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Closed, in-ground, water-based seasonal storage systems for thermal energy – State of technology in Europe

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ABSTRACT

In thermal geoengineering applications, the storage of thermal energy offers a large potential for increasing and optimizing the efficiency of renewable energies. During the past decades, research programs in Europe have particularly focused on buried, technically closed thermal energy storage systems (TES). During low demand phases, these systems allow energy to be stored on a seasonal basis to contribute cost-effectively to energy supply during periods of high demand. As preferred technical variants, three concepts have emerged: Pit Thermal Energy Storages (PTES), Tank Thermal Energy Storages (TTES) and Water-Gravel Thermal Energy Storages (WGTES). Placed in-ground, they have different (geo-)thermal properties, which vary from system to system and represent individual advantages or disadvantages.

Based on a comprehensive database, our presentation reviews the state-of-technology in TES, whereby most systems and those with the highest storage volumes are located in Denmark, Germany and Sweden. Through innovations in the field of thermal geoengineering, materials, and construction techniques, a consistent trend towards further improved efficiency can be observed, both energetically and economically. However, we identify the remaining key challenges in technical, environmental and socio-economic terms, which impede global market availability and require further research. Critical issues are the optimization of thermal insulations to minimize energy losses, the improvement of long-term stabilities of used materials, and the mitigation of substantial construction and maintenance costs. Furthermore, our presentation uncovers unexploited potentials in the field of performance optimization. Some of these arise with the advanced integration in heating and cooling networks. Linkages to excess energy from industry, data centers, or geothermal systems offer further possibilities for an enhanced use of TES. Finally, we point out concepts for further increasing the prospective potential of this geothermal technology, for example by dynamically linking differently configured storage systems.

1. INTRODUCTION

Thermal energy is an essential form of energy and it plays a key role in everyday life. For example, the highly developed central European countries are substantial consumers of heat energy in the industrial and residential sector (BP p.l.c. 2019; Eurostat 2019). As conventional primary energy resources for producing heat become scarcer, energy prices rise and environmental standards become stricter, the demand for alternative sources of thermal energy is very high. Renewable energies as well as smart district heating networks are especially gaining ground. In order to maximize yield and minimize losses in energy systems, production variations due to long-term and short-term fluctuations need to be compensated. This is facilitated by application of seasonal thermal energy storage (TES) technologies. In general, TES can be connected to all available energy sources for charging and collect thermal energy when demand is low. In contrast, they provide stored energy when demand is high, but production cannot provide the required amount of heat. Thus, their role can be crucial as a options for peak shaving and minimization of total energy consumption. TES can be applied at different time scales (diurnal vs. seasonal), which is expressed in storage cycles (for seasonal applications one or two cycles per year). While diurnal storages are nowadays common for every household and for many larger industrial buffer storages, seasonal storages are less technologically mature. In this paper, we examine the technological status of closed in-ground TES with a focus set on the conditions in central Europe. The objective thus is to also reveal their enormous development potential.

Schematic concepts of the three most common closed TES designs are shown in Fig. 1. All of them are artificially enclosed basins, which ideally operate unaffected by the environment (e.g. groundwater levels and temperatures as well as other climatic conditions). In contrast, open storage technologies (e.g. aquifer and borehole storages) commonly utilize natural ground as storage medium and thus strongly depend on ambient conditions. The closed TES employ a filling material as a storage medium, which is accessed via a thermal charging-discharging system.

We focus on large scale sensible TES, which are different than the less common latent and thermochemical systems, especially for seasonal storage. The filling material is capsulated by a protecting sealing layer and tailored thermal insulation to stabilize the installation and minimize energy losses. Among the three variants shown in Fig. 1, tank thermal energy storages (TTES) have an additional structural component, while pit thermal energy storages (PTES) and water-gravel thermal energy storages (WGTES) are delimited by their wall slopes.

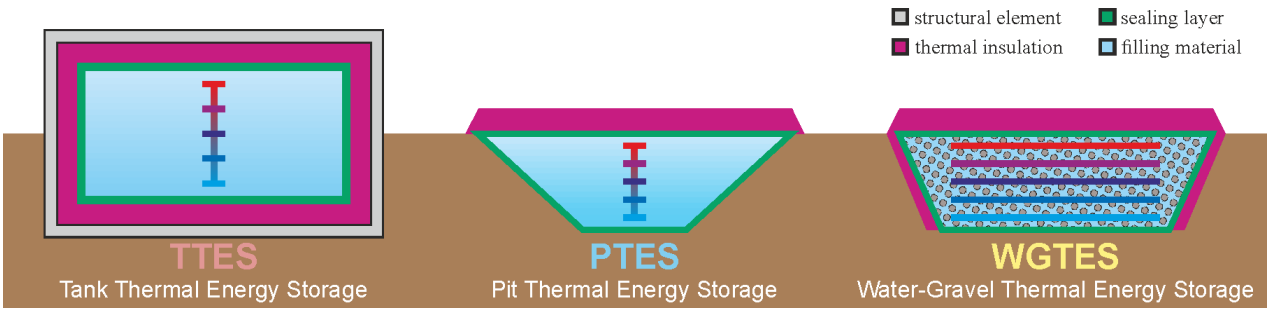


Figure 1: Storage types considered in this article.

