Solar DH – network hydraulics and supply points

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Subject:	Large-scale thermal energy storage systems to increase the ST share in DHC
Description:	Role of seasonal thermal energy storage systems in SDH/SDC Overview of state of the art and of selected development projects Recent studies on large-scale hot-water storage modeling and model-based feasibility analysis
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Contents

This factsheet focuses on large-scale hot water storage technologies adopted to integrate large shares of ST in DHC systems. After an overview of role and integration schemes of large storage systems in existing and future-oriented DHC, the state of the art is described and the highlights of international applications are reported, including a comparison of the different technologies in terms of strengths and weaknesses. The factsheet illustrates then more recent technologies and recent studies in deeper detail (cavern storage and investigation of atmospheric two-zone hot water storage) and presents selected recently finished or ongoing international development and implementation projects: CHESTER (H2020), SANBA, ATES Vienna, Heat Harvest, and the German subproject of HEATSTORE. The final part of the factsheet describes selected acitivites of the last years performed by the University of Innsbruck, AIT Austrian Institute of Technology, and Technische Universität Dresden to model the hydrothermal behavior of large hot water storage systems and surroundings. Model-based studies of technical and economical feasibility aim at providing a reliable support for optimizing the storage design, operation, load management, and reducing the investment risk.

The role of seasonal thermal energy storage in SDH/SDC

Thermal energy storage (TES) is largely adopted in DHC systems to bridge up the mismatch between instantaneous production and instantaneous demand. From a broad perspective, TES systems can be classified into three categories according to the lenght of the charge-discharge cycles: short-term (diurnal), mid-term, seasonal. Table 1 gives an overview of these TES categories applied in combination with solar thermal (ST) source in district heating.

Table 1. Storage categories for ST integration in DH systems (Source: klimaaktiv, Austria)

Parameter	Short-term	Mid-term	Seasonal
Cycle length	1 to max. 2 days	Ca. 2 weeks	Up to 1 year
ST usage	DHW	DHW and space heating	DHW and space heating
ST share in the yearly heat supply	10% to 20%	30% to 40 %	40% to 70 %
Solar collector area per heat user	2 to 4 m²	4 to 10 m²	10 to 40 m²
Storage volume per collector area	50 to 70 l/m²	200 to 400 l/m²	2,000 to 4,000 l/m²

A main difference between small and large TES is that the former ones typically work at the pressure of the network, which, if needed, allows hot-water temperatures above 100 °C, while large TES systems (with some exceptions) typically operate at atmospheric pressure.

Large-scale TES solutions are essential to achieve high shares of ST as well as of other volatile heat sources. Figure 1 illustrates a basic integration scheme of ST and large hot-water tank storage in Danish state-of-the-art DH systems. In more advanced concepts, large-scale storage technologies enable several additional system integration possibilities, including intersectoral energy systems, which have increasingly gained in importance in the development of next-generation energy scenarios (example in Figure 2 from the H2020 project FLEXYNETS). As stated in [1], seasonal TES technologies offer *"a buffer capacity enabling increased utilization of renewable energy sources such as solar thermal and wind turbines (when using P2H-technology to provide the heat) […] The increased buffer also allows cheap baseload units to operate at high capacity during longer periods independent of the seasonal changes in heat demand. This raises the utilization of those units and decreases the need for more expensive peak load units*."

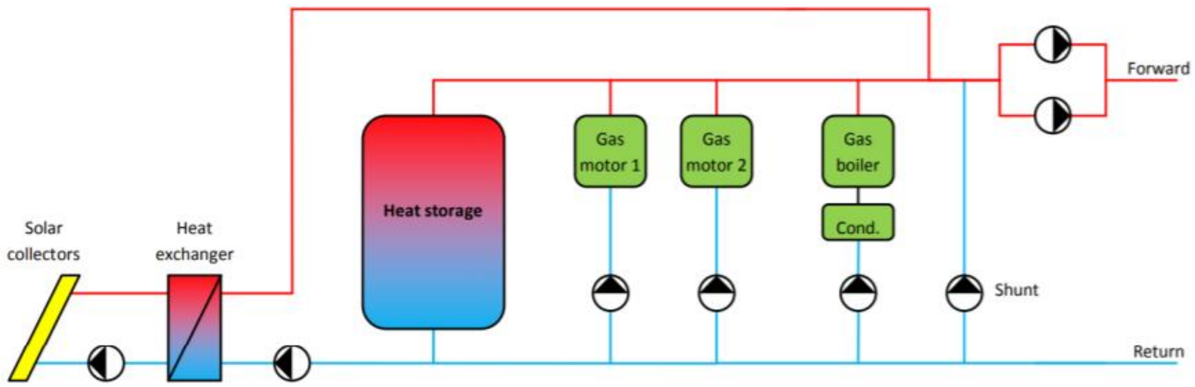

Figure 1. Basic integration scheme of ST and large water tank in a Danish state-of-the-art DH system (Source: [2])

