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State-of-technology review of water-based closed seasonal thermal energy storage systems

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ABSTRACT

Continuous use of fluctuating renewable energy resources is facilitated only by temporal storage solutions. For long-term and seasonal heat storage, many large-scale closed seasonal thermal energy storages (TES) have been built in the recent decades. Still there is no consistent picture available that contrasts the different technologies and summarises the major findings from the implemented storage facilities. This review reports the state-of-the art of these TES and offers future perspectives based on 31 locations in Europe with a total available storage volume of nearly 800,000 m^3, corresponding to a capacity of 56,600 MWh in the case of optimised storage utilisation. Three construction types prove to be the most promising concepts: tank thermal energy storages, pit thermal energy storages, and water-gravel thermal energy storages. The characteristic technological elements such as filling, waterproofing, and thermal insulation are discussed in detail to highlight successes and failures, as well as to display the latest innovations and research trends. Novel materials substitute conventional, less efficient alternatives while innovative methodologies are shown to reduce the risk of failure and significantly improve storage performance. The main challenges on the way to global market maturity include avoidance of primarily defective waterproofing, mitigation of energy and exergy losses caused by long-term material fatigues, and reduction of the often substantial construction costs.

1. Introduction

Sustainable energy management aims to reduce the carbon footprint by utilising higher shares of renewables through smart coordination of centralised and decentralised supply, and by integrated storage concepts. Future energy supply, ideally, relies on a combination of mostly fluctuating renewable sources such as wind, biomass, solar, and geothermal energy [1,2]. These sources are especially needed for decarbonisation of the heating, cooling, and hot water supply sector which is responsible for a large fraction of energy consumption. Today, however, worldwide space heating and hot water production is dominated by burning fossil fuels. Since 2010, despite auspicious green energy plans on all political levels, global direct emissions from heating in buildings have not declined, representing the fastest growing end-use in buildings [3].

The slow pace of sustainable energy transformation has many causes, one being the high dependency of renewable sources on environmental conditions. These are difficult to describe, predict, and quantify for guaranteeing a reliable supply. Thermal energy storage systems (TES) offer the opportunity to collect the thermal energy from different fluctuating renewable and non-renewable sources independent of the demand, and to transfer temporarily available energy into permanently accessible energy. Thermal energy storage allows peak shaving of cost-intensive energy productions [4,5]. In combination with renewable energies, it ultimately facilitates savings in heat consumption on the one hand and substitution of heat provided by fossil fuels on the other [6–9].

All types of energy storage systems are equipped with a storage medium and a loading and unloading system. At times of low demand and high supply, the storage is charged to enable low-loss provision at times of shortage and high demand. TES are differentiated from other types of storage by their low price, longevity, and sufficiency of resources [10]. According to Ref. [11], there exist various methods of classification. For instance, they differ with respect to storage material (sensitive, latent, thermochemical), and in their technological concepts (underground, hot water and above ground, use of phase change materials (PCM), thermochemical storage [4]). In practice, sensible heat storage is still most common [11–14]. During recent years, attention has been growing towards seasonal sensitive heat storage. This is especially of interest for storing the huge surplus of solar heat collected during summer, thus compensating for the limited availability of solar heat during the primary heating period in winter (Fig. 1). Seasonal

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Nomenclature

a	year
A	surface (m^2)
G	monthly solar yield (kWh)
Q	monthly energy demand (kWh)
V	volume (m^3)
AT	Austria
ATES	Aquifer Thermal Energy Storage
CHP	Combined Heat and Power
CTES	Cavern Thermal Energy Storage
CSHPSS	Central Solar Heating Plant with Seasonal Storage
DEN	Denmark
EPDM	ethylene propylene diene monomer rubber
EPS	expanded polystyrene
GER	Germany
GRP	glass fibre reinforced plastic
HDPE	high-density polyethylene
IEA	International Energy Agency
IEA SHC	International Energy Agency Solar Heating & Cooling Programme
ITA	Italy
PE	polyethylene
PCM	Phase Change Materials
PP	polypropylene
PTES	Pit Thermal Energy Storage
PUR/PIR	polyurethane/polyisocyanurate
PVC	polyvinyl chloride
SWE	Sweden
SWI	Switzerland
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage
WGTES	Water-Gravel Thermal Energy Storage
XPS	expanded polystyrene

applications differ fundamentally in their requirements and designs from diurnal storage systems and are more difficult to apply. Long-term or seasonal TES have only one to two cycles per year [15]. Clearly, such long-term storage of sensitive heat requires a substantial volume of storage space. Only large scale applications can meet the heat demand for months while minimising the continuous conductive heat loss during storage.

The best-known types of seasonal TES variants are aquifer storages (ATES), borehole storages (BTES), cavern storages (CTES), pit storages (PTES), and seasonal tank storages (TTES). ATES, BTES, and CTES are geothermal applications utilising natural ground that is mechanically not contained [16]. In the present study, the focus is exclusively on a family of closed artificial storage systems, which are less dependent on (hydro-) geological boundary conditions and therefore conceivable at almost any location [17,18]. This work reviews the current technological status of closed seasonal TES based on the information which is widely dispersed in heterogeneous scientific literature sources and languages. This is complemented by the experience reported from the growing number of applications in practice, in order to arrive at a condensed overview of the state of the art storage systems.

Since water is the most common seasonal heat storage medium by far, the scope of this study is only on water-based TES. As major categories, solely water-based technologies and those with multi-component filling materials are distinguished (Fig. 2). Exclusively water-based technologies are either TTES systems, which represent constructed basins that stick partially or completely out of the ground surface, or water-filled sealed pits (PTES) without any structural element for

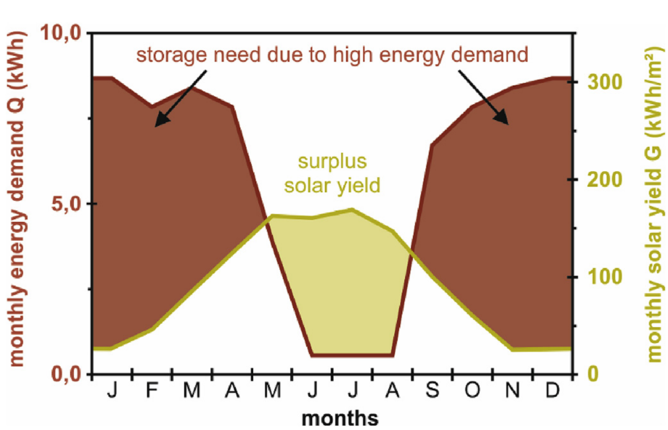

Fig. 1. Heat demand and solar heat yield of a hypothetical example household in Munich (heated area: 150 m^2, energy demand: 70 kWh/(m^2·a), solar thermal area: 10 m^2, assumed long-term efficiency: 0.5).

stabilisation. All applications with a multi-component filling material are classified as water-gravel thermal energy storage systems (WGTES). Strictly speaking, gravel is not always used for WGTES in practice, and thus multi-component based variants can be further subdivided into earth-water and gravel-water storages according to their filling [19]. For convenience, however, these variants are not separately discussed here.

In the following paragraphs, first a statistical view is presented, also including the historical evolution of large-scale closed TES. Furthermore, the developments of closely related large-scale non-seasonal heat storage buffers are shown. Although their type of usage varies from those of PTES, WGTES, and TTES, there exist common technological features, and therefore buffers are added here for comparison. Then, the technological characteristics such as fillings, structural components, thermal insulations, waterproofing methods, and construction techniques are examined. The regional focus is set on Europe, where the major developments in seasonal TES have been installed.

2. Evolution and statistics of seasonal thermal energy storage in Europe

2.1. Historical development

Well-known early, pre-industrial applications of long-term thermal energy storage were subsurface depots of ice used to conserve food. The recent history of closed seasonal TES (Fig. 3) can be traced back to 1959, when Ref. [20] presented a first technically sophisticated attempt for seasonal storage of thermal energy in subsurface rock chambers. A few years later, Ref. [21] published ideas for storing solar energy in the subsurface. However, both studies represented mainly theoretical thoughts without any practical applications. According to Refs. [16,22–24], pioneering works can be found especially in the early 1970s, when the oil crisis raised the public awareness of the importance of energy supply (Fig. 3).

The first buried closed seasonal heat storage system was built in 1978 as a PTES in Studsvik (Sweden) and had a volume of just 800 m^3 [25]. WGTES projects were firstly realised in 1983 in Stuttgart [26] and Vaulruz (Switzerland [19]). A few years later, the appearance of central solar heating plants with seasonal storages (CSHPSS) was an additional factor to push the research from 1980 onwards [27]. During this time, Sweden was leading the technology with many projects (e.g. Studsvik [25], Ingelstad [28,29], Lambohov [28,30], Malung [31]) focusing on solar power generation and the development of a strategy with seasonal solar thermal energy storage systems [18]. In these years, the technology of seasonal storages also got attention by the International

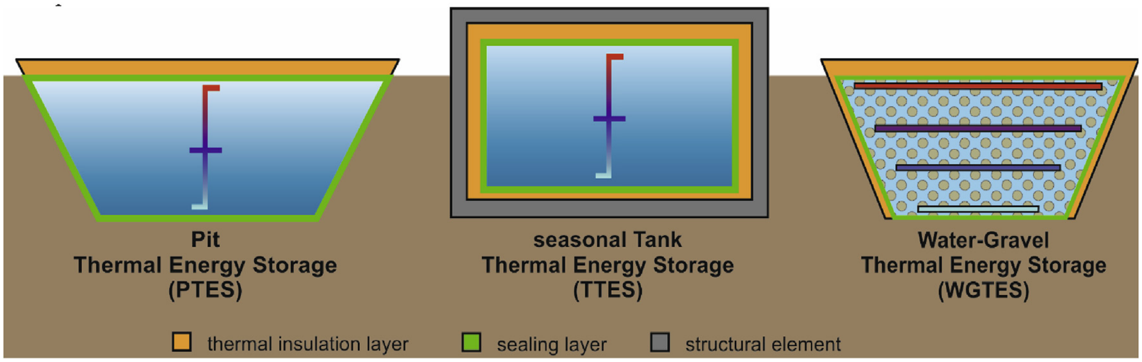

Fig. 2. Schematic layouts of the systems selected for further analysis.

