Life Cycle Assessment of Thermal Energy Storage in Buildings

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Abstract Thermal energy storage (TES) plays an important role in enhancing energy efficiency and flexibility in building systems. This study develops a method for conducting life cycle assessment (LCA) studies for evaluating the environmental performance of TES in different configurations. A case study is carried out, comparing phase change material (PCM)-TES, water-TES, and borehole-TES. Cradle-to-grave life cycle inventory is analyzed over a 25-year lifetime, and ReCiPe 2016 midpoint (H) is used for midpoint impact categories quantification. Results show that TES integrations yield the lowest life cycle impact in global warming potential (GWP), surplus ore potential, marine eutrophication and water consumption among others against non-TES reference during operational phase. It is also shown that the predominant GWP impact of TES integration comes from production, installation, and end-of-life phases.

1 Introduction

Building operations are responsible for 30% of global final energy use and 26% of energy-related emissions worldwide (IEA 2023). A global transition of the building sector requires increasing use of renewable energy and energy efficient buildings design and operation. Thermal energy storage (TES) systems play a crucial role in balancing the energy supply and demand and enabling tariff-based operation strategy and peak shaving for cost saving. Technical and economic studies on TES in buildings have been substantially developed, whereas life cycle assessment (LCA) is a relatively new topic that has emerged over the past decade through the performed literature survey presented in the current work. TES can evolve from a purely technical component to a policy-aligned solution that contributes to both emissions reduction and circular resource use. Designing TES with recyclable or bio-based materials,

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disassembly potential, and robust end-of-life recovery is no longer optional; it is essential for regulatory compliance and long-term sustainability.

This paper addresses a timely and underexplored topic: the integration of energy storage into building systems as a pathway to more sustainable energy solutions. The aim of this study is to evaluate the environmental impact of TES by benchmarking the life cycle performance of a TES-integrated building against that of a conventional reference building without TES. The assessment focuses on key environmental indicators, including energy consumption and greenhouse gas (GHG) emissions. A case study is conducted on a 3,000 m^2 office building in Bergen, Norway, comparing phase change material (PCM) TES, water-TES, and borehole TES configurations over a 25-year life cycle. Realization of TES's full potential as a policy aligned, circular resource solution hinges on involvement beyond the construction sector. Norway's circular buildings roadmap highlights the need for clearer legislation, stronger value chain collaboration, and integrated research infrastructure actors across the entire TES value chain should therefore be included in circularity analyses (Knoth et al. 2022).

2 Methodology

2.1 Proposed Method for LCA Study of TES in Building Application

Components of the building heating and cooling system, including heat pumps, TES, electric heaters and chillers, circulation pumps, and fans, adhere to Product Category Rules (PCR) 2019:14 "Construction products (EN 15804 + A2)" v2.0.1 (Swedish Environmental Research Institute 2025). According to this PCR, the life-cycle information modules are specified as follows: A1–A3 product stage; A4–A5 construction process stage; B1–B7 use stage; C1–C4 end-of-life stage; D benefit and load beyond system boundary.

While interest in TES within building systems is gaining momentum, LCAs of different TES solutions in building applications remain limited in the existing literature. This study proposes a systematic method for conducting LCA of TES solutions in building heating and cooling systems, in accordance with the LCA standard ISO 14040/44 (International Organization for Standardization 2020) and covering the full life cycle from cradle to grave, as shown in Fig. 1. The goal of the study is to benchmark the environmental impact of different TES integrations and support early-stage design decisions.

The functional unit is defined as the annual heating and cooling provided by the heating and cooling system, in kWh/yr. Thus, all key components in the system that are involved in the energy and material flow are included in the life cycle inventory analysis. ReCiPe 2016 midpoint (H) method is used to translate inventory flows into environmental indicators.

