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Comprehensive life cycle assessment of selected seasonal thermal energy storage systems

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ABSTRACT

The utilization of seasonal thermal energy storage (sTES) systems is essential for balancing fluctuations between demand and surplus of heating/cooling in modern energy systems and to reduce overall greenhouse gas emissions from space heating. However, large storage volumes are required to store the heat over extended periods leading to a high demand for construction materials and processes. Yet, no comprehensive environmental evaluation compares sTES technologies across their life cycle phases. This study employs life cycle assessment to quantify the environmental impacts of three different type of sTES: a tank thermal energy storage (TTES), a water-gravel thermal energy storage (WGTES), and a pit thermal energy storage (PTES). Aquifer thermal energy storage (ATES) systems are also included as reference for evaluating the results. Greenhouse gas emissions from the construction phase vary between 1.4 (PTES) and 29.4 g $CO_{2\text{-eq}}/kWh_{th}$ (WGTES), depending on the type of installation, storage size, and construction materials. Utilizing water as a filling material and large storage volumes with reduced surface-to-volume ratios enhance environmental performance. Controversely, materials such as concrete, steel, foam glass gravel, and related transport processes contribute significantly to the environmental impact. These should be replaced wherever possible by sustainable alternatives without compromising storage capacity and efficiency.

Abbreviations and Symbols

A	Surface area (m^2)	PE	Polyethylene
A/V	Surface-to-volume	PF	Polymer foam
ATES	Aquifer thermal energy storage	PP	Polypropylene
BTES	Borehole thermal energy storage	PTES	Pit thermal energy storage
c	Specific heat capacity ($J\ kg^{-1}\ K^{-1}$)	PVC	Polyvinyl chloride
CN-E	Carbon-nanotube enhanced	SHS	Sensible heat storage
CTES	Cavern thermal energy storages	sTES	Seasonal thermal energy storage
EGG	Expanded glass granulate	TES	Thermal energy storage
FGG	Foam glass gravel	TFE	Tetrafluoroethylene
GHG	Greenhouse gas	THS	Thermochemical heat storage
HDPE	High-density polyethylene	TTES	Tank thermal energy storage
HF-E	Halogen-free enhanced	UTES	Underground thermal energy storage
HWTES	Hot-water thermal energy storage	V	Volume (m^3)
LC	Life cycle	WEV	Water equivalent
LCA	Life cycle assessment	WGTES	Water-gravel thermal energy storage
LCI	Life cycle inventory		
LCIA	Life cycle impact assessment		
LHS	Latent heat storage		

1. Introduction

For enabling sustainable future energy supply, the investigation of alternative, renewable energy sources is of central importance [1,2]. Fossil fuel, oil, and coal, are estimated to be depleted within a few decades as a result of increasing global energy demand, which is placing considerable strain on these resources [3,4]. Therefore, it is essential not only to reduce energy consumption in the long term but also to accelerate the transition to clean and renewable energy sources [5,6]. In mid- and high-latitude countries, space heating and hot water demand account for a substantial share of total energy consumption. Reported values range from approximately 50 % in Germany [7] to around 79 % [8,9] and even close to 80 % [10] in Europe. These also contribute significantly to greenhouse gas (GHG) emissions, with heat responsible for up to 40 % of global CO_2 emissions [10,11] and up to 33 % of GHG emissions in Europe [12]. The majority of this energy is currently being supplied by fossil fuels [12,13]. Although seasonal thermal energy storage (sTES) has a significant potential to reduce primary energy, GHG emissions, and other environmental impacts, its current use remains

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limited due to high investment costs, and technological challenges [3, 14]. Large storage volumes are required to store substantial amounts of heat over extended periods [15], as considerable heat losses can occur during a storage time of several months. Additionally, there are high demands of the used materials, which should not only be as cost-effective as possible [8], but also technically reliable in terms of durability, leak-tightness, etc. [3]. The environmental performance of these technologies, particularly its potential to reduce GHG emissions, is a key factor for the widespread acceptance [16]. Life cycle assessments (LCAs) facilitate the identification and quantification of the environmental impacts of technologies [17,18], enabling comparison between different options, and identifying improvement strategies without burden-shifting [19,20]. An increasing number of studies is focusing on the techno-economic and environmental analysis of sTES, as their potential for reducing GHG emissions has been recognized [21]. Most of these studies focus on a limited selection of thermal energy storage (TES), predominantly aquifer thermal energy storage (ATES). While some studies, such as Bloemendal et al. [22] and Fleuchhaus et al. [5], examine ATES systems from a global perspective or related in Germany in general [23], others investigate specific sites in detail, for example the study by Schüppler et al. [24] on an ATES system in Karlsruhe, Germany. However, there is no comprehensive environmental assessment available yet that compares the advantages and disadvantages of different variants, especially considering variable building material types and amounts used in different sTES installations.

Thermal storage systems are categorized according to their storage mechanism into thermochemical heat storage (THS), latent heat storage (LHS), and sensible heat storage (SHS) [8,25], where SHS represents the most established, widely implemented [21] and socially accepted technology [26]. The latter is further subdivided into ATES, borehole thermal energy storage (BTES), cavern thermal energy storage (CTES), pit thermal energy storage (PTES), and tank thermal energy storage (TTES), amongst others [13,27]. ATES, BTES, and CTES utilize the natural subsurface, whereas PTES and TTES are closed and often ground-based storage systems [13]. All concepts for sensible thermal energy storage face similar challenges. Key challenges include energy losses over the storage period of several months [8], proper regulation of storage temperature, geometrical design, large volume and space demand of storage facilities, and suitable thermal properties of the storage medium. Therefore, the sTES type must be carefully selected while considering (hydro-) geological conditions, local circumstances, and the form of utilization, particularly in relation to the specific energy demand [28]. TTES systems, which usually contain a supporting structure made of stainless steel or reinforced concrete [29], are less dependent on local (hydro-) geological conditions than ATES and BTES systems [10,28]. TTES are typically cylindrical tanks, which use water as a storage medium to achieve a high specific heat capacity (c = 4 200 J kg^{-1} K^{-1} [29]) [26]. In this case, they are classified as hot-water thermal energy storage (HWTES). They are often built as artificial, self-supporting structures, covered with earth for aesthetic reasons if necessary. However, the disadvantages of this storage type include high construction costs per water equivalent volume (WEV) [30] (e.g., TTES 150–330 €/m$^3_{\mathrm{WEV}}$ [31,32]; in comparison PTES: 20–40 €/m$^3_{\mathrm{WEV}}$ [32,33]) and size limitations resulting from static requirements. PTES consists of an artificial, subsurface basin covered by a heat-insulating lid. As this storage type is entirely underground, its performance is often influenced by specific (hydro-) geological conditions, such as the presence or absence of groundwater and soil stability. However, their underground structure allows for scalability, enabling large storage volumes (e.g., Vojens: 203 000 m^3, Gram: 122 000 m^3 [34]), while simultaneously reducing costs, as some static requirements are eliminated [26,29]. This is further enhanced by the use of excavated material to create an embankment, which improves overall storage efficiency. In some cases, PTES can be divided into HWTES and water-gravel thermal energy storage (WGTES). Strictly speaking, the term 'water-gravel' is misleading, as the WGTES often consists of multi-component filling material that can include sand-, gravel-, or soil-water mixtures [13]. WGTES offers advantages in terms of statics, as the top surface is supported by the gravel filling [35]. This not only reduces the technical and financial expense for the cover but also offers the possibility of utilizing the space above the sTES more effectively [28,31,36]. One disadvantage of WGTES is that they can only be repaired at significant financial costs. Additionally, the charging and discharging capacities of WGTES are lower compared to HWTES of the same size due to the reduced water equivalent volume (WEV). The WEV refers to the volume of water that would store the same amount of thermal energy, as in case of a WGTES the actual storage medium consists of materials with different specific heat capacities [13]. As a result, the use of a buffer tank is typically required [35].