Energy Agency Solar Heating & Cooling Programme (IEA SHC), mostly under Task VII "Central Solar Heating Plants with Seasonal Storage" carried out from 1979 to 1988 [25]. According to this program, knowledge and commitment of 18 IEA member states was brought together, resulting in the definition of basic concepts and designs [32,33], methods for cost analysis [34], and a significant number of project sites, e.g., Herlev (Denmark), Stuttgart, Ingelstad, and Vaulruz.

Apart from research on how to store energy for longer times, international climate treaties (e.g., Agenda 21 climate action plan in 1992 or Kyoto protocol in 2005) represented important motivations for the development of new technologies. With the Paris agreement in 2016, new applications and further developments in combination with renewable energy sources will also be needed in the future.

Most of the existing seasonal TES are located in Germany and Denmark. This is the result of several dedicated research programs in these countries. In Germany, these were, among others, the programs Solarthermie-2000 (1993-2002 [9,35,36]) and Solarthermie2000-plus (2004-2008 [9,37–39]). In Denmark, the main driver for developing new energy technologies was the government's "Energy Strategy 2025" (published in 2005) first and second the "Energy Strategy 2050" (published in 2011) with an ambitious goal to achieve an energy market independent of fossil fuels (Fig. 3, [40]).

Apart from storing only heat in storage systems, combined systems for heating and cooling in the context of district heating and cooling networks were already proposed in 1997 for WGTES [41]. A corresponding test was conducted at the storage facility in Stuttgart, which had been built in 1985 [26], proposing a heating and cooling concept to develop the technology further. More recently, Ref. [42] discussed various locations in Spain with special focus on the respective climatic conditions. Annual energy demands for cooling and heating were estimated and numerical simulations showed that solar district heating and cooling systems with long-term storages can be an economic viable alternative to conventional systems.

2.2. Numbers, volumes and spatial distribution

Since the first construction of a seasonal TES in 1978, there has been a small but continuously growing number of systems installed (Fig. 4b). Around 1995, an increase in the total number of seasonal TES was stimulated by the research programs in the early 1990s. Among the technological variants (Fig. 4a), TTES were most popular with a significant rise in installed systems around 1995. The PTES were less popular than TTES during 1978–1995, but their number increased at almost the same rate. There was a pause from 1995 to 2012, then after 2012 new systems were built again in Denmark (e.g. Marstal [43,44], Dronninglund [45–47], Fig. 4a). The past development of WGTES was similar to that of PTES; however, a constant growth in numbers was found without interruptions. In contrast to the seasonal storage systems, sizeable heat buffer storage applications are listed first in 1999 with an installation in Aeroeskoebing (Denmark [48–50]). Subsequently, the number of these systems stepped up rapidly. This was caused particularly by the growing popularity of district heating in countries such as Denmark (Samsø [51]), Austria (Linz [52], and Salzburg [10,53]), and Germany (Nuremberg [54]).

The evolution of the installed storage volume shows a moderate development until 2010 (Fig. 4c). This is due to the initial construction of only smaller systems within pilot projects. From 2010 onwards, a nearly exponential trend is found in the total installed volume, being coincident with the recently rising number of PTES (Fig. 4a). Fig. 4c shows the total installed storage volume for each year, whereas Fig. 4d depicts the average size of the single installed storages. On this basis, it is evident that the exponential volume increase is not the result of an exponential increase in the number of built systems (Fig. 4b), but that the volumes of individual systems (Fig. 4d) have followed an exponential growth trend since 2010. To date, the largest seasonal storage facility is located in Vojens (Denmark) as a PTES with a volume of around 200,000 m^3 of water at a former gravel pit [44,46,55,56]. In contrast, until 2010, the largest seasonal storage system only had a

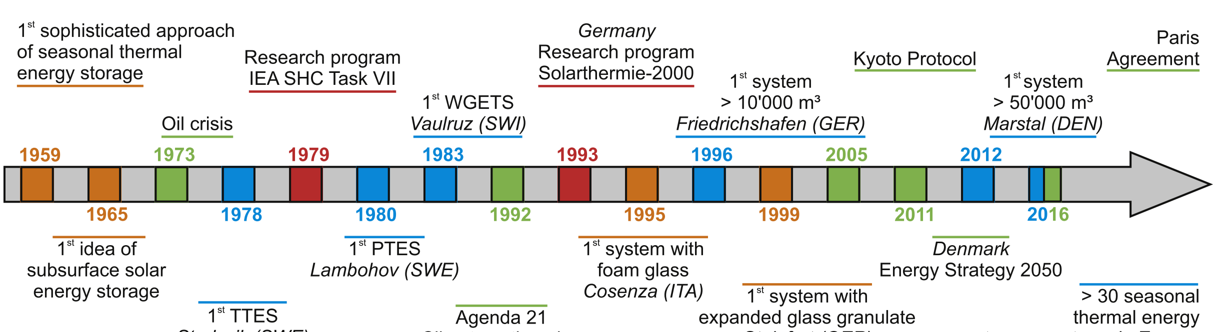

Fig. 3. Timeline showing some of the important steps in the history of the development of seasonal Thermal Energy Storage (orange: inventions; green: climate actions; blue: milestone systems; red: research activities). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

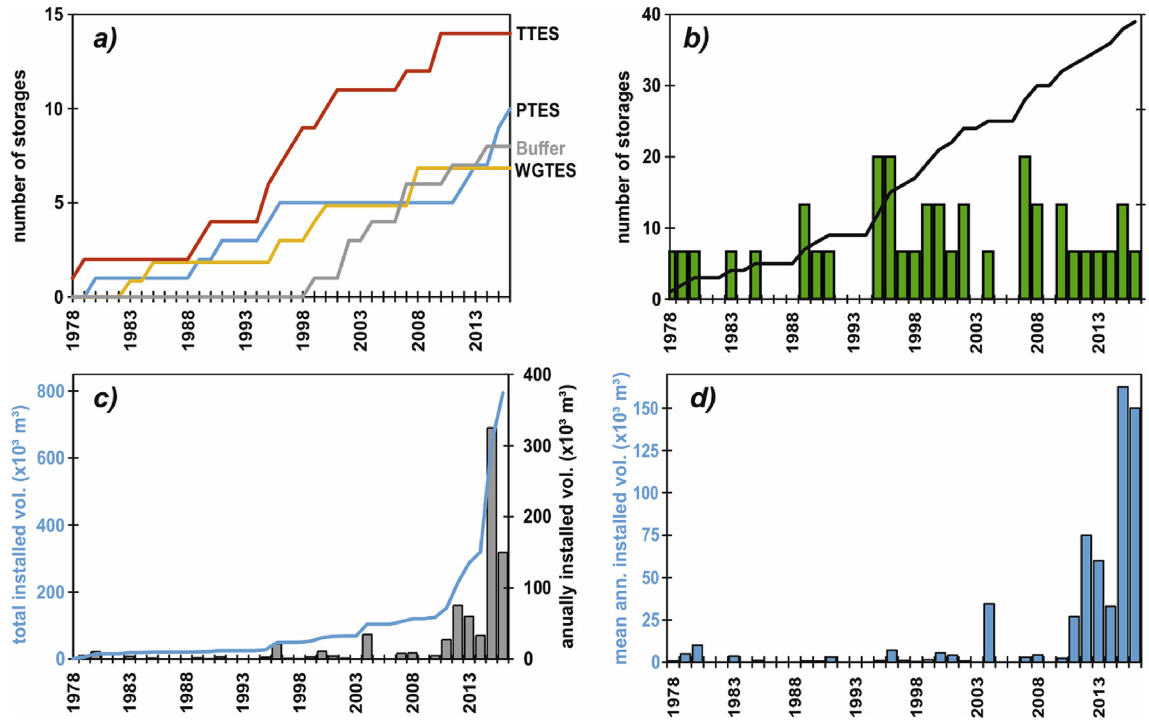

Fig. 4. a) Evolution of the number of different seasonal storage systems and large buffer storages. b) Development of the total number and annual newly built systems (TTES, PTES, WGTES and large buffer storage) and cumulative number of storages (black line). c) Development of the installed volume in Europe for seasonal thermal energy storage (TTES, PTES, WGTES, incl. large buffer storage) with annual newly-installed volumes. d) Development of the average size of newly installed seasonal storage systems (TTES, PTES, WGTES) and large buffer storages.

volume of 12,000 m^3 (TTES Friedrichshafen, Germany [41,48,57–59]). Due to their more challenging design, the typical WGTES is smaller in size, with the largest plant situated in Eggenstein (Germany), having a volume of 4,500 m^3 [60–62]. In summary, the exponential growth of total storage volume and average individual storage volume is in contrast to the almost linear development of the number of systems. This clearly points towards a trend of larger facilities during the last decade, stimulated by ongoing technological advancements, experience and economies of scale.

Considering the present-day state statistics, it is also useful to differentiate between the various types of thermal energy storage (Table 1). Apart from seasonal systems (PTES, WGTES, TTES), there is also a relevant number of sizeable short-term buffer storage systems. Regarding these four types of storage systems, TTES are predominant, followed by PTES and WGTES. Although the number of PTES is lower than the number of TTES, the volume of PTES is larger than that of any other storage system, both in terms of individual storage volumes and the total sum of all storage volumes in Europe (Fig. 5). It is also noticeable that WGTES are on average larger than TTES, but at lower total volume. This is because WGTES balance their reduced heat storage capacity due to the use of gravel by a larger volume.

