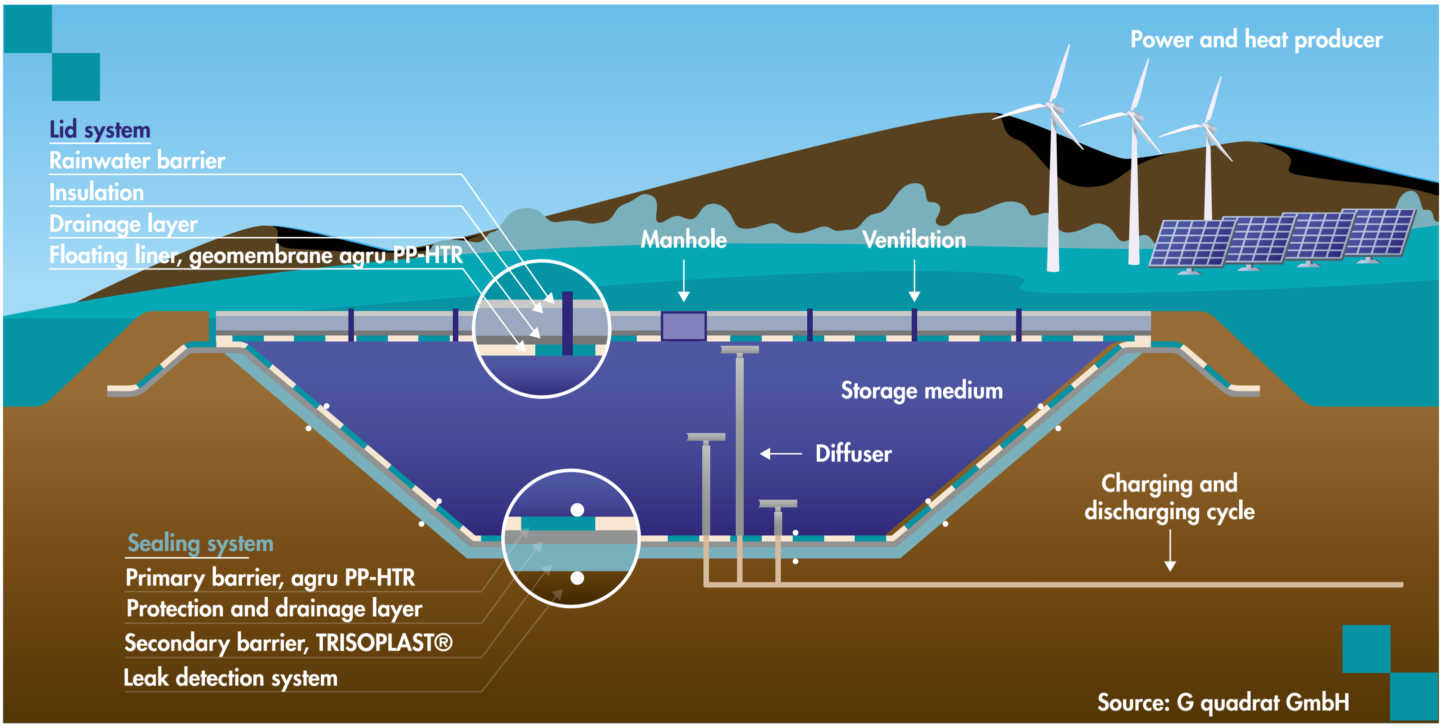

Illustration of the construction of a pit thermal energy storage as part of modern district heating networks.

Agru & G quadrat: Durable Pit Thermal Energy Storages using functional geomembranes

Flexible energy storages are an essential component for decarbonizing energy infrastructure. Due to storage temperatures of up to 95°C, the geomembranes are exposed to particularly high levels of environmental stress. The predicted lifetime is a fundamental basis for reliable project planning. Research shows that innovative PP-HTR geomembranes significantly outperform traditional polyethylene (PE)-based geomembranes.

