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Life cycle assessment of the construction phase of a water-gravel thermal energy storage system with reused infrastructure

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ABSTRACT

Seasonal underground thermal energy is increasingly recognized as a key technology for decarbonizing the heating and cooling sector. Among the different types of underground thermal energy storage (UTES) systems, water-gravel thermal energy storage (WGTES) systems consist of artificially constructed basins filled with water-saturated gravel. This dual-component filling material provides strong structural stability, making such systems particularly suitable for locations with space limitations, such as dense urban areas. Compared to geothermal storage systems that utilize the natural subsurface, installation of WGTES is more demanding due to the greater resource input required for the water-saturated gravel filling, and their overall environmental impact generally depends on the materials and construction methods used.

This study presents a preliminary evaluation of the environmental impact of a WGTES currently being implemented at the “incampus” demonstration site in Ingolstadt, Germany, employing the “Reno-seasonal thermal energy storage (sTES)” concept, a type of UTES system that uses a reused concrete basin for efficient heat storage. Building on previous life cycle assessment (LCA) analyses of three UTES case studies, this research aims to assess the environmental performance and the potential for using recycled and reused materials in different geothermal storage technologies, with a focus on the construction phase following ISO 14040 and ISO 14044 standards. Preliminary findings suggest that reusing existing concrete basins as structural elements can significantly reduce material consumption and environmental impacts. Further, findings emphasize the importance of optimized material choices and construction processes for the implementation of seasonal UTES in general.

1 INTRODUCTION

The construction sector contributes 40–50% of global greenhouse gas (GHG) emissions and consumes up to 60% of raw materials, primarily due to energy-intensive production of concrete and steel (Shukla *et al.*, 2022). As operational emissions decline with improved building efficiency, embodied carbon (emissions caused by materials and construction (Zimmermann *et al.*, 2021)) is becoming increasingly significant, accounting for nearly half of a building’s life cycle emissions (Densley Tingley and Davison, 2012). To address this, circular economy strategies, e.g., material reuse and recycling, are becoming increasingly important in sustainable construction (Zheng *et al.*, 2025). Although recycling has been the dominant approach to managing construction and demolition waste, off-site recycling still generates significant emissions due to transportation, sorting, and processing (Bao *et al.*, 2020). In contrast, reuse – particularly of structural elements designed for disassembly – offers enhanced environmental benefits by avoiding the need for new material production and reducing waste (Peng *et al.*, 2022; Jayawardana *et al.*, 2023). It should be noted that concrete elements often have a technical lifespan exceeding that of the buildings they support, making their reuse a promising solution for reducing embodied carbon (Bertin *et al.*, 2022; Al-Najjar and Malmqvist, 2025). Despite this obvious potential, large-scale utilization and comprehensive life cycle assessments of reused concrete infrastructures remain limited (Al-Najjar and Malmqvist, 2025).

Building on prior LCA results of existing UTES projects, this study conceptually evaluates the Reno-sTES, focusing on reusing an existing concrete basin regarding a WGTES system. Although the focus is on the Reno-sTES as the subject of investigation, the insights gained are relevant to all similar UTES technologies, including aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES). A holistic view enables the

identification of shared advantages and challenges, which could lead to improvements across geothermal storage technologies.

2 METHODS

Since 2007, a 6,000 m^3 tank thermal energy storage (TTES) in Munich has supplied heat to around 320 units using steel and concrete precast elements for structural stability (Mangold *et al.*, 2007; Al-Najjar and Malmqvist, 2025). In Marstal, Denmark, a 75,000 m^3 pit thermal energy storage (PTES) uses plastic liners and repurposes excavated soil to form embankments and to avoid transportation to landfill (Dannemand Andersen *et al.*, 2013; Sørensen and Schmidt, 2018). To preserve the surface for playground use, a WGTES in Eggenstein-Leopoldshafen, Germany, was filled with sand and gravel, largely sourced from the excavation itself. Similar to the PTES, it relies on the surrounding ground for stability without additional support structures, like concrete (Ochs *et al.*, 2008; Marx *et al.*, 2012). In 2018, the incampus project in Ingolstadt has developed a WGTES (Reno-sTES) using existing concrete basins from a former refinery site. The total volume of these basins is about 18,000 m^3. The concrete basins was built without structural modifications, thereby avoiding excavation and transport of the basin material, which should help to reduce resource consumption.(INCampus GmbH, 2019). As shown in Table 1, the different UTES systems differ significantly, making direct one-to-one comparisons difficult. However, in LCA analyses, parameters such as the area-to-volume (A/V) ratio can be utilized as evaluative metrics, since they influence factors like thermal losses and thermal capacity. The volume of pure water used in storage is also an important consideration for assessing system performance.