The distribution of seasonal thermal energy storage locations varies geographically in Europe (Fig. 6a). In total, our survey identified 39 storage facilities. Most systems are installed in Germany, followed by Sweden, Austria, Switzerland, and Italy (Fig. 6a and b, Table 1). Because of the recent developments with several large scale applications, the greatest storage volume is installed in Denmark, followed by Germany, Austria, Sweden, Switzerland, and Italy (Fig. 6c). This is a result of the continuous research activities and public interest that stand out in these countries.

3. State of technology

3.1. Buried vs. elevated

Closed TES that are partially or fully buried in the ground (PTES, WGTES) rely on certain (hydro-)geological conditions such as ground stability and absence of groundwater. Applications above the ground are less site-dependent, and so most TES are constructed above ground. This is also a favourable option due to excavation cost savings, and because constructive elements and tank casings handle the stress caused by the filling [5,108]. Sometimes, a useful hydraulic pressure gradient from the storage device to the heating network can be achieved by construction of elevated applications.

Ref. [12] describe a fully buried concrete storage system and emphasise that the surrounding soil is advantageous as it offers additional storage capacities, which is also supported by simulations [124]. According to the numerical modelling results by Ref. [54], buried facilities exhibit higher storage temperatures at greater depth. For reasons of better storage performances and aesthetics, it is often recommended to bury and integrate the storages into the visible environment [125]. The TTES in Hannover (Germany) was integrated into an urban playground. In Munich (Germany), soil was piled up around the storage in order to integrate it into the landscape [18]. Also in Sweden, there has been a shift to buried storage facilities, and the last above-ground storage facility in Ingelstad was built in 1979 [25]. In many cases, excavation costs could be minimised by reclamation of former gravel pits.

3.2. Geometry and filling

3.2.1. Size and volume

The size and volume of a TTES facility might be restricted by regulations on maximum height above the surrounding terrain, depending on the location and the respective building laws (e.g. Hamburg (Germany) [99], Supplementary Table S–1) or due to requirements on

Table 1
Overview of all seasonal thermal energy storage and large buffer storage locations recorded in this survey.

#	name	year	country	storage type	volume (m^3)	water equivalents (m^3)	reference
1	**Lambohov**	1980	SWE	**PTES**	10,000	10,000	[5,14,25,63–65]
2	**Malung**	1989	SWE	**PTES**	800	800	[64,66]
3	**Herlev (Tubberupvaenge)**	1991	DEN	**PTES**	3,000	3,000	[14,24,25,47,49,63,64,67–70]
4	**Ottrupgaard**	1995	DEN	**PTES**	1,500	1,500	[18,26,28,31,47,48,64,68,69,71–73]
5	**Jülich**	1996	GER	**PTES**	2,500	2,500	[5,64,71,74]
6	**Marstal (SUN STORE 4)**	2012	DEN	**PTES**	75,000	75,000	[43,53,71,73,75–77]
7	**Dronninglund**	2013	DEN	**PTES**	62,000	62,000	[45,46,64,65,73,75,78]
8	**Gram**	2015	DEN	**PTES**	122,000	122,000	[44,46,78–80]
9	**Vojens (1 + 2)**	2015	DEN	**PTES**	203,000	203,000	[53,55,56,81,82]
10	**Logumkloster**	2016	DEN	**PTES**	150,000	150,000	[82,83]
11	**Studsvik**	1978	SWE	**TTES**	800	800	[63,64,68,71]
12	**Ingelstad**	1979	SWE	**TTES**	5,000	5,000	[5,6,24,25,28,29]
13	**Särö**	1989	SWE	**TTES**	640	640	[25,26,31,64,68,70,71]
14	**Hoerby**	1990	DEN	**TTES**	500	500	[5,13,29,64,69,84–86]
15	**Rottweil**	1995	GER	**TTES**	597	597	[5,26,41,87–89]
16	**Cosenza (Calabria)**	1995	ITA	**TTES**	500	500	[5,90,91]
17	**Friedrichshafen (Wiggenhausen)**	1996	GER	**TTES**	12,000	12,000	[7,26,35,37,41,48,57,59,64,88,92–94]
18	**Neuchatel**	1997	SWI	**TTES**	1,000	1,000	[4,13,28,48,95]
19	**Ilmenau**	1998	GER	**TTES**	300	300	[31,36,88,89,96–98]
20	**Hannover (Kronsberg)**	2000	GER	**TTES**	2,750	2,750	[7,37,38,57,88,92,99,100]
21	**Rise**	2001	DEN	**TTES**	4,000	4,000	[47,78,83,101,102]
22	**Munich (Ackermannbogen)**	2007	GER	**TTES**	5,700	5,700	[7,38,48,57,58,92,103–106]
23	**Hamburg (Bramfeld)**	2010	GER	**TTES**	4,500	4,500	[7,15,18,26,38,48,58,71,93,98,99]
24	**Mühldorf**	2010	GER	**TTES**	16.4	16.4	[107]
25	**Vaulruz**	1983	SWI	**WGTES**	3,500	*n.a.*	[19,25,108–110]
26	**Stuttgart**	1985	GER	**WGTES**	1,050	725	[5,17,19,25,26,111]
27	**Augsburg**	1996	GER	**WGTES**	6,500	3,250	[19,48,64,68,85,88,108]
28	**Steinfurt (Borghorst)**	1999	GER	**WGTES**	1,500	1,000	[7,15,35,37,48,57,64,99,109,111,112]
29	**Chemnitz**	2000	GER	**WGTES**	8,000	5,300	[5,7,13,17–19,24–26,37,48,88,109,113–117]
30	**Eggenstein (Leopoldshafen)**	2008	GER	**WGTES**	4,530	3,000	[18,37,38,48,57,58,61,104,118–121]
31	**Sonderborg Vollerup**	2008	DEN	**WGTES**	4,000	*n.a.*	[48]
32	**Aeroeskoebing**	1999	DEN	**Buffer**	1,400	1,400	[49,50,86]
33	**Attenkirchen**	2002	GER	**Buffer**	500	500	[7,37,58,92]
34	**Samsø**	2002	DEN	**Buffer**	800	800	[51]
35	**Linz**	2004	AUS	**Buffer**	34,500	34,500	[52,64,85]
36	**Braedstrup**	2007	DEN	**Buffer**	2,000	2,000	[75,122,123]
37	**Crailsheim (Hirtenwiesen)**	2007	GER	**Buffer**	580	580	[7,18,36–38,57,64,93,120,121]
38	**Salzburg (North)**	2011	AUS	**Buffer**	27,000	27,000	[10,53]
39	**Nuremberg**	2014	GER	**Buffer**	33,000	33,000	[54]

structural properties. PTES can be scaled to enormous volumes [58], especially because these are built beneath the ground surface and thus contained by the surrounding soil.

To minimise conductive energy losses through the shell, the geometry of the TES should always aim at the lowest possible surface to volume (A/V) ratio (m^{-1}) [15,62,109]. By referring to typical geometries such as cubes or spheres, Ref. [126] illustrate this with the third power increase in the volume compared to the second power increase in the surface area. Simultaneously, the A/V ratio behaves reciprocally to the height or diameter of the system. This also means that larger storage volumes have a positive effect [58] on the storage efficiency. Ref. [18] states that energy-efficient seasonal storage only works with a volume of 1,000 m^3 or more. The values listed in Supplementary Table S–1 confirm that generally A/V ratios decrease with the volume of the installed TES, even so a closer look reveals that a strong variability exists. This indicates that other site-specific aspects play a crucial role for the layout of each system. In addition to the A/V ratio, often the height to diameter (h/d) ratio is given and also listed in Table S–1

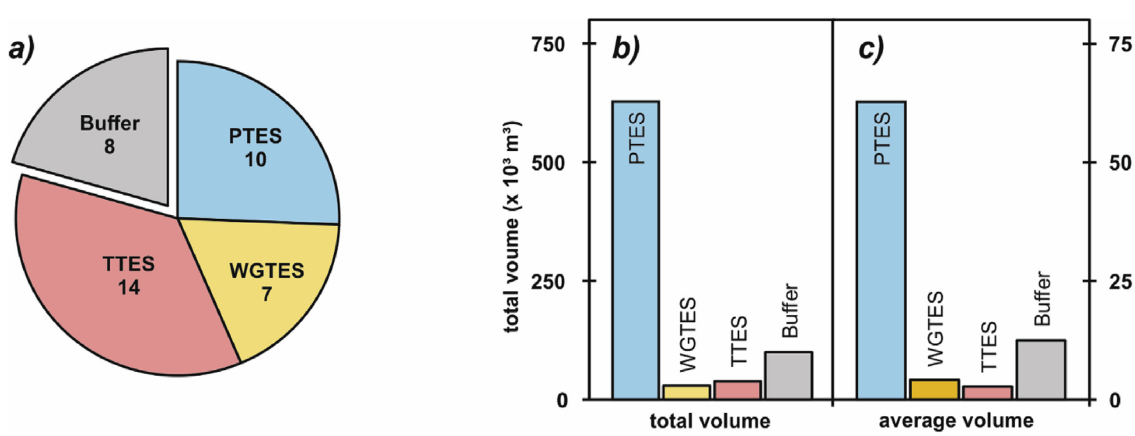

Fig. 5. a) Installed number of different TES types compared to b) the total available installed storage volume and c) the average individual storage volumes.