Seasonal TES with large volumes are most established in Europe, where a total of 31 installations can be found. In other continents, these three types of seasonal TES are very rare, reflecting their limited availability in the global market. In terms of numbers, the currently leading countries are Germany (16 facilities), Denmark (13) and Sweden (5). Considering the historical development of the technology, the number of seasonal storages has been constantly growing with a linear trend (Fig. 2), which indicates further growth also in the future. Scientific activities for developing such heat storage concepts first emerged in 1959. Significant impacts of research activities are seen in Fig. 2 as a surge in numbers and overall storage volumes in the early 1990s. This was triggered by (climate-) political decisions (oil crisis, 1973; Agenda 21, 1992; Kyoto Protocol, 2011; Paris Agreement, 2016), and for example in Denmark the national Energy Strategy 2025 (2011) and Energy Strategy 2050 (2016). Accordingly, a strong correlation of TES development with public awareness of energy supply is observed. The first TTES installment was implemented in 1978 in Studsvik (Sweden, V: 800 m³ (Dalenbäck 1990)), while the first WGTES were built in Vaulruz (Switzerland (Ochs et al. 2006)) and Stuttgart (Germany (Hahne 2000)) five years later. The developments were accelerated by the concurrent evolution of solar thermal systems. Many systems were built within the International Energy Agency Solar Heating and Cooling Programme Task VII “Central Solar Heating Plants with Seasonal Storage” (CSHPSS), which started in 1979 (and their effects seen as an increase in Fig. 2 a and b for all countries (Dalenbäck 1990)). Altogether 18 European members joined their forces to optimize storage design concepts. Initially, Sweden was the leading country, but following research projects in Germany (solarthermie-2000 and solarthermie2000-plus) led to a number of different proof-of-concept facilities (Schirmer et al. 2004) and thus more systems and the largest volume in Germany (Fig. 2 b, d). Recently, important new developments were stimulated by Denmark’s “Energy Strategy 2050” with the goal of market independency from fossil fuels until 2050 (OECD and IEA 2012). Therefore, Denmark is now the leading country in terms of volume (Fig. 2 d), mostly due to the existing facilities in Denmark being large pit storages (PTES). This variant accounts by far for the largest installed volume (Fig. 2 c). Correspondingly, Fig 2 a and 2 d reflect a correlation between the average size of storage types and growth. The development of WGTES has become stagnant since 2008. This is because WGTES were found to be the most complex systems that carry the highest technological risks.

The largest storage facility until 2010 was the TTES in Friedrichshafen (Germany), with a capacity of 12,000 m³. However, it was replaced in 2012 by the first storage system to ever have a volume of more than 50,000 m³. This is the Sun Store 4 in Marstal (Denmark, Volume: 75,000 m³ (Lasse 2013). Meanwhile, the 200,000 m³ Pit Storage in Vojens (Denmark) is the world's largest seasonal storage, which is a re-used former gravel pit (Ulbjerg 2017). The newest WGTES is located in Sonderborg (Denmark) and has a size of 4,000 m³ (Guadalfajara et al. 2014), which is only half of the largest WGTES in Chemnitz (Germany) with a volume of 8,000 m³ (Benner 2003; Urbaneck et al. 2002).

2. STATE OF TECHNOLOGY

2.1 Basic design aspects

The question of whether a storage system should be installed above or below ground is essential for issues of performance and the choice of building materials and methods. Fig. 1 shows that TTES can be built as standing facilities through their structural element. PTES and WGTES, in contrast, are constructed without such stabilization and are therefore exclusively installed in pits. The storages can be well integrated into the environment and, for example, their surface can serve as green spaces in cities or playgrounds (Mangold 2007). Ideally, storages are independent from the environment, but PTES and WGTES depend on favorable ground conditions. These include, among others, a low groundwater level and good stability of the subsoil. TTES installed above the ground therefore have a greater independence from the surroundings, but this is at the expense of the additional materials and costs for artificial stabilization. New PTES and WGTES entail excavation costs, but these can be avoided by reusing e.g. former gravel pits. Finally, the thermo-physical properties of the ambient soil need to be considered. Different types of soils have specific effects on the storage performance. This has been demonstrated by Dinçer and Rosen (2011) and they also conclude that surrounding soil can serve as additional thermal insulation.

