SEASONAL THERMAL ENERGY STORAGE: A CHALLENGING APPLICATION FOR GEOSYNTHETICS

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Abstract: Seasonal storage of solar thermal energy or of waste heat from heat and power cogeneration plants will significantly contribute to substitute fossil fuels in future energy systems. More than 30 international research and pilot seasonal thermal energy stores (TES) have been realized within the last 30 years. The dimensions of these pilot and research seasonal TES range from some 100 m³ up to more than 10 000 m³. Even larger volumes are considered for future systems.

Construction above ground is preferable from the technical point of view. However, the majority of the seasonal TES are buried or at least partially buried due to visual considerations. Integration into the landscape is of major importance, especially as in most cases a seasonal TES will be placed within or next to residential areas.

Several geosynthetics, such as drainage grids, protective fleeces, polymer or bentonite liners, are utilized in the envelope of both, tank TES and pit TES. Innovative concepts are realized using geosynthetics. For example, in the most recent project, where a 4500 m³ gravel-water TES in Eggenstein-Leopoldshafen (Germany) is provided with a novel leakage detection system: chambers made of HDPE-Al composite membranes were filled with bulk insulation material and then evacuated. A warning system signals in case of increasing pressure.

Due to the high operation temperatures of up to 95 °C, the availability of appropriate materials is limited. A durability of at least 30 to 40 years is required. Experiences on long term durability of geosynthetics exposed to hot water have still to be gathered.

This paper gives an overview about international research and pilot projects. In the focus are design variations and construction techniques of buried TES with regard to the use of geosynthetics in the envelope of these stores.

Keywords: geomembrane, liner, service life, thermal degradation, diffusion

DISTRICT HEATING WITH SEASONAL THERMAL ENERGY STORAGE

Seasonal storage of solar energy or waste heat from combined heat and power generation (CHP), i.e. with biogas, offers a great potential to substitute fossil fuels in future energy systems. Compared to stores in small decentralized systems both, the specific costs and the specific thermal losses of large-scale seasonal thermal energy stores (TES) are lower.

For seasonal storage in solar assisted district heating systems (see Figure 1) several concepts have been realized within the last 30 years. At least one of each concept shown in Figure 2 has been realized in Germany. The decision for a certain concept depends on the geological and hydrological conditions in the bedrock of the respective location.

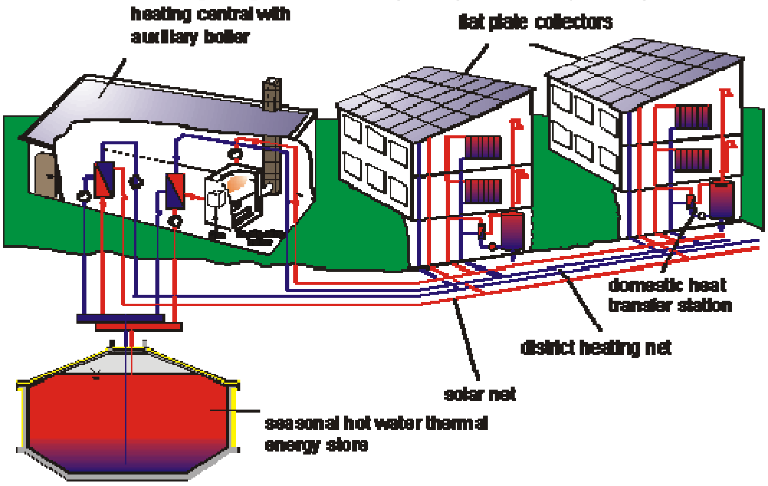

Figure 1. Configuration and components of a solar assisted district heating system with seasonal storage (source: ITW)

In contrast to borehole thermal energy stores (BTES) and aquifer thermal energy stores (ATES), where a special geology is required, tank and pit TES can be build nearly at every location. The volumetric thermal capacity of hot water tanks is with 60 to 80 kWh/m³ 50 % higher than of gravel-water stores and 100 % higher than of ATES. BTES show the lowest volumetric thermal capacity ranging from 15 to 30 kWh/m³ depending on the soil properties. However, tank and pit TES feature the highest specific construction costs. Dimensions of pilot and research tank and pit TES range from some 100 m³ up to more than 10 000 m³. So far, the largest projects are the hot water tank TES in

Friedrichshafen (D) with a volume of 12 000 m³ and the pit TES in Marstal (DK) with 10 000 m³ (Benner et al., Bodmann et al. und Ochs et al.).