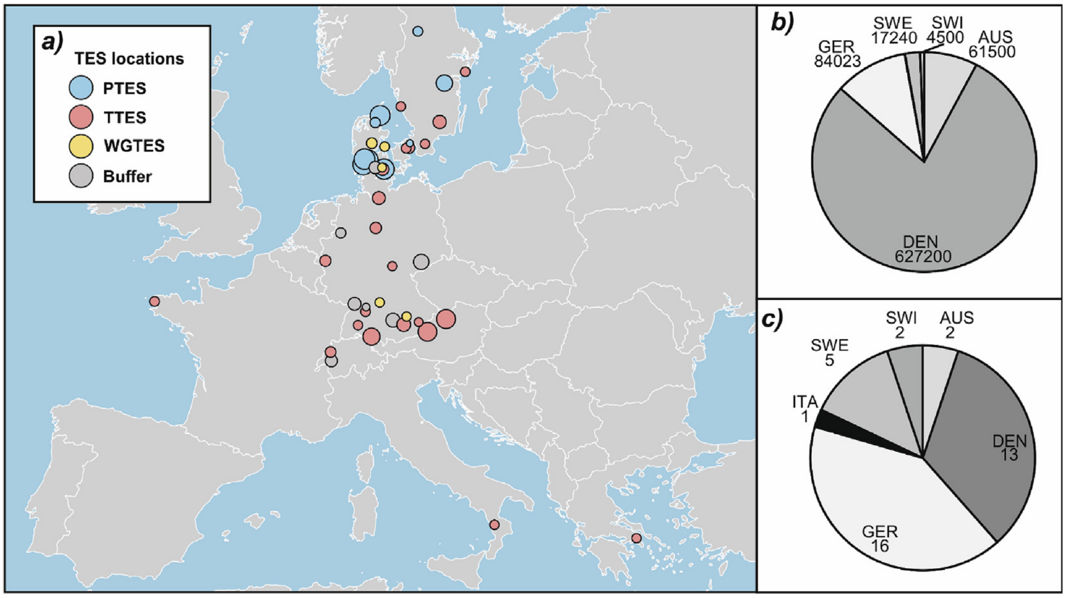

Fig. 6. a) Map showing the locations of the different seasonal storage types, including large buffer storages in Europe, b) country-wise installed volumes (m^3) and c) numbers.

(supplementary material). With values close to one, the outer surface tends to be smallest, but generally also the h/d ratio decreases with the filling volume of the reported case studies. This is especially the case for the Danish large scale PTES, where h/d ratios of around 1/10 are found. These values reflect that the TES forms are strongly defined by size and geometry of the original pit, where the TES was constructed. As the PTES and WGTES are preferably built in existing subsurface basins, their form is much more predefined than that of TTES. PTES and WGTES are commonly constructed as inverted truncated cones or pyramids (e.g., two German facilities: Steinfurt [112,127], and Stuttgart [26]). The TTES in Hamburg is built as a combination of an inverted truncated cone (bottom) and a cylinder, and therefore has an optimised A/V ratio [99]. A reverse configuration can be found at the storage in Hannover, where the truncated cone is located at the top and the A/V ratio is even better due to optimised dimensioning [99].

Modelling of storage performance in energy systems is often done with the commonly used software TRNSYS for large and small facilities (e.g., Refs. [128,129]). However, Ref. [58] conclude that simulations under ideal conditions usually result in underestimated heat losses, in comparison to measured values of built systems [130,131]. Ref. [132] conducted numerical simulations to find an optimal storage geometry and the best boundary conditions. Basins that have cubical, cuboidal, and vertical cylindrical geometries, as well as interconnected large pipes, were investigated. A cylindrical basin was found to be the best geometry for large facilities, providing the best approximation to a sphere. Furthermore, Ref. [132] proposed the implication of internal walls for an even better thermal stratification. This study focused exclusively on geometrical design optimisation, but the different costs for the different layouts were not examined. Thus, theoretically, a sphere would always be optimal by minimisation of conductive heat loss (and lowest A/V ratio). Due to the constructional challenges, however, a cylinder may be economically more efficient. Also in practice, cylinders represent a standard form, especially when no critical layout constraints need to be obeyed, such as revealed in Supplementary Table S–1 for many TTES and buffers.

3.2.2. Water as filling material

Water is by far the most common filling material. It is a natural media, harmless and nearly available everywhere, which is a particular advantage compared to custom-designed phase change materials and high quality gravel fillings [133]. Water is favoured because of its thermodynamic properties [11,58]. According to Ref. [10], the heat storage capacity of water is around 1.16 kWh/m^3K (4.18 MJ/m^3K) in a temperature range from 0 °C to 100 °C. This value is only around 0.69 kWh/m^3K (2.50 MJ/m^3K) for soil or 0.33 kWh/m^3K (1.20 MJ/m^3K) for a gravel bed with 45% pore space. Within a temperature range from 35 °C to 60 °C, resulting storage capacities are 15–30 kWh/m^3 for ground material, such as soil or rock, and 30–50 kWh/m^3 for gravel-water mixtures compared to 60–80 kWh/m^3 for water only [5]. This means a reduced storage capacity of 60% for soil and of 20% for gravel [48].

To avoid clogging, and because flow paths within the matrix are difficult to control, WGTES require heat exchangers which reduce efficiencies and amplify heat losses. In contrast, water can serve as storage media and heat carrier at the same time. Heat exchangers thus are avoided and the storage can be integrated into the connected heating/cooling system when the water is directly used as fluid [11]. Negative properties of water include the low operating range between melting and boiling points, corrosive effects on other storage elements, and the complication of natural convection on maintaining thermal stratification [11]. Additionally, the thermal conductivity of water (0.6 W/m K) is below that of water-saturated soil (0.6–4 W/m K) [95].

For systems with small volumes, the use of a combination of water and custom-designed phase change materials has been suggested [134]. This yields a higher storage capacity by latent heat conversion. Because such special phase change materials are relatively expensive, they are not common in seasonal storage systems; instead, it is often more economical for seasonal storages to design a larger storage volume of water. However, in several applications also the phase change from water to ice (or snow) is used [135]. Here, the working temperatures of the storage device are low, but latent heat is stored and released in addition to the release of sensible heat [4,136,137]. Ice ponds were first introduced in 1984 by Ref. [138] as a technical variant for storing thermal energy, and are further discussed by Ref. [135]. In the recent work by Ref. [139], the combination of ice and cold water storage units for cooling applications are revealed to be economically advantageous.

3.2.3. Water-gravel fillings

For WGTES, the filling consists of a solid phase and a liquid phase [114]. Soil, sand, gravel, or various mixtures of these are mostly used as fillings [11,58]. Compared to unsorted soil grains, well-sorted gravels offer a higher permeability when using direct loading systems, higher homogeneity, and a higher water content, which results in increased storage capacities. Backfilling of excavated material can be economically advantageous, since costs for disposal and purchase of gravel or soil are avoided [19]. For example, during the construction of the storage in Eggenstein it was found that the building ground consisted of well-permeable sand. Accordingly, costs were reduced by using the ground material as filling [61].

Detailed descriptions of gravel and soil fillings are given by Refs. [19,26] for the two German WGTES in Stuttgart, and by Refs. [114,140] for Chemnitz. The water-gravel mixture in Chemnitz consists of coarse gravel with an average diameter of 22.3 mm (range of 16–32 mm). With a porosity of 0.43, the mean density of the two-phase system is 1,928 kg/m^3 and the heat capacity 0.83 kWh/m^{3}K (2.98 MJ/m^{3}K). A value of 2.4 W/m K was determined as thermal conductivity [114,140], which is four times larger than the thermal conductivity of water (0.6 W/m K). WGTES have a lower heat capacity, caused by the gravel or soil components [58,121]. A comparison between WGTES and the water-filled systems (TTES, PTES) can be done by water equivalents. The gravel used in WGTES reduces the volume of water but at the same time contributes to the system with its own heat capacity. To compare the storage capacity with installations only filled with water, the resulting heat capacity is expressed as water equivalent volumes. For example, the 1,050 m^3 WGTES storage facility in Stuttgart contains 355 m^3 of water and 960 m^3 of gravel. This is equivalent to a TTES or PTES with a water volume of 725 m^3 [26]. For the other WGTES, the additional gravel material reduces the water volume by 30–50% (for example in Chemnitz from 8,000 m^3 to 5,300 m^3 [18,26,140], Table 1).

WGTES provide static advantages as they can be integrated into the subsurface as self-supporting, loadable bodies, obviating the need for structural elements like load-bearing sidewalls and complex roof constructions [111]. As a result, WGTES allow using their top surface and are preferred for areas with denser population [58]. At the WGTES in Steinfurt, the highly stress-resistance cover facilitate to use it as gardens [111,112]. In contrast, TTES need a technically more complex construction with pilings to carry the top construction (e.g. Hamburg [85,99,131]). The necessary complex thermal structure of the storage diminishes operation and maintenance performance of WGTES. It is almost impossible to carry out maintenance inside the storage or repair leaks in the waterproofing elements [58,85]. Also, it is important to note that modelling of WGTES using a multi-component system with liquid and solid phases is more complex than considering systems with water only [114].

3.3. Structural elements

As TTES are commonly built above ground, they need a structural element to carry stresses. Mostly, these are fabricated of concrete reinforced by steel to improve mechanical properties (Fig. 7a). The high-performance concrete that was used for the TTES in Hannover represents both the static and waterproofing component (due to an abated permeability) but at disproportionally high costs [18,99,141]. Simultaneously, optimised shapes and construction methods can help to increase the concrete's stability. For example, a high stress resistance was required for the top of the storage in Friedrichshafen, and it was achieved by constructing a pre-stressed shelled roof [87,100].

According to Fig. 7b, there are a few systems that only use stainless steel. This is common for large buffer storages, but also for smaller seasonal TES. Stainless steel may be advantageous because no further sealing barriers are needed. However, at the same time, the storage volume is limited due to its lower stress resistance.

As an alternative, glass fibre reinforced plastic (GRP) profiles with a thickness of 10 mm were tested at a pilot site in Ilmenau (Germany [9,97,142], Fig. 7b). The aim was to reduce costs, and to benefit from a low thermal conductivity of this material. However, limited static properties of this material restrict the maximum volume of a storage tank.

For the storages built underground (PTES and WGTES), the stability requirements for structural elements are reduced by the enclosing ground. Nevertheless, the geometry of some facilities entails the need for specific structural elements: the WGTES in Chemnitz (Germany) was built with a pile wall to stabilise the excavation hole [37,94,116]. The steeper the slope angles of a given excavation hole, the larger the storage volume. This is particularly important in areas with limited space. Further examples for non-TTES with structural elements are the PTES in Herlev (steel profiles [69]) and in Lambohov (concrete [5]).