Various studies have applied LCA to evaluate the environmental impact of different sTES, primarily focusing on ATES (Table 1). This focus is largely due to the fact that more than 2 500 ATES systems have already been implemented worldwide, providing a substantial basis of real-world data for such assessments [26,29]. A common finding across these studies is that while both the construction and operational phases contribute to the environmental impact, the operational phase is often identified as the dominant phase, mainly due to electricity consumption for heat pumps [37–39]: Tomasetta et al. [37] and Moulopoulos [38] came to this conclusion when they analyzed Dutch ATES systems. Ni et al. [39] reached a similar conclusion in a study of a hypothetical ATES system in China. The study found that electricity consumption accounted for more than 96 % of the global warming potential. Godinaud et al. [40] observed similar results for an ATES system installed on the campus of the Polytechnic Institute of Bordeaux (France), where the operation was responsible for approximately 60 % of total GHG emissions. Stemmle et al. [16] provided a broader application of LCA to multiple ATES systems in Germany, offering a comparative approach across different sites. Additionally, Stemmle [16] examined an ATES similar to Limoges' [41] study (Bonner Bogen, Germany) and observed that 98 % of the total environmental impact was attributed to the operational phase, aligning closely with previous results, which reported 98.5 % for the operational phase [41]. In contrast to the ATES studies, Karasu et al. [42] investigated a BTES system in Canada, concluding that it significantly reduces GHG emissions compared to conventional heating systems, with a reduction of 4.5 tons of CO_2 per home annually. However, similar to previous studies, the operational phase was identified as the dominant contributor to environmental impact.

Although most LCA studies on thermal energy storage systems consider both construction and operation, the focus on a broader range of storage technologies beyond ATES and BTES remains limited. Furthermore, some studies are based on hypothetical storage sites rather than real-world applications. While hypothetical models allow for controlled comparisons and scenario analysis, real storage sites provide more reliable data as they take into account site-specific facts such as geological conditions and different applications with different materials. Only Mangold et al. [43] reported the results of an LCA exclusively on the construction processes for various types of sTES and locations, including ATES, BTES, TTES, PTES, and WGTES. The results highlight the importance of selecting appropriate construction materials in terms of their environmental impact.

The current work analyses the environmental impacts of three sTES types (TTES, PTES, and WGTES) associated with their construction phases, based on three real-world examples (TTES in Munich-Ackermannbogen, Germany; PTES in Marstal, Denmark; WGTES in Eggenstein-Leopoldshafen, Germany). By considering the site-specific conditions of each sTES, the study provides a literature-based assessment of their construction-phase environmental impacts, aiming to identify common trends and key differences. In this regard, the results should be understood primarily as an identification of overarching environmental trends and as providing insights into the advantages and limitations of different sTES technologies, based on real-world examples, rather than as a comprehensive technical evaluation of individual

Table 1
Comparison of life cycle assessment studies on different seasonal thermal energy storages. LCIA: life cycle impact assessment, LC: life cycle.

Author & year	Type	Real/ hypothetical	Location	Functional unit/system boundary	Heating/ cooling	LCIA method/software/database	Dominant LC phase
Mangold et al. (2012) [43]	ATES, BTES, TTES,PTES, WGTES	Real	Different	n.a./cradle-to-gate	n.a.	n.a./EcoPro, SimaPro, Umberto, GEMIS, GaBi, openLCA/Ecoinvent Ökobau.dat, GaBiE, KBOB	n.a.
Moulopoulos (2014) [38]	ATES	Real	Delft, Netherlands	175 MWh of cooling and 268 MWh of heating per year for a period of 15 years/cradle-to-grave	Heating & cooling	ReCiPe Midpoint/SimaPro/ Ecoinvent	Operation (45.8 %)
Tomasetta et al. (2015) [37]	ATES, BTES	Hypothetical	Netherlands	25 years (2 000 h/year)/n.a.	Heating	Eco-Indicator 99/SimaPro 7/n.a.	Operation (88.7 %)
Limoges (2019) [41]	ATES	Real	Bonner Bogen, Germany	1 kWh/cradle-to-grave	Heating & cooling	Impact2002+/SimaPro/Ecoinvent v3, ELCD, Industry Data 2.0	Operation (98.5 %)
Ni et al. (2020) [39]	ATES	Hypothetical	Shanghai, China	Energy produced from 30 years' operation of an ATES system/ cradle-to-grave	Heating & cooling	-/eBalance 4.7/CLCD-China-ECER 0.8.1,ELCD 3.0.0, Ecoinvent 3.1.0	Operation (96 %)
Karasu et al. (2020) [42]	BTES	Real	Okotoks, Alberta, Canada	1 m^2 floor area of a Drake Landing house over its lifetime/ cradle-to-grave	Heating	CML 2001/SimaPro 7.3/Ecoinvent	Operation (45 %)
Stemmle et al. (2021) [16]	ATES	Real & hypothetical	Bonner Bogen, Germany	n.a./cradle-to-grave	Heating & cooling	Impact2002+/SimaPro 9.0.0.35/ n.a.	Operation (98 %)
Godinaud et al. (2024) [40]	ATES	Real	Bordeaux, France	1 kWh/cradle-to-gate	Heating & cooling	ReCiPe 2016/n.a./Ecoinvent 3.8	Operation (63 %)

systems. To achieve this, in the following, the three storage systems are introduced, followed by a description of the procedures for the LCA of the construction phase. Then environmental impacts of the sTES are presented, and considered in relation to results from related LCA studies of ATES systems.

2. Application cases

This work focuses on representative application cases of a TTES (Munich-Ackermannbogen, Germany), a water-filled PTES (*SUNSTORE4* project in Marstal, Denmark), and a WGTES (Eggenstein-Leopoldshafen, Germany), which are second- and third-generation storage systems reflecting advancements in construction technology [44]. A comparative overview of the selected sTES is shown in Table 2. The construction materials used for each sTES are briefly characterized below in terms of their properties, while the exact quantities are detailed in the life cycle inventory (LCI) in Chapter 3.2.

Table 2 highlights that a direct comparison of the three sTES is not meaningful, as each system was constructed under different conditions, for different applications and energy systems, etc. Factors such as site-specific constraints, storage volumes, and material choices further complicate a one-to-one comparison. Although each sTES was built under different conditions, common trends and key differences can be identified. Analyzing these aspects allows for a broader assessment of their environmental impacts and provides insights into the advantages and limitations of different sTES technologies.

2.1. TTES

Since its construction in 2007 [44], a residential area in Munich-Ackermannbogen (Germany) with 320 residential units in apartment blocks has been supplied by a solar thermal-based local heating system [50]. Thereby, the solar district heating plant at Ackermannbogen benefits from the experience gained from the sTES in Friedrichshafen, Hamburg, and Hannover (Germany) that have been in operation since 1995 [44,46]. Considering (hydro-)geological site conditions, customer requirements, and requirements of the heating supply system, a TTES (Fig. 1) was constructed. As the TTES is an above-ground storage that is only partially buried, structural reinforcements such as steel and concrete were required to ensure stability [44,50]. Due to economic reasons, the high cost of delivering gravel, and the unsuitability of the limestone gravel found on-site for a WGTES, a water-filled storage system with a capacity of approximately 6 000 m^3 was constructed [44,50]. Additionally, the excavated soil was not transported off-site but was reused on-site to cover the storage system [44].

2.2. PTES

Until 2012, the district heating system in Marstal, a town with 2 400 inhabitants on the Danish island of Ærø, relied on oil as its primary fuel source. In 2012, the city decided to switch the district heating system completely to renewable energy: 50 % of heat demand is covered by solar heat, with the remaining 50 % supplied by biomass energy [54]. To store the surplus solar energy from the summer for the heating period, planning indicated that a PTES (Fig. 2a) with a water volume of approximately 75 000 m^3 was required [57,60]. The geometry of the pit was designed as an inverted truncated pyramid, which is typical for PTES, with the excavated earth forming an embankment around the facility [52,54]. Instead of excavating the full volume, only approximately 30 000 m^3 were removed, while the remaining portion of the total 75 000 m^3 was achieved by backfilling and shaping the embankment [31,52]. The PTES is fully embedded in the ground, eliminating the requirement for supporting structural elements such as steel or concrete. Instead, plastic foils were used for lining (Fig. 2b). The cover includes an insulating floating membrane, which is not structurally reinforced and therefore not suitable for any use of the surface above.

