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Review

Review on the Life Cycle Assessment of Thermal Energy Storage Used in Building Applications

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Abstract: To reduce building sector CO_2 emissions, integrating renewable energy and thermal energy storage (TES) into building design is crucial. TES provides a way of storing thermal energy during high renewable energy production for use later during peak energy demand in buildings. The type of thermal energy stored in TES can be divided into three categories: sensible, latent, and sorption/chemical. Unlike sensible TES, latent TES and sorption/chemical TES have not been widely applied; however, they have the advantage of a higher energy density, making them effective for building applications. Most TES research focuses on technical design and rarely addresses its environmental, social, and cost impact. Life cycle assessment (LCA) is an internationally standardized method for evaluating the environmental impacts of any process. Life cycle sustainability assessment (LCSA) is an expansion of LCA, including economic and social sustainability assessments. This paper aims to provide a literature review of the LCA and LCSA of TES, specifically for building applications. Concerning the low technology readiness level (TRL) of several TES systems, the challenges and benefits of conducting LCA for these systems are highlighted. Furthermore, based on published studies on emerging technologies for LCA, a suggested procedure to carry out the LCA of TES with low TRL is presented.

Keywords: thermal energy storage (TES); thermochemical energy storage (TCES); phase change material (PCM); life cycle assessment (LCA); life cycle sustainability assessment (LCSA); emerging technology; technology readiness level (TRL)

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1. Introduction

The building and construction sector accounted for 37% of total CO_2 emissions in 2020, with approximately 40% of the building's final energy consumption utilized for space heating and cooling [1]. One of the recommended roadmaps toward low-CO_2 buildings is integrating onsite renewable energy (e.g., solar energy) in the building design and increasing the number of buildings connected to the low-CO_2 heating supply [2]. However, daily and seasonal fluctuation of renewable energy generation leads to a periodical mismatch between supply and demand. Thermal energy storage (TES) provides a way of storing thermal energy during high renewable energy production for use later during the peak energy demand. Therefore, it could support the deployment of renewable energy in the building sector.

TES can be categorized based on the nature of stored energy, namely sensible, latent, and sorption/chemical [3], as shown in Figure 1. In sensible TES, the stored heat causes the storage medium's temperature to rise. The sensible TES is the most conventional, mature, and extensively used TES system because of its ease of operation and low cost [4]. However, sensible TES has the lowest energy density compared with latent TES and sorption/chemical TES (often referred to as thermochemical energy storage (TCES)) [3].

In building applications, latent TES employ phase change materials (PCM) to maintain thermal comfort and electrical peak load shifting [5]. The application of PCM in the building can be achieved through a passive or active approach [6]. In passive application, PCM is integrated into the building component, providing thermal inertia to low-thermal-mass structures, leading to a reduction in internal temperature variation [7]. Meanwhile, in an active application, PCM is contained in a thermal storage unit positioned inside or outside the building structure [6].

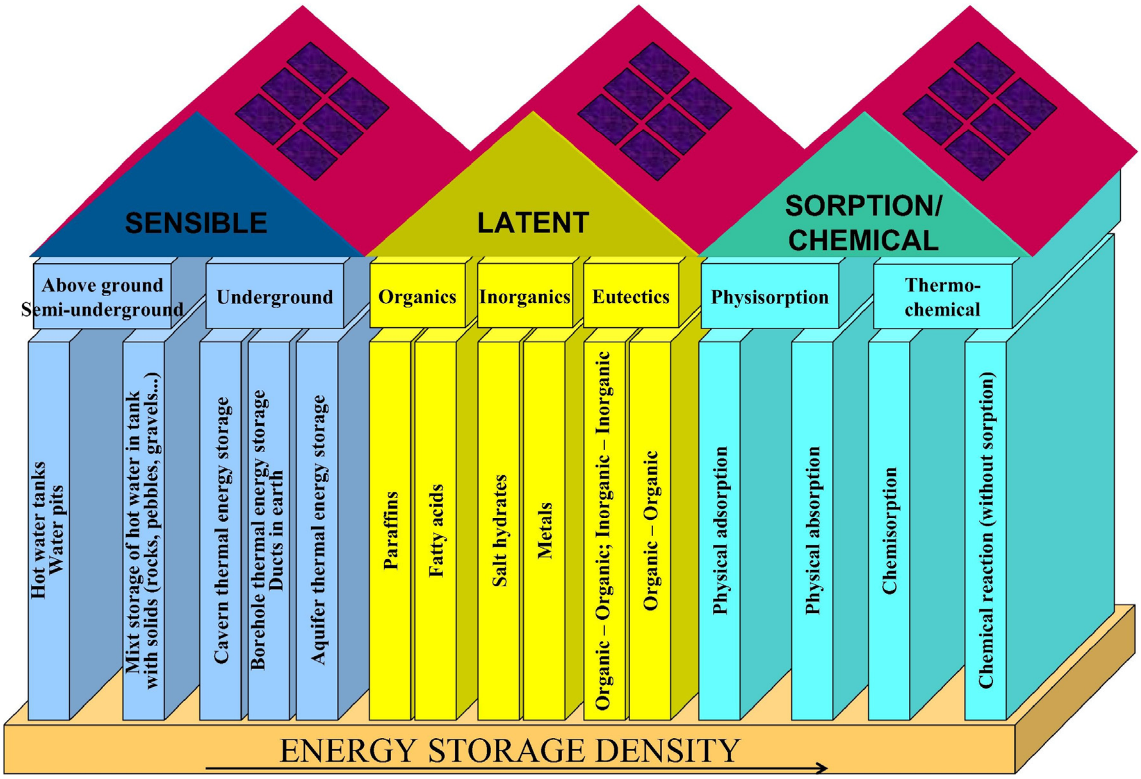

Figure 1. TES classification (reprinted from [3], with permission from Elsevier).

TCES utilizes a thermochemical material (TCM) and has the highest theoretical energy density among all TES [3]. It also allows for a long-term energy storage period, storage at an ambient temperature, low to no heat losses, and the possibility of long-distance energy transportation [8,9]. Current research suggests that salt hydrates are the most suitable TCM for building applications [10]. An example of a salt hydrate-based TCES application for building space heating is utilizing the solar heat collected during summer to dehydrate the salt hydrate (one of the thermochemical materials). The dehydrated salt is then stored at an ambient temperature, and subsequently, during winter, the salt is re-hydrated to generate the heat required for space heating [11].

As they are unconventional technologies, a large part of latent TES and TCES research currently focuses on the technical design aspects. However, as the technology advances, the research will expand to energy efficiency improvement, economic feasibility assessment, and environmental and social impact evaluation. Assessment of TES's environmental impact during its whole lifecycle can be done by implementing a life cycle assessment (LCA) [12]. Furthermore, the life cycle sustainability assessment (LCSA) is an expansion of LCA, including economic and social impact assessments [13].