The integration of heat storage systems into our energy infrastructure enhances overall efficiency by increasing flexibility, reduces dependency on fossil fuels and contributes to a secure and more sustainable energy future. Pit thermal energy storages (PTES) can be implemented at various scales. Thanks to their cost-effective construction, they are particularly economical (~40-50 €/m³). This has been successfully demonstrated in numerous projects in Denmark, such as those in Dronninglund and Vojens, as well as in first projects in Germany. Large-scale storage systems were initially designed to cover seasonal energy demands. Solar thermal energy and industrial waste heat are stored during summer and returned to district heating networks in the winter. Recent projects, such as the PP-PTES in Høje Taastrup (Denmark), demonstrate that next-generation pit thermal energy storages can also be utilized as buffer storages.

Suitable locations for pit thermal energy storages include former coal-, gravel- or sand pits, landfills or agricultural land on the city's edge. Preferably, the storage is situated near an industrial facility with significant waste heat or close to district or local heating networks. The excavated material is reused to construct an embankment around the pit. With an equalized mass balance, economic advantages are achieved and environmental compatibility is improved by avoiding soil transportation. After profiling the basin, it is sealed with a geomembrane. A continuous leak detection system monitors the integrity of the entire sealing structure. Once the water filling of the basin is completed, a floating high temperature resistant geomembrane provides the basis for the insulated lid structure, finalized with a suitable rainwater management system.

In recent years, research has made significant progress in the efficiency of pit thermal energy storages. The Austrian research projects SolPol®, gigaTES and CDL-AgePol have contributed significantly to this. More durable materials and innovative system combinations have been developed, leading to increased durability, safety, operational opportunities and consequently higher profitability. ■ ■ ■

This development allows for the integration of PTES systems into existing district heating networks, where higher storage temperatures of over 80 °C are required due to the network temperatures. The recently developed geomembranes allow for constant storage temperatures up to 95 °C, with predicted operation periods of over 20 years. In particular, the shift from polyethylene (PE) to polypropylene (PP) as the base material and optimization through a unique additive package have enabled this performance increase.

For the first time, the newly developed geomembranes were installed in the pioneering project in Høje Taastrup, successfully enabling short-term energy buffering. The storage system is integrated into the Copenhagen district heating network (VEKS) and connected to various heat producers such as other storage systems. It operates at a constant temperature of 90 °C with over 30 charging and discharging cycles per year. This operational model optimizes the energy production of the connected CHP plants, balances peak loads, compensates supply and demand fluctuations, and enhances sector coupling. As a result, the efficiency of the pit thermal energy storage increases from an average of 75% to over 90% on a long-term basis.

In addition to key components such as lid structure and continuous leak detection systems, proving the long-term stability of geomembranes used as basin linings and floating liners is crucial. Lifetime estimations significantly impact the evaluation of functionality, operational models and ultimately the profitability of the entire system. The Institute of Polymeric Materials and Testing at Johannes Kepler University Linz (Austria) has developed a method to more accurately predict the lifespan of these materials. This approach relies on extrapolating material durability based on factors such as temperature, geomembrane thickness and the surrounding medium. Using simulations of temperature loads from finished and planned heat storage projects, the lifetime of geomembranes has been estimated for storages in Denmark, Germany, France and Austria.

Accelerated Ageing

For this study, an established polyethylene-raised temperature (PE-RT) and the novel polypropylene-high temperature resistant (PP-HTR) were investigated for their long-term properties. The automated production of the test specimens was carried out using a specially developed planing tool (see **Figure 1**) on a CNC machine from semi-finished sheet material. Micro-specimens with a thickness of 50 to 500 µm and a thickness accuracy of ±1 µm were produced. The ageing process of the micro- and macro-specimens was performed in deionized water or air at elevated temperatures between 65 and 135°C. While polyethylene exhibits a more pronounced degradation behavior in hot water, polypropylene grades tend to fail more quickly in hot air [1].

The determination of the long-term properties of the test specimens was performed using monotonic tensile testing and determination of the strain-at-break. So far, the material properties have been characterized up to 70,000 hours (~8 years), and embrittlement times of micro-specimens have been determined at temperatures up to 105°C. To further improve the predictive model, tests are being continued at lower exposure temperatures.