2.3. WGTES

The WGTES in Eggenstein-Leopoldshafen was the first to be implemented in existing buildings for refurbishment, including a primary and secondary school, further associated buildings, and a fire department [61,62]. To facilitate the accessibility of the schoolyard located above the planned sTES, a WGTES was chosen (Fig. 3), which was covered with a 30 cm thick layer of soil and filled with gravel in the upper and lower thirds. The remaining volume of the double truncated cone was filled with sand excavated on-site to reduce construction costs [31,63]. Approximately 84 % of the excavated sand was used to fill the storage, while the remaining 16 % was utilized for covering the storage (Appendix **Table A**). Since this system is an *underground thermal energy storage* (UTES), lining materials such as high-density polyethylene

Table 2
Comparison of key parameters of three selected seasonal thermal energy storage systems: TTES (HWTES) in Munich-Ackermannbogen (Germany), WGTES in Eggenstein-Leopoldshafen (Germany), and PTES in Marstal (Denmark). WEV: water equivalent volume as defined in **Chapter 1**, A/V ratio: surface-to-volume ratio.

		TTES (HWTES)	WGTES	PTES
Planning	Field site	Munich	Eggenstein	Marstal
	Year of commissioning	2007 [7,43–47]	2008 [44,45,48]	2012 [34,48]
	Generation	III [44]	III [44]	II [49]
	Heat demand (MWh/a)	2 300 [46]	1 150 [44]	32 000 [48]
	Heated area (m^2)	30 400 [50]	12 000 [44]	n.a.
Construction	Geometry	Two mirrored truncated cones with a cylinder in between [50]	Two successive truncated cones [36,51]	Inverted truncated pyramid [52–54]
	A/V ratio	0.287[b)]	0.428 [48]	0.233 [48]
	Underground installation below groundlevel (m)	5 [50]	7.5 [51]	12 [54]
	Volume (m^3)	6 000 [50,55]	4 500 [43–45,48,51]	75 000 [34,45,48]
	Filling material	Water [43,44,50]	Gravel-sand-water [43,44,51]	Water [53]
	WEV (m^3)	5 700[a)] [43–47,50,55]	3 000 [43]	75 000 [53]
	(Dis-)charging system	Stratified (dis-)charging system with automatic height adjustment [44,46,50]	Two wells [43,56]	Three inlet and outlet pipes [57]
	Cover utilization	Sledding hill [46]	Schoolyard [58]	n.a.
Operation	Number of charge cycles (per year)	n.a.	n.a.	0.7–1.1 [48]
	Min./max. storage temperatures (°C)	10/90 [47,55]	10/80 [48,51]	20/82 [48]
	Storage capacity (MWh)	480 [55]	n.a.	6 960 [34,53]
	Charging/energy input (MWh)	969 [43,55]	287 [43]	7 538 [15]
	Discharging/energy output (MWh)	809 (2008/09) [43,55]	226 (planned) [43]	4 141 (2013) [15]
	lifetime (years)	30[b)]	30[b)]	30[b)]

[a)] Storage not completely filled with water (see Fig. 1).
[b)] Data based on assumption or calculation.

(HDPE) were used, as they do not need to fulfill any static functions. Additionally, a significant amount of insulation material was used to enhance thermal efficiency [51,61].

3. Life cycle assessment

The LCA performed in this study is aligned with the standardized procedure according to DIN EN ISO 14040 [64] and DIN EN ISO 14044 [65]: First, the goal and scope of this assessment are defined, including the objective of the study, system boundaries, and the functional unit, which is used to standardize all input and output data to a common reference [64,65]. The next step is to build an LCI that contains all relevant data on material and energy flows. In the subsequent life cycle impact assessment (LCIA), the associated environmental impacts are analyzed using the *IMPACT2002+* [66] method and compared for previously defined mid-point categories. In the evaluation, all results are summarized and interpreted according to the goal and scope [65,67].

3.1. Goal and scope

This work employs the *SimaPro 10.0.0.28* software, and the *ecoinvent 3.10* database, and focuses on the construction phase of the facilities; the operational and decommissioning phases are not considered due to missing data. The goal of the LCA is a specific analysis of the three selected storage types at each location. The LCA for the three sTES in Munich, Eggenstein-Leopoldshafen, and Marstal are evaluated using the mid-point categories of *global warming*, *non-renewable energy*, and *mineral extraction* of the *IMPACT2002+* method [66]. Global warming was selected for its policy relevance and comparability, while non-renewable energy and mineral extraction were chosen due to their importance for the construction of sTES systems.

The three selected sTES sites provide thermal energy in the form of heat. All three sTES have different energy inputs, outputs, and losses due to different characteristics in terms of volume, materials, energy demand, year of commissioning, etc. Therefore, the functional unit is defined as 1 kWh_{th} of thermal energy output provided by each system within one (reference) year, based on an assumed lifetime of 30 years (Table 2). The LCIs consist of the following processes: (1) *excavation and filling*, (2) *backfilling and compaction* (not relevant for PTES), (3) *cladding and lining*, and (4) *(dis-)charging system and filling material*. As detailed in the subsequent chapter, these processes represent the main construction stages and are all orientated toward the defined functional unit.

The system boundaries are defined to contain the whole product system of the respective sTES, including the filling, the (dis-)charging system, the sealing layer (with vapor barriers, if applicable), the insulation material, and the cover. Components located outside the facilities, such as the solar system, heat pumps, pipes, valves, are not included.

3.2. Life cycle inventories

In this section, the properties of the three selected sTES prototypes are explained. The processes include components for construction and operation, as well as material transport. The components illustrated in Figs. 1–3 are assigned to the four (construction) processes and their function. Further, the relationships between transport, materials, and processes are illustrated in Fig. 4.

The process of *excavation and filling* includes the subsoil removed at the beginning of sTES construction to integrate the structure partially or fully into the ground. For *backfilling and compaction*, bulk material, primarily consisting of insulation material, is used. The process of *cladding and lining* includes vapor barriers, such as foils, and also pipes, cables, prefabricated wall elements, and other materials. The fourth process *(dis-)charging system and filling material* considers all materials within the storage facility including water, gravel, sand, and the stratified (dis-)charging system. The main difference between the TTES and the other two storage types is that the materials of the TTES are primarily used for the cover of the above-ground construction, which plays a key role for the stability of the system. The WGTES system comprises four processes, similar to the construction of the TTES. Approximately 84 % of the excavated sand has been used to fill the storage volume, while the remaining excavated material was employed to cover the structure. Since this sTES is a UTES, most of the lining materials do not have static functions. Similar to the WGTES, the PTES primarily uses lining materials, and no static materials are required. Compared to the other two systems, PTES only involves three processes. The process of *backfilling and compaction* is not necessary because the sides of the PTES are not insulated (Fig. 2). As with the other two sTES, the excavated material has been re-used, in this case as an embankment to increase the

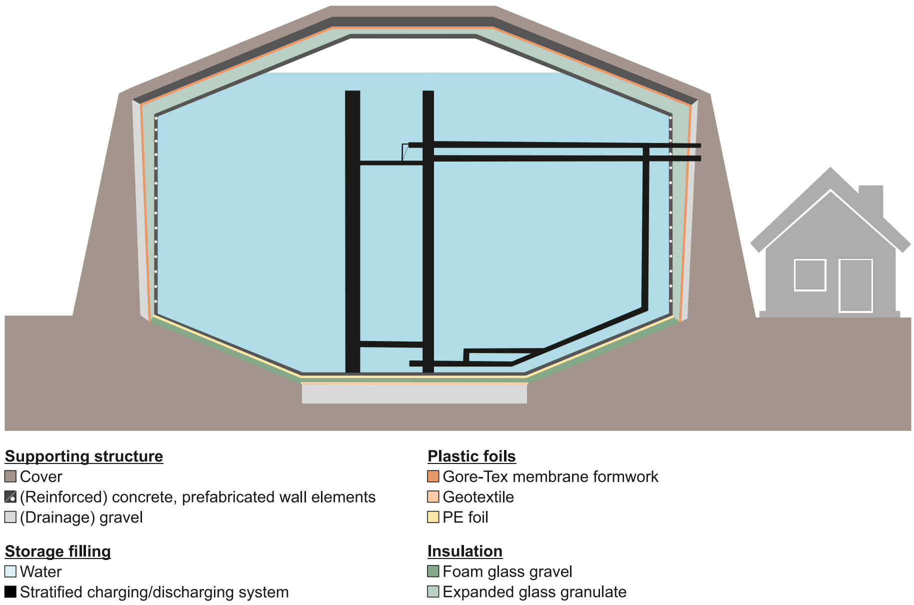

Fig. 1. Schematic layout of the tank thermal energy storage (TTES) based on the storage in Munich-Ackermannbogen in relation to a typical single-family house for a general size indication (not to scale; based on [36,44,50,59]). PE: Polyethylene.