Regarding geometry, surface dimensions, feasible construction heights and excavation depths may be restricted by local regulations. As Fig. 3 a shows, PTES can include large volumes (Marx et al. 2011). This is also evident in the further geometric characteristics (Fig. 3 c – e). It also revealed that TTES have the smallest range of lengths and widths. Moreover, the shortest and longest sides are dimensioned roughly similarly, giving the storage a more symmetrical shape. With regard to WGTES, this difference is the largest; these storages are generally flatter, with average heights of approximately 5 m. The specific geometric design of the storage systems leads to a characteristic surface-to-volume ratio (A/V ratio, Fig. 3 b). Energy-optimal storage systems are those that come close to the ideal A/V ratio of a sphere (purple dashed line). Clearly, the deviation becomes very large as the storage volume of the large PTES increases. Nevertheless, these facilities achieve decent performance values due to the much larger distances between the loading unit and the surroundings. Therefore, TES sizes of > 1,000 m³ are recommended for efficient operation (Marx et al. 2011). At the same time, the ratio of height to diameter (h/d ratio) is also important and should be close to 1.

The best values for TTES are achieved by the storage in Neuchatel (Switzerland), for PTES by the storage in Ottrupgaard (Denmark), and for WGTES by the storage in Chemnitz (Germany).

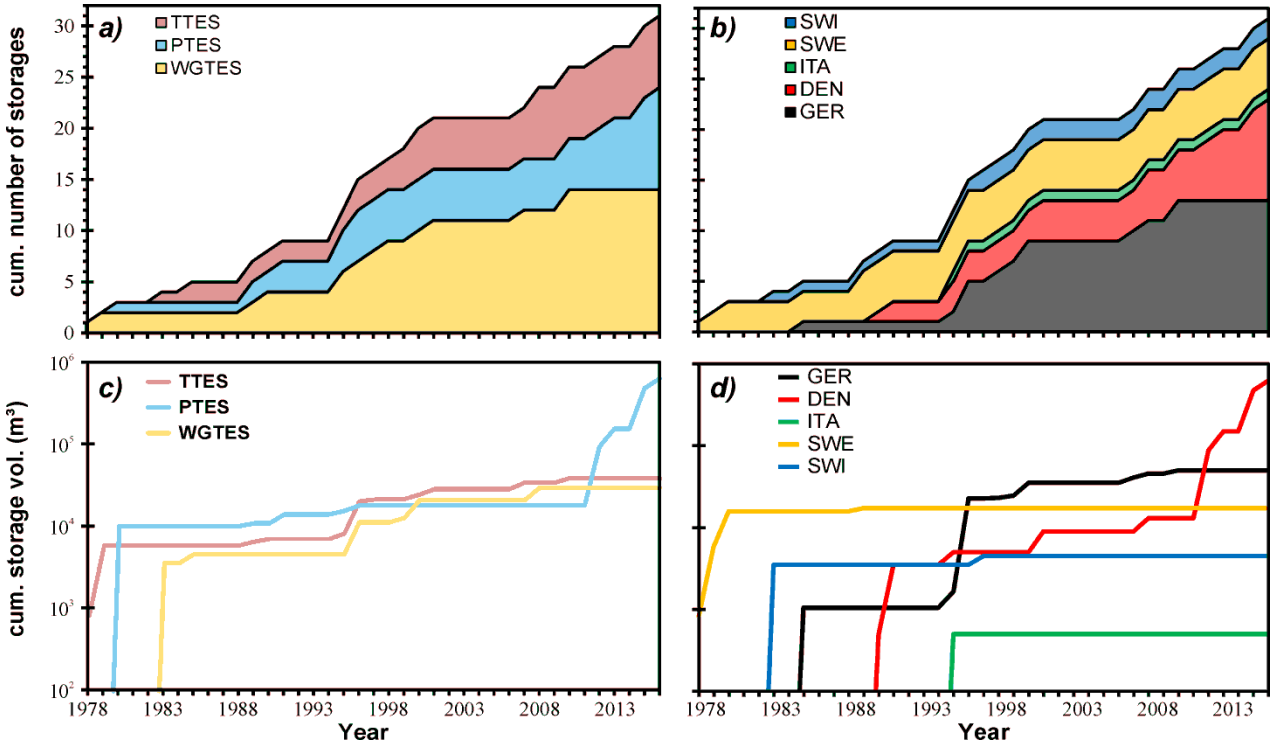


Figure 2: (a) Numbers of different storage types, (b) in different countries, (c) available storage volumes per storage type, and (d) country (SWI: Switzerland, SWE: Sweden, ITA: Italy, DEN: Denmark, GER: Germany). Note the logarithmic scales of cumulated storage volume in c) and d).