The performance of seasonal TES does not only depend on their construction elements, but also on the surrounding (hydro-)geological conditions. Ref. [143] provide a theoretical investigation on effects of various surrounding materials, comparing density, thermal conductivity, diffusivity, and heat capacity. It is found that coarse gravel is the preferred surrounding material compared to granite and limestone. For the selected seasonal TES of this study, design parameters regarding the structural elements are illustrated in Table S–2 (supplementary material).

3.4. Thermal insulation

3.4.1. Thermal insulations of top, bottom and sidewalls

Thermal insulation at the top, bottom and sidewalls is fundamental to mitigate conductive heat loss (Fig. 8a and b). A summary for the thermal insulation designs of selected systems can be found in supplementary Tab S-3. For instance, measurements taken at the facility in Stuttgart showed ground heat losses of 40%, because the sidewalls and bottom were not insulated [26]. Ref. [144] demonstrates that heat losses in uninsulated PTES mainly occur at the cover and the upper edges. By simulating the operation of an exemplary system, a stationary

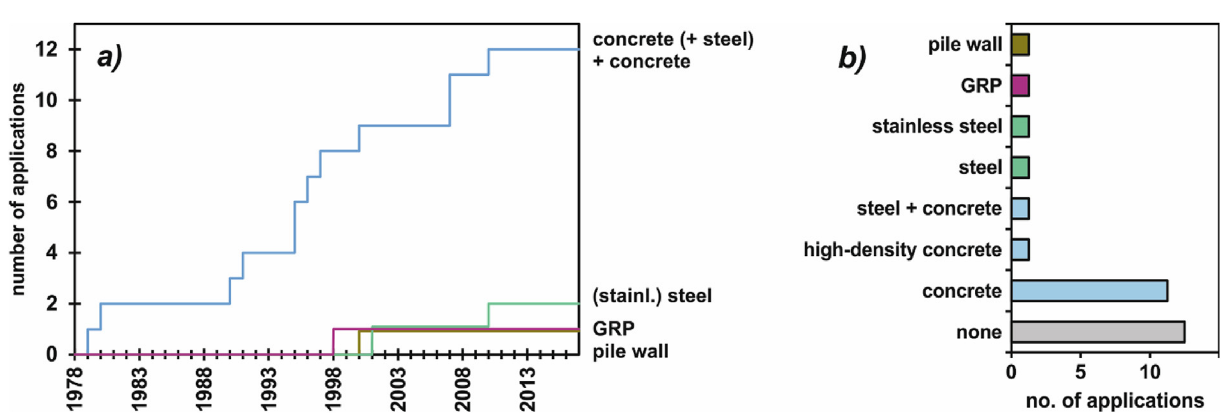

Fig. 7. Development of number of applications a) and today's application distribution b) for the different materials for structural elements. Concrete and reinforced concrete clearly predominate, while pile walls or GRP were only used in single pilot projects. (GRP: glass fibre reinforced plastic).

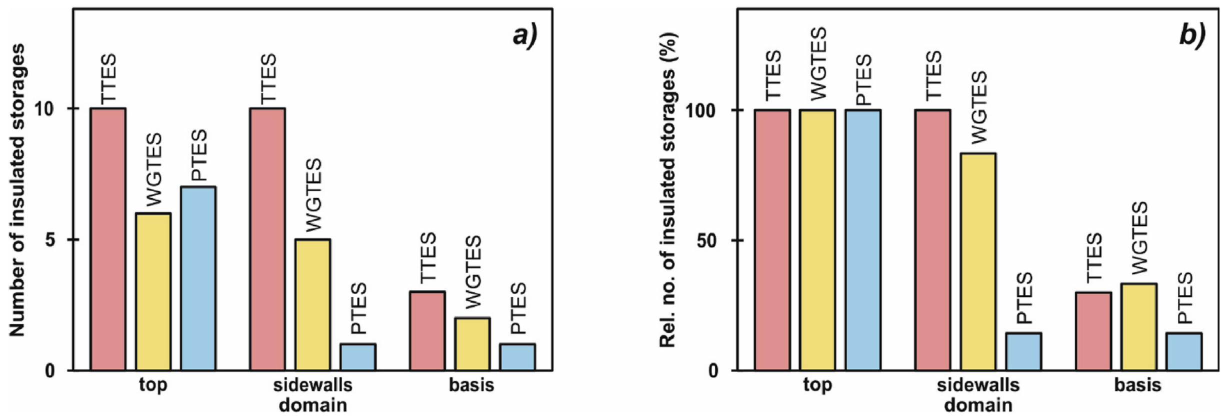

Fig. 8. Absolute a) and relative b) numbers of the insulated storage domains, differentiated according to the different storage types. While TTES always represent top and laterally insulated storages, particularly PTES lack sidewall insulations. The bottom is rarely insulated for all system types.

heat loss was observed at the bottom of the storage, while the remaining storage surface had not yet reached a steady state. In the modelled case, a warming of the ground at a distance of 1 m by 43 °C was revealed.

The top of all three storage types (TTES, PTES, WGTES) have already been insulated in the very first projects, as here the largest heat losses are expected [144]. The early facilities in Hamburg (1996) and Rottweil (Germany, 1995) used thermal insulation at the top and at the sidewalls, but due to the high expected costs no insulation was implemented at the bottom [59,87,99,113]. By using materials that are resistant to mechanical stress, like foam glass, the insulation of the bottom was realised for example at the TTES in Cosenza (Italy [90,91,112]). According to this improvement, subsequent TTES and WGTES were preferably insulated on all sides (e.g. Munich [62,113]). In contrast, PTES avoid the costs of lateral and bottom insulations, but try to compensate the elevated thermal losses by their larger storage volumes. Insulation of the storage top is nevertheless recommended for all system types [92]. As a result, currently existing PTES and some WGTES often do not have lateral thermal insulations, while these are always present in TTES (Fig. 8b). This is also because insulation is easily applicable during construction of the sidewalls of TTES.

3.4.2. Requirements for insulation materials

The different sides of a storage device are ideally equipped with different insulation materials [58,113]. A high mechanical resistance is especially required for the bottom and sidewalls. As a consequence of the higher density of gravel, requirements on resistance to the mechanical stress caused by the weight of the storage material are highest for WGTES. Among other requirements for material properties are uniform and continuous application of insulation, durability, insensitivity to thermal stress or external natural influences, and good drying abilities. For example, Ref. [31] recommend a high temperature resistance of up to 100 °C in the short term and 90 °C in the long term, ageing and pressure resistance, as well as resistance to hydrolysis. In addition, Ref. [31] tested various materials and demonstrated that even with new materials (e.g. foam glass) the thermal conductivity increases by 30% on average when the temperature is raised by 20 °C. This emphasises the need for uniform material behaviour. Not only are moisture problems reported in the old storage systems from Denmark (Herlev, Ottrupgaard [28,31,47,69]), but from newer systems as well. In Steinfurt, moisture permeation in the insulation (expanded glass granulate) occurred when the drainage system failed [7]. To solve this problem, the expanded glass granulate had to be dried [113]. Measurements revealed that it took more than one year before the insulation material regained its initial value [7].

3.4.3. Materials for thermal insulation

Conventional insulation materials include mineral fibre, extruded polystyrene foam (XPS), expanded polystyrene foam (EPS), polyethylene foam (PE), and polyurethane/polyisocyanurate (PUR/PIR) foam. Fig. 9 demonstrates that these represent over 50% of the materials used for the sidewalls and top. According to Ref. [85], PUR/PIR foams are useful for both sidewalls and top insulations, whereas mineral fibres are only utilised at the top of the storage. Further, mineral fibres were consistently used with TTES. Due to insufficient stress resistance, such conventional materials however are not considered for bottom insulation.

A main disadvantage of conventional insulating materials is their

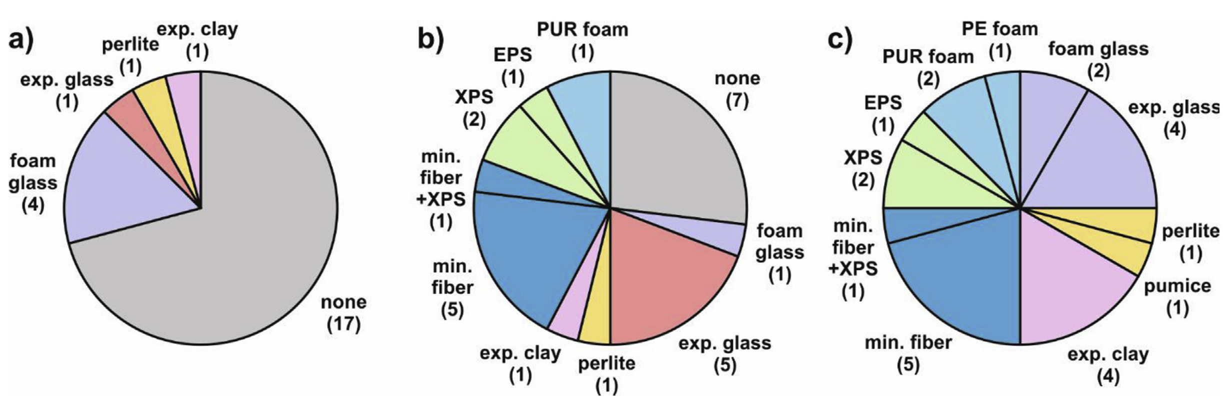

Fig. 9. Number of materials used for a) bottom, b) sidewall, and c) top insulation. Foam glass is primarily applied at the bottom, whereas the sidewalls are insulated mainly with conventional mineral wool and expanded glass. The largest variability is found in the top insulations, where natural, conventional, and recycling materials are used.

non-uniform thermal behaviour [109]. For mineral fibre, thermal conductivity significantly declines at 40 °C–90 °C [113]. However, if water infiltrates the insulating layer in the case of leakage, the thermal conductivity strongly increases [31,113]. Ref. [99] measured growing heat losses caused by moisture permeation into the insulation from the outside, which was accelerated by a high groundwater level at the storages in Hamburg and Steinfurt. To avoid this, Ref. [113] recommends costly wrapping of XPS or PUR sheets into waterproofing membranes. As an example, in Ottrupgaard, PUR foam was applied in sandwich elements to avoid ingress of moisture [47,145].