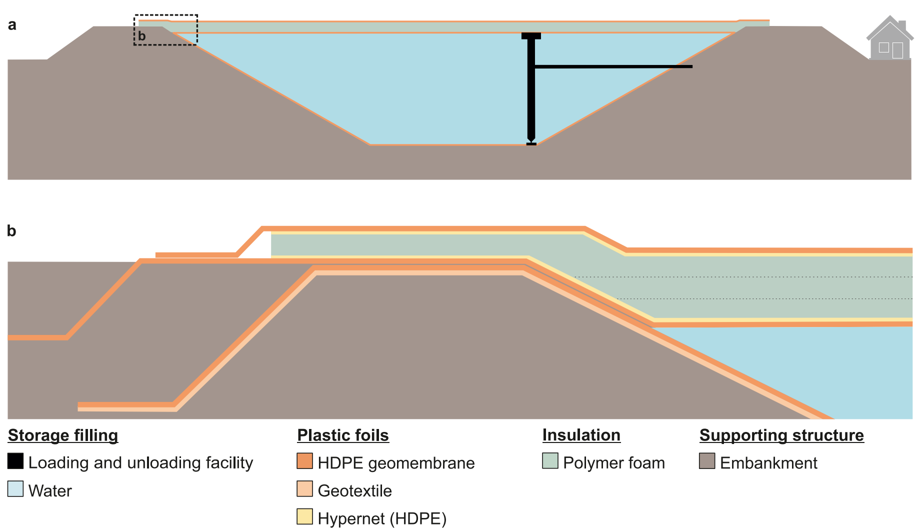

Fig. 2. a. Schematic layout of the pit thermal energy storage (PTES) based on Marstal in relation to a typical single-family house for a general size indication (not to scale); **b.** detailed section of the PTES, highlighting the specific materials used, based on [31,52,53,57]. HDPE: High-density polyethylene.

filling volume. In addition to the PTES materials listed in Fig. 2, the inventory includes the weight pipes made of HDPE filled with concrete, which are located on the floating cover. They are designed to direct rainwater toward the center of the storage cover, where it can then be pumped out [31].

To create the LCI, the following general assumptions are made for the construction of all three sTES.

- The excavators used are crawler excavators with a backhoe bucket capacity of 1–2.15 m^3, an excavation rate of approx. 25 m^3/h in total and an average fuel consumption of 15.91 l/h (diesel). The weight of the excavator used to calculate the transportation is approx. 3.5 t [68].
- To determine transport distances, a representative company nearby is identified in case specific supplier information is not available. If this is not possible, an average transport distance of 250 km is assumed, as this reflects the average regional company density in Germany required to source the necessary materials. In all cases, it is assumed that materials are sourced as locally as possible and transported by road only, with no consideration given to other modes of transport (e.g., air, rail, and sea).
- In case of insufficient data on the materials used, average values of the same or similar materials from literature sources are used.
- Tap water is sourced locally to fill the three sTES, eliminating the need for transport.
- Where storage dimension data is missing or inconsistent, the dimensions are reconstructed, and the missing measurements are graphically determined for the calculations.

The detailed specifications regarding material parameters and transportation distance are listed in Appendix Table A. This includes all construction materials used for the three sTES, their corresponding transport, and alternative materials selected from the *ecoinvent* database when necessary. Additionally, material-specific details and uncertainties

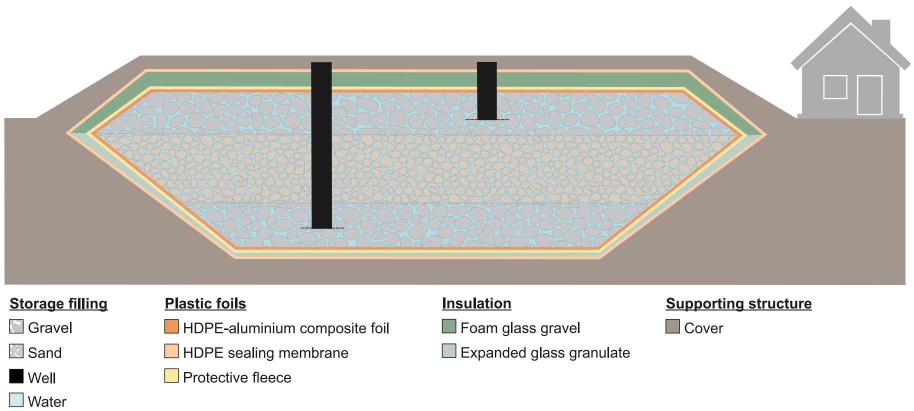

Fig. 3. Schematic layout based on the water-gravel thermal energy storage (WGTES) in Eggenstein-Leopoldshafen in relation to a typical single-family house for a general size indication (not to scale; based on [36,44]). HDPE: High-density polyethylene.

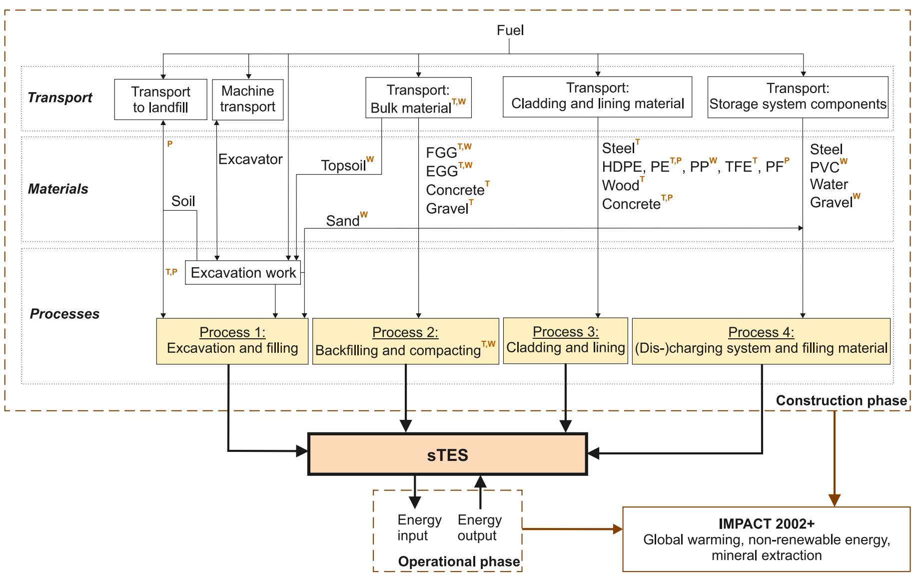

Fig. 4. Process visualization of the three selected sTES prototypes, according to Ref. [41]. T: Processes only applicable to TTES; P: Processes only relevant to PTES; W: Processes only relevant to WGTES. FGG: foam glass gravel, PP: polypropylene, PF: polymer foam, PE: polyethylene, HDPE: high-density polyethylene, EGG: expanded glass granulate, TFE: tetrafluoroethylene, PVC: polyvinyl chloride.

due to missing data in the literature are highlighted. The uncertainty classification is presented in Appendix **Table B**.