Table 1. Key parameters and life cycle inventory of the selected seasonal thermal energy storage (sTES) systems, A/V ratio: surface-to-volume ratio, WEV: water equivalent volume, based on Weise *et al.*, 2025.

Storage	Parameter			Reference
	A/V ratio	Volume (m^3)	WEV (m^3)	
TTES	0.287	6,000	5,700	(Keil *et al.*, 2008; Spliethoff and Stimming, 2010; Guadalfajara *et al.*, 2014; Reuß, 2016)
PTES	0.233	75,000	75,000	(Jensen and PlanEnergi, 2014; Holm and PlanEnergi, 2021; Xiang *et al.*, 2022)
WGTES	0.428	4,500	3,000	(Mangold *et al.*, 2012; Guadalfajara *et al.*, 2014; Xiang *et al.*, 2022)
Reno-sTES	0.739	18,000	7,320	(INCampus GmbH, 2019)

This study applies the standardized LCA frameworks of DIN EN ISO 14040 (2021) and 14044 (2018) to evaluate the environmental implications and potential of reused infrastructure within the Reno-sTES concept. The assessment builds on the life LCA study established by Weise *et al.*, 2025, providing a comparative basis for evaluating construction phase impacts of the WGTES currently being implemented at the incampus demonstration site in Ingolstadt. The evaluation uses results from previous studies of (sTES) to estimate the potential environmental impacts of concrete reuse in reducing embodied carbon and material demands during construction. The analysis focuses on global warming, applying the IMPACT2002+ method implemented in SimaPro 10.2.0.1, using data from ecoinvent 3.11. The functional unit is defined as 1 kWh of thermal output per year over a 30-year lifespan.

3 RESULTS AND DISCUSSION

The LCA results indicate clear differences in the global warming potential among the analyzed UTES systems (Figure 1). The ATES and PTES systems show the lowest construction-related global warming potential with 1.0 gCO_2/kWh_{th} and 1.4 gCO_2/kWh_{th}, respectively. In the case of an ATES system in Bonner Bogen, Germany (Limoges, 2019), the absence of additional structural elements is responsible for the low emissions. The majority of the materials used are plastic pipes, which have a low environmental impact.

The TTES system shows an increased global warming of 7.9 gCO_2/kWh_{th}, mainly caused by the use of concrete (41%) and steel (26%) for the structural components. This is consistent with findings by Malmqvist *et al.*, 2023, who identified that concrete, steel, reinforcement, and other metals are responsible for approximately 60% of the climate impacts averaged across examined buildings. These results further highlight the significant role that

structural materials play in determining the environmental impact of sTES, emphasizing the need for material-efficient design and increased use of recycled or reused construction material in future projects.

Regarding the WGTES system in Eggenstein-Leopoldshafen, no concrete is employed as a structural material. The comparatively higher greenhouse gas emissions primarily result from the use of extensive insulation, which is required for high-temperature sTES. In contrast, the Reno-sTES project is designed as a low-temperature sTES and therefore does not require additional insulation. Based on the expected material composition, lower values for the global warming are anticipated. To further limit emissions associated with construction at the incampus, it is planned to utilize reused concrete, thereby reducing both raw material consumption and the environmental impact linked to the production and transport of new concrete.