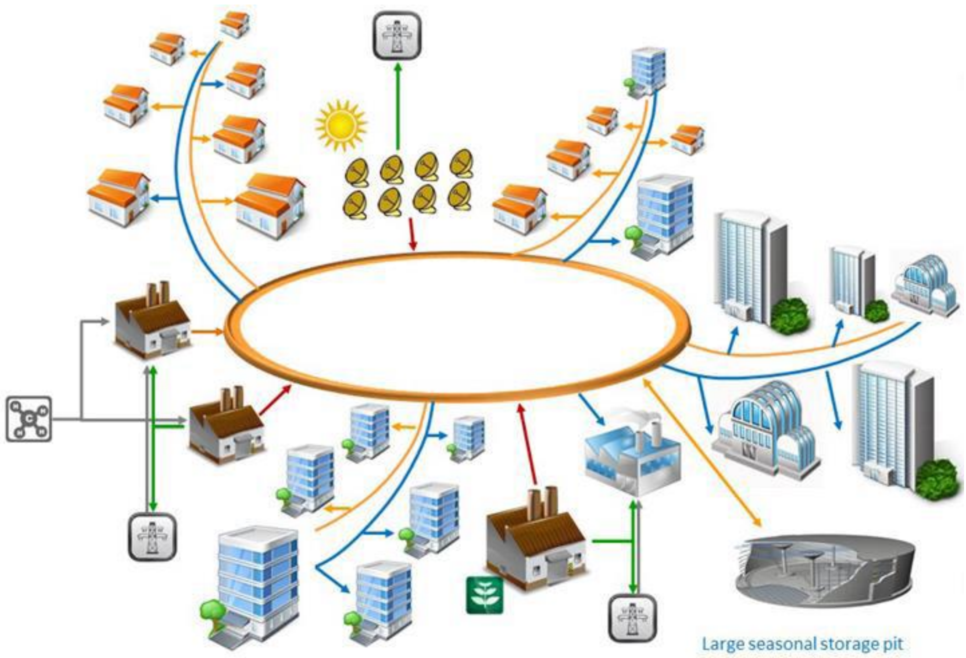

Figure 2. Example of intersectoral energy system proposed in FLEXYNETS (Source: [3])

State of the art of seasonal TES systems for SDH/SDC

Overview

Currently implemented options for seasonal TES in solar district heating (SDH) base on sensible heat. As reported in [4], they are:

- Tank storage (TTES)
- Pit storage (PTES)
- Borehole storage (BTES)
- Aquifer storage (ATES)

Figure 3 gives a schematic representation of these seasonal TES systems, while Table 2 reports their main characteristics. While TTES can be at the ground level, the other options are underground. Except BTES, the other technologies use water as storage medium. Gravel-water is another option for PTES, and in ATES the rock formation of the aquifer also concurs in the thermal storage. Water is the most cost-effective storage medium in the temperature range of DHC, as it is a relatively cheap and environmentally friendly material with a very high volumetric heat capacity and good heat transfer properties (allowing cost savings for the heat exchangers). Furthermore, water enables a temperature stratification in TTES and PTES systems.