4. Results and discussion

4.1. LCA results

4.1.1. Impact assessment of the processes

The environmental impact of the four categorized processes are shown for the three selected sTES in Fig. 5. Here each impact indicator — *global warming*, *non-renewable energy*, and *mineral extraction* — is standardized at one hundred percent. All specific absolute and relative values can be obtained from **Table C**. Aspects such as storage volume, the A/V ratio, and the type of filling material are important when evaluating sTES systems from a techno-economic perspective [13,69]. The results from Fig. 5 suggest that larger storage volumes with a low A/V ratio and water-based filling tend to have lower environmental impacts. Specifically, the PTES, which has the lowest environmental impact (1.44 g $CO_{2\text{-eq}}/kWh_{th}$, 9.23 kJ/kWh_{th}, 0.137 kJ/kWh_{th}), has the largest water volume (75 000 m^3). In contrast, the WGTES, which exhibits the highest environmental impact (29.39 g $CO_{2\text{-eq}}/kWh_{th}$, 197.6 kJ/kWh_{th}, 0.977 kJ/kWh_{th}), has only half the WEV (3 000 m^3) compared to the TTES (5 700 m^3), even though the total storage volume of the TTES (6 000 m^3) is only approximately 1.5 times larger than that of the WGTES (4 500 m^3). This difference arises because a significant portion of the total storage volume in the WGTES is filled with gravel and sand, which reduce the effective amount of water available for heat storage (WEV). In contrast, regarding the TTES only water is used as storage medium, so nearly the entire storage volume contributes to the WEV. As a result, despite similar total storage volumes, the TTES can store more thermal energy than the WGTES. The lower environmental impact can be explained by the fact that larger storage volumes and a lower A/V ratio result in a more favorable ratio of water volume to surface area, which also reduces the need for construction materials.

For all three sTES, process 1 *excavation and filling* is of minor importance for the three impact categories, contributing less than 3 % to the TTES and WGTES. Only for the PTES, the impact of 0.138 g $CO_{2\text{-eq}}/kWh_{th}$ (9.6 %) has a higher, but still negligible influence on the category *global warming*. While process 2 *backfilling and compaction* has no impact on the PTES, as it is not considered in this sTES, it contributes significantly to the impacts of the TTES (*global warming*: 62.3 %, *non-renewable energy*: 56.2 %) and the WGTES (*global warming*: 94 %, *non-renewable energy*: 89 %). Regarding the impact category of *mineral extraction*, the process has a large impact on WGTES (72.4 %, 0.674 kJ/kWh_{th}), while

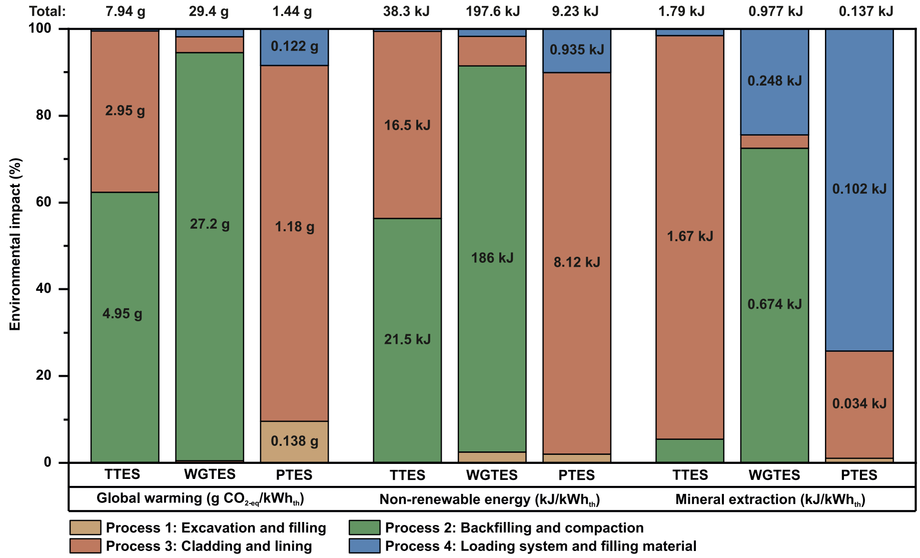

Fig. 5. Distribution of environmental impacts of tank thermal energy storage (TTES), water-gravel thermal energy storage (WGTES), and pit thermal energy storage (PTES) across the impact categories of *global warming*, *non-renewable energy*, and *mineral extraction*, divided into the life cycle processes of *excavation and filling*, *backfilling and compaction*, *cladding and lining*, and *(dis-)charging system and filling material*.

the effect on TTES is negligible (5.4 %). Process 3 *cladding and lining* emerges as a major contributor across several impact categories. For the category *global warming*, this process has an impact of 37.1 % (2.95 g $CO_{2\text{-eq}}/kWh_{th}$) for TTES and 82 % (1.18 g $CO_{2\text{-eq}}/kWh_{th}$) for PTES.

A similar trend can be observed for the impact category *non-renewable energy* (TTES: 43.1 %, PTES: 87.9 %). The picture is reversed in the category of *mineral extraction*. Here the process *cladding and lining* dominates with 93 % (1.67 kJ/kWh_{th}) for TTES and has only a smaller influence with 24.7 % (0.034 kJ/kWh_{th}) for PTES. For the WGTES, this process has a relatively minor impact, contributing less than 7 % to all impact categories considered. Finally, process 4 *(dis-)charging system and filling material* only has a noticeable effect on the category of *mineral extraction*. This corresponds to 74.2 % (0.102 kJ/kWh_{th}) for PTES and 24.2 % (0.248 kJ/kWh_{th}) for WGTES. Regarding the TTES and the other impact categories, this process has a negligible impact.

The results underscore the demand of system-specific optimization, especially concerning the construction processes of *cladding and lining*, as well as *backfilling and compaction* (excluding PTES), as these have the most significant overall impact on the LCA. The differences in process contributions across the three sTES indicate that materials should be selected according to the specific requirements of each system. For example, in the case of PTES, optimization efforts should prioritize the process of *cladding and lining*, while for WGTES, the focus should be directed more toward the *backfilling and compaction* processes. For TTES, both processes of *cladding and lining*, as well as *backfilling and construction*, should be evaluated with an emphasis on the substitution of environmentally harmful materials, such as foam glass gravel, steel, and concrete.

4.1.2. *Impact assessment of materials and transport*

This chapter examines the contributions of individual materials and transport to the overall environmental impact to better understand the underlying causes, with fuel consumption, particularly relevant in process 1. Additionally, the processes *backfilling and compaction* and *cladding and lining* are considered, and the transport of materials across all four processes is thoroughly analyzed.

The impact of fuel consumption associated with process 1 *excavation and filling* is low for all analyzed sTES (Fig. 6). This is due to the reuse of excavated soil within the construction process: in the case of the TTES, it was used as a cover, for the WGTES as filling material (sand), and in the case of PTES it was used to form an embankment (Figs. 1–3). Only for the PTES part of the excavated soil was transported off-site (Fig. 4) and subsequently excluded from the LCA. This is reflected in the results, where the impact from fuel consumption for excavation and transport remains below <0.2 kWh_{th} and <0.3 g $CO_{2\text{-eq}}/kWh_{th}$ for all sTES (Fig. 6). The PTES still has a low impact despite the removal of the excavated soil, demonstrating the importance of on-site reuse. In this case, excavation and transport were minimized by reusing as much material as possible on-site. By avoiding unnecessary transport and reducing excavation, fuel consumption, and emissions can be kept low. To address the potential for further reduction, it is important to note that, according to Fig. 6, the contribution of transport to the overall environmental impacts is relatively low (5–10 %) compared to the material-related impacts for all sTES. So, even if transportation was further minimized, the overall ranking of the TES systems in terms of global warming potential, non-renewable energy, and mineral extraction would remain unchanged.

For process 2 *backfilling and compaction* the material selection, and the use of foam glass gravel in particular, has a substantial effect, as evidenced by the results (Fig. 6) for WGTES (25.6 g $CO_{2\text{-eq}}/kWh_{th}$, 164 kJ/kWh_{th}, 0.66 kJ/kWh_{th}) and TTES (1.18 g $CO_{2\text{-eq}}/kWh_{th}$, 7.59 kJ/kWh_{th}). This is primarily due to the volume of foam glass gravel used for insulation at the WGTES (837.25 m^3) and, to a lesser extent, at the TTES (139.02 m^3). In contrast, the PTES does not include foam glass gravel but instead utilized polymer foam (2 422.02 m^3) as an insulation material, which represents a more environmentally friendly alternative (Fig. 4). These results are consistent with those of Mangold et al. [43] who also identified foam glass gravel as a major contributor to the environmental impact of TTES in Munich-Ackermannbogen and WGTES in Eggenstein-Leopoldshafen. Consequently, substituting or minimizing the use of foam glass gravel as insulation material with a lower environmental footprint could substantially reduce the overall environmental impacts of TES systems.