1.1. Life Cycle Assessment (LCA)

The first partial environmental LCA studies were conducted in the late 1960s and early 1970s [14]. It was in 1993 when LCA became a tool with a specific methodology as described in the document titled "The Guidelines for LCA: A Code of Practice" [15]. Currently, LCA has become a standardized framework with the guidance for conducting an LCA provided in the following two documents issued by the International Organization for Standardization (ISO):

- ISO 14040: "LCA principles and framework"
- ISO 14044: "LCA requirements and guidelines"

The definition of LCA in these standards is a technique to comprehend and address the environmental aspects and possible environmental impacts throughout products'/services' life cycle [16]. The purpose of LCA is to evaluate the implications of the system, identify the largest source of impacts and insufficiencies for further improvement at various points of its life cycle [16,17], compare the impacts of competing systems [18], and provide information to governments or non-government organizations for strategic planning or policies and regulatory and commercial decision making [15,19].

There are four steps in the framework of conducting LCA: (1) goal and scope definition, (2) life cycle inventory analysis (LCI), (3) life cycle impact assessment (LCIA), and (4) life cycle interpretation [16]. The objectives and scope of the LCA research are set in the first step, considering the intended use and stakeholders. This step also determines the system boundary, functional unit, method, and data requirement. The LCI step comprises data acquisition and quantifying inputs and outputs for the product system throughout its life cycle, as determined by the specified functional unit. Potential environmental consequences are determined and categorized during the LCIA step based on the results of the LCI step. Lastly, all of the results are evaluated against the LCA objectives during the interpretation step, and the recommendations are made based on the interpretation result [17].

The scope of LCA studies may differ, as shown in Figure 2. The terminologies description is provided below [16,20,21]:

- Cradle-to-grave: a full assessment of a product throughout its entire life cycle (acquisition of raw material, manufacturing/production, utilization, and disposal).
- Cradle-to-gate: a partial assessment of the product from raw material acquisition to manufacturing/production. This scope ends at the factory fence (i.e., excluding distributions to the users).
- Gate-to-gate: a partial assessment of the product life cycle, focusing on only one process in the overall manufacturing/production, usually within the factory fence.
- Gate-to-grave: a partial assessment of the product life cycle, which includes the distribution to users, the utilization phase, and disposal.
- Cradle-to-cradle: this evaluation adopts a circular economy perspective, where the disposal of the product is recycled back to the input and closes the loop.

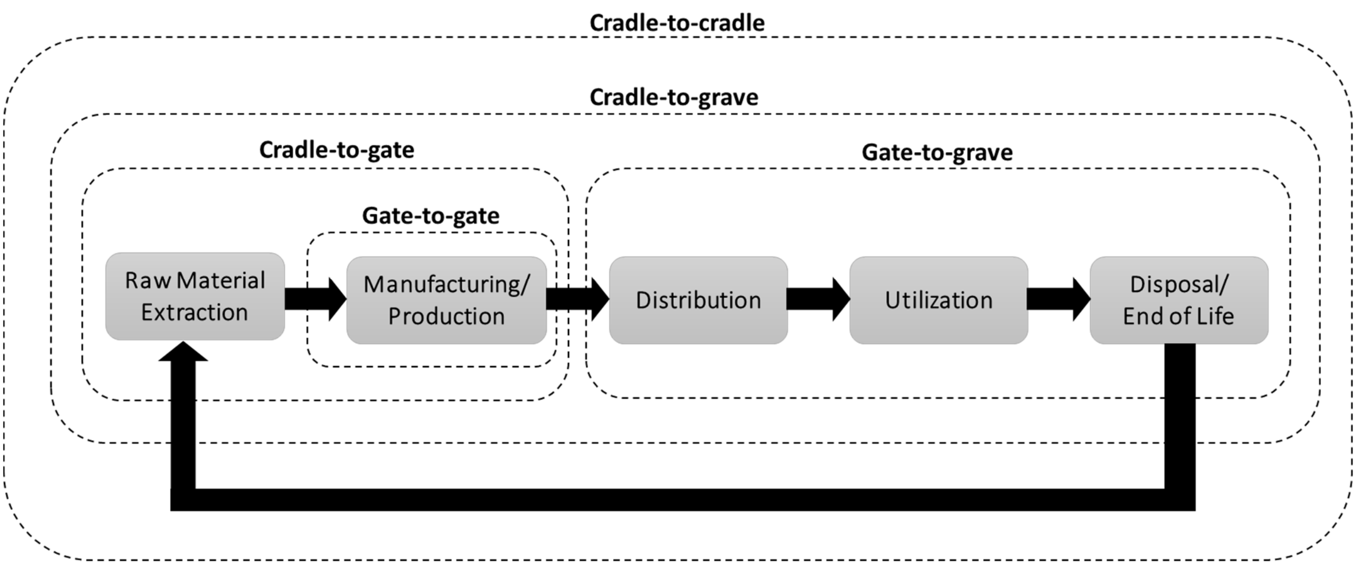

Figure 2. Scope of LCA.

During the inventory analysis phase of LCA, the background data required for the analysis are obtained from LCA databases. Various LCA databases are available for specific industries, countries, or fields. LCA software is the primary tool for conducting LCA. Software selection is based on the field, the availability of connected databases, the use, and the reason for specific studies [18]. The following tables (Tables 1 and 2) list several databases and software commonly used for LCA.

Table 1. LCA databases [18].

LCA Database	Description
US NREL LCI Database	US Data
ELCD database	Europe data
JLCA database	Japanese data
The Evah OzLCI2019	Australia data
Ecoinvent	Global data
Global LCA Data Access	Global Data

Table 2. LCA software [18].

LCA Software	Developer
Athena	Athena Institute (Sinking Spring, PA, USA)
BEES	National Institute of Standards and Technology (Gaithersburg, MD, USA)
CMLCA	Institute of Environmental Science (CML) (Leiden, The Netherlands)
GaBi	Sphera (Chicago, IL, USA)
SimaPro	Pre Consultants (Amersfoort, The Netherlands)
Umberto	Institute for Environmental Informatics (Hamburg, Germany)
OpenLCA	GreenDelta GmbH (Berlin, Germany)
OneClickLCA	One Click LCA Ltd. (Helsinki, Finland)

1.2. Life Cycle Sustainability Assessment (LCSA)

LCA is an assessment that focuses on the environmental dimension and does not cover the evaluation of the overall sustainability aspects [13]. The definition of sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [22]. It has three pillars: environmental sustainability, economic sustainability, and social sustainability [23]. Therefore, to achieve a comprehensive approach to sustainability, LCA has also expanded to include "life cycle costing" (LCC) and "social life cycle assessment" (SLCA), which forms a "life cycle sustainability assessment" (LCSA) [14]. With LCSA, the three pillars of sustainable development are integrated into a single formulation, while maintaining the life cycle perspective [24].