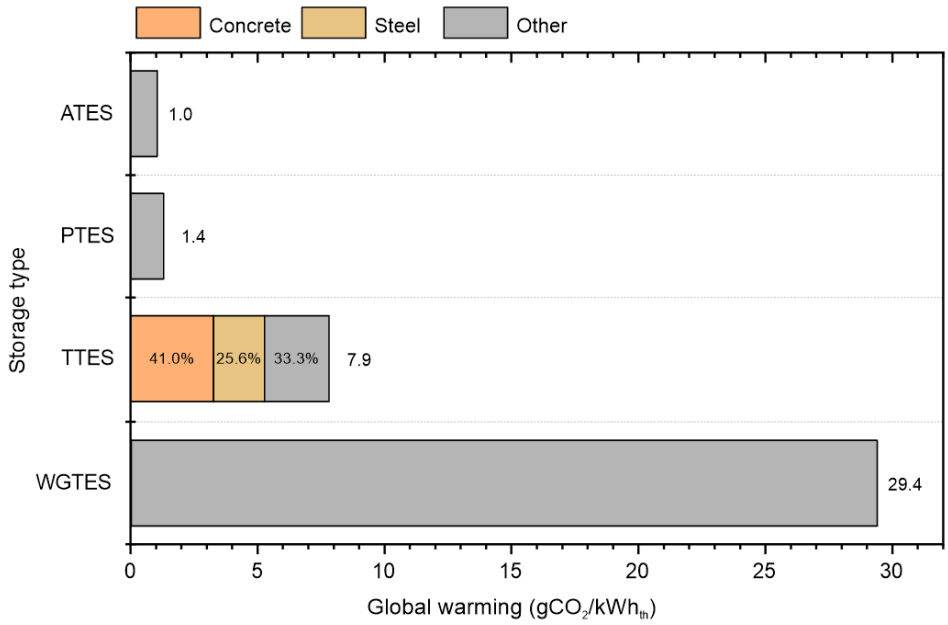


Figure 1. Comparison of construction-phase global warming (gCO_2/kWh_{th}) for different underground thermal energy storage (UTES) systems. For TTES, material contributions from concrete and steel are illustrated; for ATES, PTES, and WGTES, concrete and steel are not used as structural materials, according to Weise *et al.*, 2025.

Reused infrastructure is usually preferred but faces practical limitations, such as limited reusability of some materials, e.g., conventional cast-in-situ concrete (Xia *et al.*, 2020). Numerous LCAs have examined reuse and recycling across various materials and construction methods. However, no single study fully captures the differentiated impacts across all cases (Zheng *et al.*, 2025). Differences in system boundaries, inventories, and impact assessment methods further complicate direct comparisons of reuse versus recycling benefits (Peng *et al.*, 2022). Therefore, it remains difficult to make generalized statements, and such conclusions must be considered dependent on the specific case.

4 CONCLUSION

Seasonal underground thermal energy storage systems play an increasingly important role in decarbonizing heating and cooling sectors. This study examined the environmental impacts and potential benefits of reusing structural concrete regarding sTES. The findings emphasize that material choices and reuse strategies significantly influence embodied carbon during construction. While the reuse of concrete infrastructure offers clear advantages, a full environmental evaluation must also include operational and end-of-life phases to avoid shifting impacts across the life cycle or outside the system's boundary. Preliminary results indicate that reuse or recycling can be beneficial in many cases, highlighting the need for further research. However, given the variability in regional conditions, design, and material reusability, general conclusions remain difficult, and case-specific assessments are essential to guide sustainable implementation and circular economy integration. Therefore, to enable holistic improvement of geothermal utilization through sTES, it is crucial to analyze a broad variety of systems to reach well-founded, generalizable conclusions.

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REFERENCES

Al-Najjar A and Malmqvist T 2025. Embodied carbon saving of reusing concrete elements in new buildings: A Swedish pilot study. Resources, Conservation and Recycling 212, 107930. doi:10.1016/j.resconrec.2024.107930.

Bao Z, Lee WMW and Lu W 2020. Implementing on-site construction waste recycling in Hong Kong: Barriers and facilitators. The Science of the total environment 747, 141091. doi:10.1016/j.scitotenv.2020.141091.

Bertin I, Saadé M, Le Roy R, Jaeger J-M and Feraille A 2022. Environmental impacts of Design for Reuse practices in the building sector. Journal of Cleaner Production 349, 131228. doi:10.1016/j.jclepro.2022.131228.

Dannemand Andersen J, Bødker L and Jensen MV 2013. Large Thermal Energy Storage at Marstal District Heating. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, 3351-3354.

Densley Tingley D and Davison B 2012. Developing an LCA methodology to account for the environmental benefits of design for deconstruction. Building and Environment 57, 387–395. doi:10.1016/j.buildenv.2012.06.005.

