# Life cycle assessment (LCA) and life cycle costing (LCC) analysis for existing and new container concepts of ice stores for cold solar district heating networks

**Stephan Lang[1], Stefanie Lott[1], Harald Drück[1], Jonas Hilpert[2] and Corinna Leonhardt[3]**

[1] Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE), University of Stuttgart (Germany)

[2] Viessmann Deutschland GmbH, Allendorf (Eder) (Germany)

[3] Viessmann Holding International GmbH, Allendorf (Eder) (Germany)

**Abstract**

This study presents results of a life cycle assessment (LCA) and life cycle costing (LCC) analysis for existing and new container concepts for underground ice stores. The LCA is primarily based on the European standard EN 15804, and the LCC analysis is conducted in accordance with the European standard EN 60300-3-3. The container concepts investigated in this study are concrete tanks and pit thermal energy stores (PTES) with and without gravel filling. In this study PTES are investigated for the first time with regard to LCA and LCC in an application as an ice store. This work is part of the research project "innoBeLs", which aims to reduce environmental impact and resource consumption of underground ice store containers by at least 50 % and to reduce costs by at least 20 %. The LCA and LCC results indicate that these project targets are achievable.

*Keywords: life cycle assessment, LCA, life cycle costing, LCC, latent heat storage, ice store, cold solar district heating network, pit thermal energy store, PTES*

## 1. Introduction

The work described in this paper is part of the research project "innoBeLs", which aims at the development and implementation of innovative economically and ecologically beneficial underground container concepts for ice stores for commercial use in solar cold district heating networks. The project partners are the Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE) at the University of Stuttgart, Germany, and Viessmann Deutschland GmbH. The project duration is from 01/2025 to 12/2028 (IGTE, 2026-1).

Ice stores are gaining increasing importance in the heating and cooling supply of buildings and districts. They can serve both as a long-term heat store in combination with a heat pump and as a cold thermal energy store for the cooling of buildings. Especially ice stores with heat pumps in combination with cold solar district heating networks have a great potential for decreasing $CO_2$ emissions from space heating in the building sector. (Aluntas and Erdemir, 2022; Associated Press, 2023; ENGIE Refrigeration, 2026; Guelpa and Verda, 2019; Mehdipour et al., 2025; Osterman and Stritih, 2022; Siválk et al., 2020; Viessmann, 2019; Vivian et al., 2023)

Currently, ice stores mainly use cost-intensive concrete tanks equipped with two heat exchanger coil loops (Baukobox GmbH, 2026; GNV GmbH, 2026; LowTEMP Project, 2021). Their production is relatively energy-intensive, leading to significant greenhouse gas emissions (Barbhuiya et al., 2024). In contrast, the newly developed innovative container concepts aim to reduce the environmental impact and resource consumption by at least 50 % and costs by at least 20 %. This would enhance market penetration and reduce the ecological effects of this promising technology.

The main stages of the research project include the elaboration of new container concepts, the realization of the most promising container concept as a pilot in a field environment, pilot testing under various scenarios, life cycle assessment (LCA) and life cycle costing (LCC) analysis for both existing and new container concepts as well as the standardization of the concept, preliminary design, documentation and handover.

This contribution contains a LCA and a basic LCC analysis for the manufacturing, construction and end-of-life stages of the following existing and newly developed underground container concepts for ice stores:

- Concrete tank concept


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- Pit thermal energy store (PTES) concept
- Gravel-water pit thermal energy store (GW-PTES) concept

The concrete tank concept is currently the most widespread solution for ice stores (Baukobox GmbH, 2026; GNV GmbH, 2026; LowTEMP Project, 2021). PTES and GW-PTES have so far mainly been used for seasonal hot water stores (Dahash et al., 2019; Novo et al., 2010; Xiang et al., 2022). In this study these storage technologies are investigated for the first time with regard to LCA and LCC in an application as an ice store. While the inclusion of gravel in the GW-PTES reduces the volumetric heat capacity of the ice store, it offers the advantage of a cost-effective load-bearing structure and heat exchanger mounting. In contrast, a PTES without gravel requires additional structural elements for heat exchanger mounting and a load-bearing roof, if trafficability by motor vehicles like trucks is desired. Based on the LCA and LCC analyses, these container concepts were preselected for further detailed investigation regarding their suitability for ice stores. Fig. 1 and fig. 2 illustrate the investigated container concepts.