LCC is a technique to summarize all of the costs during the product or service's life cycle. The objective is to obtain a complete understanding of the monetary flows throughout their whole life cycle so that not only the initial cost is included in the decision-making process, but also the operation, maintenance, distribution, end-of-life treatment, and disposal costs [24,25]. LCC is typically conducted in four steps: (1) goal, scope, and functional unit definition; (2) inventory costs; (3) cost aggregation by cost categories; and (4) result interpretation [26]. Unlike LCA, LCC is not standardized to date. A code of practice document to perform LCC is issued by SETAC [27].

SLCA is an evaluation method of the social impacts throughout a products' life cycle. SLCA delivers information on social and socio-economic aspects for decision-making, aiming to improve an organization's social performance and, eventually, the well-being of stakeholders [28]. An SLCA is typically conducted in four steps: (1) goal and scope definition, (2) inventory, (3) impact assessment, and (4) interpretation [26]. As with LCC, SLCA is not standardized. A guideline document for performing SLCA has been published by UNEP [28].

Klöpffer [13] proposed LCSA as an integration of three individual assessments (LCA, LCC, and SLCA) conducted with consistent and identical system boundaries. This proposed concept is preferred to the other idea in which LCC and SLCA are included as the additional impact categories in the impact assessment step of an LCA. A document outlining the introduction to the LCSA concept, a guideline to implement LCSA into practice and also covering some case studies, was published by UNEP/SETAC [26]. The benefits of conducting LCSA, according to this document, include the following:

- LCSA provides a structured form that allows practitioners to unify complex environmental, economic, and social information and data.
- LCSA provides a more inclusive picture by examining the trade-offs between the three sustainability pillars along the product or technology life cycle.
- LCSA assists decision-makers in selecting sustainable products or technologies.

A study by Fauzi et al. [24] shows a growing number of LCSA-related publications, as shown in Figure 3 below.

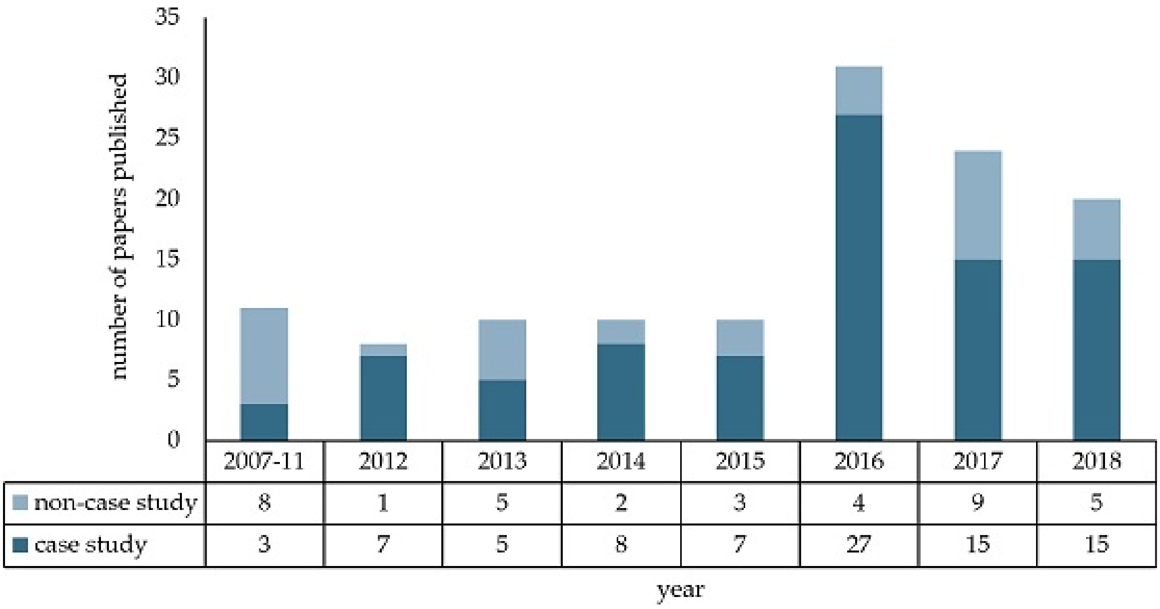

Figure 3. LCSA-related papers published from 2007 to October 2018 [24].

Visentin et al. [29] conducted bibliometric research on LCSA publications. It concluded that energy is the second largest thematic area in LCSA publication. The bibliometric research was based on of the all published papers up until the end of 2019 with the LCSA keyword (which resulted in 366 publications). It shows that there is increasing interest in LCSA applications related to energy. To date, there is no standardized framework for LCSA. The integrated databases and tools/software to perform LCSA are not yet available.

2. Literature of LCA/LCSA of TES for Building Applications

A literature search was conducted using the Scopus database in November 2022 in order to find the research publications on the topic of LCA or LCSA of TES. Scopus was selected as the most common search engine used by researchers. The results were filtered to only include "article" and "conference paper" document types. The chosen keywords and the number of publications found are summarized in the table below (Table 3).

Table 3. Literature search keywords and results.

Keywords	Result
("Life cycle assessment" OR "life cycle analysis" OR LCA) AND ("thermal energy storage" OR "thermochemical energy storage" OR "thermochemical storage" OR "sorption storage")	106 publications
("Life cycle sustainability assessment" OR "Life cycle sustainability analysis" OR LCSA) AND ("thermal energy storage" OR "thermochemical energy storage" OR "thermochemical storage" OR "sorption storage")	1 publication
("Life cycle sustainability assessment" OR "Life cycle sustainability analysis" OR LCSA) AND ("thermal energy storage" OR "thermochemical energy storage" OR "thermochemical storage" OR "sorption storage" OR "energy storage" OR "heat storage")	4 publications

The 106 publications found from the first keywords were further screened manually to confirm their relevance to LCA and TES, which resulted in 73 publications. The screened papers were then classified based on the type of TES and the applications. The results are shown in Figure 4 below.