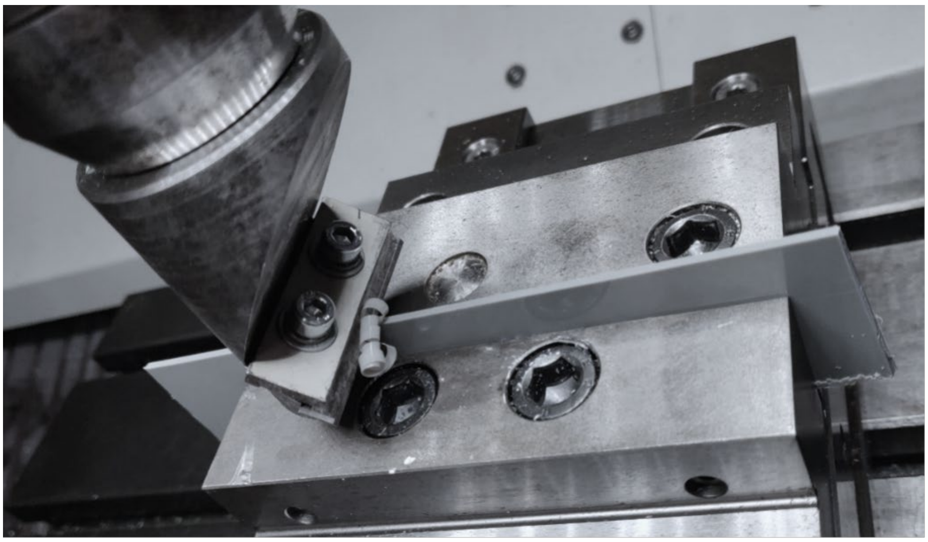

Figure 1:
Planing tool for the production of micro-specimens for accelerated aging.

Long-Term Properties and Service Life Estimation

Figure 2 illustrates selected strain-at-break values for 100 µm thick PP-HTR specimens as a function of exposure time at constant temperatures between 85 and 135°C. In the reference state, the strain-at-break was 530%. A drop below the yield limit of 20% was defined as the failure criterion.

Hot-air exposure led to a significant decrease in strain-at-break during the early aging phase. The initial reduction in strain-at-break is attributed to re- and post-crystallization effects rather than to chemical degradation. Further exposure, results in polymer degradation and ultimately failure. Full embrittlement of PP-HTR micro-specimens was observed after 8,100; 14,000; 32,000; and 65,000 hours at 135, 125, 115, and 105°C, respectively. As indicated by the arrows, ageing tests for micro-specimens exposed to hot air at 95 and 85°C are still ongoing.

The extrapolation of service life (according to DIN EN ISO 2578) from elevated exposure conditions to lower, service relevant temperatures is shown in **Figure 3**. The long-term performance of the novel PP-HTR was compared to the commercially available PE-RT [2]. For PE-RT micro-specimens, embrittlement times of 2,200, 3,900, and 5,900 hours were determined at temperatures of 115, 105, and 95°C, respectively. Hence, the novel PP-HTR achieved up to 17 times longer endurance times for 100 µm thick specimens compared to PE-RT.

Based on extensive experimental investigations of specimens with varying thicknesses from polyethylene [2] and polypropylene [3], thickness-dependence factors were calculated. Increasing the thickness from 100 µm to 2 mm resulted in a factor of 5 and 1.75 longer endurance times for PE and PP, respectively. The lower thickness effect in polypropylene compared to polyethylene liner materials is based on the higher degree of crystallinity in PE-RT.