Tank storages offer more flexibility in design due to the structural elements used. They exhibit the best surface/volume (A/V) and height/diameter (h/d) ratios on average. This is reflected in the geometric shape as well, since TTES can contain complex shapes with combinations of truncated cones, cylinders and domes (e.g. Hannover (Bodmann and Fisch 2004)), while PTES and WGTES are mostly truncated pyramids (e.g. Steinfurt (Bodmann et al. 2001) and Stuttgart (Hahne 2000)). These are influenced significantly by the natural slopes (cf. Fig. 4 d). Modeling procedures to determine the optimal storage geometries were presented by Forkel and Daniels (1995). Cylindrical basins with internal subdivisions for optimized thermal stratification while reaching an A/V ratio close to that of a sphere were found to be the optima.

2.2 Construction materials and methods

2.2.1 Filling materials

Regarding filling materials, WGTES stand out against the variants considered here. While TTES and PTES contain only water, WGTES employ a two-component mixture of e.g. gravel, sand or soil, and water (Urbaneck et al. 2002). Well-sorted gravel is favorable as WGTES filling because of its good permeability and porosity. Due to the solid content, WGTES can be statically loaded, the surface can be used for other purposes and no complex coverings are necessary (Marx et al. 2011). WGTES, however, are more demanding in terms of charging technologies. To prevent clogging, heat exchangers are used as coil systems.

Water is used as a transport and storage medium at the same time (Socaciu 2011). As a storage material, water has economic, ecological (Hasnain 1998) and thermodynamic advantages (Marx et al. 2011; Socaciu 2011). Costs for high-quality WGTES fillings can be reduced by refilling the excavated material if applicable (Ochs et al. 2006). A negative aspect for water is its low thermal conductivity (0.6 W/m K compared to 0.6 to 4 W /m K for water-saturated soils (Hadorn 2004)). Capacities of TTES and PTES in the operating temperature range (35 °C to 60 °C) are 60 to 80 kWh/m³ (Novo et al. 2010). For a gravel-water mixture this value is reduced by 80 %, for soil by 40 % (Guadalfajara et al. 2014; Marx et al. 2011; Schmidt and Mangold 2009). In Chemnitz, a gravel-water mixture with a four times higher thermal conductivity value than water of 2.4 W/m K and a comparatively high thermal capacity of 2.98 MJ/m³K (water: 4.18 MJ/m³K) was applied (Benner 2003; Urbaneck et al. 2002). To relate the capacities of the WGTES mixtures to those of PTES and TTES, volumes of WGTES are converted into water equivalents. That is, the theoretical volume of the WGTES is given assuming that it would be filled exclusively with water. As a result, a reduction of 30 % to 50 % is computed (Chemnitz: 5.300 m³ water equivalents at a real storage volume of 8.000 m³ (Benner 2003; Hahne 2000; Mangold 2007), Stuttgart: 725 m³ water equivalents at a volume of 1.050 m³ (Hahne 2000)). Alternative storage fillings, such as phase change materials, are not used due to their high cost. However, water is recommended as a latent material as ice storages (Taylor 1985), where both latent and sensitive heat storage processes can be utilized at low temperatures (Gorski 1986).