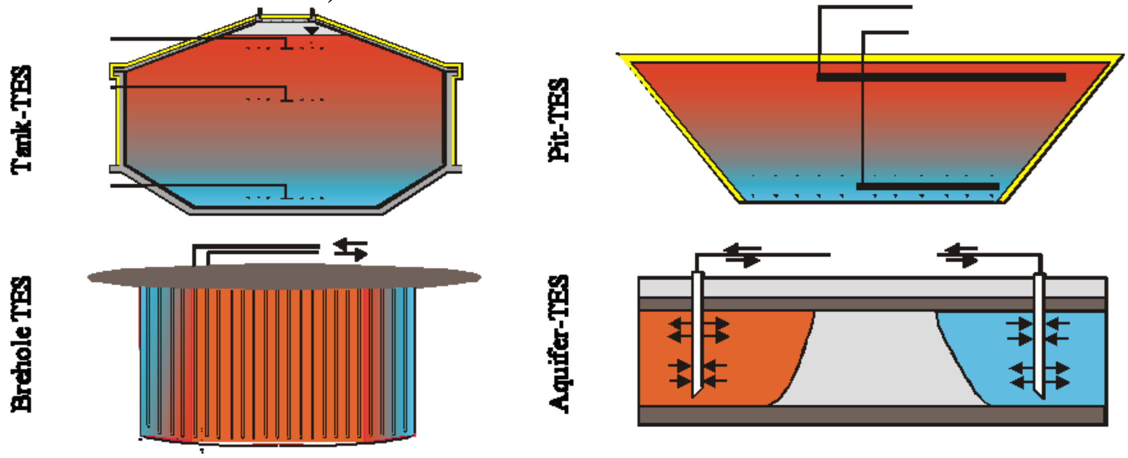

Figure 2. Types of seasonal thermal energy stores (TES) (source: ITW)

CONSTRUCTION OF TANK AND PIT TES

General aspects

Pit TES are constructed without further static means by mounting insulation and a liner in a pit. According to their storage medium seasonal TES are distinguished into gravel-water (GW) TES, soil/sand-water (SW) TES or hot water (HW) TES. Both tank and pit TES may be constructed as hot water TES or as gravel- or soil/sand-water TES. However, for economic reasons only pit TES have been built as gravel-water or soil/sand water TES to date.

The hot water TES is preferable over the gravel-water TES in terms of thermal capacity and operation characteristics. Due to the improved dynamic behaviour compared to the other seasonal TES types, the integration of a hot water TES into the heating system is less problematic, i.e. no additional buffer store is required. In case of leakage, a hot water store may be repaired, whereas it may be more economic to build a new gravel-water pit TES depending on required maintenance and repair.

Gravel- or soil/sand-water TES are advantageous, if static concerns are of major importance as in the case of the gravel-water TES in Chemnitz, where a parking lot has been built on top of the store. A cover for a hot water TES with comparable static characteristics requires enormous technical and financial efforts. For hot water stores three types of covers may be distinguished, see Ochs 2007, Ochs et al. 2007:

- self-supporting (shell shaped) covers,
- supported covers and
- floating covers.

In the case of the most recent project, a 4500 m³ TES, gravel-water was favoured over hot water as the storage medium as it is located in the area of a schoolyard. Unrestricted accessibility for the pupils and also trafficability was demanded by the customer. Obviously, a 100% safe construction - even in the case of a total failure of the liner - was required.