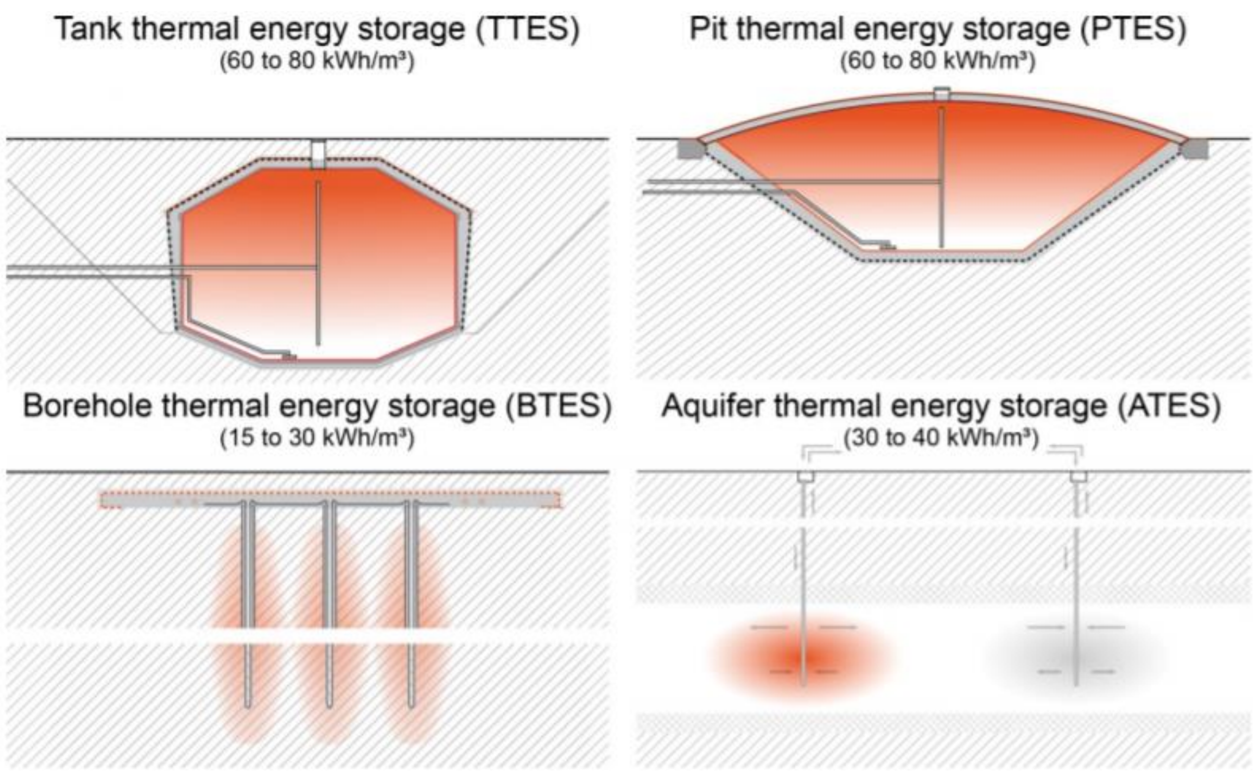

Figure 3. Overview of currently implemented large-scale TES technologies (Source: [4])

Table 2. Main characteristics of the different large-scale TES technologies (elaborated from [3] with contribution of AIT and Geological Survey of Austria)

Parameter	TTES	PTES	BTES	ATES
TRL	8-9	≤2 GWh: 7-9 >2 GWh: 3-4	8-9	T ≤ 25 °C: 7-9 T > 25 °C: 5-6
Depth	Surface or underground	Surface to 30 m	30 to 1000 m	10 to 1000 m
Technical temperature limit	>100 °C if pressurized	<100 °C	30 to 100 °C depending on depth	20 to 100 °C depending on depth
Storage medium	Water	Water or gravel / water	Formation surrounding the borehole	Aquifer (water + rock)
Storage volume per 1 m^3 water equivalent	1	1 (1.3 to 2 if gravel/water)	3 to 5	2 to 3
Specific storage capacity	60 to 80 kWh/m^3	60 to 80 kWh/m^3 (30 to 50 kWh/m^3 if gravel / water)	15 to 30 kWh/m^3	30 to 40 kWh/m^3

Data of seasonal TES systems operating in German and Danish DH networks is reported in Table 3.

Table 3. Overview of large-scale TES systems operating in German and Danish DH networks (Source: [5])