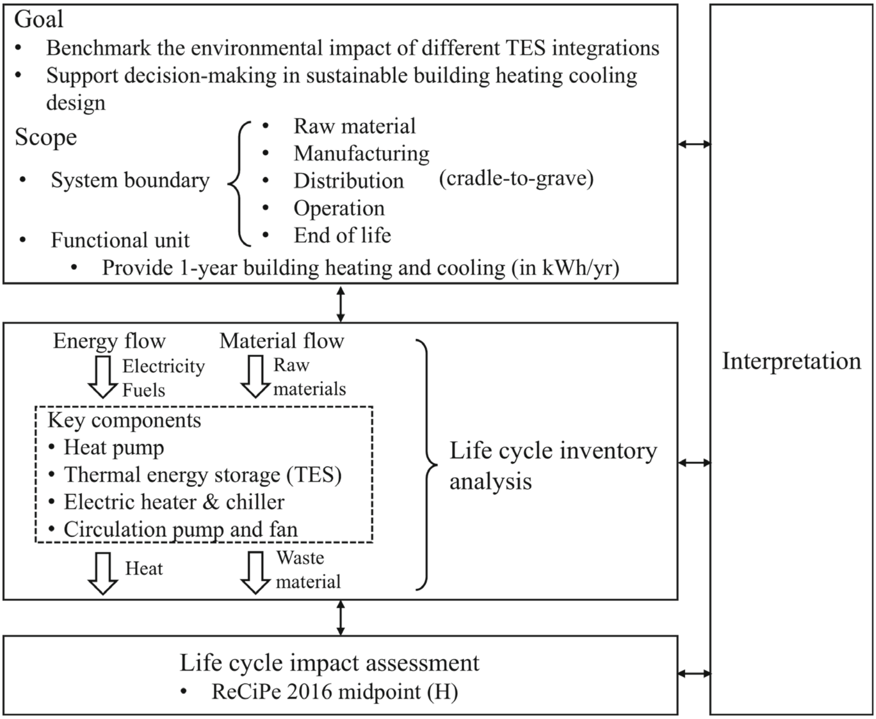

Fig. 1 Proposed framework of LCA study for TES in building heating and cooling application based on ISO 14040

2.2 *Case Study*

2.2.1 System Description

The case study is a heating and cooling system of an office building in Bergen called Sigba, Norway, which utilizes a ground source heat pump (GSHP) system coupled with boreholes thermal energy storage (BTES) of 1250 m length. The system provides space heating, domestic hot water (DHW), and comfort cooling across a 3,000 m^2 area. Heating is primarily delivered via an 11–44 kW heat pump (Thermia Mega M, R410A refrigerant) supported by a 90 kW electric boiler as peak backup. For cooling, the system combines direct free cooling from the borehole loop, active cooling via the heat pump, and a 146 kWh PCM-TES using Axiotherm 15 (organic and encapsulated), with the PCM charged at night. Thermal response testing confirmed a ground thermal conductivity of 3.0 W/m·K and borehole thermal resistance of 0.10 m·K/W. The system diagram is displayed in Fig. 2.

Figure 3 displays the yearly heating and cooling demand profile of the Sigba office building, based on monitoring from March 2023 to March 2024. A heating load is consistently present most of the year due to DHW demand, with peak demand

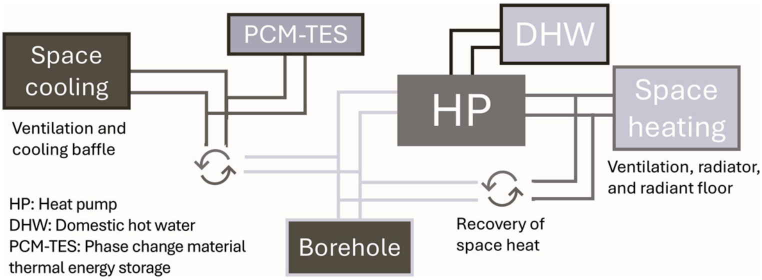

Fig. 2 System diagram of the case study

occurring during winter months due to peak space heating needs. Cooling demand is concentrated in summer, particularly in July. The system reaches a maximum heating demand of 118.9 kW and a maximum cooling demand of 78.2 kW. The total annual heating demand amounts to 186 MWh, while the total cooling demand is 13 MWh. PCM-TES went through 9.1 cycles in one year of operation with a thermal efficiency of 76%. The annual electricity consumption by the pumps of PCM-TES and borehole TES is 158 kWh and 15,250 kWh, respectively.