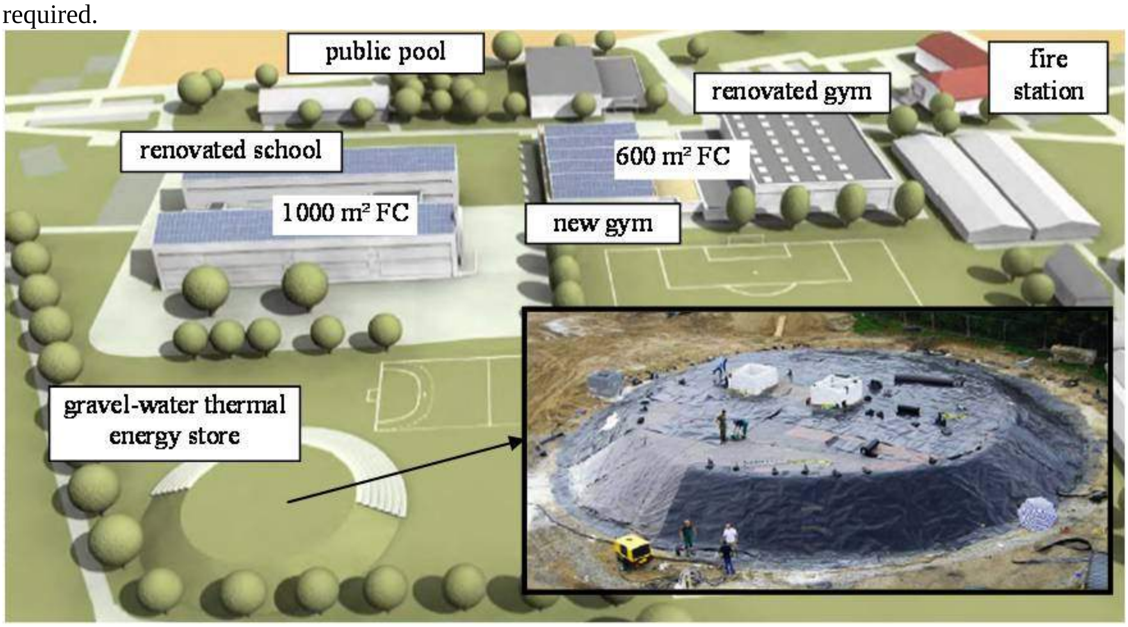

Figure 3. Solar assisted district heating system with 1600 m² flat plate collectors (FC) and seasonal storage in Eggenstein-Leopoldshafen (Germany), (source: PKi)

Although construction above ground may be preferable from the technical point of view, for visual reasons seasonal TES are buried or at least partially buried. Integration into the landscape is of major importance especially as in most cases a seasonal TES will be located within or next to residential areas. Several disadvantages occur as a result of constructing below surface level. First of all additional costs arise for the excavation. Secondly, due to the soil pressure the static is more complex. Furthermore, a construction in moist soil requires measures preventing the insulation from getting wet. Above ground surface a construction with rear ventilation would be a possible solution.

Buried thermal energy stores may be constructed as cuboid, cylinder, as inversed (and truncated) pyramid or cone or as a combination of one of these geometries. Minimization of thermal losses requires minimization of the surface to volume ratio (A/V). Additionally, for seasonal storage an aspect ratio of h/d = 1 should be aimed for.

The geometry of tank thermal energy stores, constructed with in-situ concrete or with prefabricated elements, is more flexible than of pit TES. The pit geometry is restricted to certain slope angles depending on the friction coefficient of the soil. Furthermore, the depth of the pit may be limited due to ground water. Steeper slopes or construction in ground water can be realized by applying special geotechnical works, such as sheet wall or bore pile wall. Eventually, the construction costs have to be minimized. Earth works contribute significantly to the total construction costs.

The wall of a buried TES is an assembly of several layers. The complexity of the design of such a composite wall arises due to the fact that on the one hand the envelope has to guarantee protection of the thermal insulation from moisture penetration from the inside from the storage medium and the outside from the surrounding soil. Desiccation in case the thermal insulation is already wet has to be enabled.