**Fig. 1: Concrete tank ice stores. Left: 3D graphic providing an internal view of the ice store, showing the heat exchanger coils and their mounting (LTTT, 2025). Right: photograph taken during the construction phase (Krug, 2019)**

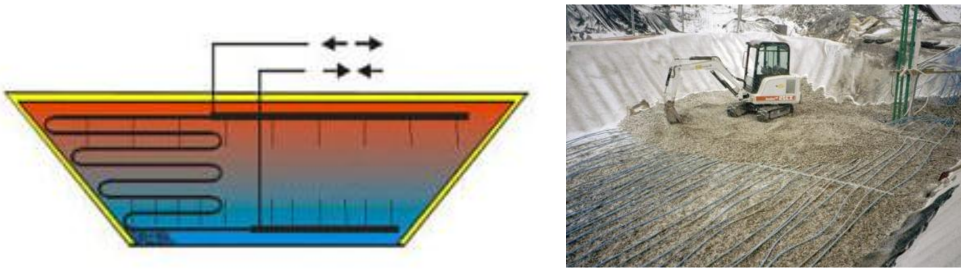

**Fig. 2: Pit thermal energy stores (PTES). Left: simplified illustration of the typical shape of seasonal hot water stores with various heat exchangers (Benner et al., 2003). Right: photograph of a gravel-water-PTES (GW-PTES) under construction (Solites, 2025)**

## 2. Fundamentals

The ice stores investigated in this study utilize the enthalpy of fusion of water at 0 °C, which is 334 kJ/kg. This is equivalent to the enthalpy difference for a temperature change of approx. 80 K in liquid water. These ice stores can be used for both cooling and heating applications (Aluntas and Erdemir, 2022; Mehdipour et al., 2025; Sivák et al., 2020; Vivian et al., 2023). For heating applications, heat pumps are used to increase the temperature level of the stored thermal energy to meet the requirements of end uses such as space heating. During discharging, the water in the ice store freezes, starting at the heat exchanger surfaces. The charging of the ice store is usually achieved via solar thermal air-brine collectors (Lott et al., 2022; LowTEMP Project, 2021; Sivák et al., 2020). Ice stores are particularly well suited for integration into cold solar district heating networks, especially with volumes between 100 and 1 000 m³, which corresponds to the scale addressed by the research project (IGTE, 2026-1; IGTE, 2026-2).

LCA is a methodology used to evaluate the environmental impacts associated with all stages of the life cycle of a product, process, or service. This includes the extraction of raw materials, transportation, production, use, and end-of-life treatments such as disposal or recycling. LCA provides a comprehensive framework for quantifying environmental burdens, supporting decision-making and the development of sustainable technologies and products.

LCC is an approach used for calculating the total financial costs associated with a product or system over its entire lifetime. It includes expenses for acquisition, operation, maintenance, and end-of-life processes such as dismantling or disposal. LCC enables a transparent assessment of economic performance and supports balanced investment and planning decisions.

# 3. Methodology

Initially, in this chapter the container concepts, their materials and assumptions are described before the methods for the LCA and LCC are presented.

The shape of the PTES and GW-PTES ice store is assumed to be a truncated pyramid with a square base. The excavation pit is sealed by lining it with different layers of polymer membranes, mostly high density polyethylene and polypropylene. The pit is then equipped with the heat exchangers and filled with water (PTES) or gravel and water (GW-PTES). Hot water stores usually require thermal insulation to reduce heat losses. In contrast, ice stores that are predominately used for heating applications benefit from heat transfer from the surrounding soil. Therefore, thermal insulation is not required for these ice stores. The roofing for the GW-PTES consists of polymer membranes. For PTES without gravel there are different roofing options, that can be divided into floating covers and load-bearing covers. For the PTES examined in this study, a floating cover, consisting of polymer membranes is assumed. The concrete tank is assumed to be cylindrical in shape.

For the concrete tank and the GW-PTES concept, a soil layer of 1 m above the roofing is assumed, whereas the floating cover of the PTES is in direct contact with the ambient air. The near-wall region of the ice store must remain unfrozen to prevent structural stress from ice expansion. Therefore, usually a thermal insulated floating cover would be necessary to prevent freezing of the upper part of the PTES ice store, which is not considered in this early stage of the project.

This study analyzes ice store heat capacities of 0.95 MWh, 9.5 MWh, 95 MWh and 952 MWh. The heat capacities take into account the waters' enthalpy of fusion and sensible heat between 0 °C and 20 °C. For each container concept, this results in different overall inner container volumes and inner surface areas, see table 1. The inner surface areas are also influenced by the containers' shapes, described above. For the heat capacity calculations, 81 % of the water-accessible storage volume is considered to be filled with water. This takes i. a. into account the volume increase during solidification. The GW-PTES concept needs significantly higher volumes and thus surface areas to reach the respective heat capacities than the other two concepts, due to the gravel filling, which consumes 65 % of the storage volume while providing only a heat capacity of sensible heat and no latent heat. Moreover, the assumed volumetric heat capacity of the gravel grains is 2 846 kJ/(m³·K), which is lower than that of water (4 171 kJ/(m³·K)).