The case study evaluates four TES configurations, summarized in Table 1. The base case (nr. 0) uses PCM-TES for night charging and daytime discharge. The sensible TES scenario (nr. 1) replaces PCM-TES with a chilled water TES to assess material and energy trade-offs. The extended BTES scenario (nr. 2) doubles the total borehole depth to 2000 m to enhance seasonal TES without additional cooling peak backup devices. The district heating scenario (nr. 3) eliminates on-site TES and BTES, relying instead on a chiller as a cooling device.

The functional unit is defined as annual heating (186MWh/yr) and cooling (13 MWh/yr) provided by the system. All scenarios assume identical building thermal loads and operational schedules. A 25-year system lifetime is assumed in order to take into account the replacement of mechanical equipment such as heat pump and

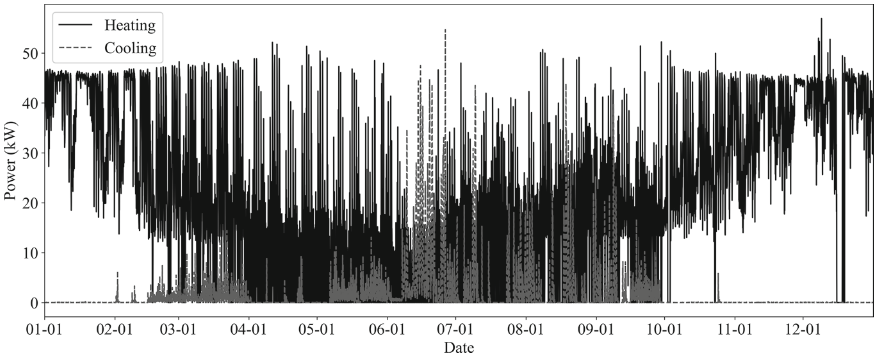

Fig. 3 Annual heating and cooling demand profile of Sigba office building (hourly average)

Table 1 Scenario of different TES solutions

Scenario	Cooling		Heating		BTES length (m)
	Base load	Peak load	Base load	Peak load	
0	BTES	PCM-TES	GSHP (44 kW)	Electric boiler	1250
1	BTES	Water TES	GSHP (44 kW)	Electric boiler	1250
2	BTES	BTES	GSHP (70 kW)	Electric boiler	2000
3	Chiller	Chiller	District heating (90 kW)	Electric boiler	–

chiller, which commonly have a lifetime less than 20 years. The geographical location is Europe by default, and is chosen as global when the specific data for Europe are not available. Reuse, recovery, and recycling potential (module D as defined in the PCRs for construction products) at the end of life are not considered.

2.2.2 Life Cycle Inventory (LCI)

The life cycle inventory (LCI) is generated based on each TES and related equipment in the production of heating and cooling. Environmental product declarations (EPD) and Ecoinvent v3.11 (Ecoinvent 2025) of technical equivalent products are selected covering all raw material, process and energy used in the stage of production, distribution, and end of life. The geographical focus is centered on Europe, with global data integrated where regional sources are lacking. Transportation emissions are included in the analysis. An extrapolation factor is utilized to scale the product to the demand side of the case study in terms of size of the tank, power capacity, length of the borehole for instance, i.e., an extrapolation factor of 2.8 is used for scaling 5600 L of steel tank from available data on heat storage tank of 2000 L. Table 2 summarizes the inventory of the key components. Electric heaters are assumed to be installed in all scenarios, which are only considered during the operation stage as the backup and peak device. The column "Inventory data" refers to the exact activity name from Ecoinvent, as well as the product name from the Norwegian EPD Foundation (2024) and EPD International AB (2023).

Operational LCI accounts for electricity used by circulation pumps, heat loss through storage systems, and replacement of mechanical equipment according to estimated service life. LCI during operational stages from the real case studies, projected over the 25-year lifetime, is summarized in Table 3. Here, the inventory of operational phase only considers electricity and heating.

2.2.3 Life Cycle Impact Assessment (LCIA)

ReCiPe 2016 midpoint (hierarchist) is selected in this study. To transfer different impact category units used in EPDs, conversion factors suggested by Dong et al.

