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Description:	This fact sheet provides information on construction concepts, costs and design guidelines for large-scale or seasonal thermal energy storages.
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Why storage?

When heat from solar collector fields is integrated into a district heating network thermal energy storage is necessary. The main reason is that the storage of thermal energy enables to cope with the deviating solar heat production during the course of one day, several days or even of a year. So the surplus heat supply during high solar irradiation can be stored for heat demand phases with low solar fraction e.g. during the night or winter time. This increases the solar contribution to the system. At the same time the thermal energy storage helps to balance the demand of varying heat capacity rates.

Furthermore the storage of thermal energy decouples the supply of electricity from the supply of heat. This is of importance when e.g. CHP plants are integrated into district heating networks.

Storage categories

There are three applications of thermal energy storage:

a) Buffer storage for short term energy storage

b) Large scale thermal energy storage (1,000 - 50,000 m³) for long term / seasonal thermal energy storage

c) Large scale thermal energy storage for multiple usage (e.g. solar heat and waste heat)

Application a) is state of the art. Consequently this fact sheet deals with large scale thermal energy storages of application b) and c) (see figure 7.2.1). Of special interest is the sub-function within a district heating network with large scale solar thermal collector fields or replaceable thermal energy sources (e.g. surplus heat or waste heat from CHP plants in biogas and waste incineration).

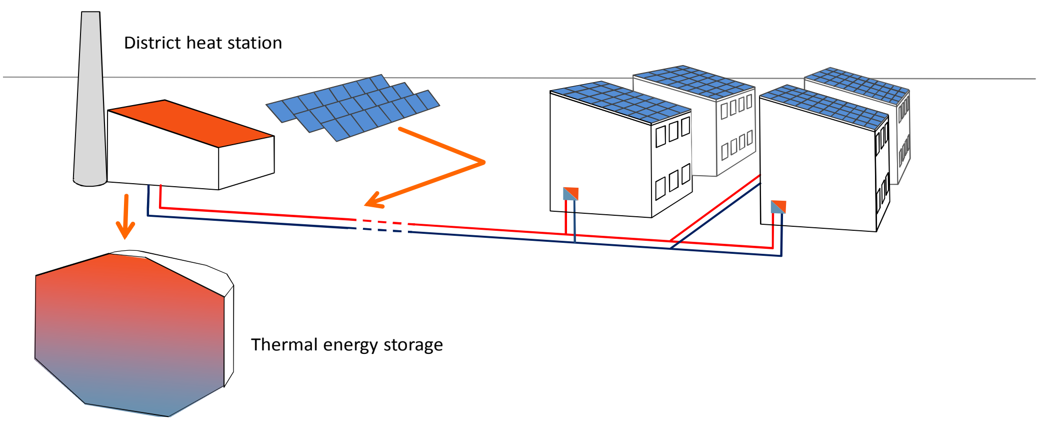


Fig. 7.2.1. Seasonal thermal energy storage within a district heating network. (Source: Solites)

Construction concepts for large-scale or seasonal thermal energy storages

Four main types of large-scale or seasonal thermal energy storages are used worldwide. The four storage concepts shown in figure 7.2.2 include tank and pit thermal energy storage (TTES and PTES), borehole thermal energy storage (BTES) and aquifer thermal energy storage (ATES).