This section further examines the role of concrete and steel in the process of *cladding and lining* (Fig. 6). Regarding the construction of the TTES, a substantial amount of concrete (898 t) and steel (34 t) was used due to the static requirements. This leads to considerable emissions (steel: 1.69 g $CO_{2\text{-eq}}/kWh_{th}$, 15.5 kJ/kWh_{th}, 0.26 kWh_{th}; concrete: 3.3 g $CO_{2\text{-eq}}/kWh_{th}$, 8.24 kJ/kWh_{th}, 0.06 kJ/kWh_{th}). In contrast, the PTES and WGTES have lower environmental impacts regarding the process of *cladding and lining* due to their underground construction method. These systems rely on the surrounding soil for structural stability, reducing the

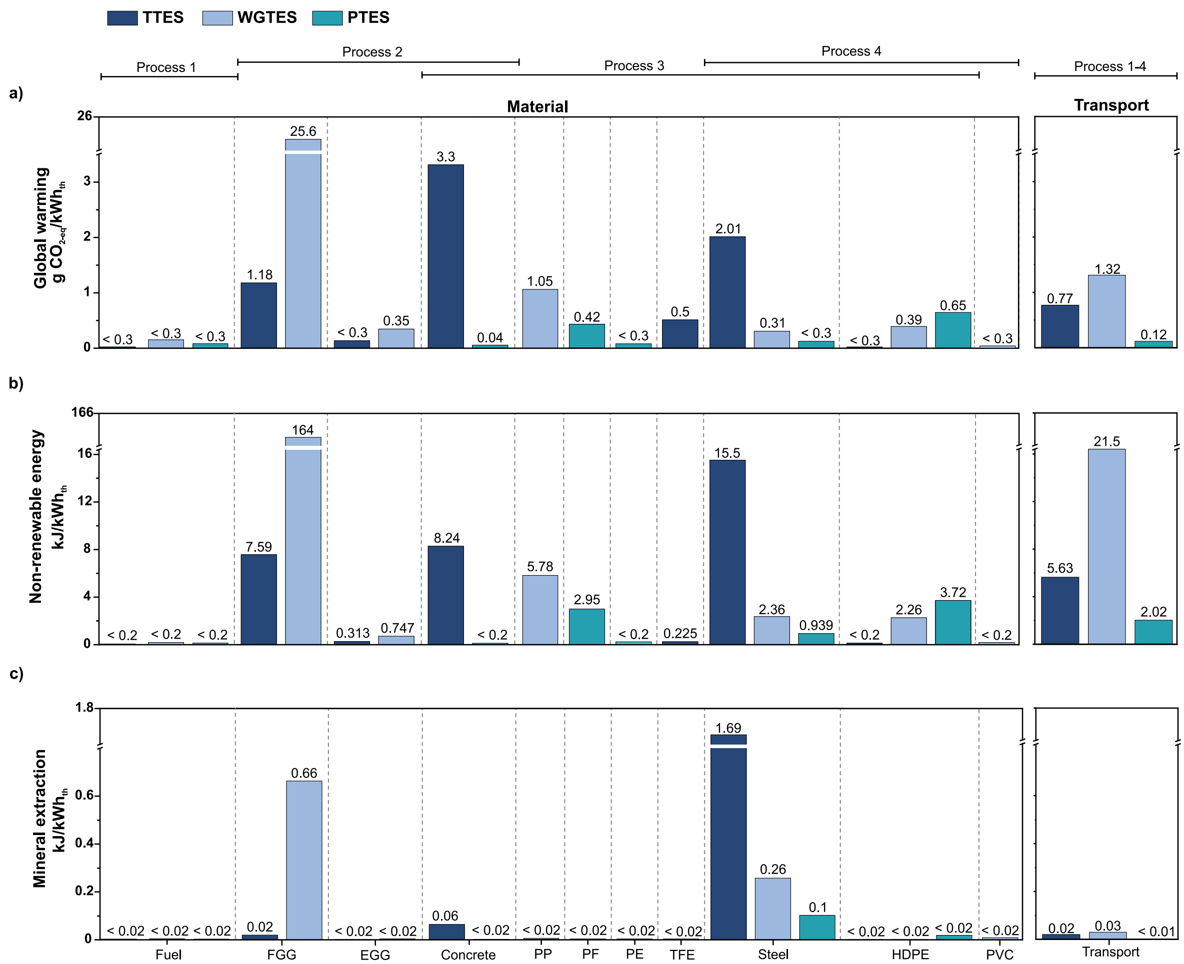

Fig. 6. Material contributions to environmental impacts categories of (a) *global warming*, (b) *non-renewable energy consumption*, and (c) *mineral extraction*. FGG: foam glass gravel, PP: polypropylene, PF: polymer foam, PE: polyethylene, HDPE: high-density polyethylene, EGG: expanded glass granulate, TFE: tetrafluoroethylene, PVC: polyvinyl chloride. The specific classification of materials and transport to the processes of each storage system can be derived from the process visualization (Fig. 4).

need for additional reinforcement. Therefore, different materials such as HDPE for lining are used, which have significantly lower impacts (0.65 g $CO_{2\text{-eq}}/kWh_{th}$). These results are comparable with those of Mangold et al. [43] who also identified steel and concrete as the main contributors to the environmental impact of TTES. For this reason, fully buried sTES should be preferred to reduce the need for static materials such as steel and concrete, as the embankment provides structural stability. In addition, alternative materials with lower environmental impact such as HDPE should be considered.

The extent of excavation and material transport differs between the various storage types in the LCI. Therefore, this aspect is examined in more detail here, considering the transportation of all materials involved in the different processes. The distance and frequency of transport trips, especially for materials with high volume and low density, can significantly increase the system's *global warming* (Fig. 6). This is reflected in the results of TTES and WGTES, where the transport of foam glass gravel and expanded glass granulate contributes a large proportion to the impacts on the categories *global warming* (TTES: 0.77 g $CO_{2\text{-eq}}/kWh_{th}$, WGTES: 1.32 g $CO_{2\text{-eq}}/kWh_{th}$) and *non-renewable energy* (TTES: 5.63 kJ/kWh_{th}, WGTES: 21.5 kJ/kWh_{th}), because these materials require extensive transport due to their large volume (see Appendix **Table A**). In contrast, the delivery of the PTES materials does not rely on these long transport routes, resulting in lower transport requirements and, subsequently, lower emissions (0.12 g $CO_{2\text{-eq}}/kWh_{th}$, 2.02 kJ/$kWh_{th}$). To minimize the environmental impact of sTES construction, the transport distances and the frequency of trips should be reduced as much as possible. Therefore, attention should be paid to a regional selection of materials in order to significantly reduce emissions and fuel consumption.

It should also be noted that Fig. 6 already provides some insight into the potential of alternative insulation materials, as the different sTES use different materials (e.g., PTES: PF instead of FGG), which is directly reflected in the environmental impact results. This comparison illustrates how the choice of insulation material can significantly influence the environmental performance of each storage type. However, it should be emphasized that not every insulation material is equally suitable for all storage concepts, and therefore, one single material does not necessarily represent the optimal solution for every sTES type. The selection of insulation must consider technical requirements and compatibility with the specific storage design.

4.2. Comparison with other studies

In this section, the differences and similarities of the construction and operation phase for the three storage systems — TTES, WGTES, and PTES — are identified and analyzed, as well as compared with different ATES systems, based on the same functional unit of 1 kWh_{th} (Fig. 7). The comparison focuses on the impact category of *global warming*. The remaining two impact categories and the end-of-life phase are not analyzed further due to a lack of sufficient comparative results from existing studies.

The uncertainty of the LCA results for the three sTES is represented as error bars in Fig. 7. The error bars were determined based on the assumptions outlined in the description of the LCI and the uncertainties of the values listed in Appendix **Table A**. The TTES and WGTES exhibit the highest uncertainties, although the margin of error for these ranges is minimal (<1.0 g $CO_{2\text{-eq}}/kWh_{th}$) and does not change the ranking of the storage systems in the comparison.

