grid	25 GWh heat annually delivered to the district heating grid cradle-to-gate	CML 2001 Midpoint OpenLCA Ecoinvent v3.1, GaBi v5, Gemis v4.93	GWP CED	CHP + BTES 100,518 t-CO_2eq STC + BTES 94,852 t-CO_2eq CHP + STC + BTES 98,362 t-CO_2eq	Integrating an MD-BTES system reduces GWP by more than 40%
Stemmle et al. [40]	2021 Germany	Low temperature aquifer TES (ATES) system that has six wells with a depth of 28 m is used for heating and cooling.	Present a novel LCA regression model to be used for a wide range of ATES systems	gCO_2eq/ kWh Cradle-to-grave	IMPACT 2002+ v2.10 SimaPro v9.0.0.35	GWP HH EQ RE	83 gCO_2eq/kWh	Compared to natural gas & heating oil, 67% & 74% GHG reductions are achieved by the ATES system. Overall, a reduction of 59% in GHG emissions is achieved.
Karasu & Dincer [28]	2020 Canada	Bore-hole TES system. Pipes pass through 144 holes & this stretches 37 meters underground & covers an area of 35 m in diameter	Conducting an LCA on a solar based borehole TES system and applying it to DLSC (Real world application)	1 m^2 floor area of a Drake Landing house over its lifetime Cradle-to-grave	CML 2001 SimaPro v7.3 Ecoinvent	9 ICs with GWP	Drake Landing house with borehole TES 1910.02 kgCO_2eq/year Conventional Canadian house with fossil fuel 6344.50 kgCO_2eq/year	DLSC produces about 4.5 tonnes less GHG emissions per year
Roux et al. [29]	2021 France	Thermocline storage tank for SHS that is using air as the HTF and bauxite as filler materials	Optimize an existing industrial air-ceramic packed-bed TES system called EcoStock	Provide a discharge thermal exergy equal to that of the reference system during its life time of 25 years. Cradle-to-grave	ILCD 2016 Midpoint OpenLCA v1.8 Ecoinvent v3.5	GWP ADP PM CED	EcoStock 56,600 kgCO_2eq Exergy-optimized 52,900 kgCO_2eq LCA-optimized 50,700 kgCO_2eq	Environmental impacts of the exergy-optimized scenario increase by 6%. In the LCA-optimized scenario, the environmental impacts decrease by 9%.

Functional unit – FU, impact categories – ICs, Human health – HH, ecosystem quality – EQ, Resources – RE, human toxicity potential – HTP, particulate matter formation – PMF, photochemical ozone formation – POF, heat transfer fluid – HTF, concentrated solar power – CSP, water consumption – WC, ozone layer depletion – ODP, marine aquatic ecotoxicity – MAETP, Compressed air energy storage, drake landing solar community – DLSC, vanadium redox flow batteries - VRFB

In general, the GHG emissions from renewable energies are lower than those caused by fossil fuels. For renewable energies, the average emissions vary between 4–46 g of CO_2eq/kWh while the values vary between 469-1001 g CO_2eq/kWh for fossil fuels. In the LCA study conducted by [31] on the environmental impacts from a concentrated solar power (CSP) plant with and without TES, it was revealed that the total impacts without storage were more than double that for a plant with storage. When the impacts were further broken down into the impacts from the operational and manufacturing phases, nearly all the impacts were generated during the manufacturing phase for a CSP with storage. The same was true for the GWP impact category, kg-CO_2 emitted by the plant without TES storage was 67% higher than for a CSP plant with storage (Without TES – 31 g-CO_2eq/kWh, with TES 9.8 g-CO_2eq/kWh). The study by [38] discovered that molten salt TES has the least impact on GWP with a value of 0.0306 kg-CO_2eq/kWh in comparison to compressed air ES & vanadium redox flow batteries. Through the LCA study, they concluded that using electricity from solar PV rather than from the grid electricity critically reduces the overall environmental impacts, emphasizing the importance of integrating RE sources into the grid mix.