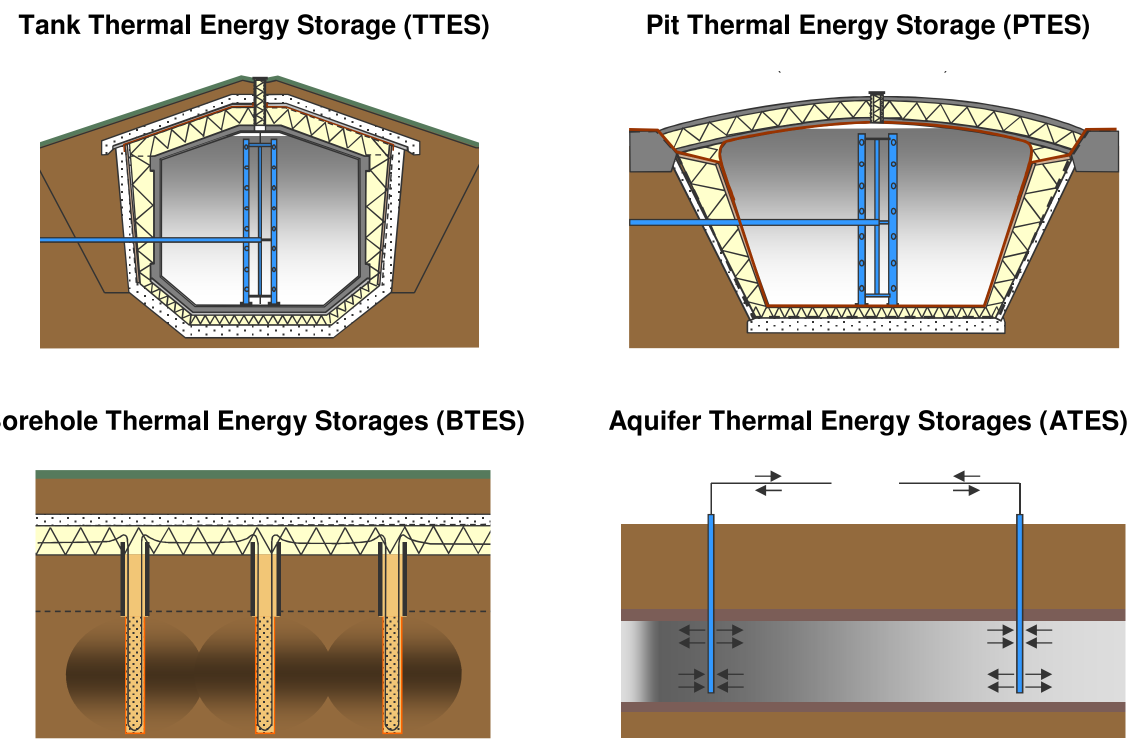


Fig. 7.2.2. Construction concepts for large-scale or seasonal thermal energy storages. (Source: Solites)

New advanced storage techniques are phase change materials (PCM), thermo chemical storages and sorption storages. These techniques are not yet ready for the use in seasonal thermal energy storage applications. For more details see [1].

Table 7.2.1 shows a comparison of the in figure 7.2.2 mentioned storage concepts regarding heat capacity and geological requirements. Because of the lower specific heat capacities of a gravel-water mixture and different underground materials storage volumes have to be significantly higher compared to a water storage to be able to store the same amount of heat at the same temperature difference.

Tab. 7.2.1. Comparison of storage concepts regarding heat capacity and geological requirements (source: Solites)

TTES	PTES		BTES	ATES
storage medium				
water	water*	gravel-water*	soil / rock	sand-water
heat capacity in kWh/m³				
60 - 80	60 - 80	30 - 50	15 - 30	30 - 40
storage volume for 1 m³ water equivalent				
1 m³	1 m³	1.3 - 2 m³	3 - 5 m³	2 - 3 m³
geological requirements				
- stable ground conditions - preferably no groundwater - 5 – 15 m deep	- stable ground conditions - preferably no groundwater - 5 – 15 m deep		- drillable ground - groundwater favourable - high heat capacity - high thermal conductivity - low hydraulic conductivity ($k_f < 10^{-10}$ m/s) - natural ground-water flow < 1 m/a - 30 - 100 m deep	- natural aquifer layer with high hydraulic conductivity ($k_f > 10^{-5}$ m/s) - confining layers on top and below - no or low natural groundwater flow - suitable water chemistry at high temperatures - aquifer thickness of 20 - 50 m

*: Water is more favourable from the thermodynamic point of view. Gravel-water is often used if the storage surface is to be designed for further usage (e.g. for streets, parking lots etc).