**Table 1: Inner container volumes and inner surface areas for the different container concepts and ice store heat capacities**

| Heat capacity of ice store | 0.95 MWh | 9.5 MWh | 95 MWh | 952 MWh |
|---|---|---|---|---|
| **Volume of concrete tank concept** | 10 m³ | 100 m³ | 1 000 m³ | 10 000 m³ |
| **Volume of PTES concept** | 10 m³ | 100 m³ | 1 000 m³ | 10 000 m³ |
| **Volume of GW-PTES concept** | 23.6 m³ | 236 m³ | 2 360 m³ | 23 604 m³ |
| **Inner surface area of concrete tank concept** | 26.9 m² | 150.3 m² | 620.2 m² | 2 811.2 m² |
| **Inner surface area of PTES concept** | 28.8 m² | 141.4 m² | 691.4 m² | 2 851.6 m² |
| **Inner surface area of GW-PTES concept** | 52.0 m² | 256.4 m² | 1 307.2 m² | 5 218.1 m² |

The heat exchangers are assumed to consist of cross-linked polyethylene (PE-X) pipes with an outside diameter of 32 mm and a wall thickness of 2.9 mm. The specific pipe length for all container concepts for heat capacities of ≥ 9.5 MWh is assumed to be 122.2 m/MWh and for 0.95 MWh it is 573.7 m/MWh. These values are based on existing ice stores of Viessmann Deutschland GmbH. The ice store with a heat capacity of 0.95 MWh is used for short-term storage together with a system with higher charging and discharging power relative to the ice stores' heat capacity. Thus, the heat capacity specific heat exchanger length for the 0.95 MWh concepts is 4.7 times higher than the one for the stores with higher heat capacities. In the concrete tank and the PTES concepts an aluminum framework is necessary for mounting the heat exchanger pipe coils, whereas in the GW-PTES concept these pipe coils are fixed by the gravel. All materials considered for the container concepts in this study are listed in table 2.

The LCA methodology applied in this study follows the European standard EN 15804:2012+A2:2019+AC:2021 standard, and the primary data source is the database "Sphera MLC" accessed via the German "ÖKOBAUDAT" platform, maintained by the German government. The data were obtained in September 2025. EN 15804 divides the life cycle i. a. into the product stage, construction process stage, use stage, and end-of-life stage, see fig. 3.

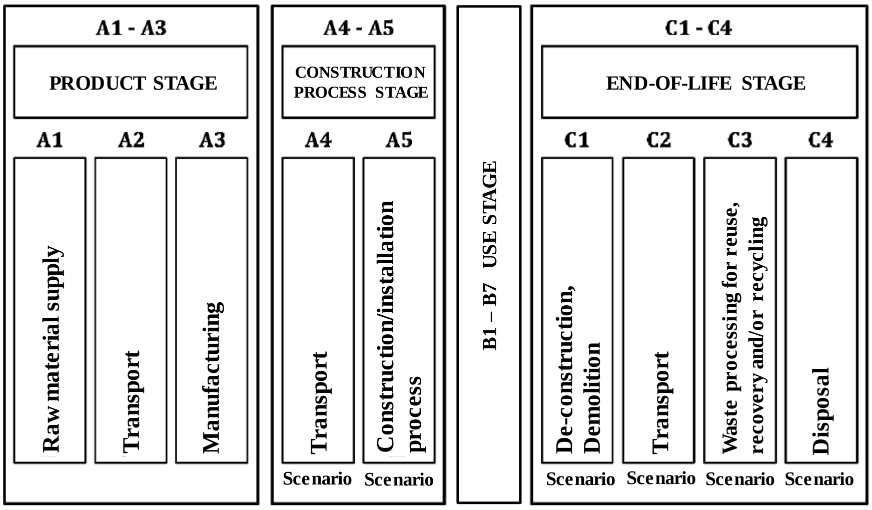


**Fig. 3: Life cycle stages A - C according to EN 15804**

For the comparison of the different container concepts' LCA and LCC, the use stage is neglected in this study, as the service life of the containers is assumed to be similar and the effects of maintenance and repair of the containers themselves – excluding peripheral components – are expected to be low. However, the use stage will be considered in a later phase of the project, as e. g. a greater heat exchanger pipe length per unit of heat capacity may be required for the GW-PTES concept compared to the other container concepts. This, in turn, would result in higher electricity demand for pumping the heat transfer fluid. Moreover, the recycling stage is neglected, since the ice stores can be considered durable goods for which emission-reducing credits can be omitted in accordance with EN 15804. Furthermore,

- the ecological and economic impacts of water consumption for the storage medium are low and nearly the same for all container concepts and therefore neglected,
- heat transfer between the ice store and the surrounding soil is neglected for the analysis presented in this study, but will be considered in a later stage of the research project,
- peripheral systems and auxiliary energy for charging and discharging are neglected, as they are assumed to be identical for all container concepts for this preliminary study.