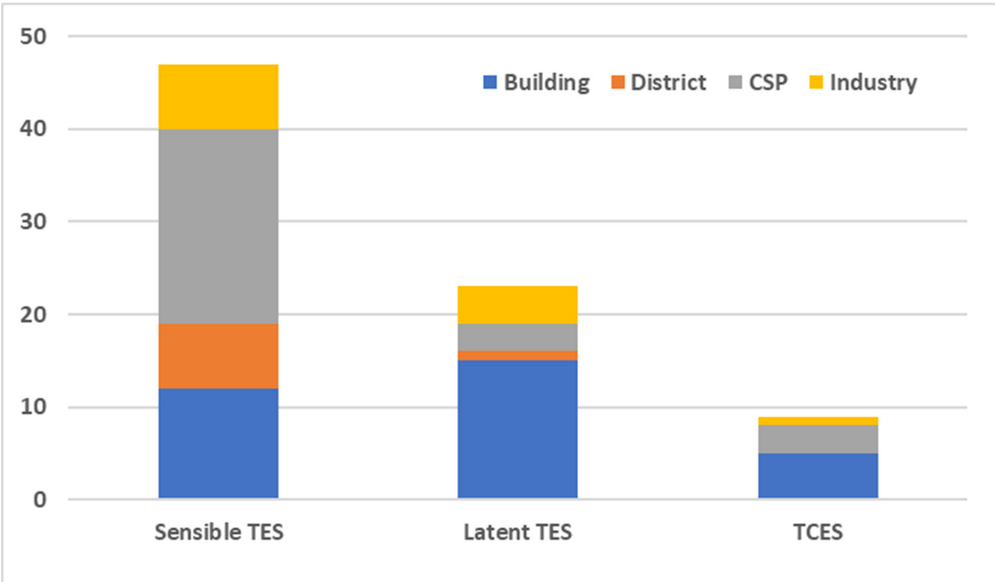

Figure 4. Number of publications on LCA of TES.

The above graph shows the largest number of LCA studies were done for the sensible TES, with concentrated solar plant (CSP) and buildings/district being the dominant applications in these studies. The high number of sensible TES publications indicates the maturity of this technology and its wide applications. Water is the most common medium of sensible TES for building applications [30]. The LCA studies of sensible TES [31–36] suggest that the implementation of water-based sensible TES results in environmental performance improvement compared with conventional buildings.

Meanwhile, for latent TES, the majority of LCA studies were for buildings application (63% of the publications). Some studies assessed water-based (steam/ice) latent TES [37,38], but overall, PCM was the most common material evaluated for latent TES in buildings. PCM can increase the thermal inertia of lightweight building construction, improving the thermal comfort inside the building [7]. In PCM's building applications, LCA examines the environmental impact of the integration of PCM into building material/components [39–41], or PCM as a substitution to/integrated with conventional energy storage [42,43], or to compare between different PCM materials [44,45]. The LCA results suggest that integrating PCM into building material reduces its environmental impact during the use phase due to lowering the electricity energy consumption [40]. However, using PCM to replace conventional building energy storage, such as hot water, is not always beneficial [43].

Among all of the TES types, the lowest number of LCA publications were found for TCES. There were nine LCA papers published for TCES, and only five of these articles were for building applications. The five articles for building applications consist of three LCA studies of TCES at the material/component level [12,46,47], meaning that the LCA study boundary only included the TCM or energy storage system component, not the overall building space heating system. The remaining two articles of TCES LCA for building applications assessed the overall building space heating system. However, these articles were written by the same authors and discussed the same system (SOLARSTORE) [48,49]; therefore, basically, there is only one LCA study on TCES at a system level.

The study by Masruroh et al. [48,49] assessed SOLARSTORE, a novel system based on endothermic/exothermic reactions of salt hydrate/water working pairs for solar heating/cooling applications. The study also compared the LCA results with conventional solar and fossil fuel-based heating systems. The system boundary of this study is shown in Figure 5. It was concluded that the SOLARSTORE system has the least negative environmental impacts compared with other heating/cooling systems, and 99% of the overall environmental effects were generated during raw material extraction and system components manufacturing.

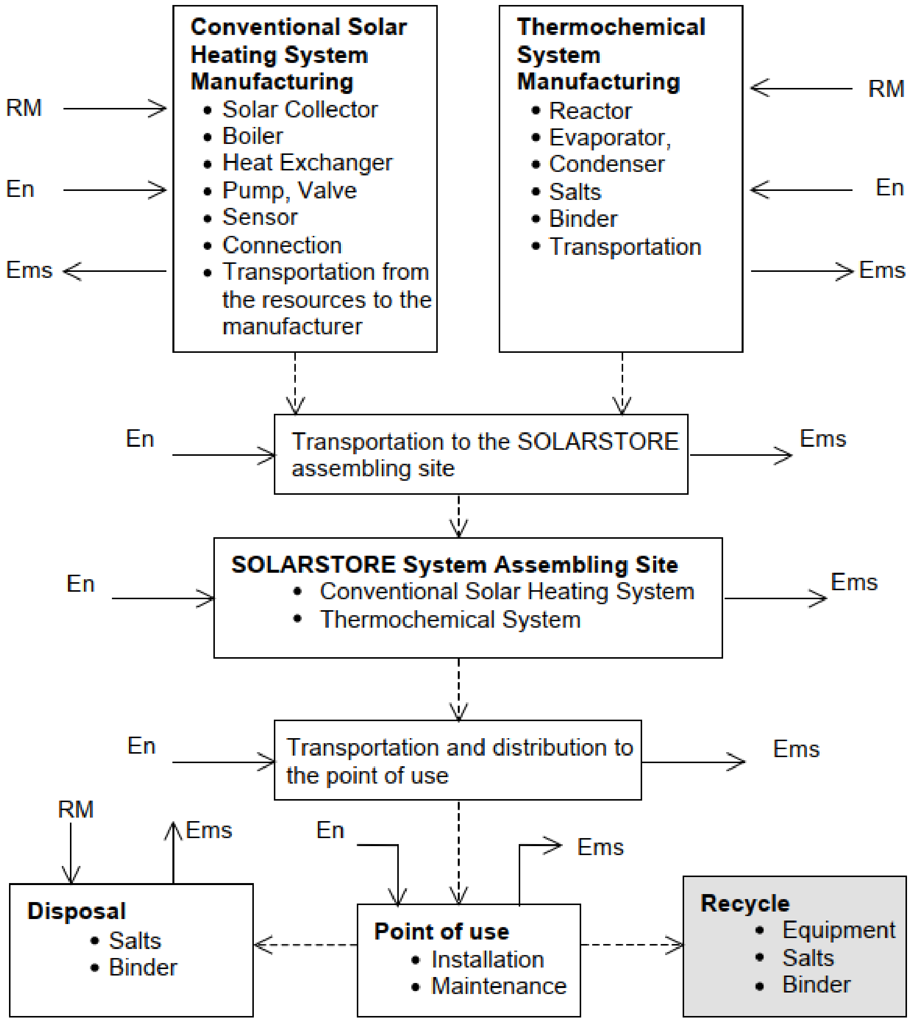

Figure 5. LCA boundary of conventional solar heating and a thermochemical heating system (reprinted from [49], with permission from Elsevier).