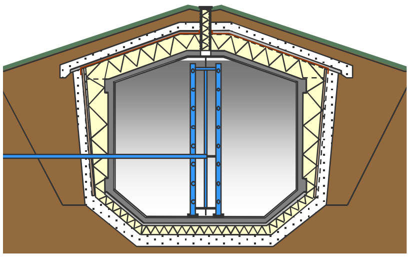
TTES and PTES

For the construction of ground buried thermal energy storages there are no standard procedures regarding wall construction, charging device, etc. available.

Due to the size and geometry and also due to the requirements in terms of leakage detection and lifetime most techniques and materials have their origin in landfill construction. However, with respect to high operation temperature materials and techniques cannot be simply transferred.

Dimensions of pilot and research tank thermal energy storages and pit thermal energy storages that have been realized over the last 25 years for solar assisted district heating systems, range from several 100 m³ up to 75,000 m³ [1, 7].

Tank Thermal Energy Storage (TTES)



Tank thermal energy storages have a structure made of concrete, of steel or of glass fibre reinforced plastic (sandwich elements). Concrete tanks are built utilizing in-situ concrete or prefabricated concrete elements. An additional liner (stainless steel) is normally mounted on the inside surface of the tank to ensure water- and steam diffusion tightness. The insulation is fitted outside the tank.

Above ground tanks (see figure 7.2.3) are state of the art. Because of the high investment cost they are in general only used as buffer tanks with volumes up to 200 m³. Yet some above ground large-scale steel storage tanks are available in Austria, Denmark and Sweden [1].

In Crailsheim a 100 m³ buffer storage was built using prefabricated concrete elements and a stainless steel liner. A further 480 m³ in-situ concrete storage serves as a buffer for a 39,000 m³ BTES. Both tanks can be operated at temperatures up to 108°C as they are operated with a pressure level of three bars [2].

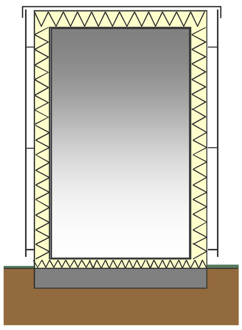
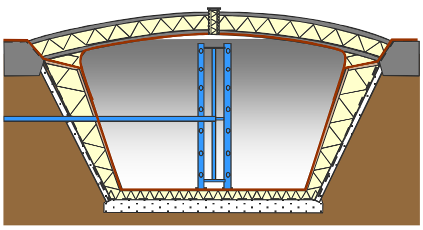


Fig. 7.2.3. Above ground tank (source: Solites)

Additional TTES facts:

- Multifunctional application area (short / long term storage)
- Special case: Retrofitted TTES in Hamburg (DE): Used as seasonal thermal energy storage of solar heat and for optimization of the connected CHP-heating network [3]
- Charging equipment has to avoid mixture of the thermal stratification
- Waterproof liner made from stainless steel panels (if no special concrete mixture is used)
- Un-pressurized operation temperature up to 95°C
- Wall construction has to consider combined heat and mass transport (steam)
- To avoid corrosion in steel tanks an automatic nitrogen application is often installed in the top of the tank to remove the oxygen in the air above the water level.

Pit Thermal Energy Storage (PTES)



Pit thermal energy storages are constructed without static constructions, by means of mounting insulation and a liner in a pit. The design of the lid depends on the storage medium and geometry, whereas in the case of gravel- or soil / sand-water thermal energy storages the lid may be constructed identical to the walls. The construction of a lid of a water PTES requires major effort and is the most expensive part of the thermal energy storage. Typically it is not supported by a construction underneath but floats on top of the water.

By definition, pit thermal energy storages are entirely buried. In large PTES the soil dug from the ground is used to create banks which make the storage somewhat higher than the ground level. The lid can be only equipped with a membrane for rain and UV protection.

In Denmark a number of large water-filled PTES were realised. The largest one is in Marstal and has a storage volume of 75,000 m³ [7].