The ice stores' location is assumed to be in Germany and transport is assumed to be carried out by a truck-trailer combination. The assumed transport distances for the modules A4 and C2 are listed in table 2.

**Table 2: Container concepts' materials and corresponding assumed transport distances for the transport modules A4 and C2**

| **Material** | **Transport distance A4** | **Transport distance C2** |
|---|---|---|
| Concrete with concrete strength class C 30/37 | 11 km | 11 km |
| Reinforcing steel | 350 km | 11 km |
| Blinding layer concrete with concrete strength class C 20/25 | 11 km | 11 km |
| Levelling layer of crushed stone 2/15 | 11 km | 11 km |
| Heat exchanger pipe: PE-X pipe | 350 km | 11 km |
| Heat exchanger frame: mill finish aluminum profile | 11 km | 11 km |
| Underlay membrane PP | 350 km | 11 km |

| Material | Transport distance A4 | Transport distance C2 |
|---|---|---|
| Sealing incl. protective fleece: HD-PE with PP fleece | 350 km | 11 km |
| Protective fleece: PE/PP fleece | 350 km | 11 km |
| Formwork: reinforced PE underlay membrane | 350 km | 11 km |
| Gravel 2/32 | 11 km | 11 km |

2/15: grain diameters 2…15 mm; 2/32: grain diameters 2…32 mm
PE-X: crosslinked polyethylene; PP: polypropylene; HD-PE: high density polyethylene

The methodology for the LCC is based on the European standard EN 60300-3-3:2004 with consideration of the following life cycle stages:

- concept and definition,
- design and development,
- manufacture and installation,
- demolition and disposal.

Cost estimation was mainly based on the German standard DIN 276:2018-12. The data sources used are Kalusche (2021) and a quotation from the project partner Viessmann Deutschland GmbH from 2021 that cannot be disclosed.

The concept and definition stage is calculated with 2 % and the design and development stage with 9 % of the total costs for manufacture and installation, in agreement with the German statutory order "Honorarordnung für Architekten und Ingenieure - HOAI", which regulates the fee structure for architects and engineers.

The cost perspective is considered that of the plant operator and operation-related as well as demand-related costs are not included, as they are assumed to be equal across the concepts.

## 4. Results and Discussion

Initially, in this chapter detailed LCA results for ice stores with a heat capacity of 95 MWh are shown and discussed, before the overall LCA results are displayed and analyzed. Finally, the LCC results are introduced and discussed in detail for a heat capacity of 95 MWh and an overview is provided for all heat capacities.

### 4.1 LCA results

The LCA result most important for this study is the overall Global Warming Potential (GWP) for the container concepts. The GWP summarizes the mass of $CO_2$-eqvuivalent ($CO_2$e) greenhouse gas emissions from all materials and processes across all considered life cycle stages. In fig. 4, the GWP values, expressed in tons of $CO_2$e, for all materials and processes of the container concepts with a heat capacity of 95 MWh are presented, corresponding to the life cycle stages A1 to A5 and C1 to C4 in fig. 3.

Overall, the concrete tank concept with 95 MWh heat capacity causes 92.6 t of $CO_2$e. The main $CO_2$e sources of the concrete tank concept are the concretes with 38.1 t and the reinforcing steel with 26.7 t $CO_2$e. Moreover, the heat exchanger, including the aluminum mounting frame, causes high $CO_2$e emissions of 23.4 t. The excavation is responsible for 2.8 t $CO_2$e and the levelling layer of crushed stone for 1.6 t $CO_2$e.

The PTES concept reaches 25.2 t of $CO_2$e emissions. Thus, the overall emissions can be reduced by 61.9 % in comparison with the state-of-the-art concrete tank concept. The largest share of the GWP is caused by the heat exchanger including the aluminum mounting frame. As these elements are assumed to be equal to those of the concrete tank concept, the mass of $CO_2$e is also equal, at 23.4 t. The polymer shell elements, consisting of PP, PE and HD-PE, depicted in green colors in fig. 4, cause $CO_2$e emissions of 9.2 t and the excavation accounts for 2.6 t.