The most important layers of the composite wall are the liner with or without vapour barrier and the thermal insulation. Furthermore, several geosynthetics such as geogrids, geonets, drainage grids and (protective) fleeces are part of the envelope. Generally, the geosynthetics used have various functions such as separation, filter, drainage, reinforcement, protection, lining, sealing and origin from several sectors. Specialized products are not (yet) available.

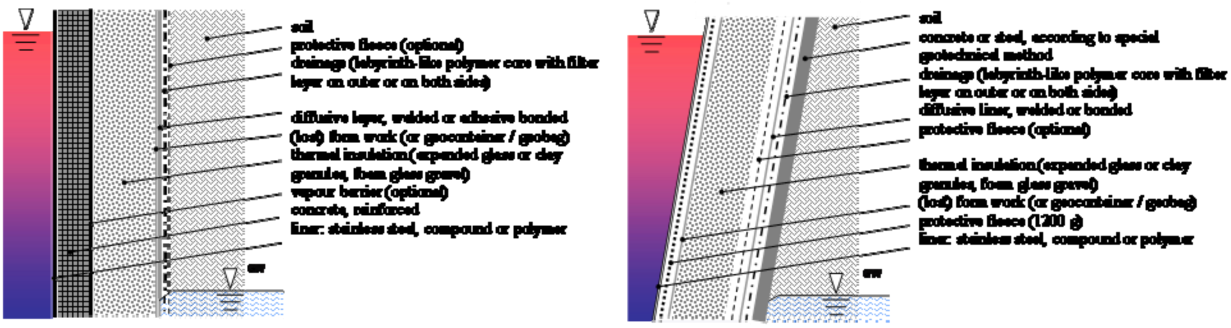

Figure 4. Multilayered (composite) side wall of a seasonal TES, left: tank, insulation inside with respect to the concrete/steel structure; right: pit, insulation outside with respect to the concrete/steel structure, GW=ground water

Thermal Insulation

Depending on the insulation material, mode of operation and local boundary conditions, the insulation is built in layers with a thickness of up to 1 m. The thermal conductivity of porous materials increases with increasing moisture content and with increasing temperature. Already for dry insulation materials an increase of 30 % of the thermal conductivity at a temperature of 80 °C compared to the value at 20 °C can be observed. This effect is more pronounced with wet insulation (see Ochs et al.).

Due to the required pressure resistance at temperatures of up to 95°C, the application of polymeric materials is limited; nevertheless, polymeric insulation was applied in several projects. Whereas in earlier TES, such as in Lombohov (S), Vaulruz (CH), Friedrichshafen (D), Chemnitz (D) or Sjökulla (FN) sheets of rock or mineral wool, polyurethane (PUR), extruded (XPS) or expanded (EPS) polystyrene were installed at the side walls and on the cover, the more recent TES such as in Hannover (D), Steinfurt-Borghorst (D), Munich (D) or Eggenstein-Leopoldshafen (D) are insulated with bulk insulation material i.e. expanded glass granules or foam glass gravel (see table 1).

Table 1. Thermal insulation of pilot and research TES (see Ochs 2007)

XPS	Vaulruz, Lyngby, Chemnitz, Augsburg, Attenkichen
EPS	Marstal (HW), Rottweil, Egenhausen
PUR	Ottrupgaard, Sjökulla, Herlev Växjö, Lombohov, Studsvik, Illmenau
Mineral-/rockwool	Särö, Rottweil, Friedrichshafen, Sjökulla, Lyngby, Marstal (HW)
Foam glass	Berlin, Lisse
Expanded glass granules	Steinfurt, Hannover, Crailsheim, München
Foam glass gravel	Eggenstein

Particularly for large thermal energy stores (V > 2000 m³), installation of bulk material by pouring or by air-injecting from silo trucks (see Figure 5) is much more effective with regard to costs and time than mounting insulation sheets or plates. This is in particular the case if scaffolding can be avoided.