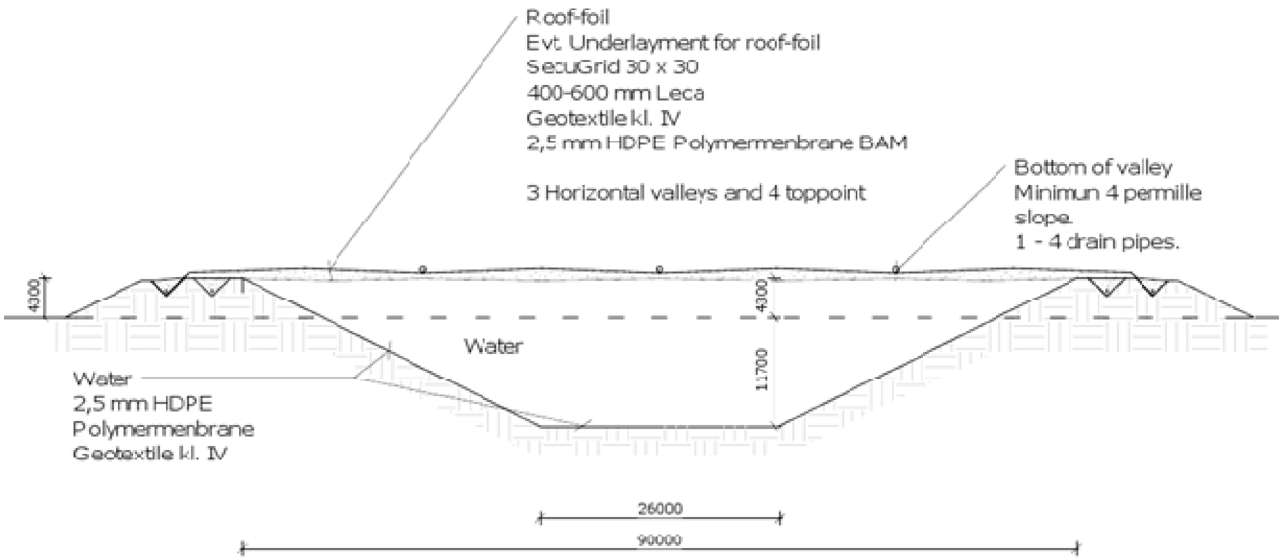


Fig. 7.2.4. Construction Cross section of the 75,000 m³ PTES in Marstal. (Source: PlanEnergi)

Tab. 7.2.2. Hot water vs. gravel water pit thermal energy storage [1]

Hot water pit thermal energy storage	**Gravel / sand / soil water pit thermal energy storage**
+ thermal capacity + operation characteristic + thermal stratification + maintenance / repair	+ low static requirements + simple cover
- sophisticated and expensive cover - low static cover load - costs for landfill of excavated soil (if applicable)	- thermal capacity - charging system - additional buffer storage (if applicable) - maintenance / repair - gravel costs

Additional PTES facts:

- Gravel fraction of 60 to 70 % (*if* gravel is used)

- Soil / sand instead of gravel can be used alternatively
- Thermal insulation of cover (optionally of side walls and bottom) is necessary (depending on storage volume)
- Charging and discharging process, indirect by plastic pipes in gravel layer or by direct water exchange
- Max. storage temperature 80 - 90°C, depending on temperature stability of liner
- Wall construction has to consider combined heat and mass transport (steam)
- Less vertical thermal stratification with gravel-water compared to pure water as storage medium

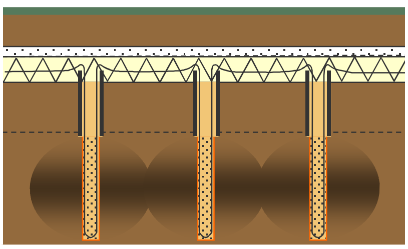
BTES and ATES

Underground thermal energy storage systems can be divided into two groups [4]:

- Systems where a technical fluid (water in most cases) is pumped through heat exchangers in the ground, also called "closed" systems (BTES)
- Systems where groundwater is pumped out of the ground and injected into the ground by the use of wells, also known as "open" systems (ATES)

An advantage of closed systems is the independency from aquifers and water chemistry, an advantage of open systems is the generally higher heat transfer capacity of a water well compared to a borehole. This makes ATES usually the cheapest alternative, if the subsurface is hydrogeologically and hydrochemically suitable.