The conclusion from the above study that the TCES system exhibits a better environmental performance than the conventional system is not supported by the LCA studies of TCES at the material/component level [12,46,47]. These studies concluded that the solid sorption-based TCES is viewed as less environmentally beneficial than conventional water storage due to the high global warming potential (GWP) during its material production phase. The LCA results showed a higher environmental impact per storage capacity of 2.5 to 100 times. These TCM are also deemed unsuitable for seasonal storage because of the low lifetime cycle count.

The summary of the most cited LCA publications of each TES type for building applications is presented in Table 4.

Table 4. LCA studies of TES for building applications.

TES Type	TES Description	LCA Software/Method	LCA Database	Main Findings	Ref.
Sensible	Water tank Seasonal Thermal Energy Storage (STES)	SimaPro/IPCC GWP 2007 100a, CED	Ecoinvent, ELCD	- The addition of STES to residential solar systems results in annual energy savings of 21.4 GJ; however, it doubles the energy payback period compared with using solar thermal for domestic heat water only.	[31]
Sensible	Water tank	OpenLCA/CED	Ecoinvent	- The usage of a hybrid PV/thermal solar system (including TES) as opposed to a separate system is more efficient and may enable a primary energy saving of roughly 4% over the life cycle of the plant.	[32]
Sensible	Borehole seasonal (long-term) TES	SimaPro 7.3	Ecoinvent	- Integration of borehole-type TES to a house (case study in Canada) results in a reduction of approximately 4.5 tones/year GHG and 11 times less acidification potential impact than a conventional house.	[33]
Sensible	Aquifer Thermal Energy Storage (ATES)	SimaPro 9.0.0.35/IMPACT 2002+ V2.10	Ecoinvent 3.5	- ATES exhibits a better environmental performance: - 74% less GHG emissions compared with the oil heating system - 67% less GHG emissions compared with the natural gas heating system - 59% GHG emission reduction compared with conventional cooling methods.	[34]
Sensible	Water tank	n.m.	n.m.	- When taking into account the entire investment lifetime and the ideal configuration for emissions, the proposed integrated poly-generation energy system (including TES) offers discernible environmental benefits that exceed 1200 tCO_2eq reductions.	[35]
Sensible	Water tank	n.m.	Ecoinvent v3.8	- Using thermal energy storage systems can significantly improve a building's environmental performance by preventing the emission of 34.77 t CO_2-eq over 30 years, or 21.42% less emissions.	[36]
Latent	Macroencapsulated PCM (salt hydrate SP-25 A8)	Eco-Indicator 99 (EI99)	Ecoinvent 2009	- Under the tested experimental conditions, PCM use did not considerably lessen the total environmental impact. However, in other hypothetical cases, the environmental advantages of PCM are increased (12–14% less pollution than without PCM).	[39]
Latent	PCM in brick walls	GaBi	Ecoinvent	- When compared with brick walls made of rock and glass wool, the integration of PCMs in brick walls lessens the overall environmental impact by more than 15%.	[40]
Latent	Organic PCMs	n.m.	n.m.	- Using PCM produced from palm oil for domestic hot water application reduces GHG emissions by 16 tons over ten years and a payback period of <2 years. - The use of PCM produced from algae is more energy intensive, and its payback period exceeds the building's lifetime.	[44]

Table 4. *Cont.*

TES Type	TES Description	LCA Software/Method	LCA Database	Main Findings	Ref.
Latent	PCM-Underground TES	SimaPRo v9.0.0/CML-IA, ReCiPe 2016	Ecoinvent v.3.5	- The use of PCM significantly reduces the storage volume by 1/10 and enhances the COP, leading to an electricity energy reduction of 18% - The global warming potential (GWP) with the proposed system is lowered by 0.108 kgCO_2e/kWht for the grid scenario.	[42]
Latent	PCM integrated into building-like cubicles	n.m.	Ecoinvent, CES Selector 2018	- A design based on a circular economy, such as integrating recycling and reusing materials and components in buildings with PCM, can significantly reduce the overall environmental impact.	[41]
Latent/Sensible	Thermal battery (steam/water)	OpenLCA 1.10.3	ELCD 3.2 database	- The thermal battery has less of an environmental impact (80% reduction) and less of a natural resources impact (e.g., fossil fuel and water depletion) compared with the lithium iron phosphate battery.	[37]
Latent	PCM energy storage (heating & cooling)	GaBi v8	n.m.	- For building heating systems, PCM is less advantageous than hot water storage. - For cooling systems, PCM has a better environmental performance than cold water storage. - Large PCM storage systems result in a higher environmental impact due to production; thus, it is unsuitable for long-term storage.	[43]
Latent	Ice storage	SimaPro 8	Ecoinvent 3	- The use of ice storage in an office building in a tropical climate (Thailand) reduces the energy demand by 3.5% over the building's lifetime.	[38]
Latent	PCM (Parrafin, Salt Hydrate)	GaBi	n.m.	- For cooling applications, PCM use has environmental benefits compared with water storage. - Solid sorption energy storage is viewed as not environmentally beneficial because of the high GWP during its material production phase.	[12]
Thermochemical	Solid sorption (Silica gel, zeolites, Metal-Organic Frameworks (MOFs))				
Latent	PCM (Parrafin, Salt Hydrate)	n.m.	n.m.	- The main challenge in evaluating innovative energy storage material with different system levels is the functional unit-specific definition. - The environmental amortization time must also be considered for the innovative material to be used in long-term (seasonal) energy storage applications.	[47]
Thermochemical	zeolite, silica gel, MOFs, salt hydrate, and salt solution				
Thermochemical	SOLARSTORE (Salt Hydrate)	n.m.	n.m.	- The SOLARSTORE system has the least negative environmental impacts compared with other heating/cooling systems - 99% of the total environmental effects were generated during the extraction of a raw material and the manufacturing of system components	[48,49]
Thermochemical	Silica gel, SAPO-34, Zeolite 13X, CAU-10-H, Aluminum-Fumarate, LiCl/Vermiculite	GaBi	n.m.	- Closed adsorption storage has a higher environmental impact per storage capacity in the order of 2.5 to 100 times compared with conventional water storage	[46]

The literature search revealed that the availability of LCSA publications on TES is significantly less than LCA publications. Screening by using the second keyword in Table 3 yielded only one article. Yet, this article did not cover a complete LCSA study; instead, it only covered the LCC evaluation [50]. The scarcity of TES LCSA publications contradicts the finding from other papers [24,29] about increasing the number of LCSA publications on the energy theme, as mentioned in Section 1.2. Therefore, this finding suggests that limited sustainability assessments on TES have been performed.