Table 2 Inventory of the key components in the stages of production, distribution, and end of life

Item	Product	Quantity	Unit	Stage	Inventory data	EF
PCM-TES	Paraffin PCM	2562	kg	P, D	Market for paraffin	1
	Paraffin PCM	2562	kg	EoL	Treatment of waste plastic, mixture, municipal incineration	1
	Steel tank, 5600 L	1	–	P, D, EoL	Market for heat storage, 2000 l	2.8
	Circulation pump, 0.5 kW	1	–	P, D	Market for water pump, 22 kW	0.05
	Circulation pump, 0.5 kW	6.8	kg	Eol	Market for waste steel	1
Water TES	Steel tank, 12,300 L	1	–	P, D, EoL	Market for heat storage, 2000 l	6.15
	Circulation pump, 0.5 kW	1	–	P, D	Market for water pump, 22 kW	0.05
	Circulation pump, 0.5 kW	6.8	kg	EoL	Market for waste steel	1
BTES	Borehole 1250 m	1	–	P, D	Market for borehole heat exchanger, 150 m	8.33
	PE100 collector	661	kg	EoL	Treatment of waste plastic, mixture, municipal incineration	1
	Brine, 35 wt% ethanol solution	1500	kg	EoL	Treatment of spent anti-freeze liquid, hazardous waste incineration	1
	Circulation pump, 1.4 kW	2	–	P&S	Market for water pump, 22 kW	0.05
	Circulation pumps, 1.4 kW	38.2	kg	EoL	Market for waste steel	1
Heat pump	Brine-water heat pump 44 kW	1	–	P&S	Market for heat pump, brine-water, 10 kW	4.4
	Refrigerant	4.4	kg	EoL	Treatment of used refrigerant R134a, reclamation	1
	Steel	201	kg	EoL	Market for waste steel	1
	Copper	69	kg	EoL	Market for waste copper	1

(continued)

Table 2 (continued)

Item	Product	Quantity	Unit	Stage	Inventory data	EF
	Plastic insulation	1.1	kg	EoL	Treatment of waste plastic, mixture, municipal incineration	1
Chiller	Chiller 100 kW	1	–	P, D, EoL	Chiller and heat pump VLS 160–315 kW (EPD International AB 2025)	0.4
District heating	Heat	1	kWh	P, D, EoL	District heating in Bergen area (The Norwegian EPD foundation 2024)	1

[*] Note: P, production; D, distribution; EoL, end-of-life; EF, extrapolation factor

Table 3 Life cycle inventory of the scenarios during operational phase

Scenario	Electricity (MWh)	District heat (MWh)	Equipment replacement	Number of replacements
0	2005.8	0	Heat pump	1
1	2005.8	0	Heat pump	1
2	1634.2	0	Heat pump	1
3	118.2	4650	Chiller	1

2021 are applied. For instance, 1 MJ is converted to 41.9 kg oil-eq for fossil fuel depletion. The electricity emission factor of Norway is 0.018 g/kWh in 2024 (IEA 2024).

3 Result Interpretation and Discussion

Table 4 summarizes the estimated midpoint impacts of all four scenarios. Scenarios 0 (PCM-TES) and 1 (water-TES) exhibit comparable overall impacts, although the PCM-TES system, due to its reliance on paraffin by-products, yields higher fossil-fuel potential and GWP, while the water-TES system has higher impacts across most categories due to its greater steel-related activity. Scenario 2's expanded BTES field substantially increases impacts during borehole installation (a highly fuel-intensive process) and heat pump installation with higher capacity, which drives up acidification, ecotoxicity, and fossil-fuel impacts. Scenario 3, which is based on conventional chillers and district heating, shows the highest impacts overall, particularly in terrestrial acidification, marine eutrophication, and water-consumption potentials.