Figure 5. Bulk insulation material in membrane-formwork with diffusible liner (source, ITW: left and middle, Solites: right, SNAB, München-Ackermannbogen)

Liner

General Aspects

Liners for seasonal TES have to fulfill following requirements:

Table 2. Requirements for the liner material

"Must"	remark	"Nice-to-have"	remark
water proof		water vapour proof	< 0.001 g/m²d at 95 °C
temperature resistant	max. 95 °C, cont. 90 °C	uv-resistance	during construction
resistant to hydrolysis	contact to hot water	robust	tensile strength, elongation at break, tear resistance
long term durable	min. 20 to 30 years	economic	installed and leakage proofed
weldable	hot air or wedge and extrusion	maintainable/repairable	weldable also after years of operation
available	also in relatively small amounts	proccessable	flexible, at all ambient conditions

Table 3. Lining of pilot and research TES., (see Ochs 2007)

Liner	Tank (11)	Pit (20)
stainless steel (10)	6	4
geomembrane (16)	3	13
others (clay, bentonite, waterproof concrete) (5)	2	3
project	**polymer**	
Stuttgart (GW), Berlin (HW), Chemnitz (GW), Egenhausen (SW), Augsburg (GW), Marstal (HW), Stuttgart (lab), Hamburg (ground water protection)	HDPE	
Marstal (SW), Steinfurt (GW)	PP	
Friedrichshafen (ground water protection), Marstal (HW): rain cover	PVC	
El Paso[#)]	PVC-PE (reinforced)	
Sjökulla (HW), Stuttgart (lab)	TPE	
Herlev, Stuttgart (lab)	EPDM	
Studsvik, Lambohov	IIR (reinforced)	
Berlin (repair of liner)	Bitumen (ECB)	

[#)] Solar pond, see Lu (1996)

At present liner with the required temperature resistance are not available. Hence, standard geomembranes known e.g. from landfill constructions had to be used for the lining of the store. Several materials were utilized as liner. The most common are (stainless) steel, polymers such as polyolefines (HDPE, LDPE, PP) and elastomers (EPDM, IIR). But also bitumen, clay, resin, high performance concrete and asphalt were considered and/or applied in research and pilot projects.

The majority of the tank TES are sealed with (stainless) steel liners, which are advantageous with respect to temperature resistance, aging and permeation resistance. However, (stainless) steel liners feature the highest costs. Only the very first Swedish stores, Studsvik and Lombohov, and the TES in Lisse were sealed with elastomeric (IIR) or polymeric liner (HDPE), respectively. The majority of the pit TES were sealed with HDPE liners, but PP, EPDM and TPE were also applied.

Aging

Geomembranes were applied in several pilot and research projects. However, the experiences are not sufficient to draw reliable conclusions in terms of temperature resistance and aging behaviour. On the one hand the data basis is too small due to the limited number of projects and on the other hand the observation period was too short to give substantiated statements. Some of the first pilot and research TES ceased operation (Studsvik, Lambohov, Stuttgart, Berlin, Chemnitz) others are operated at lower temperatures compared to what is demanded today (e.g. Steinfurt, Augsburg and Marstal).

The service life of polymeric liners strongly depends on the surrounding medium (water/air) and the service temperature (up to 95 °C). Geipel (1983) and Großkurth (1984) investigated the aging of geomembranes for seasonal TES. Their results indicated only a very limited service life under the investigated conditions. Till today systematic research on service life of polymeric and elastomeric liners for seasonal TES is sparse. Pedersen 2004 compared HDPE and PP liner, however, using three products only. Other investigations such as Körner (2005) or (Schröder) et al. did not focus on specific conditions in terms of temperature, stress, medium and duration as found in seasonal TES. Due to the different exposure conditions results are neither transferable nor comparable. Most investigations in the literature focused on HDPE tubes.

Nevertheless the results lead to the conclusion that a service life of more than 20 years cannot be guaranteed with available polymeric and elastomeric materials for the required conditions (temperature, water/air).

As reliable information about service lifetime of polymer liners under operation conditions which are typical for seasonal TES is not available, the maximum operation temperature of the gavel-water TES in Eggenstein is limited to 80 °C, which implies a reduction of the thermal capacity of 20 % compared to an operation temperature of 95 °C.