ATES is a geothermal system that allows long-term storage of TE in groundwater and it's a promising energy generation technology that can reduce GHG emissions. The study by Stemmle et al. [40] presents a novel LCA regression model that enables the analysis of environmental impacts caused by any hypothetical ATES system. This study shows that with the use of ATES systems, it is possible to have GHG reductions of up to 97% compared to conventional oil heating systems, with the growing share of RE sources in the electricity mix. Also, this study estimated that an amount of 2100 kgCO_2eq per household per year in Germany could be saved if natural gas and heating oil were to be completely replaced by ATES systems. The work by Karasu & Dincer [28] on integrating a solar-assisted borehole TES system into a Canadian housing community (DLSC) found that a conventional Canadian house powered by fossil fuels produces 6.34 tonnes of CO_2 emissions per year. In comparison, a DLSC house produced only 1.91 tonnes of CO_2 emissions per year, showing a reduction of 4.5 tonnes of GHG emissions per house per year. Considering the fact that TES systems contribute to 20% of the environmental footprint of a CSP plant, using a basalt-air packed bed storage system caused a reduction of about 12% for the GWP indicator, in the study by [37]. Further, in comparison to a conventional two tanks molten salt TES system, there was a 60% reduction in the GWP.

Estimation of the environmental impacts of a solar-integrated thermo-electric energy storage (TEES) system was conducted by [36]. Considering its operations, since this TEES system is powered by solar PV, the overall environmental burden drops during the months of high solar radiation; i.e., from June-August, it was 202.84 Pts/MWh, while it dropped to 122.59 Pts/MWh during May-September due to powerful radiation. Also, this study discovered that extending the work time also reduces the overall environmental burden. For instance, in the case of its full-year operation from January-December, the overall environmental burden dropped down to 62.99 Pts/MWh. Although the solar energy converting devices contributed most to the impact indicators, the overall LCA results revealed that the TEES system has a lower environmental impact than hydrogen storage systems.

3.4. LCA studies of latent heat storage systems & the potential to mitigate climate change

Berger et al. [41] evaluated the potential of encapsulated PCMs for increasing the storage capacity of a hot water tank, in comparison to a conventional battery storage system and discovered that the LHS system with encapsulated PCM leads to 10 times fewer CO_2 emissions per kWh of thermal energy delivered. This study further evaluated the performance of high-density polyethylene (HDPE) versus metal encapsulation materials for PCMs and discovered that HDPE performs better than metal in terms of the CO_2 payback time. The related emissions values are given in Table 4. Table 4. summarizes 8 recent publications related to LCA studies on LHS systems.

Buildings contribute dramatically to GHG emissions, and space conditioning in buildings is one scenario that is responsible for the majority of these GHG emissions. As a solution, RE sources coupled with upstream TES (uTES) with sensible heat storage (SHS) have been proven to be effective in reducing environmental impacts from buildings. The study by [42] makes further improvements to this system by incorporating PCMs, making the switch from SHS to LHS. Through this improvement, the authors were able to provide the benefit of dramatically reducing the volume of storage by a factor of 10. SHS systems require higher storage volumes with relatively high costs. LHS on the other hand requires only small storage volumes because they make use of the PCMs with higher energy densities than sensible systems. Many researchers have highlighted that the use of energy-efficient district heating systems (DHS) allows for decreased atmospheric pollution resulting from lower GHG emissions. Through the utilization of dispersed PCM heat storage systems, the energy efficiency of the existing district heating systems could be further enhanced [43]. When integrated with RE sources, these novel TES systems show great potential in reducing GHG emissions, thereby aiding in climate change mitigation. However, one major problem with dispersed PCM heat accumulators is the use of different solutions and the inconsistency in selection criteria. Hence, [43] proposed a standardization method for the selection of dispersed PCM heat accumulators for a DHS, which is presented along with an LCA analysis that takes all the environmental impacts into account. Due to the use of dispersed PCM heat storage, a 41% increase in system efficiency was achieved.

In the work by [48], paraffin, salt hydrates, zeolites, silica, organometallic structures and water-based PCMs were compared as a model for construction applications, as heat and cold storage materials. For heating & cooling, a useful temperature difference of 15K and 6K was represented, respectively. In the case of solutions with a small useful temperature difference of 6-10K, PCMs were found to be beneficial in comparison to water storage, with a difference in GWP of 0.54 $kgCO_2/kWh$. The LCA study conducted by [44] evaluated the potential of solar-integrated LHS technology with PCMs (S-LHTES-PCM), in meeting the goal of becoming carbon neutral by 2050 in UK homes. Lifetime-based sensitivity analysis of this study revealed that when the lifetime increases from 20 years to 40 years, the environmental performance significantly improves, leading to a lower GWP than natural gas, which is the primary source of energy in households in the UK. The main environmental hotspots identified in this study were mainly associated with the system's raw materials and energy consumption in the production stages. Due to this reason, extending the lifetime of the systems improve the environmental performance according to circular economy principles. TES by means of PCMs is a great opportunity to accelerate the use of RE sources, which could have a huge impact on mitigating climate change. Results from the study by [45] conclude that the GWP from organic PCMs is higher than the GWP by inorganic PCMs. While the GWP of the inorganic PCM was only 7,000 $kgCO_2eq/m^2$, the GWP from the organic PCM was 12,000 $kgCO_2eq/m^2$.