Table 4 Life cycle impact in the midpoint impact categories

Impact category	Scenario				Unit
	0	1	2	3	
Terrestrial acidification potential (TAP)	205	207	296	632	kg SO_2-Eq
Global warming potential (GWP) 100	92,731	88,530	102,500	120,689	kg CO_2-Eq
Freshwater ecotoxicity potential (FETP)	25,570	26,159	38,517	–	kg 1.4-DCB-Eq
Marine ecotoxicity potential (METP)	31,267	32,061	46,886	–	kg 1.4-DCB-Eq
Terrestrial ecotoxicity potential (TETP)	272,852	299,069	378,455	–	kg 1.4-DCB-Eq
Fossil fuel potential (FFP)	14,886	12,694	17,695	29,476	kg oil-Eq
Freshwater eutrophication potential (FEP)	15	17	21	38	kg P-Eq
Marine eutrophication potential (MEP)	1,2	1,4	1,4	292	kg N-Eq
Human toxicity potential carcinogenicity (HTPc)	28,438	43,748	23,333	–	kg 1.4-DCB-Eq
Human toxicity potential non-carcinogenicity (HTPnc)	167,598	188,887	217,549	–	kg 1.4-DCB-Eq
Ionizing radiation potential (IRP)	892	1004	1151	–	kBq Co-60-Eq
Agricultural land occupation (LOP)	770	1039	753	–	m^2*a crop-Eq
Surplus ore potential (SOP)	3351	4457	3781	4899	kg Cu-Eq
Ozone depletion potential (ODPinfinite)	0.033	0.031	0.046	0.063	kg CFC-11-Eq
Particulate matter formation potential (PMFP)	90	94	129	–	kg PM2.5-Eq
Photochemical oxidant formation potential: Humans (HOFP)	228	228	339	–	kg NOx-Eq
Photochemical oxidant Formation potential: ecosystems (EOFP)	236	237	352	–	kg NOx-Eq
Water consumption potential (WCP)	204	225	251	44,122	m^3

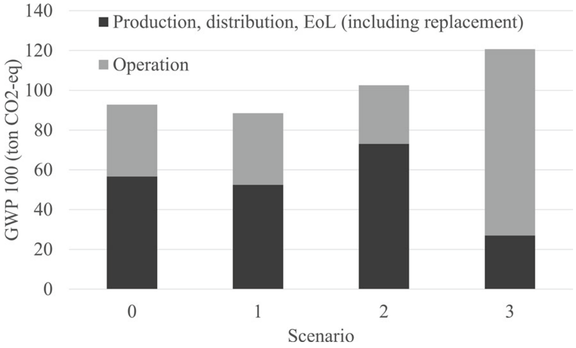

Fig. 4 Life cycle GWP of different cooling and TES solutions

Figure 4 shows the GWP of the scenario in the non-operation and operation phases. Systems with BTES (Scenarios 0–2) shift most of the CO_2 emissions into the non-operation phase by installing boreholes plus either PCM- or water-tank TES with roughly 50–60 t CO_2-Eq. Scenario 2 (only with BTES and heat pump) reaches around 73 t due to its larger BTES field and larger heat pump. Operational emissions for scenarios with BTES and heat pump remain comparatively low, since the ground-source heat pumps are efficient in heating production. The lowest, 29 t, is achieved in scenario 2, where the electric heater is used the least. In contrast, the conventional chiller with district-heating layout (Scenario 3) has the minimal non-operation carbon emissions (27 t) but has the highest carbon emission during operation (94 t) contributed by district heating (77%) and chiller (23%).

4 Conclusions

The study presents a methodology for system-level cradle-to-grave LCA for TES in buildings. A case study is carried out based on a 3,000 m^2 office building in Norway yielding the following key findings:

- As a peak shaving and load shifting component, PCM-TES has higher impacts on GWP and fossil fuel depletion due to the use of a paraffin product (PCM) compared to water-tank TES, whereas the latter shows a higher impact in other categories due to higher usage of steel.
- In a 25-year lifetime, TES integration reduces the environmental impacts compared to a system without TES, mainly due to the much lower life cycle impact during operational phase.
- In the long term, GSHP (heat pump with BTES) is a more sustainable solution compared to district heating and chiller configuration, either with or without TES. This is so because, even though the production, distribution and EoL generate higher impacts due to, e.g., drilling work, the operation phase impact is significantly lower than district heating.

The present case study is constrained by the use of a single year of operational data and projected future impacts. Future research should encompass dynamic operational modeling that captures the interaction between TES performance, variable renewable energy supply, and real-time grid conditions. It should also integrate end-of-life considerations and life-span extension strategies such as reuse, recycling, repurpose, and components and material recovery to fully reflect the circular economy model potential of TES systems. Moreover, expanding the scope to encompass a wider range of building typologies and climatic contexts, including hotter, drier, and tropical regions, would enable more comprehensive validation.

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