Systematic research on the enhancement of the temperature and aging resistance of lining materials is required. Aging mechanisms have to be understood and accelerated aging test methods have to be developed.

Permeation

Polymeric and elastomeric liners are not 100% water vapour proof. However, the insulation has to be protected from moisture penetration over the operation period of more than 20 years. Hence, knowledge about the vapour diffusion resistance of lining materials is required. For the water vapour diffusion at high temperature and thus high vapour pressure the equation for unidirectional diffusion applies:

$$WVT = \frac{\delta_a}{\mu} \cdot \frac{p}{p - p_{v,m}} \cdot \frac{\Delta p_v}{\Delta x}$$

with the vapour pressure gradient Δp_v, the thickness of the liner Δx, the water vapour diffusion resistance index μ and the permeability of water vapour in air

$$\delta_a = \frac{D_v}{R_v \cdot T}$$

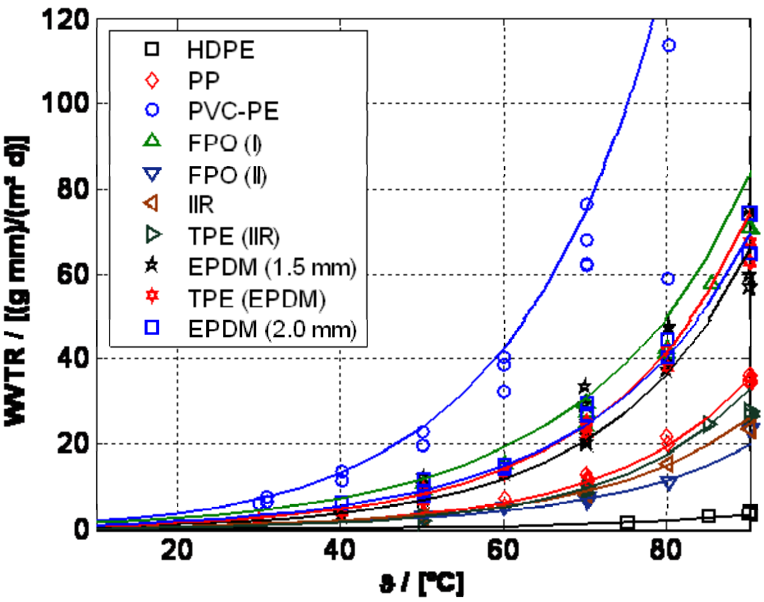

Figure 6. Water vapour transmission rate (WVTR) measured data (Marker) and model predictions (lines) of lining materials measure for isothermal diffusion (100% vs. 0%r.H.)

The temperature dependence of the permeation coefficient

$$P = \frac{\delta_a}{\mu}$$

can be described using Arrhenius law.

$$P = P_0 \cdot \exp\left(\frac{-\Delta E_D}{R \cdot T}\right)$$

The permeation resistance of geomembranes was measured with an especially developed permeation measurement device within the temperatures range from 20 to 90 °C at ITW.

Measured water vapour transmission rates (WVTR) and model predictions are shown in Figure 6. The WVTR of flexible materials such as EPDM, TPE, FPO is much higher compared to more crystalline materials such as polyolefines. The water vapour transmission (WVT) through a 1.5 mm EPDM roofing membrane amounts to 40 g/(m² d) for diffusion from water to dry air/insulation. About 18 g would accumulate in the insulation per sq.m per day under the same conditions for a 2 mm fPP-membrane. The water vapour diffusion resistance of HDPE is the lowest measured. But also the permeation resistance of HDPE is too low to protect the insulation from getting wet over the required operation period at the given boundary conditions. Hence, it is recommended to use a composite material as liner (i.e. a membrane with Aluminium layer).

In Table 5 stainless steel liners and geomembranes are compared.