The GW-PTES concept causes the highest GWP with 112.0 t $CO_2$e, which is 20.9 % more than that of the concrete tank concept. The main source of $CO_2$e emissions in this concept is the gravel, with 67.0 t. As indicated in fig. 5 this is mainly caused by transport and waste processing of the 4 367 t of gravel required to fill the 2 360 m³ store volume. Due to the assumed porosity of gravel of 35 % the store volume is 2.36 times larger than that of the other two container concepts. This leads to higher $CO_2$e emissions of 6.7 t for the excavation compared to the other concepts. Additionally, it leads to a higher store surface, resulting in greater material consumption and $CO_2$e emissions for the polymer shell elements compared to the PTES without gravel. The polymer shell elements' $CO_2$e emissions for the GW-PTES concepts sum up to 17.5 t. As the same heat exchangers length per heat capacity is assumed for all container concepts and the GW-PTES does not require aluminum profiles for mounting, the $CO_2$e emissions of 21.0 t are slightly lower than those of the other container concepts.

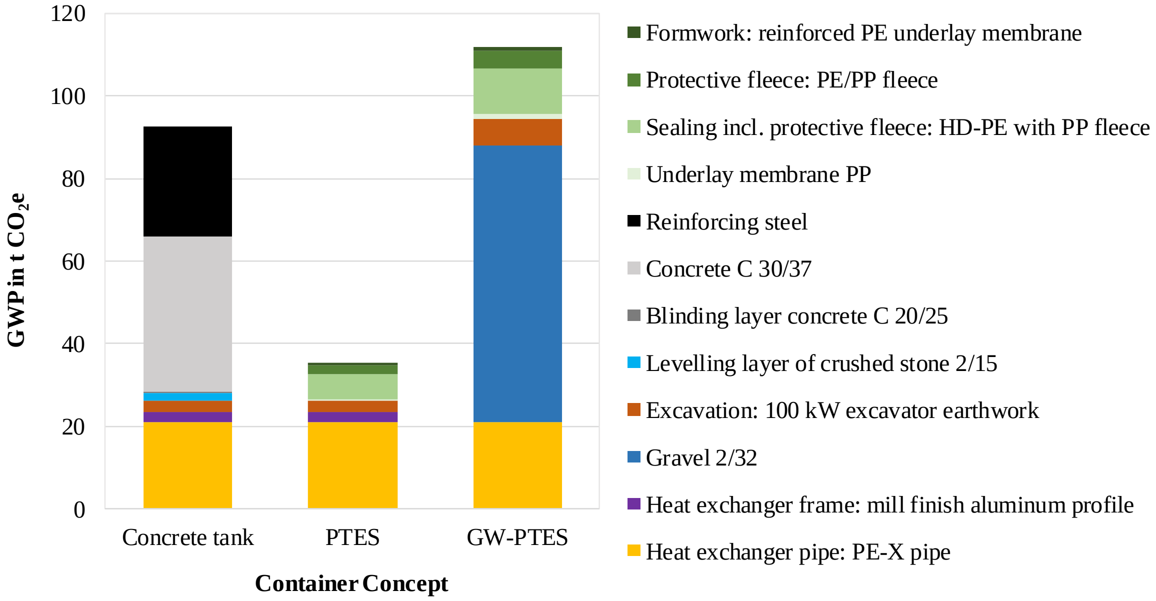


**Fig. 4: GWP for all materials and processes of the container concepts with a heat capacity of 95 MWh, corresponding to the life cycle stages A1 to A5 and C1 to C4 in fig. 3.**

Fig. 5 shows the GWP in tons of $CO_2$e of the different life cycle stages for the container concepts with a heat capacity of 95 MWh. The $CO_2$e emissions of the concrete tank occur predominantly during the product stage. For the PTES concept, the $CO_2$e emissions originate mainly from the product stage and waste processing. The largest shares of $CO_2$e emissions for the GW-PTES concept arise from the waste processing, followed by the product stage and the transport stages. However, the disposal effort for gravel assumed in the "Sphera MLC" database appears to be overestimated for the GW-PTES. This assumption is justified by the fact that the gravel will remain uncontaminated and that the extraction of the heat exchanger pipes requires only small effort.