Four publications were filtered when the keywords were expanded to include general energy storage (not limited to thermal energy storage). Out of these four, there were only two papers relevant to LCSA. The first study [51] assessed a sensible TES (water tank thermal storage). The study proposed a new comprehensive LCSA model integrated with the optimization process and machine learning method. A case study of a comparison between short-term thermal storage (water tank) and an electrical energy storage system for residential building applications was assessed using this model. However, this article focused more on the optimization model than the LCSA methodology.

The second study [52] evaluated "pumped hydro energy storage", which is not part of TES. It compared the sustainability performance between "conventional pumped hydro energy storage" (CPHES) and "underground pumped hydro energy storage" (UPHES) using abandoned mining pits. The methodology used in the study was "multi-attribute value theory" (MVAT) and scenario analysis. The sustainability indicators utilized in the study are summarized in Table 5. The study concludes that CPHES had a better economic and environmental performance, while UPHES had better social sustainability.

Table 5. Sustainability indicators used in LCSA of "pumped hydro energy storage" [52].

Economic Indicators	Environmental Indicators	Social Indicators
Levelized cost of electricity (LCOE) Levelized cost of storage (LCOS) Payback time	Global warming potential Acidification potential Eutrophication potential Photochemical ozone creation potential Human toxicity potential	Employment Availability factor Contribution to peak dependence on fossil fuel Potential of CHPES and UPHES

3. LCA Methodology for TES with Low TRL

The number of LCA publications found during the literature search was highly correlated with the maturity/readiness level of TES technologies. The technology maturity/readiness level was defined by the International Energy Agency (IEA) in the extended Technology Readiness Level (TRL) scale, as shown in Figure 6 [53].

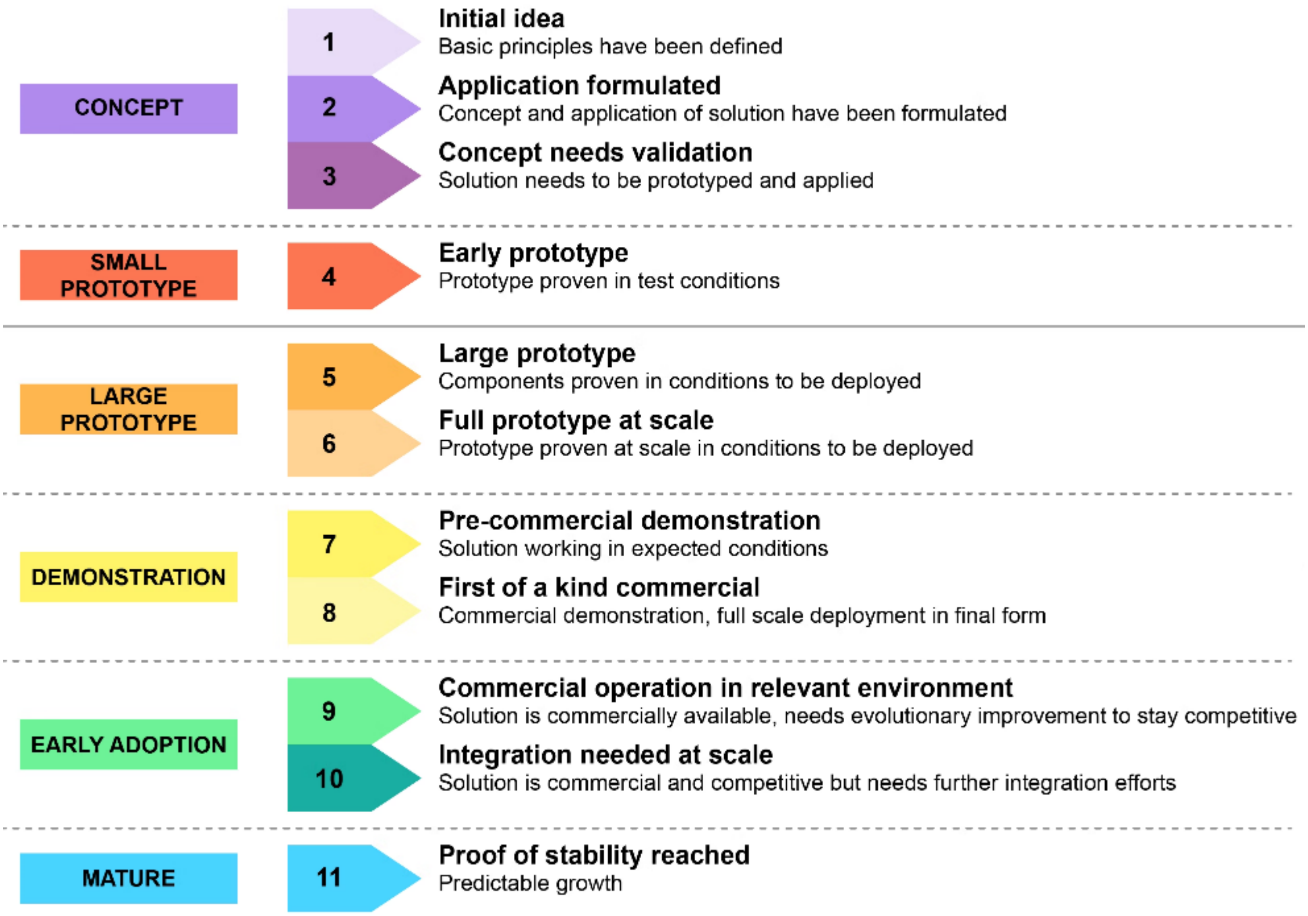

Figure 6. Extended TRL scale [53].

IEA's "ETP Clean Energy Technology Guide" was used in this paper to understand the TRL rating of TCES compared with other thermal storage technology for application in the building's heating and cooling sector. The "ETP Clean Energy Technology Guide" is an interactive database and tool to compare the readiness of more than 500 technology systems contributing to the net-zero emission goal [54]. Nineteen (19) thermal storage technologies for a building's heating and cooling application are found in this database, as listed in Table 6 below.

Table 6. TRL rating of thermal storage technologies in building's heating and cooling sectors [54].