Table 5. Comparison of different lining materials; stainless steel (VA) geomembrane (GM) and geomembrane with barrier layer (BGM)

VA	GM	BGM
+ temperature resistance + aging resistance + diffusion resistance + robust	+ web with (5 – 7m) + welding method and velocity + processing speed + leakage detection + costs	see GM, and + water vapour proof + robust
- corrosion (passivation) - welding (TIG) - delivered as plate (2m x 6m) - Required finish of surface - costs (and primary energy usage)	- temperature resistance - aging resistance - permeation/diffusion resistance	see GM, but - costs - web width (1.5 m due to aluminum layer)

EXPERIENCES WITH THE OPERATION OF PILOT AND RESEARCH TES

Overview

In table 6 a selection of the 30 international projects with buried tank TES and pit TES that have been carried out in the last 30 years is listed.

Table 6. Geometry of (partially) buried hot water tank TES and pit TES, volume (V), total surface area (A), slope angle (β), aspect ratio (h/d) and measured thermal losses (Q_{meas}), (Ochs, 2007)

Location	country	year	V [m³]	A [m²]	h/d [-]	ΔT_{av} [°C]	$\dot{Q}_{meas}$ [MWh a^{-1}]	$\dot{Q}_{meas} : \dot{Q}_{design}$ [-]
Tank-TES								
Studsvik	S	1978	800	550	0.476	n/a	n/a	1.07-1.3
Lombohov	S	1980	10 000	1750	0.371	n/a	250	3
Särö	S	1989	640	n/a	n/a	n/a	n/a	3
Hamburg	D	1996	4 500	1 650	0.416	42	360 – 430	3.8-4.5
Friedrichshafen	D	1996	12 000	2 796	0.599	49	320 – 360	1.5-1.6
Ilmenau+)	D	1998	300	262	1.14	n/a	n/a	1.2
Hannover	D	2000	2 750	1 135	0.584	33	90 – 100	1.3-1.4
Pit-TES								
Stuttgart (GW) $)	D	1985	1 050	835	0.21	8	27	<1
Malung (HW)	S	1989	1 000	n/a	n/a	n/a	n/a	1.5
Chemnitz (GW) x)	D	1997	8 000	3 375	0.180	n/a	n/a	1.4
Steinfurt (GW) §)	D	1999	1 500	1 305	0.165	26	70 – 90	n/a
Marstal (HW) †)	DK	2003	10 000	5 600	0.161	22	338	n/a

#) difference of mean storage and ambient temperature $\Delta T_{av} = T_{m,s} - T_{m,a}$
+) extrapolation of 5 month
$) 462 h simulation, operation with heat pump
x) extrapolation of 8 weeks, operation ceased in 2006
†) 6 month operation
§) incl. piping n/a not available

With every type of liner in both tanks and pits, leakage problems occurred. In the case of hot water TES, leakages may be repaired, in case of gravel/sand/soil-water TES, a leakage is the worst case scenario.

Problems with clay and bentonite liners are reported most frequently. However, leakages also occurred in TES with polymer and stainless steel liners. Due to major leakage problems operation of seasonal TES was ceased in several cases. Nevertheless, with the exception of the store in Ottrupgaard, DK, which is sealed with compacted clay, initial leakage problems could be solved in the majority of cases. Hence, all stores that are presently under operation are free from leakages.

Actual thermal losses are too high in most cases. In some cases measured losses are 30 % to 50 % higher than the predictions; in one case the thermal losses are even more than four times higher. There are several reasons that cause the high thermal losses compared to the design/simulation values:

- high mean storage temperature due to changed building development and/or system configuration;
- high return temperatures of the heating net results in higher thermal losses to the ground especially at the bottom of the TES, which is not insulated in most cases;
- the thermal conductivity of the insulation was assumed too low. The thermal conductivity of porous materials increases with increasing moisture content and with increasing temperature. For the simulation of the German projects the thermal conductivity of the insulation was taken from DIN 4108. The assumption of constant effective thermal conductivity of the insulation material leads to wrong predictions;
- Insufficient quality/accuracy of available simulation tools;

Example of a seasonal TES

In the most recent project the gravel-water TES in Eggenstein-Leopoldshafen (Germany, the internal liner is made of a HDPE membrane with vapor barrier), see Figure 7. The aluminum layer prevents water vapor diffusion from the storage medium. In order to protect the insulation from ground water penetration, in addition, an external liner has been installed. The external liner and the internal barrier liner are welded together such that they form chambers, which are filled with bulk insulation material (expanded glass granules). The 30 chambers are evacuated after filling. This procedure enables leakage detection during the construction period and if desired also during operation. A warning system signals in case of increasing pressure. Operation of the system is planned to begin early in 2008.