Borehole Thermal Energy Storages (BTES)



In a BTES the underground is used as storage material. There is no exactly separated storage volume. Suitable geological formations for this kind of storage are rock or water-saturated soils without natural groundwater flow. Heat is charged or discharged by vertical borehole heat exchangers (BHE) which are installed into boreholes with a depth of typically 30 to 100 m below ground surface. BHEs can be single- or double-U-pipes or concentric pipes mostly made of synthetic materials (see figure 7.2.5).

BTES do not have a vertical but a horizontal temperature stratification from the centre to the borders. This is because the heat transfer is driven by heat conduction and not by convection. At the boundaries there is a temperature decrease as a result of the heat losses to the surroundings. The horizontal stratification in the ground is supported by connecting the supply pipes in the centre of the storage and the return pipes at the boundaries. A certain number of BHEs are hydraulically connected in series to a row and a certain number of rows are connected in parallel. During charging, the flow direction is from the centre to the boundaries of the storage to obtain high temperatures in the centre and lower ones at the boundaries of the storage. During discharging the flow direction is reversed.

At the top surface of the storage an insulation layer reduces heat losses to the ambient. Side walls and bottom are normally not insulated because of inaccessibility.

Compared to ATES systems BTES systems are easier to realise and to operate. They need less maintenance and have a high durability. Because of the closed loop system BTES systems usually require more simple procedures for authority approvals, unless high storage temperatures (approx. more than 50℃) are foreseen. Table 7.2.3 shows typical general values for BTES systems.

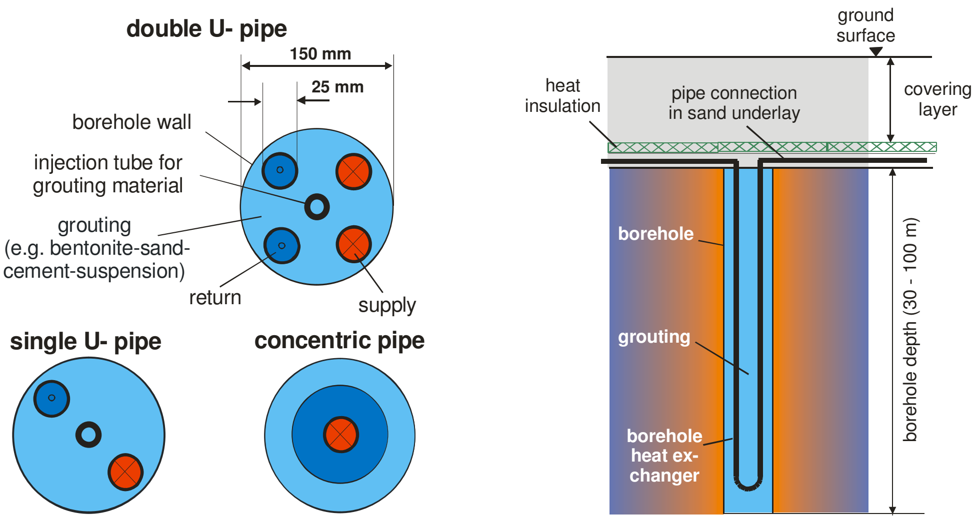


Fig.7.2.5. Common types and vertical section of borehole heat exchangers. (Source: ITW, University of Stuttgart)

Tab. 7.2.3. Typical values of BTES system for heat storage application

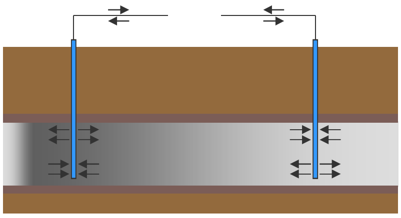
Borehole diameter	100 - 150 mm	Flow rate in U-pipes	0.5 - 1.0 m/s
Borehole depth	30 - 100 m	Average capacity per m borehole length	20 - 30 W/m
Distance between boreholes	2 - 4 m	Min. / max. inlet temperature	-5 / > +90℃
Thermal ground conductivity	2 - 4 W/(m·K)	Typical cost of BTES storage per m borehole length	50 - 80 €/m