Technology	TRL Rating
Active latent heat storage	4
Thermochemical storage	4
Shape-stabilized phase change material (ss-PCM)	4
Latent (PCM)—Solid−liquid low-temperature heat	8
Latent (PCM)—Solid−liquid high-temperature heat	8
Latent (PCM)—Solid−liquid salt hydrates and paraffin	8
Latent (PCM)—Solid−liquid fatty acids	8
Latent (PCM)—Solid−liquid sugar alcohols	8
Latent (PCM)—Solid−liquid salt	8
Latent (PCM)—Liquid−gaseous	8
Latent (PCM)—Solid−solid	8
Sensible—Vacuum-insulated high-temperature water tank	8
Combined latent and sensible storage system	8
Latent (PCM)—Solid−liquid ice storage	9
Latent (PCM)—Solid−liquid aqueous salt solution	9
Sensible—Chilled water storage	9
Underground thermal storage—Aquifer thermal energy storage (ATES)	9
Underground thermal storage—Borehole thermal energy storage (BTES)	9
Sensible—Hot water tank	11

The above table shows that for the building's heating/cooling applications, TCES had a low TRL rating (4) compared with the latent TES (such as passive PCM system) and sensible TES (such as hot water tank), which achieved a TRL rating of 8 to 11. Figure 7 shows the number of LCA publications for buildings and district applications, categorized by the TRL rating and TES type.

The standardized LCA framework (ISO 14040 and 14044) is well-suited to assess these well-defined systems [55] or commercially available technologies (TRL rating above 7) [56]. Therefore, most LCA studies were usually ex-post evaluations of these systems [57]. Technology with a low TRL rating (i.e., at the stage of experimental proof of concept, lab validation, or prototype), such as TCES for building applications, is often known as emerging technologies [57]. In a review paper, Moni et al. [56] described the main challenges in performing LCA of emerging technologies at the initial development stage (TRL 2–5) as follows:

- Comparability: challenging to make a direct comparison with established technology because emerging technologies have undefined, changing, and inequivalent functions and a different system boundary.
- Data: insufficient or inaccessible inventory data and inadequate data quality.
- Scale-up concerns: different processes, equipment, and efficiency at the lab and commercial scale.

- Uncertainty: the study integrity may be compromised by inherent variability in the LCA method, leading to inaccurate technology development and decision-making.
- Assessment time: LCA takes time, and evaluation time is crucial for advancing technology.

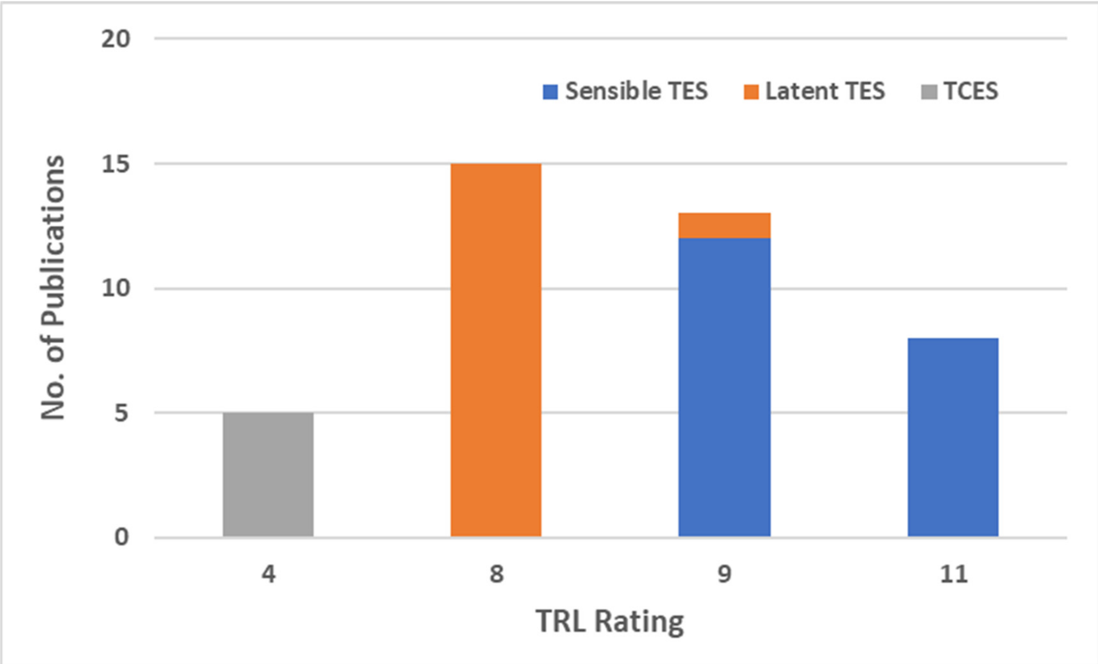

Figure 7. TRL rating of TES assessed in LCA publications for building and district applications.

The above challenges are applicable to the LCA studies of TCES systems for building applications, which explains the limited LCA studies in this area.

As the standardized (ex-post) LCA method is not suitable for emerging technologies, a specific LCA methodology for the early development stage has been proposed and exercised by several researchers [56]. The method is called ex ante LCA (also referred to as prospective, consequential, or anticipatory LCA in the literature) [57]. In principle, ex ante LCA may use the same tool as the ex-post LCA [58]. However, ex ante LCA predicts the environmental consequences of a future system's life cycle, as opposed to ex-post LCA, which is based on established system data [59]. Ex ante LCA also looks at various scenarios to support the selection of design options and decisions for the next development phase [56,58].

Thus, ex ante LCA methodology can be used to perform the LCA of the TCES system for building applications at its current TRL rating. One example is provided in Figure 8 for the application of this method to the LCA of a salt hydrate-based TCES system based on framework proposed by Villares et al. [58].

Referring to the above diagram, the laboratory process data of salt hydrate TCES were used as the study's primary data and starting point. In Stage 1, a screening-level LCA modelling was conducted based on this laboratory process system. Stage 1's objective was to perform a general preliminary assessment and hotspot analysis. The result from the Stage 1 LCA could not be directly compared to the LCA model of a mature technology system due to scale differences. However, it is useful to define the future scaled-up salt hydrate TCES system scenario.

To scale up the laboratory process system into commercial application, we proposed following an engineering-based scale-up framework, as suggested by Piccinno et al. [60]. The framework consisted of a five-step procedure, as shown in Figure 9. The proposed scaled-up application of salt-hydrate-based TCES in the study would be for space heating/domestic hot water applications in a residential house. Two scenarios could be anticipated from this application: daily thermal storage and seasonal thermal storage.