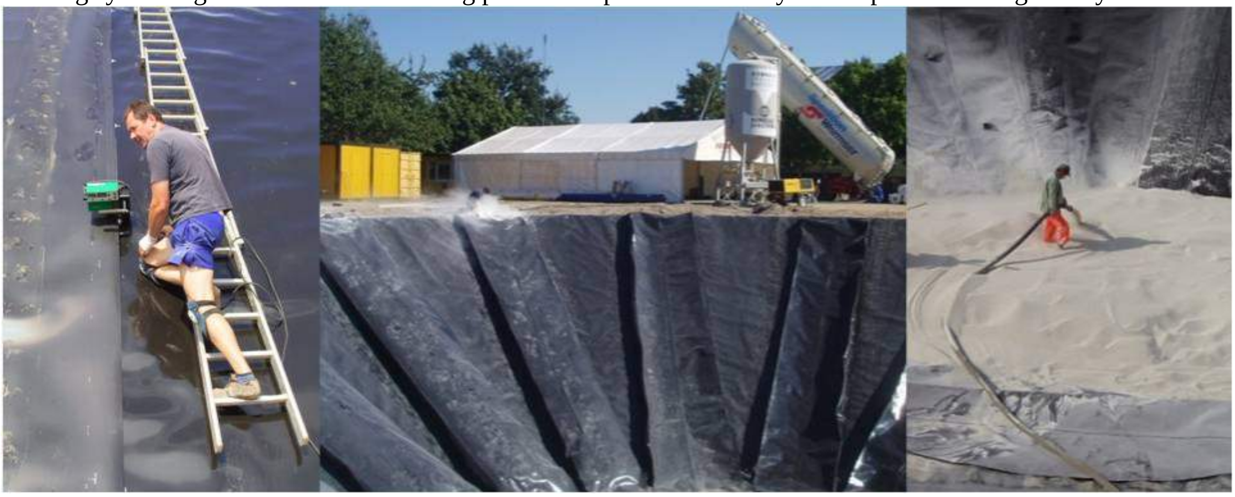

Figure 7. Installation of the insulation by blowing from silo-truck into chambers made of HDPE-barrier liners and as loose bulk onto the bottom (gravel-water TES in Eggenstein-Leopoldshafen, ITW)

CONCLUSIONS

Until today more than 30 international research and pilot projects with seasonal TES have been realized within the last 30 years. It could be demonstrated that seasonal TES are technically feasible and work.

However, the design of a composite wall of a buried TES implies a complex task in terms of building physics. Only with a well-matched design of the envelope, protection of the thermal insulation from moisture penetration over a period of at least 20 to 30 years can be guaranteed, while desiccation is enabled in case the thermal insulation is already wet. The insulation has to be prevented from moisture penetration from the inside by diffusion from the storage medium and from outside from the surrounding soil, from ground or surface water. The coupled heat and moisture transport mechanisms have to be fully understood and applied.

Hot water TES offer substantial advantages over gravel-water TES. However, the construction of a cover for hot water TES is complex and consequently costly.

By replacing the expensive stainless steel liner with geomembranes the costs of seasonal TES may be significantly decreased. Several geosynthetics are utilized in the composite wall of seasonal TES. Materials that fulfill the requirements are not yet available, hence, spite of the limited suitability in terms of temperature and aging resistance, geosynthetics known from standard applications such as landfill, water reservoir or dam construction have been applied.

Reliable statements concerning service life of geomembranes under operation conditions of seasonal TES cannot be given without detailed and systematic investigations of the aging mechanisms. The development of temperature and aging resistant geomembranes remains an important task for the future.

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