Additional BTES facts:

- Modular design: additional boreholes can be easily connected and the storage can be expanded

- Because of low capacity rate for charging and discharging often a buffer storage is integrated into the system
- Permission from water authorities normally necessary for heat storage application

Aquifer Thermal Energy Storages (ATES)



Aquifers are below-ground widely distributed and water filled permeable sand, gravel, sandstone or limestone layers with high hydraulic conductivity. If there are impervious layers above and below and no or only low natural groundwater flow, they can be used for thermal energy storage. In this case, two wells (or groups of wells) are drilled into the aquifer layer and serve for extraction or injection of groundwater. During charging periods cold groundwater is extracted from the cold well, heated up by the heat source and injected into the warm well. In discharging-periods the flow direction is reversed: warm water is extracted from the warm well, cooled down by the heat sink and injected into the cold well. Because of the different flow directions both wells are equipped with pumps, production- and injection pipes.

Because the storage volume of an ATES cannot be thermally insulated against the surroundings heat storage at high temperatures (above approx. 50 °C) is normally only efficient for large storage volumes (more than 20,000 m³ of ground volume) with a favourable surface to volume ratio. For low temperature or cooling applications also smaller storages can be feasible.

Properties and conditions that have to be considered are:

- Stratigraphy (sequence of layers)
- Grain size distribution (mainly prime porosity aquifers)
- Structures and fracture distribution (mainly fractured aquifers)
- Aquifer depth and geometry, hydraulic boundaries included
- Storage coefficient (hydraulic storage capacity)
- Leakage factor (vertical hydraulic influence)
- Degree of consolidation (hardness)
- Thermal gradient (temperature increase with depth)
- Static head (ground water level)
- Natural ground water flow and direction of flow
- Water chemistry

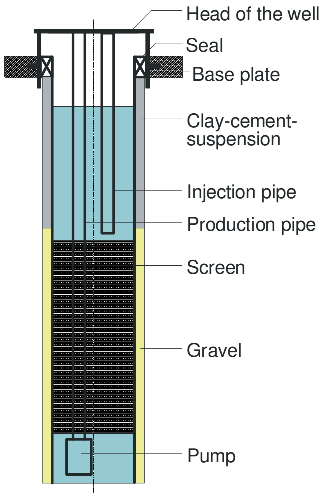


Fig.7.2.6. Layout of a well for charging and discharging. (Source: Geothermie Neubrandenburg GmbH)

Additional ATES facts:

- Aquifers near to the surface are often used for drinking water extraction
- At high charging temperatures water treatment can be necessary (chemical and biological processes can lead to deposition, corrosion and degradation in the system)
- Permission from water authorities normally necessary for heat storage application

Cost of storages

Construction cost of the four storage concepts vary significantly. However, there is not one optimum storage concept for all applications and not every storage concept can be built everywhere. Figure 7.2.7 shows a typical cost allocation for one example of each of the four storage concepts.