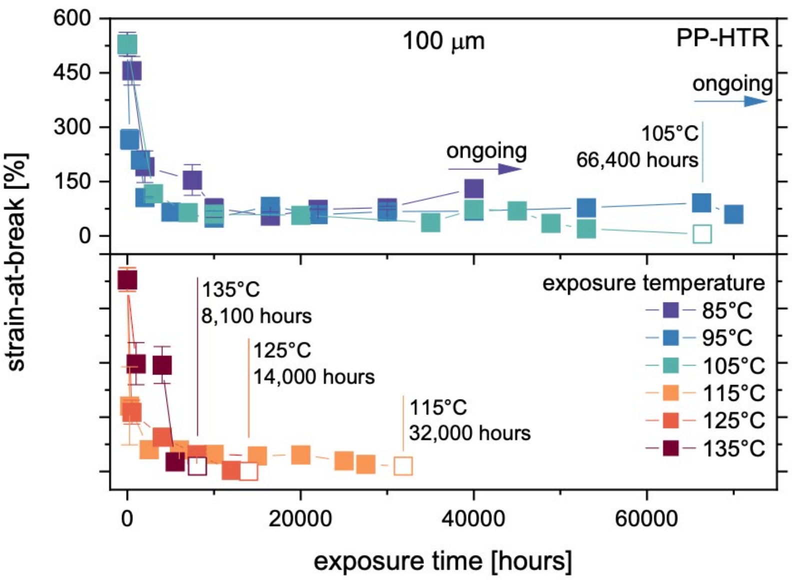

Figure 2:
Strain-at-break of PP-HTR micro-specimens exposed to hot air at temperatures ranging from 85 to 135°C.

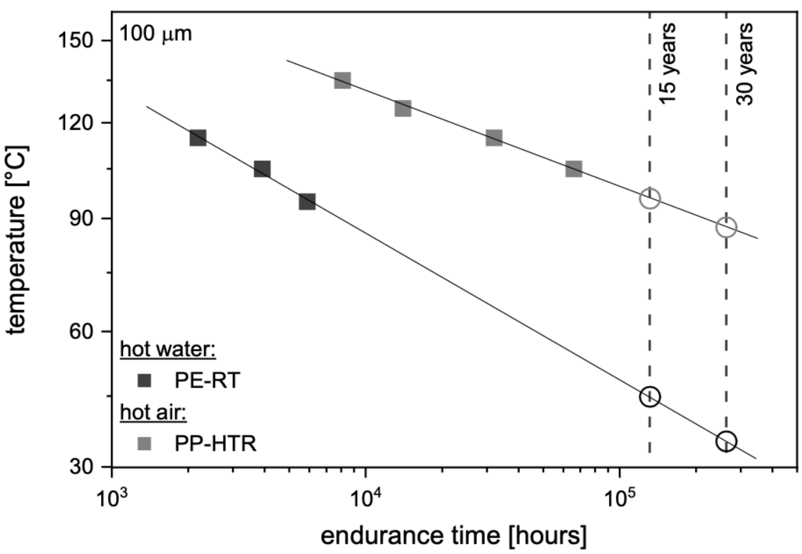

Figure 3:
Temperature-dependent service life of 100 µm thick micro-specimens made from PE-RT and PP-HTR for extrapolation to operationally relevant temperatures.

Future Storage Projects

The temperature loading profiles of the finished buffer storage in Høje Taastrup, as well as the temperature simulations of the designed storage systems in Aachen-Walheim, France, and Vienna, are shown in **Figure 4** over the course of one year.

- The storage in Aachen-Walheim is designed as a classic seasonal storage. It exhibits a pronounced discharge cycle in the winter months, during which the water temperature drops to 10 °C. In the summer months, the 65,000 m³ storage is intended to be heated to a maximum temperature of 85 °C. The heat supply will be provided by a solar thermal system. For the sealing and the floating cover, 13,500 and 10,000 m² of polymer liners would be required, respectively.
- The French company NewHeat plans a 100,000 m³ storage system. The facility is designed to utilize energy from a solar thermal system and industrial waste heat. The seasonal storage will operate at a temperature of 55 to 85 °C. Due to the shallow basin construction, approximately 13,900 and 12,500 m² of polymer liner will be required for the sealing and the cover, respectively.
- The project in Vienna is designed as a tank heat storage with a total volume of 40,000 m³. It is a buffer storage system with multiple charging cycles per year, primarily operating at 95 °C. A vertical lining of the storage with conventional polymer liners is not possible, as the creep behaviour of polyolefin materials would lead to a time-dependent reduction in thickness. A potential solution would be sealing with concrete protective liners made from high-performance polymers.