Natural materials used as thermal insulators include pumice (e.g. Stuttgart [26]), expanded perlite (e.g. Mühldorf, Germany [107]), and expanded clay (e.g. Cosenza [30,90]). The first two are fine-pored volcanic materials. According to Ref. [31], expanded perlite has the best thermal properties, but is unsuitable due to its low pressure resistance. However, at Mühldorf, a special vacuum insulation technique allowed the use of expanding perlite as thermal insulator not only at the sidewalls and top but also at the bottom ([107], Figs. 9 and 10). Expanded clay has already been used in early TES, for example in Lambohov, built in 1980 [31]. Floating covers of large PTES rely on expanded clay because of its low density (e.g. Marstal [18,43,76]). Further advantages of natural materials are the favourable environmental compatibility and often low costs. Nevertheless, most of these natural materials were not used in storage systems other than those where they have been tested (Fig. 10).

A newer trend is the use of recycling materials. These include foam glass (as sheets or granulates) and expanded glass granulates, both recovered from waste glass. As shown in Fig. 10, this development starts relatively late, beginning from years 1995 (foam glass) and 1999 (expanded glass). Recycling materials have not been available for as long as conventional thermal insulators. Foam glass meanwhile represents a commonly used material for bottom insulation, while expanded glass granulate is often applied for sidewall and top insulations (Figs. 9 and 10). Aside from attractive thermal insulation properties, they show a good mechanical resistance as well [64]. Among the recycling materials, expanded glass granulate has the lowest thermal conductivity [31]. Furthermore, all recycling materials are water-resistant and can be dried easily. Accordingly, expanded glass granulate was used as a humidity-compatible material on the outside of the storage sidewalls in Hannover, which is made of concrete of critical permeability [99]. The storage in Cosenza is one of the first facilities being equipped with foam glass gravel [30,90]. At the WGTES in Steinfurt, both foam glass and expanded granulate are used [111,112]. Foam glass is installed in 0.15 m thick plates at the bottom while expanded glass granulate is installed in geotextile bags of 0.5 m thickness. Refs. [85,94] provide a detailed overview of various insulating materials. Based on a definition and prioritisation of thermal, mechanical, and other requirements, various data sheets are evaluated. As a conclusion, foam glass gravel, expanded glass granulate, and expanded clays are considered particularly suitable for insulation.

3.4.4. Installation techniques of thermal insulations

According to Ref. [31], appropriate configurations and constructions of thermal insulation layers are challenging in terms of building physics and thermodynamics. This is because both heat conduction and vapour diffusion from the inside to the outside and water ingress from the outside to the inside must be avoided at the same time. Materials for thermal insulation are available as plates or as bulk material [85]. Plates do not require the installation of complex frames or textile bags in order to keep the insulating material fixed [85,109]. One disadvantage, however, is that plates always need additional waterproofing. Consequently, for simple installations, bulk materials are preferred as they can be directly filled into prefabricated geotextile bags [112], achieving water tightness and thermal insulation in a single work step. A 25 m^3 body of thermal insulation can thus be built in 30 min [111]. Vacuum evacuation improves stability through compaction and by negative pressure. At the same time, the material is protected against humidity. Aside from this, long-term monitoring via vacuum control is feasible [61] and floating top insulations can be constructed (e.g. at the PTES in Jülich, Germany [74], and Ottrupgaard [47,72]). In all cases, thermal bridges have to be avoided through the proper installation of connecting pipes.

Since the temperature distribution within the storage (and consequently also the heat loss) is not uniform, but it increases from the base to the top, it is recommended to raise the thickness of lateral insulation accordingly. In Hannover, the insulation thickness of the sidewalls rises from 0.3 m at the bottom to a maximum of 0.7 m at the top [99]. Due to the reduced insulation thickness at the storage bottom, a further advantage of this method is that costs can be reduced without efficiency losses, as reported for the TTES in Munich [113].

Both internal and external insulation of the mantle are possible for TTES. External insulations cause higher thermal stresses in the concrete and reduce long-term stability [31]. Nevertheless, this technique is used in Hamburg by employing pressure-resistant mineral wool [99,146] and in Munich, where expanded glass granulate is inserted in a membrane formwork between the structural element and the drainage layer [38].

3.5. Waterproofing

3.5.1. Materials for waterproofing

Leakages are a major issue of water-based storage systems. They can be caused by damage during construction, or they can occur later due to material fatigue. Accordingly, there are many methods and materials available to avoid both the loss and infiltration of water and moisture.

Materials for TES waterproofing can be adapted from a variety of other application fields. Investigations by Ref. [85] cover conventional materials for landfill, dam, canal, pond, roof, and tunnel construction. Plastic liners, such as ethylene propylene diene monomer (EPDM), high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC), are common in those areas and have also been used in seasonal TES ([77], Fig. 11a and b). Supplementary Table S–4 gives a detailed insight into designs of waterproofings for some selected seasonal TES of this study.

Linings of steel or stainless steel are used very often, but these are restricted to TTES (Fig. 11a and b). Advantages of stainless steel offer high ageing and diffusion resistances, while disadvantages include potential corrosion, more complex installation procedures, and higher costs [85]. However, by using stainless steel, the maximum storage temperature ($> > 95$ °C) is much higher than that of plastic liners (< 90 °C) [15,77]. Plastic liners are advantageous because of their

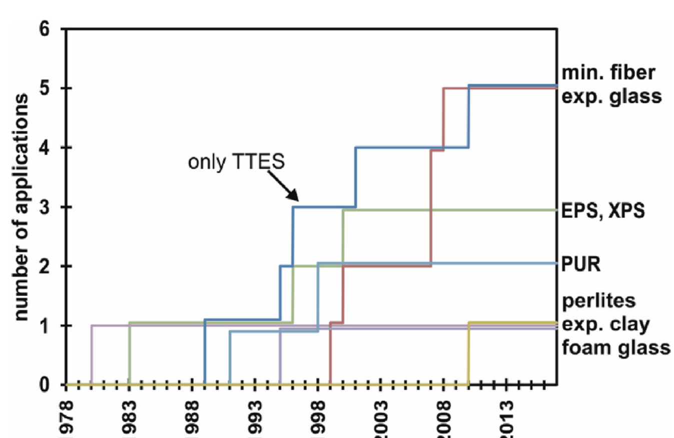

Fig. 10. Evolution of applied insulation materials used at the sidewalls for all storage types (TTES, PTES, WGTES). Mineral fibre has been used intensively since the mid-1990s, but solely for TTES. Until 1999, EPS, XPS and PUR foams gained attention. Meanwhile, expanded glass has become the preferred choice.

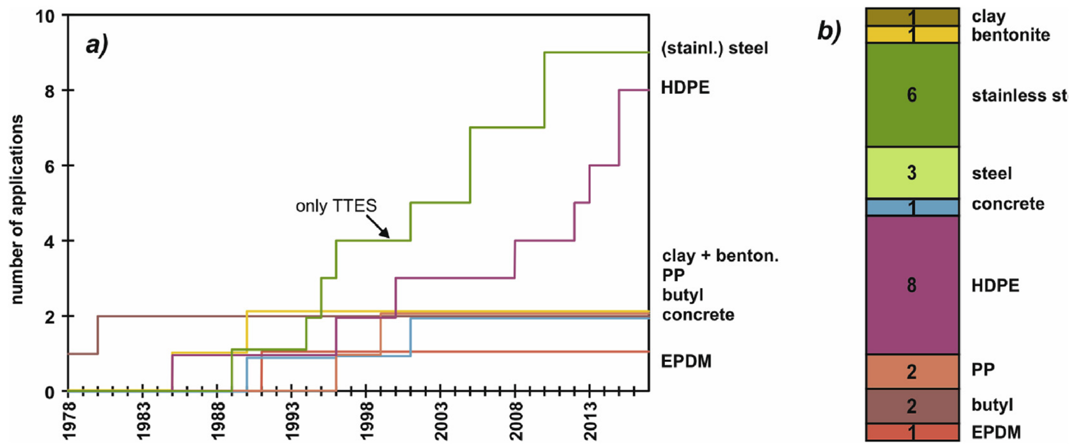

Fig. 11. a) Development of a number of applications and b) current application distribution of waterproofing materials for all storage types (TTES, PTES, WGTES).

specific costs, their packaging form as lanes, and the speed of application. HDPE clearly dominates (Fig. 11b), as it is meanwhile well proved as suitable for PTES and WGTES. HDPE is used at two of the three German WGTES storages (Stuttgart, Chemnitz) and at the WGTES in Lyngby (Denmark [69,116]). In contrast, other geomembranes (PP, butyl, EPDM) have not survived their experimental stage (Fig. 11a).

WGTES often use plastic liners to separate the storage material from the surrounding soil [11]. In addition, these liners allow for leakage control. In Steinfurt, a double-layer polypropylene (PP) liner, which can be tested by vacuum for tightness even after installation, was applied for the first time in 1999. The plastic PP was modified to ensure a better long-term temperature resistance of up to 90 °C [111]. Ref. [113] notes that costs for more temperature resistant materials such as stainless steel are significantly higher. Still, foils are generally vulnerable to leaks, as documented at the storage in Herlev for example, which was equipped with a single-layer EPDM liner at the inner side of steel sheet pilings [69]. To prevent leakage through thermally caused deformation, the PTES in Marstal was equipped with a steel grid [147].

The storage in Ottrupgaard was sealed with a 0.85 m thick clay layer at the bottom and sidewalls [47,48]. Unfortunately, no satisfactory resistance was achieved, and significant water losses occurred shortly after commissioning [69]. Ref. [68] point out that leakage is frequent for related projects with clay or bentonite sealing due to its high susceptibility, such as also observed at the storage in Hoerby (Denmark [30]). Therefore, use of this natural material also in the future is uncertain.