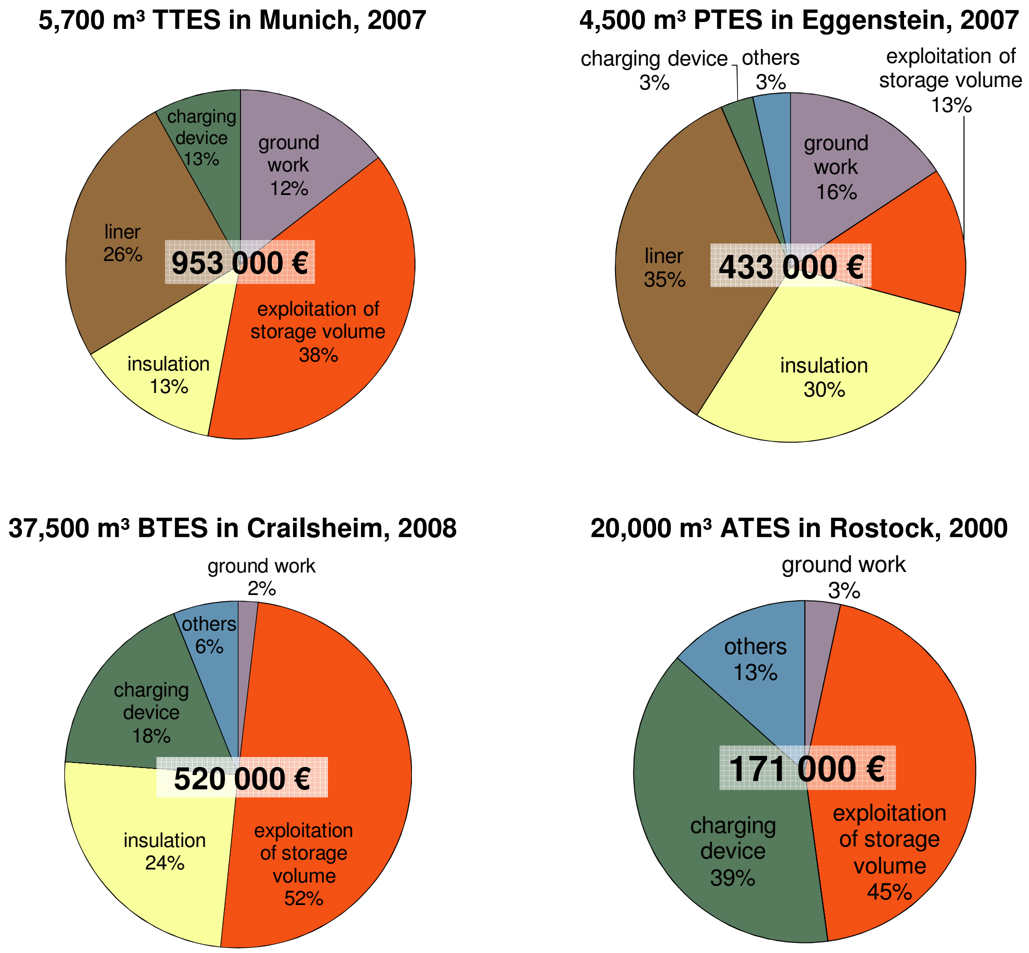


Fig. 7.2.7. Exemplary allocation of construction cost for different storage concepts (cost figures without planning and VAT). (Source: Solites)

Figure 7.2.8 presents the cost data of built pilot and demonstration plants. The listed storages are high temperature heat storages (working temperatures up to 95 °C) and are mostly integrated into central solar heating plants with seasonal storage (CSHPSS).

Figure 7.2.8 shows the cost decrease with an increasing storage volume. Appropriate volumes for seasonal heat storage are larger than 2,000 m³ water equivalent. In this case the investment costs vary between 40 and 250 €/m³. Generally, TTES are the most expensive ones. On the other hand, they have some advantages concerning the thermodynamical behaviour and they can be built almost everywhere. The lowest costs can be reached with ATES and BTES. However, they often need additional equipment for operation like buffer storages or water treatment and they have the highest requirements on the local ground conditions.