Table 4. A detailed summary of LCA studies on latent heat storage systems

Ref.	**Year**	**LHS system description**	**Goal**	**FU & system boundary**	**LCIA method, software & database**	**ICs**	**Emissions (GWP)**	**Comments**
Bernal et al. [44]	2021 UK	Solar-powered LHS system using sodium acetate trihydrate (SAT) as PCM (S-LHTES-PCM)	Asses the environmental impacts of the S-LHTES-PCM system and compare it with other domestic heat sources such as biomass, heat pumps and natural gas in the UK	1 kWh of heat produced by the S-LHTES-PCM system Cradle-to-grave	ReCiPe 2016 Midpoint (H) SimaPro v9.1 Ecoinvent v3.7	18 ICs & GWP	PCM system (20-years): 0.30 $kgCO_2eq/kWh$ PCM system (40-years): 0.19 $kgCO_2eq/kWh$ Heat pumps: 0.17 $kgCO_2eq/kWh$ Natural gas: 0.27 $kgCO_2eq/kWh$ Biomass: 0.03 $kgCO_2eq/kWh$	The solar collector, PCM, and the heat exchanger are the main environmental hotspots, contributing over 83% in all the 18 impact categories. In the GWP category, PCM tank & the heat exchanger contributes the most
Struhala et al.[45]	2019 Czech Republic	Heavy-weight PCM – S_1 Light-weight encapsulated inorganic PCM – S_2 Light-weight encapsulated organic PCM – S_3	Evaluation of environmental impacts of partition walls of PCMs utilizing LHS	1 m^2 of the evaluated partitions during a 50-year service life Cradle-to-grave	CML GaBi Ecoinvent	GWP PE	S1 8000 $kgCO_2eq/m^2$ S2 7000 $kgCO_2eq/m^2$ S3 12000 $kgCO_2eq/m^2$	Major impact on GWP is from $S_{3,}$ where the product stage & end-of-life demolition stage contributes about 94% on total GWP.
Berger et al. [41]	2022 Switzerland, Germany & Austria	Encapsulated PCM storage with a volume of 120 L powered by a decentralized heat pump. Encapsulated PCM are either HDPE or metal capsules	LCA analysis of a model PCM-enhanced hot water station to evaluate the impacts from HDPE & metal capsules	$kgCO_2eq/m^3$ of storage Cradle-to-gate	EF 2.0 Midpoint Ecoinvent v3.7	GWP	PCM with HDPE Capsule 245.75 $kgCO_2eq/m^3$ of storage PCM with metal capsule 47.84 $kgCO_2eq/m^3$ of storage	LHS with encapsulated PCM leads to about 10 times fewer CO_2 emissions per kWh in comparison to an electrical ESS with a heat pump
Guillen-Lambea et al. [46]	2020 Spain	LHS with paraffin emulsion – LTES1 LHS with sodium acetate trihydrate – LTES2	Minimization of the environmental burden through the introduction of TES systems with PCMs	Energy required to meet the energy demands Cradle-to-gate	IPCC 2013 GWP 100y, ReCiPe v1.13 Endpoint (H) SimaPro v9.0.0.35 Ecoinvent	GWP	LTES1 151,524 $kgCO_2eq/year$ LTES2 179,603 $kgCO_2eq/year$ SHS system 166,658 $kgCO_2eq/year$	LTES1 was the most environmentally friendly option, which shows a reduction of 10% CO_2 emissions in comparison to the SHS system