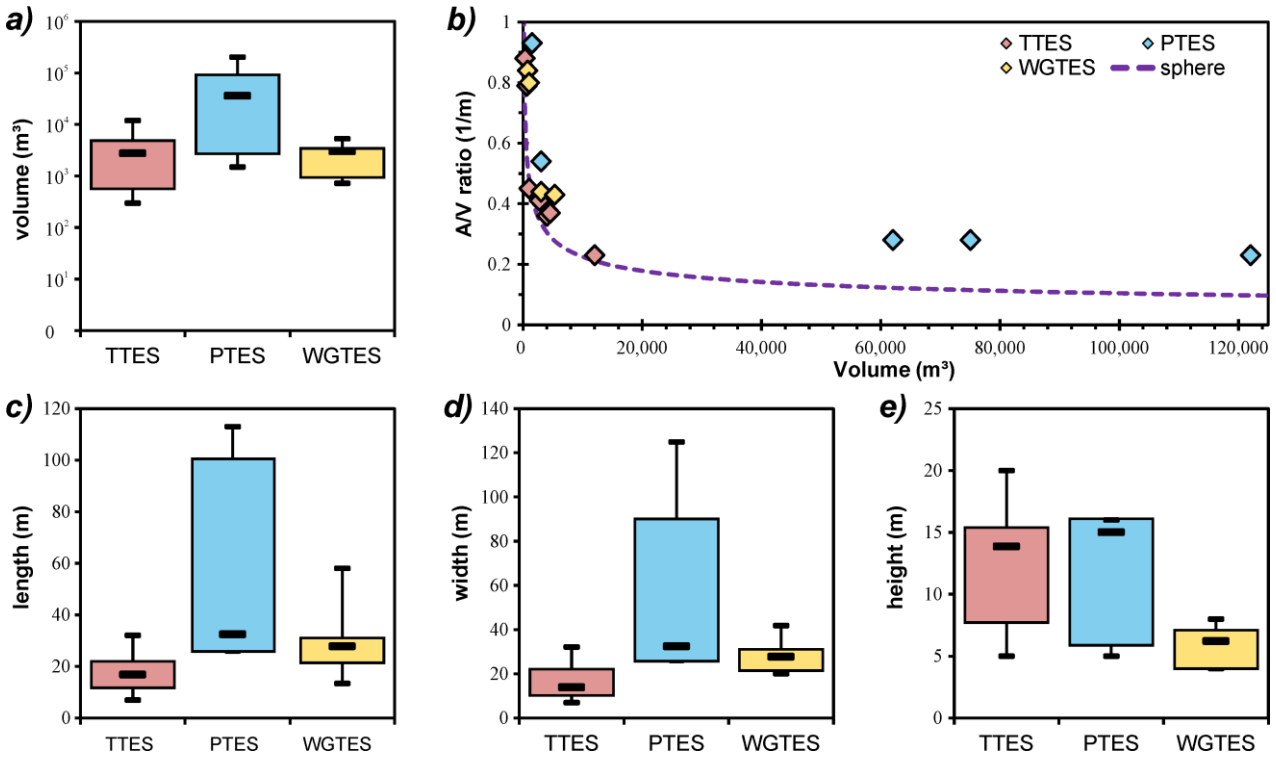


Figure 3: Basic design parameters for all three storage types (TTES, PTES, and WGTES): volume (a, note the logarithmic scale), A/V ratio (b), as well as length (c), width (d), and height (e). The length is defined as the longest edge, the width as the shortest edge.

2.2.2 Sealing layers

To prevent leakage of water and thermal losses, the storage filling needs to be surrounded by a waterproofing component. This also avoids penetration of moisture into the thermal insulation layers. For TTES, stainless steel plates are used in nearly all cases (Fig. 4 b). They are the most expensive, but also the best devices with respect to long-term stability, vapor diffusion and operating temperature (Bodmann and Fisch 2003; Mangold 2006; Ochs 2013; Sørensen and Schmidt 2018). Pressurized and completely oxygen-free, normal steel can also be used. A special concrete with reduced permeability was tested in Hannover (Germany), but it did not prove to be a more cost-effective alternative (Bodmann and Fisch 2004). This also applies to walls made of glass-fiber reinforced plastic (GRP), which cannot be fabricated on-site and may not be applicable to large volumes (Bühl 2001; Milow and Stadermann 2001; Schirmer et al. 2004).

In a further study, Ochs (2013) analyzed several materials from other application domains such as pond, tunnel and landfill construction. Various plastic liners were derived from these for PTES and WGTES (e.g. HDPE or PP (Socaciu 2011; Sørensen and Schmidt 2018), Fig. 4 b). Advantages of these materials include simple and fast processability, as well as low costs. However, a lower temperature stability is reported and this is disadvantageous (Bodmann and Fisch 2003; Sørensen and Schmidt 2018). Double-layered membranes offer proof of tightness as supported by vacuum tests after years of operation (Pfeil and Koch 2004), while vapor diffusion can be suppressed by composite foils with an aluminum barrier (e.g. Steinfurt, Germany (Bodmann et al. 2001)). Among the plastic materials used, HDPE clearly dominates, while most geomembranes have not established themselves (Fig. 4b). An experiment with a clay layer as a seal at the storage in Ottrupgaard (Denmark) failed, with large water losses occurring shortly after the start (Guadalfajara et al. 2014). Generally, leakages remain one of the main problems of existing TES. Damages occur during installation or through material fatigue. An important challenge for future storage systems is therefore to find innovative materials. For example, at the Marstal facility in Denmark a steel grid was used for this, and in Herlev (Denmark), a structural element in the form of steel sheet pilings was applied (Sørensen 2004).