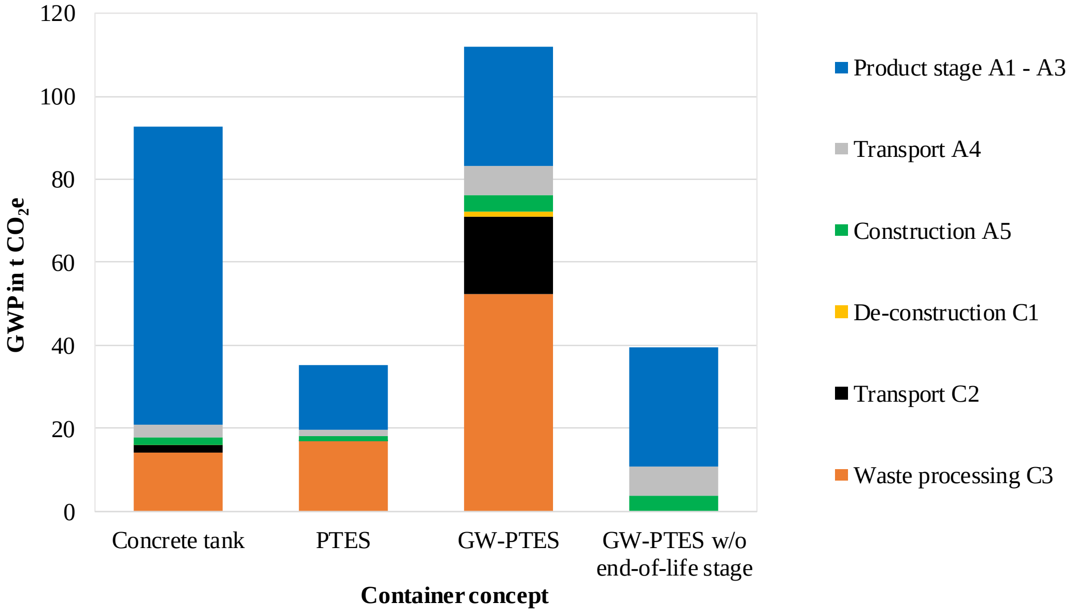


**Fig. 5: GWP for the life cycle stages of the container concepts with a heat capacity of 95 MWh.**

Given that gravel has demonstrated its excellent performance as a permanent load-bearing layer and is widely used for this purpose, de-construction of the GW-PTES can be considered unnecessary in many cases. In these cases, the whole end-of-life stage, including de-construction C1, transport C2 and waste processing C3 is not needed. As both the concrete tank and the PTES do not fulfill the same requirements as the GW-PTES with respect to permanent load-bearing structure, the end-of-life stage for these concepts needs to be considered in most cases. Thus, by neglecting the end-of-life stage $CO_2$e emissions of the GW-PTES concept, its overall emissions are reduced to 39.6 t. This is 57.2 % lower than the $CO_2$e emissions of the concrete tank concept and only 12.4 % higher than that of the PTES concept.

Fig. 6 depicts the specific GWP as a function of the ice stores' heat capacity. The decrease of specific GWP with increasing heat capacity of the store between 0.95 MWh and 9.5 MWh heat capacity is mainly caused by the significantly lower heat exchanger mass per heat capacity for values ≥ 9.5 MWh, see chapter 3. The decrease for heat capacities ≥ 9.5 MWh mainly results from the reducing surface to volume ratio. Thus, the shell materials and their GWP are decreasing with increasing heat capacity of the ice store. For the concrete tank concept with 95 MWh and higher heat capacities, increasing volumes of steel reinforced concrete are necessary for support columns ensuring the load-bearing capacity of the stores' cover. This even leads to an increase of specific GWP for the concrete tank concept between 95 and 952 MWh heat capacity, as for 952 MWh a higher number of support columns is required.

The concrete tank concept and the GW-PTES concept, when considering all considered life cycle stages, offer similar specific GWP values for all heat capacities of the ice store. GW-PTES concept without the end-of-life stage and PTES cause significantly lower GWP for all heat capacities of the ice store. The significantly lower specific GWP for the GW-PTES with 0.95 MWh heat capacity compared to the other concepts with the same heat capacity results from the exclusion of the $CO_2$e emissions related to waste processing C3 of the heat exchanger pipes', which represent a large share of the overall $CO_2$e emissions of all container concepts with a heat capacity of 0.95 MWh.