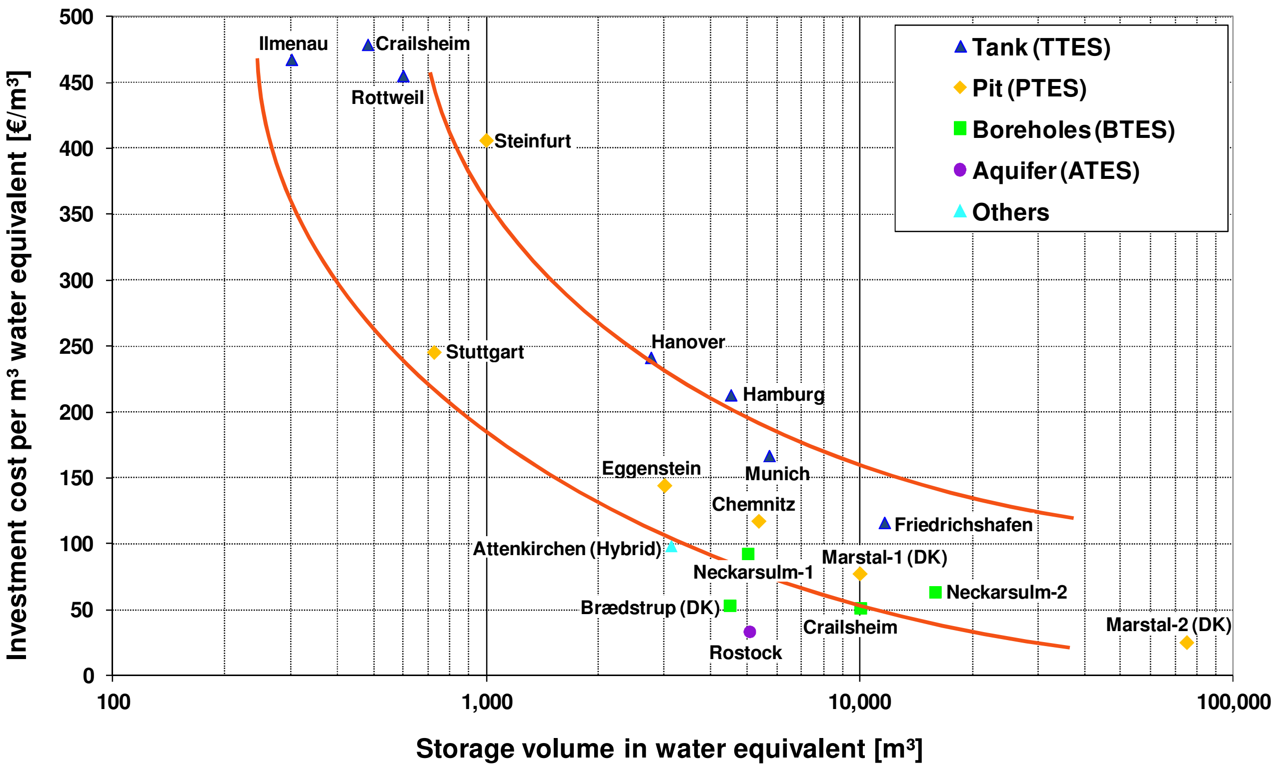


Fig. 7.2.8. Specific storage costs of demonstration plants (cost figures without VAT, storages without country code are located in Germany). (Source: Solites)

The economy of a storage system depends not only on the storage costs, but also on the thermal performance of the storage and the connected system. Therefore each system has to be examined separately. To determine the economy of a storage, the investment, maintenance and operational costs of the storage have to be related to its thermal performance.

Design guideline

For the choice of a suitable storage concept for a specific plant all relevant boundary conditions have to be taken into account: local geological situation, system integration, required size of the storage, temperature levels, power rates, no. of storage cycles per year, legal restrictions etc. Finally, decisions should be based on an economic optimisation of the different possibilities.

For all concepts a geological investigation has to be made in the pre-design phase. The highest demands with regard to this are made by ATES and BTES. The legal requirements have to be checked in the pre-design phase as well. In most countries the usage of the ground for heat storage has to be approved by the local water authorities to make sure that no interests regarding drinking water are affected. This can also become necessary if the ground surrounding a storage tank is heated up by heat losses.

After construction the storages have start-up times between two to five years, depending on the storage concept, to reach normal operating conditions. Within this time, the surrounding ground is heated up and the heat losses of the storage are higher than during long-term operation.

One crucial point in all storage applications are return temperatures from the heat distribution systems. In systems without a heat pump the return temperature defines the lowest temperature level in a system – and by this the lowest usable temperature level for discharging the storage. In many installations measured return temperatures are much higher than design values. This results directly in a strongly reduced heat capacity and a lower performance of the connected heat storage.

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