The impact of the construction phase of the PTES (1.4 g $CO_{2\text{-eq}}/kWh_{th}$) is comparable to that of the ATES system at Bonner Bogen (Stemmle: 1.9 g $CO_{2\text{-eq}}/kWh_{th}$ [16] and Limoges: 1.0 g $CO_{2\text{-eq}}/kWh_{th}$ [41]). The construction phase of the TTES, with an impact of 7.9 g $CO_{2\text{-eq}}/kWh_{th}$, is positioned between the lower values observed for the ATES systems at Bonner Bogen (1.9 g $CO_{2\text{-eq}}/kWh_{th}$ [16] and 1.0 g $CO_{2\text{-eq}}/kWh_{th}$ [41]) and the higher values reported for other studies (Moloupolous: 10.3 g $CO_{2\text{-eq}}/kWh_{th}$ [38], Tomasetta: 13.6 g $CO_{2\text{-eq}}/kWh_{th}$ [37,70]). In contrast, the construction phase of the WGTES exhibits a significantly higher impact of 29.4 g $CO_{2\text{-eq}}/kWh_{th}$. However, when considering the proportion of the operational phase in the total environmental impact of ATES systems analyzed by Moulopoulos [38] (45.8 %, 53.7 g), Stemmle [16] (98 %, 94.1 g $CO_{2\text{-eq}}/kWh_{th}$), Limoges [41] (98.5 %, 99.0 g $CO_{2\text{-eq}}/kWh_{th}$), and Tomasetta [37,70] (88.7 %, 106.4 g $CO_{2\text{-eq}}/kWh_{th}$), it becomes clear that the operational phase exerts the most significant influence on the total environmental impact. This is mainly due to the electricity consumption to operate the heat pumps and groundwater extraction/injection pumps [37,38]. If the operation phases were included for TTES, PTES and WGTES and their effects were assumed to be similar to those observed in the different ATES studies, it is probable that the overall environmental impact of these sTES examined in this study would be even higher. The fluctuations in the total environmental impact of the ATES systems, which ranges from 64.0 to 120.0 g $CO_{2\text{-eq}}/kWh_{th}$, indicates that these are distinct sites, with outcomes that are significantly influenced by the boundary conditions. Consequently, the environmental impacts of the different sTES types can also vary when considering different site-specific conditions.

Differences in the results of the various sTES amongst themselves and in comparison to the ATES case studies can be attributed to multiple factors. When comparing the sTES analyzed in this work with the different ATES, it should be noted that although the results are related to 1 kWh_{th}, some of the studies (Limoges [41], Stemmle [16], Moulopoulos [38]) also include the provision of cooling energy by the sTES in addition to heat. Thus, they do not perform the same function. Further deviations can emerge from different impact assessment methods (Tomasetta [37]: *Eco-Indicator 99*, Moulopoulos [38]: *ReCiPe Midpoint*) [66]. Additionally, deviations in the results may be explained by the utilization of different software or databases, along with the employment of different inputs with different material and transport properties.

5. Conclusions

Seasonal thermal energy storage (sTES) is the key to decarbonizing modern heat supply systems by conserving superficial summer heat for use in winter. While the operating principle of such heat storage systems is obvious, the degree of decarbonization is not well understood. In fact, a prerequisite for assessing the environmental impact of storage strategies is an understanding of the environmental impact of the often sizable sTES installations. Several technological variants are currently available, which differ significantly in terms of their design and associated environmental impact. This work investigates representative application cases not only related carbon emissions, but evaluates *global warming*, the utilization of *non-renewable energy*, and *mineral extraction* within an LCA framework. Primary focus is set on the construction phase of TTES, WGTES, and PTES. The results are compared with those available for ATES with respect to *global warming*.

This study compares the systems based on case studies in Germany and Denmark and identifies the construction processes and materials with the greatest impact. Recommendations are given on material selection and more efficient storage design to minimize the environmental impact of sTES technologies. The analysis shows that larger storage volumes with a low surface-to-volume ratio and the use of water as filling material can improve environmental performance. The results underline the need for system-specific optimizations, especially concerning cladding and insulation processes. Optimization can be achieved by minimizing transport distances, as well as by reducing the use of building materials such as concrete, steel, and foam glass gravel.

For the three sTES variants compared in detail, greenhouse gas emissions during the construction phase are between 1.4 and 29.4 g $CO_{2\text{-eq}}/kWh_{th}$. WGTES shows the highest impact in all analyzed impact categories, while PTES shows the lowest. Despite the case-specific calculations, it is expected that other implementations show a similar environmental impact that generally decreases per kWh_{th} for increasing size. While this would need to be substantiated by further analysis of other case studies, the relative material consumption is lower for larger storage facilities, so the economies of scale would also be reflected in the associated environmental impacts per kWh_{th}.

The presented comprehensive LCA already shows that there is potential for improvement in the construction phase of sTES in many respects. However, more research is needed to establish sTES as an optimized energy source. It is fundamental to include the operational and end-of-life phases to identify the potential for improvement across the life cycle and to avoid shifting the environmental burden either between life cycle phases or beyond the system boundaries. For example, a material that is used in the construction phase because of its excellent environmental performance may have a less favorable environmental performance in the other phases. The presented comparison

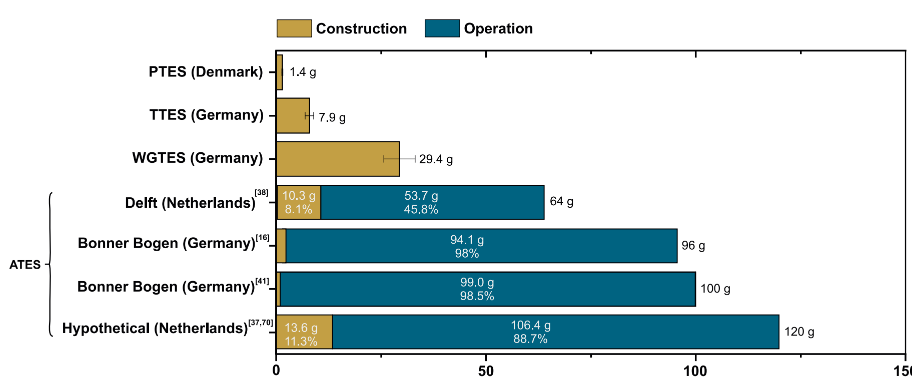

Fig. 7. Comparison of the *global warming* (g $CO_{2\text{-eq}}/kWh_{th}$) of different sTES (tank thermal energy storage (TTES), water-gravel thermal energy storage (WGTES), pit thermal energy storage (PTES), and aquifer thermal energy storage (ATES)) from several studies. The percentage impact of the two phases of *construction* and *operation* is presented in relation to the total impact.

to different ATES case studies also includes reported global warming effects for the operation phase. In all cases, these dominate the overall life cycle, but reported emissions span broad ranges with strongly different assessments of the construction phase. This leads to an equivocal picture of which sTES variant is generally favorable. Future work will need to focus on consistent functional units and system boundaries in order to facilitate direct comparability of assessments. Moreover, despite the general focus on global warming impacts, a combined consideration of different impact categories in LCA will be needed for holistic environmental evaluation of alternative sTES systems to contrast overall techno-economic benefits with environmental burdens.

CRediT authorship contribution statement

Jenny Weise: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Christoph Bott:** Writing – review & editing, Visualization, Methodology, Funding acquisition. **Kathrin Menberg:** Writing – review & editing, Validation, Conceptualization. **Peter Bayer:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A
Life cycle inventory related to the four processes of the three sTES (tank thermal energy storage (TTES), pit thermal energy storage (PTES), water-gravel thermal energy storage (WGTES)). ROW: rest of the world, RER: Europe, EwS: Europe without Switzerland, PE: polyethylene, HDPE: high-density polyethylene, CN-E: Carbon-nanotube enhanced, HF-E: Halogen-free enhanced.