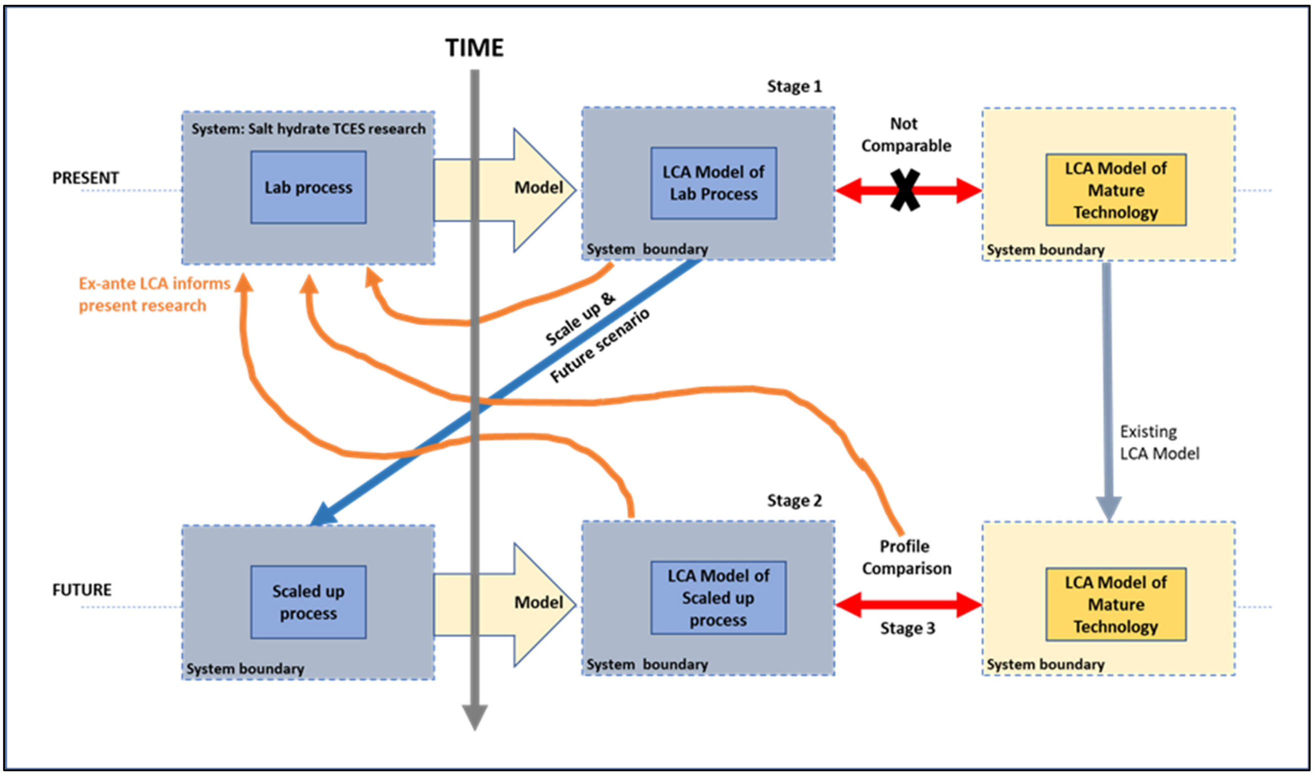

Figure 8. Schematic diagram of proposed research stage ex ante LCA of salt hydrate TCES (adapted from [58]).

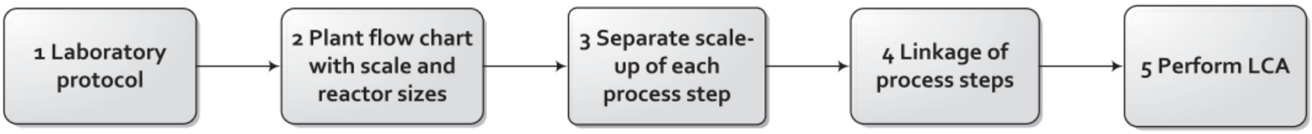

Figure 9. Scale-up framework overview (Reprinted from [60], with permission from Elsevier).

After the scaled-up process was established, Stage 2 LCA was conducted to verify the environmental consequence of salt-hydrate-based TCES for comparison with an established technology for space heating applications in a single residential house. The last step in this ex ante LCA was an environmental impact performance comparison of the scaled-up process (from Stage 2 LCA result) and the incumbent technology (obtained from existing LCA results in the literature).

The incumbent technology selection for the comparison step proposed a hot water tank (for daily thermal storage scenario) [61,62] and underground thermal storage (for seasonal thermal storage scenario) [33,34]. This selection was based on the high TRL ratings of both systems (as shown in Table 6) and the availability of existing LCA result publications of these systems.

The benefit of performing an LCA study of TCES for building applications at the current TRL rating are as follows:

- Conducting an LCA study at the initial design phase has the potential to direct emerging technology development for achieving a better environmental performance by recognizing hotspots and making a comparison with existing technology [56].
- Decisions taken during the initial development phase have extensive future impacts on functionality, cost, and environmental effects for emerging technologies [58]. Therefore, LCA can be used at this early stage to recognize the consequences of these decisions, which may avoid preventable environmental problems and foresee environmental regulation changes [57].

- LCA study, along with techno-economic analysis, are often requested by funding agencies (such as the US Department of Energy) for any proposed projects, including the early stages of technology research [56].
- Considering that the only LCA study of TCES at a system level was published 19 years ago, more LCA studies of TCES at a system level will be useful to capture the recent improvement in TCES for building applications and to confirm the positive environmental impact. GHG emission reductions from the building sector are one of the main reasons for TCES technology development.

4. Conclusions

This review provides an overview of LCA and LCSA studies on all types of TES (sensible, latent, and thermochemical), specifically for building applications. The literature search reveals that most existing LCA publications are for sensible and latent TES. These systems have a TRL rating of 8 or above, indicating that the technology has advanced to the point of commercial demonstration or more. At this level of technology maturity, inventory data have been established, and a standardized LCA technique can be applied. On the other hand, only a few LCA studies of TCES for building applications are known. TCES's TRL rating remains low, leading to more challenges to performing LCA and a specific LCA method designed for emerging technology (ex ante LCA) to be applied.

Therefore, the first identified research gap in this review is a lack of ex ante LCA method applications to assess the environmental impact of TCES systems for building applications throughout their entire life cycle. The second identified gap is the lack of LCSA studies of TES for all applications and types of TES, including the established ones. LCSA study will be required to confirm that the TES system implementation is aligned with the principles of sustainable development.

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Nomenclature

ATES	Aquifer thermal energy storage
CED	Cummulative energy demand
CPHES	Conventional pumped hydro energy storage
BTES	Borehole thermal energy storage
CSP	Concentrated Solar Plant
GHG	Greenhouse Gasses
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	International Panel on Climate Change
ISO	International Organization of Standardization
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
MVAT	Multi-attribute value theory
n.m.	Not mentioned
PCM	Phase Change Material

PENR	Primary Energy Non-Renewable Resource
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social life cycle assessment
STES	Seasonal Thermal Energy Storage
TCES	Thermochemical Energy Storage
TCM	Thermochemical Materials
TES	Thermal Energy Storage
TRL	Technology Readiness Level
UNEP	United Nations Environment Programme
UPHES	Underground pumped hydro energy storage

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