		TES type				Volume							
Country	Location	TTES	PTES	BTES	ATES	Absolut [m^3]	Water equivalent	Thermal capacity [MWh]	Absolut TES cost [€]	Specific TES cost [€/m^3.WÄ]	ST collectors aperture area [m^2]	ST share [%]	Start-up year
Germany	Attenkirchen	x		x		500 (T) + 9350 (B)	2850	165	308500	109	800		2002
Germany	Augsburg		x								2000		1998
Germany	Berlin				x					130			1999
Denmark	Braedstrup			x		19000	4500	260	240000	54	18600		2012
Germany	Chemnitz		x			8000	5360	310	629100	117	540	42	2000 & 2008
Germany	Crailsheim			x		37500	10000	580	592600	59	7500	50	2007
Denmark	Dronninglund		x			62000			1936000	31	37573	41	1989 & 2013
Germany	Eggenstein		x			4500	3000	175	433000	144	1600	35	2008
Germany	Friedrichshafen	x				12000	12000	675	1351642	117	4050		1996
Germany	Hamburg I	x				4500	4500	260	960460	213	2000		1996 - 2008
Germany	Hamburg II	x				4150	4150	240					2010
Germany	Hannover	x				2750	2750	160	664680	242	1350	39	200
Denmark	Marstal		x			75000 + 10000	10000	4350	2670000	39	33300	50	2012
Germany	München	x				5700	5700	330	953000	167	2700		2007
Germany	Neckarsulm			x		63360	21120	496	1300000	60	5670		1997 & 2001
Germany	Neubrandenburg				x								2005
Germany	Rostock				x	2000				30	980		2000
Germany	Steinfurt		x			1500				405	510	36	1998

Highlights

- 3000 ATES applications have been built worldwide until 2017, mostly in Europe:
  - 2500 ATES sites are in the Netherlands (thanks to market incentive programs), 220 in Sweden and 55 in Denmark; some other minor examples are in Great Britain, China, Japan, Germany, North America and Turkey;
  - **100 of the existing 3000 ATES are of large scale and integrated in DHC networks**;
  - In the Netherlands, ATES systems operate at temperature below 25 °C not to affect the groundwater; the depth of these systems ranges between 10 and 150 m and the TRL is 7-9.
- Thanks to the slow thermal response and the large feasible storage capacity, **BTES can be very suitable to combine with DHC systems for seasonal thermal storage**; the space requirement is very low, and the installations costs are usually not high.
- Planning and operation of seasonal storage (results from [5]):
  - The **factors determining the most appropriate TES system** are: local geological conditions, integration concept, technical requirements (storage capacity, charging/discharging power, operating temperatures), cycle frequency, regulatory framework, **cost of land** (TTES and PTES can become too expensive if the cost of land is high, and BTES or ATES can be preferable);
  - Seasonal TESs need 2 to 8 years to reach a quasi-steady-state operation;
  - The maximum storage temperature of seasonal TES integrated in German and Danish DH networks is 95 °C (85 °C is reached in the practice);
  - Heat pumps can be used to deep discharge the TES to 10 °C (in some cases the temperature does not decrease below 20 °C, therefore a margin for improvement exists);
  - **Seasonal TES coupled with heat pump are a good combination to increase the ST share**;
  - **ST shares above 50% are reached in the Danish state-of-the-art**.
- The **environmental risks** of large-scale storage, as stated in [1], are mainly linked to:
  - The **visual impact of TTES and PTES** on the surrounding landscape, which can be addressed and minimized in the planning phase (furthermore, TTES systems are typically installed next to DHC central plants, so that their installation is assessed to only have little impact);
  - **Risk of leakage** of the industrial water and contamination of aquifers, especially for PTES and BTES (very seldom for TTES);
  - **Heating of groundwater**, especially for BTES and ATES, which may result in bacterial growth.

- The Danish report [1] indicates following most important objectives of the current and next research and development regarding seasonal TES:
  - **Optimization of the operation strategies according to new boundary conditions**, including: lower temperatures and temperature differences in DHC networks, resulting in lower storage capacity per volume; use of large cold storage; operation of the storage at different temperature levels to optimize the supply temperature for heating and cooling;
  - **Improvement of modelling of seasonal TES systems** in order to enhance the planning security in the investment decisions.

Strengths and weaknesses of the existing technologies

A general limitation to the feasibility of underground seasonal TES solutions is the need for a suitable site, at least in terms of soil or groundwater conditions. More specific strenghts and weaknesses of the different TES technologies are summarized in Table 4, which relies on international experiences and include results of recent projects.

Table 4. Strengths and weaknesses of the different large-scale TES technologies (elaborated from [1])