Component	Material	Amount (kg)	Equivalent material (SimaPro)	Transport (tkm)	Uncertainty (%)
TTES					
Process 1: Excavation and filling					
Coverage	Soil [44,50]	1.28×10^3	Soil	–	10
Excavator	–	–	–	$8,75 \times 10^4$	10
Fuel	Diesel	449	Diesel	–	10
Process 2: Backfilling and compaction					
Blinding concrete	In-situ concrete [31,44,50]	3.80×10^5	Concrete, normal strenght (ROW)	$3,80 \times 10^6$	10
Protection layer	Protective concrete [44]	2.38×10^5	Concrete, normal strenght (ROW)	$2,38 \times 10^6$	20
Insulation	Expanded glass granulate [31,44,50]	1.49×10^5	Glass cullet, sorted (RER)	$3,73 \times 10^7$	10
Drainage	Drainage gravel [44]	8.40×10^5	Gravel	$1,68 \times 10^7$	5
Insulation	Foam glass gravel [31,44,50]	1.67×10^4	Foam glass (GLO)	$4,17 \times 10^6$	10
Process 3: Cladding and lining					
Protection layer	Geotextile [44]	43.3	Polyethylene terephthalate, granulate, amorphous (EwS)	$1,08 \times 10^4$	10
Structural support function	Balk [44]	117	Wood, feedstock	$1,17 \times 10^4$	20
	Reinforcing steel (pre-fabricated concrete) [44,50]	7.24×10^3	Steel, chromium steel, 18/8 (RER)	$1,81 \times 10^6$	10
Lining	PE-film [44]	925	Polyethylene, high density, granulate (EwS)	$2,31 \times 10^5$	10
	Gore-Tex membrane formwork [31,44]	146	Tetrafluoroethylene (RER)	$3,64 \times 10^4$	20
Structural wall component	Prefabricated wall elements [31,50]	2.80×10^5	Concrete, normal strength (ROW)	$7,34 \times 10^7$	5
	Reinforcing steel [44,50]	7.08×10^3	Steel, chromium steel, 18/8 (RER)		
	Piping [44]	1.05×10^4	Steel, chromium steel, 18/8 (RER)	$2,63 \times 10^6$	10
Clamping system	Steel cable [31,44]	2.27×10^3	Steel, chromium steel, 18/8 (RER)	$5,68 \times 10^5$	10
Mobile crane	–	–	–	250	10
Process 4: (Dis-)charging system and filling material					
Stratified (dis-)charging system	Zinc pipes [50]	183	Steel, chromium steel, 18/8 (RER)	$4,57 \times 10^4$	20
Filling material	Water [44,50]	5.11×10^6	Tap water	–	5
PTES					
Process 1: excavation and filling					
Excavated material	Soil [52]	3.35×10^6	Soil	$8,38 \times 10^7$	10
Excavator	–	–	–	$1,75 \times 10^5$	10
Fuel	Diesel	1.69×10^4	Diesel	–	5
Process 3: Cladding and lining					

(continued on next page)

Table A (*continued*)

Component	Material	Amount (kg)	Equivalent material (SimaPro)	Transport (tkm)	Uncertainty (%)
Sealing	Geotextile [52,53,57]	3.44×10^3	Polyethylene terephthalate, granulate, amorphous (EwS)	$1{,}14 \times 10^6$	5
	HDPE geomembrane [52,53,57]	5.28×10^4	Polyethylene, high density, granulate (EwS)	$1{,}05 \times 10^7$	10
	Hypernet CN-E [52,53]	2.92×10^4	Polyethylene, high density, granulate (EwS)	$1{,}55 \times 10^7$	5
	Hypernet HF-E [52,53]	2.92×10^4			
Insulation	Polymer foam [52,53]	7.27×10^4	Polymer foaming (GLO)	$3{,}03 \times 10^7$	5
Pipes	HDPE [52,53,57]	3.80×10^3	Polyethylene, high density, granulate (EwS)	$9{,}50 \times 10^5$	10
Weight pipe	Concrete [53]	2.98×10^4	Concrete, normal strength (ROW)	$7{,}98 \times 10^6$	10
	HDPE [53,57]	2.10×10^3	Polyethylene, high density, granulate (EwS)		10
Process 4: (Dis-)charging and filling material					
Pipes	Steel pipes [31,53]	3.40×10^3	Steel, chromium steel, 18/8 (RER)	$4{,}25 \times 10^5$	20
Filling material	Water [52,54]	7.76×10^7	Tap water	–	5
WGTES					
Process 1: Excavation and filling					
Excavated material	Sand [31,58]	4.51×10^6	–	–	5
Coverage	Sand	7.35×10^5	Sand	–	20
Excavator	–	–	–	$8{,}75 \times 10^4$	10
Topsoil	Soil [31]	75.5	Soil	$3{,}78 \times 10^5$	10
Fuel	Diesel	1.53×10^3	Diesel	–	10
Process 2: Backfilling and compaction					
Insulation	Expanded glass granulate [31,56,58,61]	1.02×10^5	Glass cullet, sorted (RER)	$2{,}56 \times 10^7$	10
	Foam glass gravel [31,56,58]	1.01×10^5	Foam glass (GLO)	$2{,}51 \times 10^7$	10
Process 3: Cladding and lining					
Sealing	Protective fleece [31,56]	2.29×10^3	Polypropylene, granulate (GLO)	$5{,}71 \times 10^5$	10
	HDPE sealing membrane [31,56,58,61]	3.58×10^3	Polyethylene, high density, granulate (EwS)	$8{,}95 \times 10^5$	10
	HDPE-aluminium composite foil [56,58,61]	308	Polyethylene, high density, granulate (EwS)	$7{,}71 \times 10^4$	20
Process 4: (Dis-)charging system and filling material					
Pipes	Steel pipes	445	Steel, chromium steel, 18/8 (RER)	$2{,}61 \times 10^3$	20
	PVC pipes	77.7	Polyvinylchloride (RER)		
Filling material	Water [58,61]	2.99×10^6	Tap water	–	5
	Gravel [31,56,58,61]	3.37×10^6	Gravel	$1{,}69 \times 10^7$	5
	Sand [56,58,61]	3.77×10^6	Sand	–	5

Table B
Classification of uncertainties*, adapted from [40].

Uncertainty (%)	Reliability, technological and geographical correlation	Example
0	Verified data, based on literature sources from the investigated field	The specification of a material, its quantity, and its property (e.g., density) is given in the literature for the selected storage system.
5	Verified data are partly based on assumptions, related to the same field	The specification of the type and quantity of a material used is given in the literature. Other material properties are based on average values.
10	Data based on information from another storage technology, from a similar field	There is information available on a material. However, there is no information on the material quantity, so the data from a comparable storage system using the same material are used.
20	Unqualified estimation	The transport distance of a material is unknown and is based on an estimate.

* For uncertainties, a triangular distribution is assumed in SimaPro.

Table C
Life cycle environmental impacts of the three sTES regarding the selected impact categories *global warming*, *non-renewable energy* and *mineral extraction*.

Impact category		Process 1	Process 2	Process 3	Process 4	Total
Global warming (g $CO_{2\text{-eq}}/kWh_{th}$)	TTES	0.01	4.95	2.95	0.034	**7.94**
		0.1 %	62.3 %	37.1 %	0.5 %	
	WGTES	0.119	27.2	1.52	0.559	**29.39**
		0.5 %	94 %	3.7 %	1.8 %	
	PTES	0.138	–	1.18	0.122	**1.44**
		9.6 %	–	82 %	8.4 %	
Non-renewable energy (kJ/kWh_{th})	TTES	0.018	21.5	16.5	0.257	**38.3**
		<0.1 %	56.2 %	43.1 %	0.7 %	
	WGTES	0.158	186	8.14	3.26	**197.6**
		2.5 %	89 %	6.8 %	1.7 %	
	PTES	0.179	–	8.12	0.935	**9.23**
		2.0 %	–	87.9 %	10.1 %	

(continued on next page)

Table C (*continued*)

Impact category		Process 1	Process 2	Process 3	Process 4	Total
Mineral extraction (kJ/kWh$_{th}$)	TTES	9.3×10^{-5}	0.0963	1.67	0.028	**1.79**
		<0.1 %	5.4 %	93 %	1.5 %	
	WGTES	0.001	0.674	0.054	0.248	**0.977**
		0.1 %	72.4 %	3.1 %	24.4 %	
	PTES	1.6×10^{-3}	–	0.0339	0.102	**0.137**
		1.1 %	–	24.7 %	74.2 %	

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