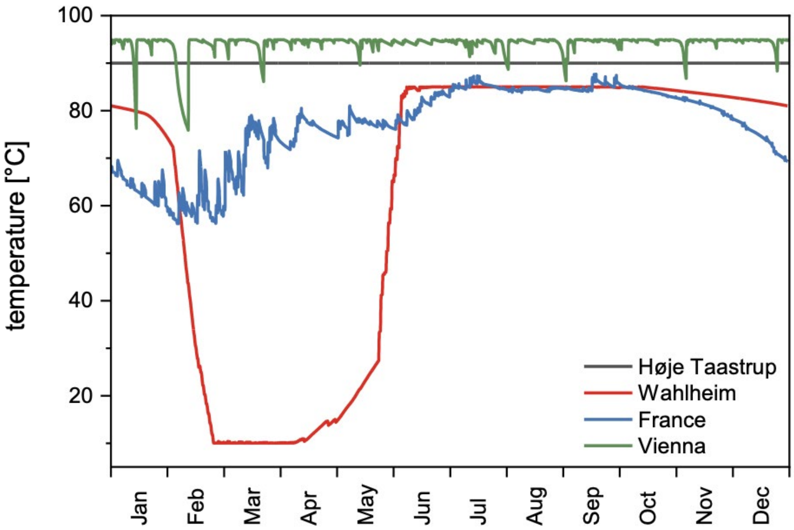

Figure 4:
Temperature loading profiles of the finished buffer storage in Høje Taastrup, such as simulated profiles of the designed storage systems in Aachen-Walheim, France, and Vienna.

Lifetime Assessment

The service life of the before mentioned storage systems were evaluated under the assumption of cumulative damage and a liner thickness of 2 mm. The service life was determined by weighting the extrapolated service times with the frequency distribution of the annual temperature profile of the storage system, based on the Miner's rule (EN ISO 13760). While the heat storage in France exhibits the longest service life, the high water temperature of up to 95 °C in Vienna results in the lowest value (**Figure 5**).

The novel PP-HTR liner enables significantly improved long-term material behaviour, with an estimated service life up to 4 times longer compared to conventional PE-RT. The service life data clearly show that the established PE-RT sealing membrane in less demanding storage systems, such as in France, is expected to have a service life below the 20-year limit. ■ ■ ■

Currently, neither the optimization of the PE-RT raw material nor a double lining with PE-RT appears to yield service life values significantly over 20 years. This is partly due to the high crystallinity of PE-RT and its limited stabilization capability, as well as the strong temperature dependence of PE-RT ageing in hot water and air. For flexible pit thermal energy storages with operating temperatures beyond 80 °C, the novel PP-HTR liner material shows a significantly better performance.

The service life calculations are based on experimental material data and temperature load simulations. Variations and real environmental conditions (water quality, installation work, [...]) were not considered. The models were validated and confirmed through systematic comparisons with literature data (e.g., from the Danish Technological Institute).

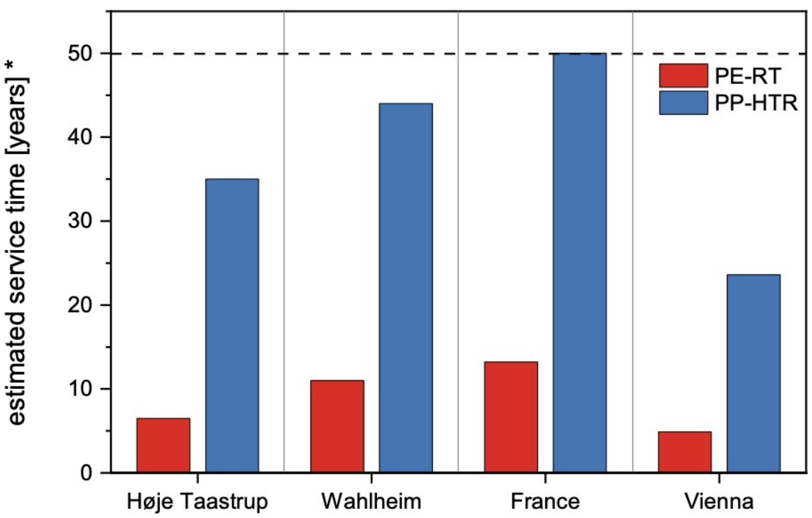

Figure 5:
Estimated service life for 2 mm thick polymer liners made from PE-RT (red) and PP-HTR (blue) for the finished buffer storage in Høje Taastrup and the planned storage systems in Aachen-Walheim, France and Vienna.

*Variations and real environmental conditions were not considered.

Literature

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