A high-performance waterproofed concrete with an optimised diffusion rate (quality level B85, 4 L/m^2·a) was tested in Hannover. The quality was achieved by adding micro silica, superseding stainless steel liners [99,141]. Cost reductions of 15% were expected but could not be accomplished due to elevated costs for reinforcement that was needed to limit fracture widths [18,94].

3.5.2. Vapour diffusion

Water losses of TES are not only caused by water in liquid phase, but also by vapour, which penetrates through the storage shell to the outside. This significantly reduces the efficiency of the insulation material and, as a result, also reduces the system's overall efficiency. Since the moisture transfer occurs mainly in areas with higher temperatures (at the top and the sidewalls), this is primarily where vapour diffusion barriers are used. For economic reasons, these are often neglected at the relatively cold storage bottom [112].

Tank storages do not need vapour diffusion barriers as they already contain an inner stainless steel lining [15,58]. For example, in Hamburg, a welded 1.25 mm thick stainless steel sheet serves as a completely impermeable layer [99]. In contrast, plastic liners exhibit a notable permeability [109]. Because the first German WGTES in Stuttgart and Chemnitz did not have vapour diffusion barriers, water losses through the HDPE liner were detected. In Stuttgart, 10–15 m^3 of water had to be refilled every year, corresponding to a fraction of 3% of the total water volume [26]. Due to these experiences, additional materials, predominantly metal foils, had to be applied to prevent moisture transfer between the storage and the surroundings [58,85,109]. In Steinfurt, a PP-Al-PE liner was installed [63,112]. The concept of composite foils is also common in other application areas (e.g. in the building sector). In Eggenstein, the aluminium barrier is placed within the plastic liner that was welded to chambers [61,94].

3.5.3. Drainage layers

Energy losses are often increased in buried systems if groundwater is present, as it promotes convective heat transfer in the storage surrounding and reduces the insulation material performance when penetrating the respective layer [99,131]. To avoid this, drainage layers should be installed to deflect rainwater from the surface of the storage. These are usually installed as gravel layers (e.g. Hannover [99]) or geotextile mats (e.g. Steinfurt [99]). Mats with an additional protection fleece are mainly used and recommended for PTES [31], for example in Marstal [77]. To minimise infiltration of groundwater, Ref. [111] recommend a bentonite layer on the outer side of the storage shell, but this also represents another cost factor, and leakage problems with clay layers are common.

3.6. Loading systems

Effective storage systems for heat and cold require reliable loading and unloading systems to establish and maintain an effective thermal stratification inside the facility [148]. In contrast, insufficient temperature stratification reduces storage efficiency enormously - often expressed as internal energy loss or exergy loss [58,149].Ref. [10] state that turbulent flows mix the storage fluid, destroying a stable stratification, while Ref. [150] point out that free convection due to density differences takes place at a temperature difference as low as 0.01 K.

Direct and indirect loading systems are distinguishable. Direct loading means that the loading system is in direct contact to the filling material, while indirect loading systems use heat exchanger and hydraulically separate the inner parts of the storage from the loading- and unloading circuit. WGTES usually only contain indirect loading systems [148]. One example is Steinfurt with a 7,500 m long PE coil system on six levels [15]. To test different strategies, the WGTES in Stuttgart offers three different possibilities to insert or extract heat [26]. The indirect system consists of an eight-level plastic tube heat exchange with a length of 4,853 m. A ring and a star distribution device facilitates water flowing in at upper levels and out at lower levels during charging (and vice versa during discharging).

TTES and PTES solely use direct systems. Ref. [112] explain that for larger storages direct loading systems are to be preferred due to economic reasons. Refs. [58,85] state that the direct loading of storage facilities is more energy efficient, due to lower rigidity. At the same time, Ref. [9,58] note that layer loading devices of small plants, which were, for example, studied by Ref. [151], are not easily scalable. Ref. [152] also investigate various direct loading devices and conclude that stationary systems working by fluid mechanics are of particular benefit. They have a longer lifetime and a simpler functional principle, only utilising density differences of the storage. However, over-simplified designs lead to insufficient thermal stratification. Part of such direct loading systems are radial diffusers, positioned close to the top and the bottom of the storages [152]. Their flow behaviour was investigated in detail by Refs. [148,153,154]. A third device in the middle of the storage height was used for the first time in Hannover in 2000 [7].

3.7. System integration

3.7.1. Networks

Proper integration of the TES facility into heating/cooling grids is essential [121]. For example, an in-depth review of modelling methods for district energy systems is presented by Ref. [155]. In many cases, the installation of new network systems connecting existing TES is expected to improve the cost-efficiency [9,18,58,156,157]. Well-known networks are large district heating networks, e.g. in Marstal where 1,500 households are linked to the PTES [43]. Generally, it is recommended that in urban applications at least 100 households are connected to a seasonal storage [96], but Ref. [111] estimate that at least 50 households enable economical operation. In Hamburg, only 124 households and in Friedrichshafen 570 households are supplied [7,9,158]. The required size of a new storage can also be defined based on the total area for residential space heating. This was the case for Hamburg, with a total area of 14,800 m^2 and Friedrichshafen with 39,500 m^2 [7].

The integration of a TES can be realised particularly well in new building projects. As an example, Steinfurt is a location in Germany with a seasonal storage as part of a "solar settlement" [112,127] and the TTES in Hannover is part of a “Solar City” [159]. TES can also be integrated in energy refurbishment projects. The WGTES in Eggenstein was incorporated into an existing district heating network in 2009 as part of a major modernisation project [104,120].

Centralised systems with central heating sources, and decentralised systems with independent additional heating systems in the individual houses, can be distinguished from each other, but are often used in parallel (Hamburg [99,146]). Different combinations of these systems are investigated by Ref. [160] with the result showing that combinations of short and long term storages are optimal. Also, Ref. [110] recommend such combined heat generation strategies.

To minimise energy losses, directly integrated systems are more suitable than heat exchangers [99]. If this is not possible, e.g. for hygienic reasons in the case of closed systems such as drinking water, efficient heat exchangers must be used [112].

Independent networks for source and target systems allow for either separation of different temperature levels or for creating a mixture of supply and return flows in order to keep stable temperatures [112]. Additionally, different operating strategies (direct energy use vs. storage) can be realised [99]. This technical variability yields opportunities, but it also incites a challenge. The risk of technical failure rises with system complexity, and optimal integration of seasonal TES into heating or cooling networks is often underestimated. For example, energy losses of networks can represent an unexpectedly important role [112]. Hydraulic problems in loading and unloading circuits in Eggenstein led to inefficient operation of the storage system [120].

3.7.2. Source and target systems

Generally, all heat or cold generating devices can be used as thermal energy sources. Since seasonal TES are often built within renewable energy projects with fluctuating sources, storage facilities try to maximise the proportion of renewable energy by using different systems. Refs. [31,111] propose waste heat from Combined Heat and Power (CHP) and biogas plants, which have a higher productivity in summer due to additional green waste. The concept in Marstal uses 100% renewable energy for heat supply and employs the PTES to help bridge supply gaps through utilisation of stored surplus. The system includes a wood chip boiler and a solar thermal system in combination with heat pumps [43,76]. Operation of the cogeneration plant in Hamburg was terminated due to economic reasons [99]. For feeding other TES, conventional source systems such as gas boilers (Steinfurt [112], Hamburg [99], Munich [58]), oil-fired boilers, condensing boilers, or electric flow heaters (Steinfurt [112]) are used. Post heating via an attached district heating system is employed in Hannover [99].

Seasonal TES aim at different target applications. These include space heating and cooling as well as the preparation of domestic hot water. Furthermore, stored thermal energy can be applied to support industrial processes or agricultural applications, such as the energy-efficient heating of greenhouses [161,162].

The volume or thermal capacity of the storage system must match both the demands of the targets and the supplied energy by the source systems. Storage systems that are designed too large require disproportionally high construction costs and often cannot be used in an optimal manner [27]. In Friedrichshafen, one reason for inefficient dimensioning of the storage system was as a result of a difference between the projected and constructed area of solar thermal collectors. Consequently, a discrepancy between calculated and actual supply energy was found [58,104]. In contrast, a small storage is not able to cover the energy demand, which causes additional costs when complementary systems must be installed, such as for post-heating. Ultimately, all components must be harmonised so that supply and return temperatures are matched and the storage potential is realised most efficiently.

3.7.3. Temperatures

Different temperature levels are required for different target systems, such as domestic hot water preparation, radiator heating, and underfloor heating. Clearly, low-temperature underfloor systems are most suitable for achieving best storage performances [7]. This is because a lowered temperature within the storage results in lower heat losses [118]. Problems arise with low-temperature storages if targets are connected that require a higher temperature (e.g. domestic hot water preparation or radiator heating) and post-heating is needed. Ref. [96] propose flow heaters as an effective alternative, while some decentralised systems (e.g. Marstal) use diurnal buffers to modulate feed-in temperatures [43]. In Marstal, resulting temperature differences between supply and return circuits reach 32 K during summer and 43 K during winter. Another solution is the admixture of cooler return flows to ensure a constant supply temperature level (e.g. in Hamburg [99]).

Heat pumps are, for example, installed in Stuttgart [26], in Marstal [43], in Munich [38,58], and in Eggenstein [58,120]. Heat pumps offer two positive features: besides providing higher supply temperatures, they also can be applied to reduce the return temperatures, cooling down the storage to obtain a larger temperature spread between storage inlet and outlet [58,119]. On the one hand, this maximises the available storage capacity. On the other hand, it promotes stratification and avoids excessively high temperature at the beginning of the next loading period. The latter was observed in the first storages in Friedrichshafen and Hamburg [100,113,131]. A suitable temperature range for optimal storage operation is considered to be 10 °C–80 °C, designed for the storage in Eggenstein [58,121]. Here, a heat pump is installed to achieve the low return temperature, and detailed information on methods of TES-coupled heat pump dimensioning can be found in Ref. [61].