Ref.	**Year**	**LHS system description**	**Goal**	**FU & system boundary**	**LCIA method, software & database**	**ICs**	**Emissions (GWP)**	**Comments**
Bonamente & Aquino [42]	2019 Italy	SH-TES system is made of a concrete tank & water as the storage material. LH-TES system uses a PCM-based storage material instead of water	Upgrading the upstream TES system that uses sensible heat, to a more compact and efficient LHS system by incorporating PCMs.	1 kWh of thermal energy (kWht) provided Cradle-to-gate	CML-IA baseline v1.03 Midpoint, ReCipe2016 v1.03 Endpoint (H) SimaPro v9.0.0 Ecoinvent v3.5	GWPAP POP EP HH RE EQ	PCM-TES, Grid 0.108 kgCO$_2$eq/kWht PCM-TES, PV 0.0321 kgCO$_2$eq/kWht SH-TES, Grid 0.132 kgCO$_2$eq/kWht SH-TES, PV 0.0323 kgCO$_2$eq/kWht	The PCM-TES shows higher GWP in the storage stage, mainly due to the steel & PCMs. However, it was compensated at the end-of-life stage
De Falco et al. [30]	2017 Italy	ColdPeak cold energy storage system that incorporates PCM (n-tetradecane) with a stainless-steel shell, 12 coils, 60 nozzles & 33 valves	Life cycle environmental assessment of the already developed ColdPeak cold storage device in comparison to a conventional air conditioning system	1 kWh$_{cold}$ generated by the two systems Cradle-to-gate	ReCiPe Midpointt & Endpoint GaBi v6	GWPAP EP ET HH FD	Conventional system 0.28 kgCO$_2$eq ColdPeak Around 0.26 kgCO$_2$eq in low saving scenario Around 0.21 kgCO$_2$eq in high saving scenario	Integration of the cold storage unit allowed significant reductions in GWP (-17%), AP (-15.5%) & EP (-18%) compared to a conventional air conditioning system
Turski & Jachura [43]	2022 Poland	PCM heat accumulator with mineral wool insulation, heat exchanger made of primary metallurgical copper, and a tank housing made of stainless steel	Propose a standardization method for the selection of dispersed PCM heat storage systems for a district heating system, taking all the environmental impacts into account	Technical potential of heat storage of the district heating system (DHS) during the heating season Cradle-to-gate	EI99 Endpoint SimaPro EcoinventELCD	HH EQ RE	Avoided impacts for paraffin -50.21 kPt Avoided impacts for salt hydrate -128.8 kPt	Through the use of dispersed PCM heat accumulators in the DHS, the negative impact on the environment through the use of paraffin and salt hydrates was eliminated.
Jachura & Sekret [47]	2022 Poland	Paraffin is used as the heat storing material in the PCM	Carry out an environmental LCA of tube-vacuum solar collector prototype with and without PCM integration	The amount of heat generated for 15 years Cradle-to-grave	EI99 SimaPro EcoinventELCD USLCI	HH RE EQ	A - Human Health 234 Pt Ecosystem Quality 29 Pt Resources 87 Pt B - Human Health 248 Pt Ecosystem Quality 31 Pt Resources 72 Pt	Emissions indicated as (A) are for PCM used as a product with 90% recycling & producing the most environmental impacts, at the endpoint level. Emissions indicated as (B) are for a system without PCM usage, 90% recycling & producing the most environmental impacts

Functional unit – FU, impact categories – ICs, Human health – HH, ecosystem quality – EQ, Resources – RE, primary energy consumption – PE, high density polyethylene – HDPE, photochemical oxidation potential – POP, photovoltaic – PV, eco-toxicity – ET, human health – HH, fossil depletion – FD

3.5. LCA studies of thermochemical heat storage systems & the potential to mitigate climate change

Table 5. gives a detailed summary of 5 recent publications related to LCA studies on thermochemical heat storage systems. The LCA approach used to assess the impacts of integrating a THS system ($CaO/Ca(OH)_2$ – based) into a CSP plant showed an additional burden on the GWP impact category, but this additional burden was quite small [49]. GWP resulted without the THS system was 8.5 kgCO$_2$eq/MWh, while the GWP with the integrated THS system was 11 kgCO$_2$eq/MWh with an energy payback time of 4 months. But when compared to other storage materials such as ceramics or liquid salts, the use of $CaO/Ca(OH)_2$ system reduces the impacts on GWP.

Table 5. A detailed summary of LCA studies on thermochemical heat storage systems