2.2.3 Thermal insulations

Conductive energy losses are prevented by thermal insulations. The performance of a TES is influenced by the position, thickness, material properties and construction technique of the thermal insulation layer (Ochs et al. 2007). Ideally, the thicknesses increase from the basis to the top, since the highest temperatures are expected in the upper storage section (Bodmann and Fisch 2004; Mangold 2006). Therefore, all storage types are equipped with the thickest thermal insulation at this position (Fig. 4 a). However, losses to the sides and to the ground are also relevant, which is illustrated by Mattheess et al. (2018) via numerical simulations. For cost reasons and due to the high static requirements on materials, the first TTES applications (Hamburg, Germany; Rottweil, Germany) dispensed with basis insulations (Bodmann and Fisch 2004; Mangold 2006; Schmidt et al. 2003). Many PTES and WGTES are still not isolated at the basis, whereby PTES compensate this shortcoming by their large volumes. WGTES became insulated at the sidewalls with the implementation of stress-resistant materials, while TTES are nowadays insulated on all sides. Marx et al. (2011) and Mangold (2006) recommend using different materials in the various domains, considering their different thermo-mechanical properties.

Over time, several materials have been tested, and they can be divided into three categories: Conventional materials have been adopted from other application areas, e.g. from the area of building construction, and include extruded or expanded polystyrene (XPS or EPS), polyurethane (PUR), and mineral fibers. They usually feature good thermal conductivity, but often have nonlinear properties with decreasing performance at higher temperatures (Mangold 2006). Furthermore, their properties degrade significantly when exposed to humidity (Ochs et al. 2007). As shown in Fig. 4 a, these are mainly used for top insulations of all storage types and wall insulations of TTES and WGTES. A new and promising approach is the use of recycled materials, which include foam glass (bulk material or sheets) and expanded glass granulate. These are recovered from waste glass and have only been used since the second half of the 1990s. Their advantages are high stress resistance at moderate costs. They facilitated basis insulations of TTES and WGTES, which were previously not feasible. Furthermore, these materials dry quickly after moisture penetration (Bodmann and Fisch 2004) and as mechanically stable granules they can be applied easily. Overall, bulk materials have the crucial advantage that, in combination with plastic liners, they can be welded into the sealing layer and then be monitored for leaks by vacuum tests. Although the thermal properties of recycling materials are not better than those of optimized conventional materials, they are favorable due to their cost-effectiveness (Ochs et al. 2007). A third category is natural materials. They are characterized by their generally low costs and very good environmental properties. They include volcanic, fine-pored products (pumice, perlites), and expanded clay. Because of their low static resistance, they can only be used for wall and top insulations and exhibit lower thermal properties. One advantage of expanded clays is their buoyancy, allowing for realization of floating covers (e.g. in Marstal (Denmark), (Lasse 2013)).

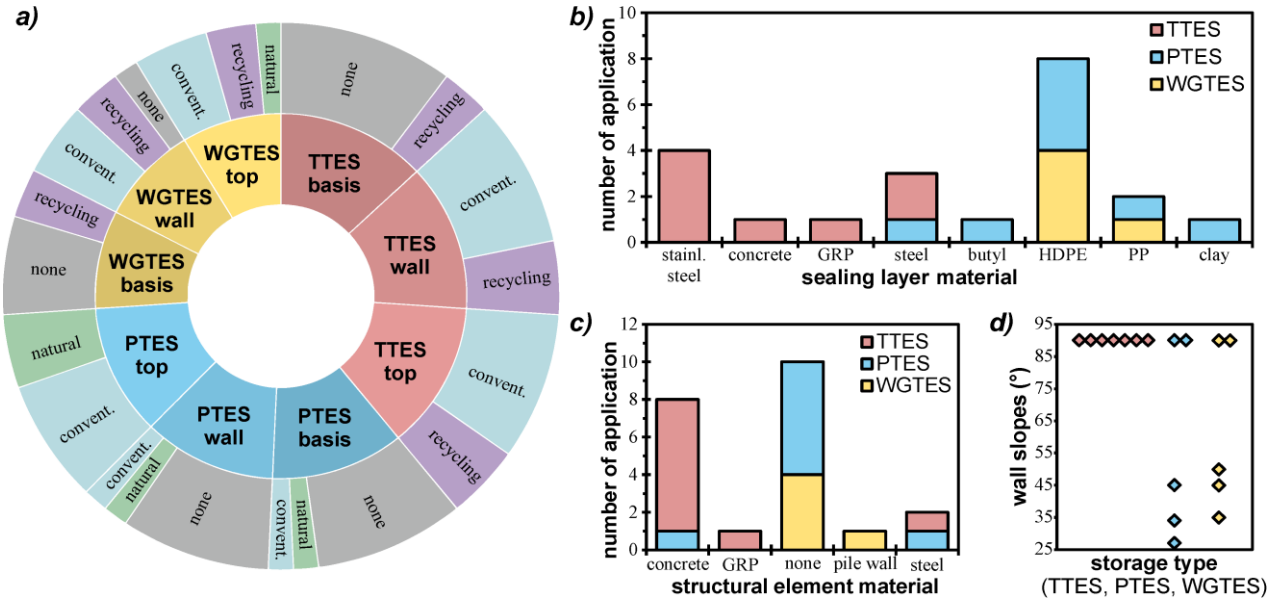


Figure 4: Materials used for (a) thermal insulation, (b) sealing layer material, (c) structural element materials, and (d) wall slopes of storage systems.