Fluid temperatures originating from the supplying systems can show a high variability, especially with solar thermal collectors [99]. Buffers in front of the loading devices are therefore recommended in order to ensure constant temperatures, avoid turbulent flows, and prevent excessive material stress [112]. This is particularly necessary for WGTES, as these have a higher rigidity (e.g. Eggenstein [58]).

3.7.4. Storage operation

The operating procedure of a seasonal storage begins with an initial heating phase [112], while the desired quasi-stationary state is reached only after some years [7]. During this stabilisation phase, the steep lateral temperature gradients promote high energy losses to the surrounding soil [99]. For example, the storage in Hannover was put into operation in 2000 and had a planned start-up phase until 2005 [7].

For the evaluation of storage efficiency, the degree of utilisation is expressed as the quotient of stored and withdrawn energy (due to internal and external energy losses). For well insulated storages, values above 90% are considered feasible [58], but currently thermal loss still accounts for up to 50% of the storage capacity.

Due to the different energy source and target systems, appropriate measurement and control systems are necessary to promptly detect malfunctions early [99]. The suitable position for control and automation in centralised networks are the heating stations [99,112]. For instance, pilot storage plants are often equipped with a sophisticated measuring grid. In Stuttgart, for example, 415 thermal sensors and nine heat flow meters were installed [26]. In Chemnitz, 20 internal and 10 external temperatures are monitored [114,117]. On the one hand, sampling of the water inside the storage system has to be carried out in order to detect corrosion at an early stage. In Stuttgart, sampling is possible at two locations within the storage [26]. On the other hand, monitoring groundwater quality around the storage is most important for storages with (potentially) greater water losses. The storage in Hannover is thus accompanied by an extensive hydrochemical measurement program [99].

4. Storage generations and remaining issues

The most important innovations during past TES development are shown as a multi-generational evolution in Fig. 12 [37,49,86,111]. While pilot projects first proved the basic feasibility of seasonal TES, new waterproofing and thermal insulation materials have already been applied in the second generation. Efficiencies were thus increased (e.g. through optimised loading and unloading systems) and the first problems (especially leakages) were solved at the same time. In the third generation, priority shifted to cost reductions, for instance by using prefabricated elements for thermal insulations or structural elements of TTES. The new insulation techniques and especially bottom thermal insulation improved the efficiencies, while composite foils with vapour diffusion layers and testable waterproofing techniques further reduced water losses. Today, at the fourth generation level, most attention focuses on effective storage integration and operation in larger networks. This is complemented by tuning of temperature levels and combining different energy sources.

Nevertheless, a number of unresolved critical issues remain which require further attention. In Fig. 12, they are attributed to the next, fifth generation. Technically, improvements and new developments of suitable materials are needed. Achieving long-term robustness is a widespread challenge of existing sites, e.g. due to structural fatigue of waterproofings. TES need to keep energy losses at a minimum over a lifetime of several decades, not only for the sake of storage efficiency, but also to minimise environmental risks. For instance, Ref. [99] measured a warming from 8 °C to 30 °C at 4 m below surface next to the storage in Hannover. Generally, such significant ground heating is rarely detected, and this is supported by simulations [144]. However, in practice, suitable monitoring and control systems are required to save the ambient ground and groundwater environment [163].

Regarding TES operation, the vast opportunities to integrate new and diverse energy sources are still not exploited. Most TES rely on solar energy, but smart integration in heating and cooling networks may also facilitate industrial excess energy, geothermal energy, and waste heat from office buildings and data centres. Aside from this, the optimal use of TES requires attuned control engineering. In many cases, for example, the return temperatures are too high, and in others the achieved thermal stratification is suboptimal. For solar-based systems, the solar fraction can be increased by one percent if the return temperature is reduced by only one degree [7]. Finally, a future approach for more flexibility is the consideration of combined storage systems that represent multi-storage solutions of different sizes and different temperature levels. Such solutions offer not only more flexibility, but also can be upgraded more easily in case of network expansion or

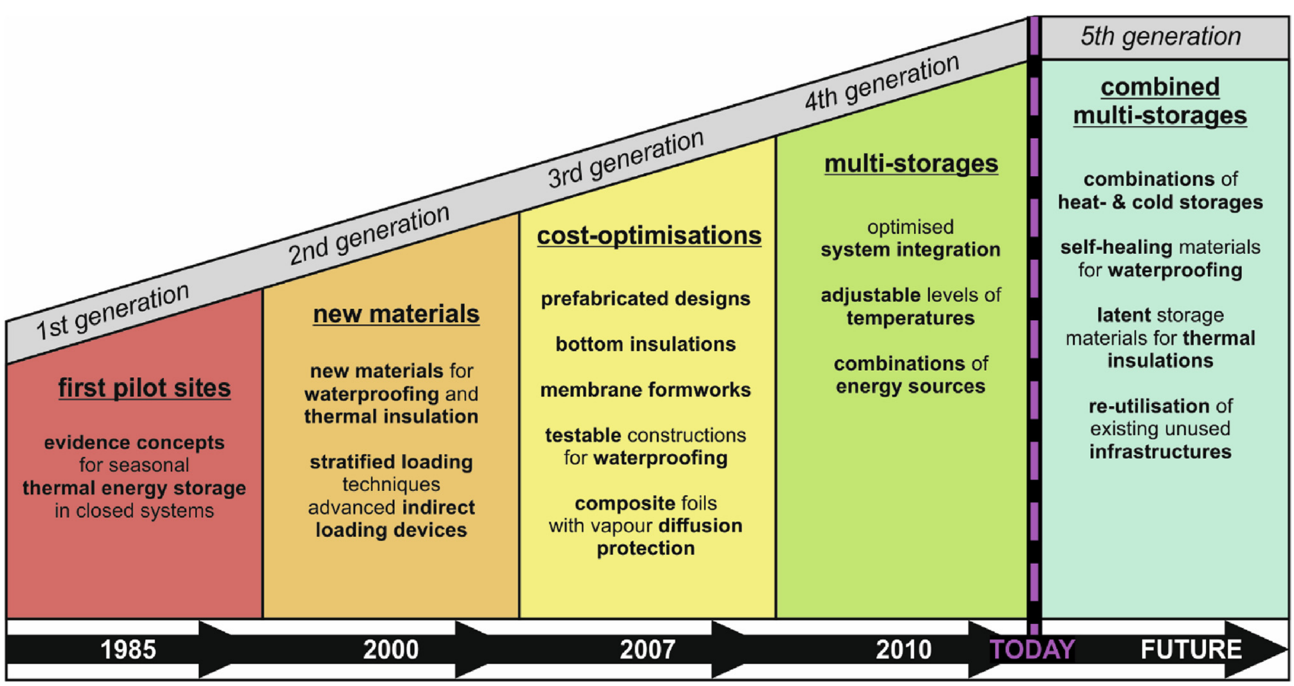

Fig. 12. Generations of seasonal storage systems with the most important inventions in the different domains.

innovative materials. Such modular implementation of TES can also reduce high initial costs of construction, which are often decisive for realisation of a project.

5. Conclusions

Seasonal storage of thermal energy is still in its early stage. This is surprising, considering its elementary role in modern heating networks that rely on multiple, often fluctuating heat sources, and that are based on smart modulation of temperatures. This study discovers the roots of the historical evolution of closed seasonal thermal energy storages in the early 1960s. After only a short time, theoretical ideas were transformed into applied pilot projects within the framework of extensive research projects. As shown, the main focus of research activities was mainly concentrated in Europe, backed up by international cooperation and activities in other countries. Recently, since the beginning of the 2010s, the installed closed thermal energy storage (TES) volumes show an exponential increase, which displays the recent transition from pilot-plants to well-functioning large-scale applications. Geospatial analysis shows that research activities in the different European countries are reflected in the present geographical distribution of seasonal storage systems. Germany, Denmark, and Sweden clearly dominate both in terms of installed volume and the number of TES built.

On a technical level, the three most attractive concepts in the field of water-based closed seasonal TES are Pit Thermal Energy Storages (PTES), Tank Thermal Energy Storages (TTES) and Water-Gravel Thermal Energy Storages (WGTES). PTES are water-filled sealed pits while TTES are enclosed basin structures. In contrast, WGTES are commonly filled with a mixture of gravel and water, allowing static loads to be placed on their top surfaces. In addition to their application as seasonal storage tanks, large-volume short-term buffer storage tanks also gained importance by growing integration into district heating networks.

Intensive research activities in the different European countries are reflected in the present geographical distribution of seasonal storage systems. Germany, Denmark, and Sweden clearly dominate both in terms of installed volume and the number of TES built. We identified 39 systems in Europe, comprising 31 seasonal TES and eight large buffer storages. The total storage volume is about 797,000 m^3, with a proportion of 87% (697,220 m^3) total TES volume. Assuming an optimal but still realistic temperature spread of 70 K for all facilities, the present TES would result in an available storage capacity of 56,600 MWh. Interestingly, TTES is the most common technical implementation, while PTES represent the largest volume. This is due to the relatively simple design of PTES without structural elements, allowing cost savings while simultaneously expanding the volume. WGTES are more complex, and are therefore more dependent on site conditions. They also entail higher technological risks.

Moreover, developments within individual system components of seasonal TES were examined, showing a steady progress. This includes advancements in the storage fillings (especially important for WGTES), thermal insulations and waterproofings, as well as in structural elements (mainly for TTES). However, deficiencies were identified in each section, which still impede global market maturity.

Ultimately, every TES case study can be assigned to four generations. Early systems of the first generation served as evidence concepts. Following this, the progress described in the individual sections lead to achievements within further TES generations. These refer to material improvements (second generation), new methods for cost reductions (third generation), and flexibilisation strategies (fourth generation). Pending enhancements and advancements are summarised in a pending fifth generation. During this next generation, innovations may achieve further economisation while simultaneously increasing the efficiency of closed seasonal thermal energy storage systems.

Declarations of interest

None.

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Appendix A. Supplementary data

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