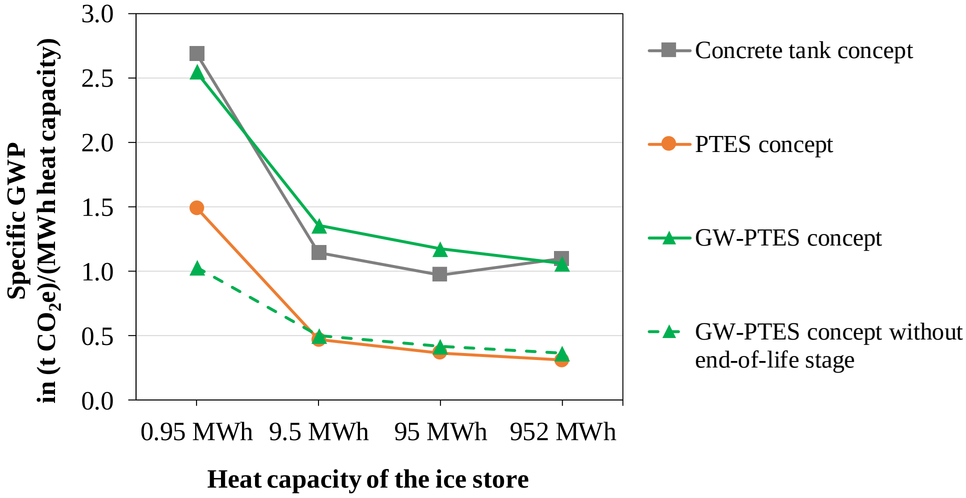


**Fig. 6: Specific GWP as a function of the ice stores' heat capacity.**

## 4.2 LCC results

Fig. 7 presents the life cycle costs of the container concepts with a heat capacity of 95 MWh for all considered life cycle stages.

The concrete tank concept has the highest life cycle costs for an ice store with 95 MWh heat capacity that sum up to 679 202 €. The PTES concept amounts to 450 099 € and the GW-PTES concept to 594 342 €. This corresponds to a cost reduction of 33.7 % for the PTES and 12.5 % for the GW-PTES compared with the state-of-the-art concrete tank concept. Assuming that demolition and disposal are not necessary for the GW-PTES (see chapter 4.1), the GW-PTES concept causes the lowest life cycle costs with 383 243 € for 95 MWh heat capacity of the ice store, which is 43.6 % lower than those of the concrete tank concept. For each concept the manufacture and installation stage, including the material costs, accounts for the largest share of financial resources, followed by the demolition and disposal stage. The costs of the other two stages – "concept and definition" and "design and development" – are comparably low according to the predefined values of 2 % and 9 % respectively, of the "manufacture and installation" stage costs, see chapter 3.

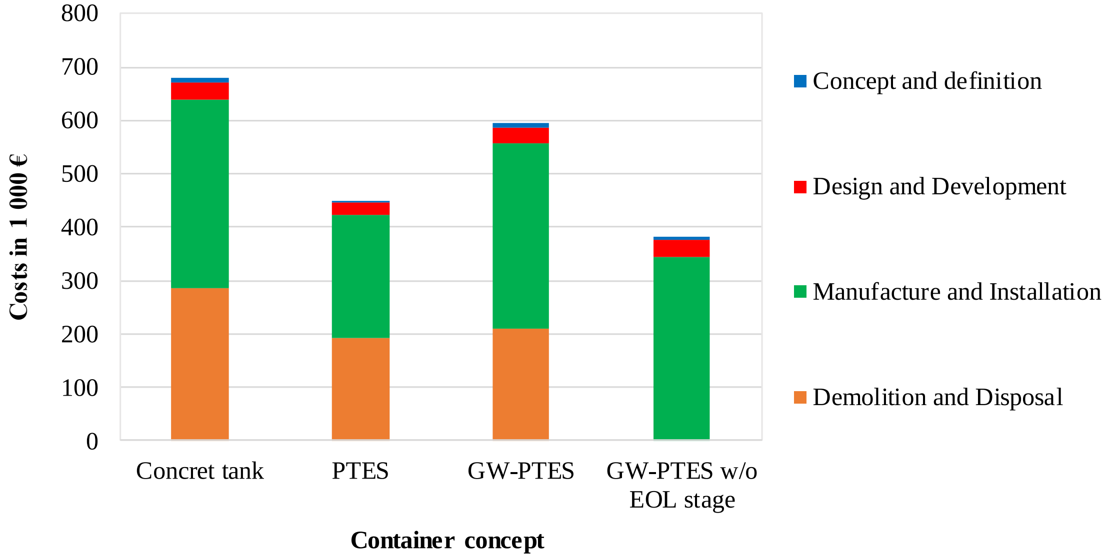


**Fig. 7: Life cycle costs of the container concepts with a heat capacity of 95 MWh for all considered life cycle stages. EOL: end-of-life.**

The heat-capacity-specific life cycle costs of the container concepts as a function of the heat capacity of the ice store are shown in fig. 8. The ranking of the container concepts regarding these specific costs remains the same for all ice store heat capacities, except for 0.95 MWh, where the GW-PTES reaches a slightly higher value than the concrete tank concept. In analogy to the LCA results, the significantly lower specific life cycle costs for the GW-PTES with a heat capacity of 0.95 MWh compared to the other concepts result from the exclusion of the demolition and disposal costs of the heat exchanger pipes, which represent a very large share of the overall life cycle costs of all container concepts with 0.95 MWh heat capacity. And again similarly to the LCA results, the decrease in specific life cycle cots with increasing heat capacity of the store between 0.95 MWh and 9.5 MWh heat capacity is mainly due to the significantly lower heat exchanger mass per heat capacity for values ≥ 9.5 MWh, see chapter 3.