Ref.	Year	THS system description	Goal	FU & system boundary	LCIA method, software & database	ICs	Emissions	Comments
Horn et al. [50]	2018 Germany	Six THS materials are considered. Zeolite 13X, Silica gel, Al-Fumarate MOF, CAU-10-H MOF, Mg-Sulphate salt hydrate, Lithium bromide salt solution.	Comparison between the TES systems based on THS materials & PCMs, through LCA	Based on storage material – 1 kg of storage material Based on component level – 1 kWh of thermal energy delivered Cradle-to-gate	Speicher LCA	GWP$_{100}$ PEC, PENRT, PERT,	Zeolite 13X ≈ 4.8 kgCO$_2$eq/kg Silica gel ≈ 1.5 kgCO$_2$eq/kg Lithium bromide ≈ 4.1 kgCO$_2$eq/kg CAU-10-H ≈ 7.8 kgCO$_2$eq/kg Mg-sulphate ≈ 0.4 kgCO$_2$eq/kg Al-Fumarate ≈ 6.3 kgCO$_2$eq/kg	THS materials require more complex manufacturing schemes, which results in higher emissions & GWP
Pelay et al. [49]	2020 France	THS material used is calcium hydroxide. Uses a reversible reaction of CaO/Ca(OH)$_2$ for high temperature operations	Life cycle assessment of a CSP plant integrated with THS	Constant production rate of 100 MW of the principal Rankine cycle and a lifetime of 25-years Cradle-to-gate	IMPACT 2002+ Midpoint SimaPro v7.3 Ecoinvent	14 ICs & GWP	With THS system 11 kgCO$_2$eq/MWh Without THS system 8.5 kgCO$_2$eq/MWh	The additional impact on GWP due to the addition of a THS system is relatively small (about 30%)
Colelli et al. [51]	2022	THS system based on Calcium Looping (CaL) technology (CaCO$_3$/CaO)	Evaluate the impacts generated from a CSP plant integrated with a CaL-based THS system, during its life cycle	1 MWh of electricity produced in a lifetime of 25-years Cradle-to-grave	CML 2001 Midpoint & Endpoint SimaPro v8.1 Ecoinvent v3.1	13 ICs & GWP HH EQ RE	Daily storage 25.3 kgCO$_2$eq/MWh Seasonal storage 23.2 kgCO$_2$eq/MWh	For daily storage higher contribution to GWP is from the storage system in the assembly phase (42%). For seasonal storage higher contribution to GWP is from the solar field (60%). In both cases end-phase has net negative contributions to GWP
Nienborg et al. [48]	2018 Germany	Solid sorption materials considered are: Silica gel, silicoaluminiumphosphates (SAPO-34), zeolite (Z13X), MOFs (CAU-10-H), Al-Fumarate), salt-composite (LiCl-Ver). Reference was water	Study the potential of five solid sorbents to be applied as TES materials for buildings, evaluated through storage capacity & GWP	Component level – 1 m^3 containment volume Cradle-to-grave	GaBi	GWP PE	Silica gel ≈ 1800 kgCO$_2$eq/m^3 SAPO-34 More than 20,000 kgCO$_2$eq/m^3 Z13X ≈ 2500 kgCO$_2$eq/m^3 CAU-10-H ≈ 2000 kgCO$_2$eq/m^3 Al-Fum ≈ 2000 kgCO$_2$eq/m^3 LiCl-Ver ≈ 2200 kgCO$_2$eq/m^3 Water ≈ 400 kgCO$_2$eq/m^3	SAPO-34 accounted for 98% from the overall GWP, while silica gel accounted for 69% from the overall GWP
Masruroh and Klemes [52]	2005 UK	THS unit, that consists of a reactor, condenser, evaporator, heat exchanger, and the reactive compounds (inorganic salts and binders)	Assess the impacts associated with the SOLARSTORE system integrated with THS, by using the LCA	1 GJ energy provided by the SOLARSTOR system Cradle-to-grave	-	GWP AD EP POP	6.3-10 kgCO$_2$	Raw material acquisition and component manufacturing stages contribute 99% to the overall environmental impacts during its whole life cycle

Functional unit – FU, impact categories – ICs, human health – HH, ecosystem quality – EQ, resources – RE, primary energy consumption – PEC, total use of non-renewable primary energy – PENRT, total use of renewable primary energy resources – PERT, photochemical oxidation potential – POP