TES type	Strengths	Weaknesses
TTES	Well-known technology Low development risk Large applicability Can in some cases operate at the network pressure Water as storage medium → high specific storage capacity Quick charging and discharging with high power Enables stratification	Space requirements High visual impact (if not underground) High investment costs N_2 or steam is necessary for corrosion protection in pressure-less tanks
PTES	Low development risk Large applicability High specific heat capacity Water as storage medium→ high specific storage capacity Quick charging and discharging with high power Enables stratification	Requires a relatively large area of land Availability of site can be crucial for feasibility Risk of difficult construction works by unfavourable climatic conditions (rainfall) Vulnerable liner and insulation materials, resulting in a risk of leakages, if not treated properly Low energy efficiency
BTES	Requiring relatively small area of land Low development risk Very limited visual impact Expandable Closed system → Limited risk of leakages (possible single-loop closure) Long lifetime	Unknown sub-surface conditions → Risk of higher investment costs Low energy efficiency and risk of heat loss due to ground water flow Slow charging and discharging → Buffer tank required Application of heat pump required in case of legal constraints for temperature
ATES	Low operating costs Small physical footprint Scalable, easy to expand High storage capacity in each borehole-pair (Danish applications reach 1.2-1.4 GWh at ΔT 10 °C and 2000 hours) High energy efficiency (when properly working)	Unknown sub-surface conditions → High investment risk Risk of thermal short circuit of ground water Several parameters influence the feasibility Risk of high investment costs if target is deep (for storage at high temperature) Open system (direct use of ground water in aquifer)

Atmospheric two-zone TTES

A TES system able to store water at temperatures above 100 °C with no need for pressurizing is two-zone tank described in detail in [6] and illustrated in Figure 4. It bases on the HEDBÄCK design, but is divided into two zones by an insulated, dome-shaped intermediate floor. Each zone has two radial diffusers for charging and discharging, and a vertical compensation pipe connects the upper and lower zone. The water level in the upper zone is free to move, so that density changes in the lower zone due to the normal storage operation are compensated by a water flow through the pipe. The compensation pipe has the additional function to prevent negative pressure or overpressure in the lower zone (e.g. due to operating errors).

The hydraulic connection of the two zones maintains the pressure of the lower zone above the atmospheric one, so that temperatures up to 130 °C are possible in existing installations and higher storage capacities are reached at the same volume than in atmospheric TES. At the same time, the constructive design of the two-zone atmospheric TES is simpler than that of a pressurized one-zone TES, since:

- To enable the same storage temperatures, a pressurized one-zone TES of the same height needs a higher pressure at the bottom;
- The two-zone TES operates as a displacement tank at atmospheric conditions;
- The wall in contact with the hottest water layer (i.e. the intermediate floor in the two-zone TES, the top in the one-zone pressurized TES) must overcome a much smaller pressure difference in the former case.

”*If the heat is to be provided at two different temperature levels, both the lower and the upper storage zone can be used actively for heat storage [...] Alternatively, the sole active operation of the lower storage zone is possible. The upper storage zone then serves as pressure load and may be used as water reservoir, for example.*” [6]

The only disadvantage of this concept is that the exchange of fluid between the two storage zones may encourage undesirable mixing effects, so that the thermal stratification can be locally negatively influenced [7]. However, according to the accurate investigation reported in [6], the compensation pipe does not affect significantly the homogeneity of the temperature field in the radial direction.

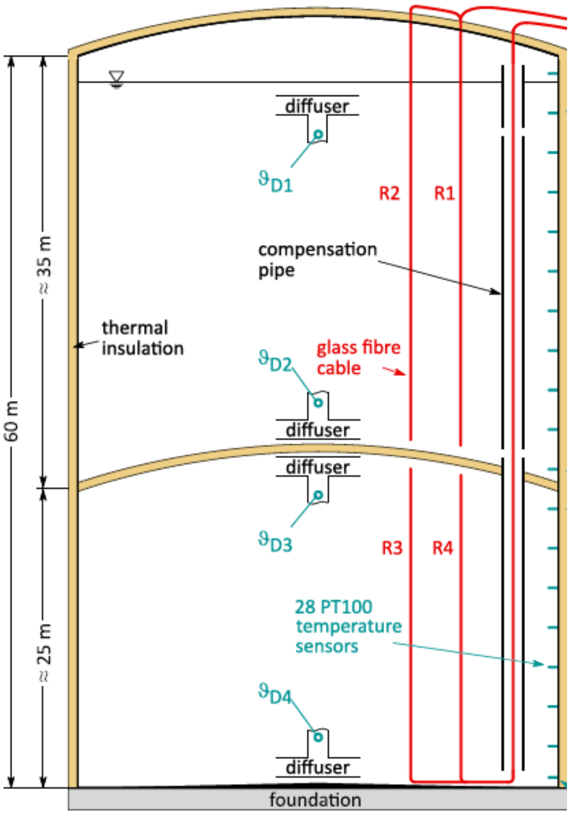

Figure 4. Atmospheric two-zone heat storage tank and measurement concept implemented by TU Dresden (Source: [6])