2.2.4 Structural elements

As depicted in Fig. 4 c, structural elements are required for all TTES facilities. This is because they are always implemented as above-ground storage parts causing static loads to the side walls. The walls of TTES are preferably made of cast-in-place concrete. Alternatively, prefabricated concrete elements (Schmidt et al. 2003) or GRP or steel can be applied. Walls of concrete are usually reinforced by steel. However, as stated in section 2.2.2, GRP elements cannot be manufactured on-site and they are not resistant to high static loads (Bühl 2001; Milow and Stadermann 2001; Schirmer et al. 2004).

The role of the applied structural element can also be seen in the wall slopes, since TTES only have 90° vertical walls (Fig. 4 d). WGTES and PTES do not require structural elements in most cases. Nevertheless, these may become necessary in difficult subsoil conditions or may serve to protect the thermal insulation. Therefore, some systems of these types were also equipped with a structural component of concrete or steel (Fig. 4 c). At the WGTES in Chemnitz (Germany), pile walls were installed for stabilization before the pit was excavated (Schirmer and Urbaneck 1998). Without structural elements, PTES and WGTES are dependent by utilizing natural soil or rock slopes (Fig. 4 d). In this case, WGTES can achieve steeper angles because the additional filling component offers higher internal stability. Drainage layers are applied as an external elements to protect the TES from moisture penetration (Bodmann and Fisch 2004). This is particularly important for buried systems, i.e. mainly WGTES and PTES. If no structural element is present, the internal elements (thermal insulation and sealing layer) may also be protected from damage. Apart from common gravel layers, geotextile mats or bentonite layers are also considered (Pfeil and Koch 2004).

2.3 Storage operation

Seasonal thermal energy storages with large volumes are intended for integration into heating and cooling networks for increasing their cost-efficiency (Mangold 2007; Marx et al. 2011; Schirmer et al. 2004). In this context, correct operation is essential for the performance of the storage itself and the entire network (Schmidt and Mangold 2009). TES are especially suitable for new building projects (e.g. the "Solar Settlement" Steinfurt, Germany (Bodmann et al. 2001)), but also for refurbishment activities of existing neighborhoods with district networks (e.g. Eggenstein, Germany (Nußbicker-Lux et al. 2012)). All system components must be well harmonized. Firstly, this concerns the dimensioning of the thermal storage, matching demand and production to achieve the

most cost-effective solution (Chung et al. 1998). Secondly, it also refers to temperature levels that vary for the different application targets. Adjusting these temperature levels can be realized by employing buffer storages or by recycling return flows (Bodmann and Fisch 2004).

The initial operating phase of a TES is characterized by several years of heating-up, where thermal losses are highest due to the initially large temperature gradients (Bodmann et al. 2001; Mangold et al. 2003). Afterwards, existing TES are usually employed for domestic heating and hot water preparation purposes. Low-temperature heating systems are favorable due to their thermal efficiency (Mangold et al. 2003). Additionally, new developments emerge that aim at integrating industrial and agricultural applications, although these often require higher temperatures and hence post-heating systems (Xu et al. 2014). The sources of energy connected to the storage can be any heat or cold generating devices setting up a centralized or decentralized network. For environmental reasons, these are mostly renewable energies, whereby TES compensate for their fluctuations. Examples are (1) solar thermal systems (Sørensen and Schmidt) (2), waste heat from cogeneration, and (3) biomass and biogas plants (Socaciu 2011). Potential post-heating for high temperatures is usually done via conventional systems such as flow heaters or oil/gas boilers (Marx et al. 2011). Heat pumps can also help to achieve required target temperatures and ranges (Marx et al. 2011).

3. REMAINING ISSUES

3.1 Efficiencies

The efficiency of a seasonal TES is defined as the ratio of retained to lost energy (external energy losses and exergy losses due to mixing). With reference to the capacity of the facility, these values are expressed relatively so that different locations can be compared. Fig. 5 shows the relative storage losses of the different system types in relation to their volume (a) and operating temperature (b). Even though it is assumed that for optimal implementation, energy losses can be reduced to only 10 % (Marx et al. 2011), the energy losses of existing storage systems are at least three times higher (around 27 %) whereas the reported values reach around 52 %. In general, WGTES achieve the lowest efficiencies. With respect to the size of TES (Fig. 5 a), a distinct fact is that there is no exaggerated energy loss with increase of volume. This proves that large PTES compensate for significantly thinner insulation. With regard to the operating temperature, Fig. 5 b shows that TTES are operated at the highest temperatures. However, energy losses rise in all types with increasing temperature inside the thermal storage. This can be attributed to the steeper radial temperature gradients to the environment. In summary, it can be concluded that large low-temperature storage tanks are the most promising, and for all variants still improvements are warranted for enhancing the thermal efficiency of the storages in practice.