Guadalfajara, M, Lozano, MA and Serra, LM 2014. Analysis of Large Thermal Energy Storage for Solar District Heating.

Holm L and PlanEnergi 2021. Entwicklung von großen thermischen Energiespeichern in Dänemark.

INCampus GmbH 2019. incampus. Innovative Technologien Smarte Energie.

Jayawardana J, Sandanayake M, Kulatunga AK, Jayasinghe JASC, Zhang G and Osadith SAU 2023. Evaluating the Circular Economy Potential of Modular Construction in Developing Economies—A Life Cycle Assessment. Sustainability 15, 16336. doi:10.3390/su152316336.

Jensen MV and PlanEnergi 2014. Seasonal pit heat storages - Guidelines for materials & construction. SHC.

Keil C, Plura S, Radspieler M and Schweigler C 2008. Application of customized absorption heat pumps for utilization of low-grade heat sources. Applied Thermal Engineering 28, 2070–2076. doi:10.1016/j.applthermaleng.2008.04.012.

Limoges M 2019. Life Cycle Assessment of Aquifer Thermal Energy Storage Systems.

Malmqvist T, Borgström S, Brismark J and Erlandsson M 2023. Referensvärden för klimatpåverkan vid uppförande av byggnader.

Mangold D, Miedaner O, Tziggili EP, Schmidt T, Unterberger M and Zeh B 2012. Technisch-wirtschftliche Analyse und Weiterentwicklung der solaren Langzeit-Wärmespeicherung. Forschungsbericht zum BMU-Vorhaben 0329607N. Wissenschaftlich-technische Programmbegleitung für Solarthermie2000Plus. Steinbeis Forschungsinstitut für solare und zukunftsfähige thermische Energiesysteme.

Mangold D, Riegger M and Schmidt T 2007. Solare Nahwärme und Langzeit-Wärmespeicher. Wissenschaftlich-technische Programmbegleitung für Solarthermie2000+.

Marx R, Bauer D and Drück H 2012. Schüttfähige Dämmstoffe für Langzeit-Wärmespeicher. Erfahrungen und Planungsempfehlungen.

Ochs F, Nußbicker-Lux J, Marx R, Koch H, Heidemann W and Müller-Steinhagen H 2008. Solar assisted district heating system with seasonal thermal energy storage in Eggenstein-Leopoldshafen.

Peng S, Ping J, Li T, Wang F, Zhang H and Liu C 2022. Environmental benefits of remanufacturing mechanical products: a harmonized meta-analysis of comparative life cycle assessment studies. Journal of environmental management 306, 114479. doi:10.1016/j.jenvman.2022.114479.

Reuß M 2016. Solar District Heating - an Innovative Approach of an Established Technology.

Shukla PR, Skea J and Reisinger AR (Eds) 2022. Climate change 2022. Mitigation of climate change. IPCC, Geneva.

Sørensen PA and Schmidt T 2018. Design and Construction of Large Scale Heat Storages for District Heating in Denmark. EnerSTOCK2018.

Spliethoff H and Stimming U 2010. Begleitforschung Solare Nahwärme Am Ackermannbogen in München - SNAB. ZAE Bayern.

Weise J, Bott C, Menberg K and Bayer P 2025. Comprehensive life cycle assessment of selected seasonal thermal energy storage systems. Renewable Energy, 124232. doi:10.1016/j.renene.2025.124232.

Xia B, Ding T and Xiao J 2020. Life cycle assessment of concrete structures with reuse and recycling strategies: A novel framework and case study. Waste management (New York, N.Y.) 105, 268–278. doi:10.1016/j.wasman.2020.02.015.

Xiang Y, Xie Z, Furbo S, Wang D, Gao M and Fan J 2022. A comprehensive review on pit thermal energy storage: Technical elements, numerical approaches and recent applications. Journal of Energy Storage 55, 105716. doi:10.1016/j.est.2022.105716.

Zheng B, Yang Y, Chan AP, Jiang H and Bao Z 2025. A meta-analysis of environmental impacts of building reuse and recycling. Journal of Cleaner Production 520, 146149. doi:10.1016/j.jclepro.2025.146149.

Zimmermann RK, Andersen CME, Kanafani K and Birgisdottir 2021. Whole Life Carbon Assessment of 60 buildings. Possibilities to develop benchmark values for LCA of buildings.