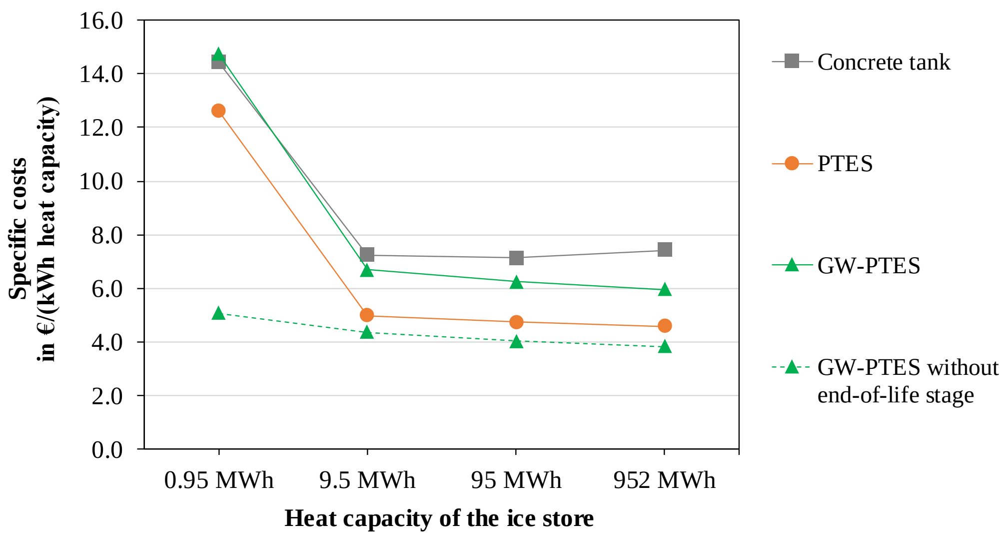


**Fig. 8: Specific life cycle costs of the container concepts as a function of the heat capacity of the ice store.**

## 5. Conclusion and Outlook

This study compares the ecological and economic effects of a state-of-the-art concrete tank concept for ice stores with a pit thermal energy store (PTES) concept and a gravel-water pit thermal energy store (GW-PTES) concept, which have so far not been used as stores with high ice fractions. For this purpose, a life cycle assessment (LCA) and a life cycle costing (LCC) analysis were carried out for all container concepts for heat capacities of 0.95, 9.5, 95 and 952 MWh. The results demonstrate that the project targets of reducing environmental impact by at least 50 % and costs by at least 20 % are achievable as shown by the following specific results.

For a heat capacity of 95 MWh, the Global Warming Potential (GWP) can be reduced by 61.9 % for the PTES concept and by 57.2 % for the GW-PTES concept without end-of-life stage in comparison with the state-of-the-art concrete tank concept. The end-of-life stage can be neglected for the GW-PTES, as it can be considered a permanent load-bearing structure. So de-construction after the use stage is not necessary in many cases. When the the end-of-life stage is considered, the GW-PTES has a 20.9 % higher GWP than the concrete tank concept.

The life cycle costs for an ice store with 95 MWh heat capacity can be reduced by 33.7 % for the PTES and 12.5 % for the GW-PTES compared with the state-of-the-art concrete tank. Without considering the end-of-life stage, the GW-PTES concept achieves 43.6 % lower life cycle costs than the concrete tank concept.

The PTES causes significantly lower GWP and life cycle costs for all considered heat capacities and life cycle stages. However, the PTES examined in this study lacks a load-bearing roof, which leads to a greater land use, as the potential utilization of the surface area above the ice store is restricted. Thus, in the next stage of the research project “innoBeLs”, PTES with load-bearing roofing will be developed and examined.

Moreover, the use stage and the heat transfer between the ice store and the surrounding soil will be taken into consideration for a further improvement of the LCA and LCC analyses for the container concepts presented in this study, as well as for further new container concepts to be developed.

New container concepts with the presented results for LCA and LCC are expected to enhance market penetration and reduce the ecological impacts of the promising ice-store technology, thereby helping to reduce the overall $CO_2e$ emissions related to the heat supply and cooling of buildings and districts.

## 6. Acknowledgments

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