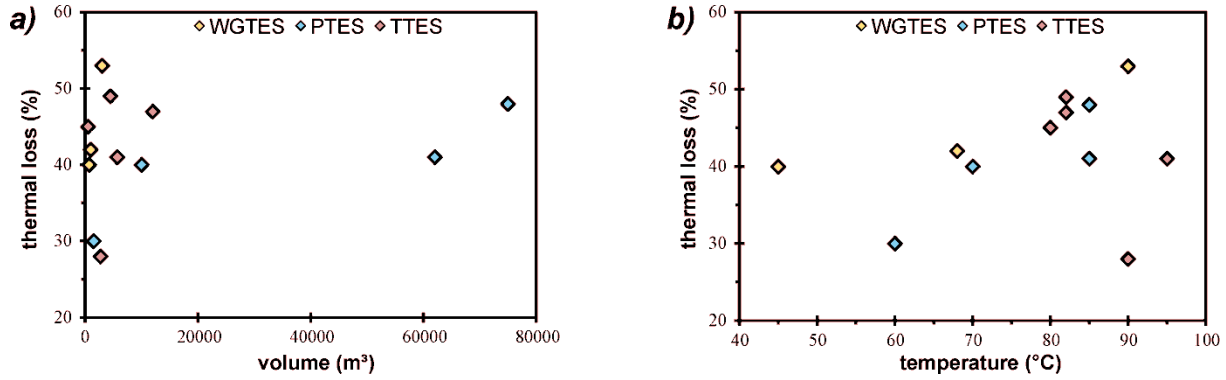


Figure 5: Performances of present storage systems in relation to volume (a) and operating temperature level (b).

3.2 Approaches for future developments

Existing seasonal thermal energy storages are often not economically viable due to their high energy losses compared to investment costs. This is the main reason why there is little attention from the global market. However, since the technology is considered promising for future projects, there are several emerging approaches to optimize performances and reduce storage costs. Basically, high costs for excavation can be prevented by reusing existing infrastructures (e.g. gravel pits, water treatment basins, etc.). Furthermore, there still exists a great potential with respect to smart connection of new energy sources to charge TES. For example, this can include waste energy from data centers, industrial processes or residential buildings. Similarly, intelligent control algorithms to achieve optimal source utilization offer further potential. Multi-storage combinations of different set-ups and temperature levels offer a great opportunity to optimize overall storage efficiencies, and can be implemented in several neighboring storages at a site. Furthermore, a crucial factor will be improvements in heat transfer coefficients of thermal insulation materials. In future projects, thermal insulations need to be adjusted precisely to their position, thickness and material properties. The leakages of existing storages need to be overcome in the future. Materials with enhanced long-term stability and innovative, controllable construction methods can support this. A further solution might be the use of latent storage materials in the storage wall, which could give the sealing layer self-healing properties through melting and solidification.

4. CONCLUSIONS

Although seasonal thermal energy storage can contribute significantly to the energy transition, there are no widespread applications of closed ground-based technologies. Intensive development and application currently takes place in only a few European countries. Especially in combination with district heating applications, progress has already been made over a period of more than 25 years. This study illustrates the state-of-the-art by presenting the major experience during the past technological evolution. This is completed by a detailed assessment of the individual TES components. Various approaches and materials are identified for each component and best practices are identified. Despite constant improvements in all areas, it is also shown that some critical issues

still prevent global market availability. This affects all system types and all components of the inspected storage variants. To address these remaining issues, solution strategies were presented. Besides the focus on novel materials and construction methods for thermal insulations and sealing layers, they reveal the potential from increased flexibility and economization strategies to enable cost-effective realizations of closed seasonal TES at any site.

Over time, the three concepts of tank thermal energy storages (TTES), pit thermal energy storages (PTES) and water-gravel thermal energy storages (WGTES) emerged as attractive choices for further research. While WGTES are filled with two storage materials, both PTES and TTES are water-filled artificial enclosed basins. The individual advantages of these types result from their conceptual differences. PTES can be scaled to very large volumes, whereas TTES are suitable for high temperature applications. In contrast, WGTES are also applicable in areas with limited space due to their statically loadable top surface. A total of 31 seasonal TES, with an available volume of around 697,000 m³, are available in Europe. This leads to an installed capacity of 56,600 MWh under optimal operating conditions. TTES are the most common, and WGTES represent the smallest number of realized projects due to their complexity. Leading countries in the application of the seasonal TES technology are Germany, Denmark and Sweden.

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