The study by Horn et al. [50] compared the GWP arising from thermochemical heat storage (THS) materials & PCM materials in TES systems. The THS sorption materials considered were Zeolite 13X, Silica gel, Al-Fumarate MOF, CAU-10-H MOF, Mg-Sulphate salt hydrate, and Lithium bromide salt solution, while the PCMs considered were paraffin RT21, salt hydrate SP21EK & salt hydrate SP58. RT21 is a fossil-based paraffin, hence it showed the highest GWP (45 $kgCO_2eq/kWh$). Salt hydrate based PCMs had significantly lower contributions to GWP, with 5 $kgCO_2eq/kWh$ for SP21EK & 38 $kgCO_2eq/kWh$ for SP58. Compared to PCMs, THS sorption materials require more complex manufacturing schemes, which results in higher emissions & GWP. Although THS materials show higher energy densities than both the sensible & latent heat materials, the production of THS materials causes higher GWP values. CAU-10-H showed the highest GWP with a value of about 7.9 $kgCO_2eq/kg$ while the lowest GWP was shown by Mg-sulphate with a value of about 0.4 $kgCO_2eq/kg$. Further, this study investigated the number of full cycles required for amortization in silica gel and Zeolite 13X. The number of cycles needed by silica gel was close to 60, while for Zeolite 13X it was nearly 260 cycles, which means that it is not possible to regain the environmental impacts of Zeolite 13X within 100 full cycles. Zeolite 13X-based THS materials are therefore not suitable for applications with a low number of cycles over its lifetime, such as seasonal storage.

Nienborg et al. [53] compared the LCA results of five solid sorption materials, Silica gel, silicoaluminiumphosphates (SAPO-34), zeolite (Z13X), MOFs (CAU-10-H and Al-Fumarate), and salt-composite (LiCl-Vermiculite). Sensible heat storage in water served as the reference. At the material level, manufacturing of the five materials leads to GWPs much higher than that of water. The GWP from SAPO-34 was approximately 10 times higher than that of Z13X, while it was almost 30 times higher than that of silica gel. At the component level, the environmental impact from these five materials was 2.5 to 100 times higher than that of water. These findings suggest that the chances of TES with solid sorption materials providing significant environmental benefits are small unless major steps are taken to reduce the emissions arising at the manufacturing stages. [52] employed an LCA technique to study the environmental impacts caused by a new solar heating & cooling system that is integrated with a thermochemical storage system to improve the efficiency of traditional solar heating units. An environmental impact of 6.3-10 $kgCO_2$ arises when producing 1 GJ of energy with the use of this novel system. Based on the findings of this study, it draws the conclusion that in comparison to traditional solar heating units and fossil fuel heating units, this novel system is a far better solution to reduce the overall GHG emissions and other associated environmental impacts.

4. Conclusions

In recent years, TES systems have been found to be a promising way to manage the intermittency of RE sources and enhance the penetration of renewables. But, in order to integrate TES systems into the grid, it is important to understand their economic as well as environmental performances. In such a context, TES technologies are increasingly attracting the interest of many researchers. With the growing concern on climate change, global warming and other environmental impacts, a generalized environmental conscience has emerged generating demands for products with enhanced sustainability. However, reductions in such environmental impacts can only be attained after adequate research calculations. Thus, LCA serves as a leading methodological tool that allows one to measure the product sustainability, both quantitatively and qualitatively, by showing the negative environmental impacts and also the benefits, which leads to proper decision-making with a sustainable approach. Under such context, this paper provided a review on the LCAs of TES systems, categorizing them more broadly as LCAs of SHS systems, LCAs of LHS systems, and LCAs of THS systems. Further, the GHG emissions arising from TES systems were reviewed, with special attention on the GWP impact category.

Following the review, the production stage was found to be the major contributing stage to GWP in all three TES systems. In some cases, this share was as high as 95% of the total life cycle GHG emissions. Some authors attributed this to the system's raw materials and the increased consumption of fossil-based electricity during the production stages. Thus, considering a system that requires the least amount of material during its production stage, or incorporating raw materials with a lower carbon footprint would significantly reduce GHG emissions, thereby aiding in climate change mitigation. In comparison to SHS and LHS, THS provides the highest heat storage capacity without causing any thermal losses during the storage period. Despite these advantages, this technology is the commercially least advanced TES system, with SHS being the most commercially available system. This is mainly due to the high costs associated with the materials and the complexity of the equipment. These limitations hinder the potential of THS systems being implemented commercially. So, in order to reduce their potential drawbacks and improve their implementation, further research studies are required. But it is crucial that LCAs of those new technologies be performed at earlier stages of their development in order to have a better understanding of the potential in real-life applications. During the course of this review study, the authors came across only a handful of articles related to LCAs of THS systems, both on a material level and system level. Hence, more studies on LCAs of THS systems are recommended.

It is quite evident from this review study that RE coupled with TES systems offer a better hope to tackle climate change, through reduced GHG emissions. Further, it can be concluded that LCAs of TES systems are effective in achieving GHG reduction goals at a global level. The insightful information presented in this article can serve as an important tool for the researchers interested in TES, and also for the energy companies and governments that are investing in RE sources and TES systems.

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