Cavern TES (CTES)

The first examples of CTES in the world are in Sweden:

- Avesta, built for research purpose in 1981. It is short-term storage of 15,000 m^3 integrated with an incineration plant.
- Lyckebo, constructed in 1984 and connected to the Uppsala DH network. It has the shape of a ring with a height of 30 m, a width of 18 m and a diameter of 75 m. The cavern roof is 30 m below the rock surface and is insulated. The volume is 100,000 m^3 and the walls are not insulated. It is operated at a maximum temperature of 90 °C and it can store 5500 MWh of heat between seasons. Lyckebo storage is working well except for fouling in the heat exchanger and high heat losses (about 52%).

A successful project involving CTES is the one of Mijnwater BV in Heerlen (The Netherlands), in which flooded abandoned mines are connected to a 5th-generation DHC system supplying the Parkstad Limburg [8].

Germany has been experiencing an increasingly interest in seasonal CTES realized within abandoned hard coal mines (named also MTES) in the Ruhr region [9]. However, a pilot has not been realized yet. Relevant projects are:

- GeoMTES, funded since 2014 by the German Federal Ministries BMWi, BMU and the BMBF "Initiative Energy Storage" program: scope of this project is to create a technically and economically feasible conceptual model of a MTES for the energetic reuse of the hard coal mine Prosper-Haniel in Bottrop. Here, the undisturbed rock temperatures range between 30 and 50 °C, the total mining area is 165 km^2 and the subsurface galleries have a total length of 141 km, at a maximum depth of -1159 m msl.
- MTES Bochum, with the aim to design and implement a technically and economically feasible pilot plant for a MTES for the energetic reuse of the abandoned Dannenbaum colliery. The mine has a maximum depth of -696 m msl and is flooded up to -190 m asl. The planned production and injection wells will be drilled to -693 and -228 m msl respectively. The assumed undisturbed rock temperature at the bottom is 36 °C. The pilot plant will include a CHP and a heat pump for the innovative heat supply of the new settlements on the former Opel premises (now marketed with the acronym Mark 51°7).

In Germany, while no pilot for seasonal CTES exists yet, successful projects concerning the utilization of mine water are well known (e.g. in Essen, Bochum, Saxony) [9]. Here, the thermal utilization of the mine water from existing mine drainage stations, show the highest economic efficiency, as no additional pumping costs are being generated. If, on the contrary, pumping costs must be added, it may happen that the energetic expense of the lifting is too high compared with the obtained heat. This is the case in the majority of the mines in the central and northern Ruhr area, with a water table at about −600 m msl temperatures up to 35 °C. Using the mines as a seasonal storage, in which the water temperature increases above the undisturbed values in the charging periods, is envisaged as a clear way to increase the energetic efficiency of the system and make the thermal exploitation of mine water feasible.

Potential structures for CTES include abandoned mines, tunnels or rock caverns, natural karst structures and artificially constructed caverns. These storage options are technically feasible, but applications are limited because of the high investment costs. In this context, artificial caverns have been demonstrated in full scale, constructing large underground water reservoirs, but they are still too expensive to become an alternative to other hot water storage systems. The reconstruction of existing caverns or abandoned mines could however be make CETS economically feasible.

In these systems, heat losses will be substantially to the surrounding rock mass. This is especially relevant during the first two years after charging. After this period, the cavern develops a relatively stable thermal halo with decreasing temperature away from the warm center. There will still be heat losses, but they should be less than 10% during one operational cycle under favorable conditions as dry rock is generally a poor heat conductor. It is also very relevant to maintain a stratified temperature profile in the cavern. To facilitate this, hot water must be injected at the top of the store and colder water must be extracted from the bottom.

In the design phase of large-scale CTES, it is necessary to consider several factors, including the estimation and control of the thermal, hydrological and mechanical behaviors of rock mass and storage caverns (to ensure the structure safety), the storage efficiency, the selection of suitable storage site, and the thermally induced environmental impact.

Recently, the energy company Helen Ltd has planned to build a CTES in Helsinki. It will be connected to the DH network and it will avoid, during the coldest winter days, the start-up of separate natural gas and oil-fired heating plants. It consists in three large caverns used previously to store heavy fuel oil. It has an expected volume of 260,000 m^3 and a heat power of 120 MW with an operating time of four full days.

Selected projects

CHESTER

The H2020 project CHESTER (Compressed Heat Energy Storage for Energy from Renewable sources) aims at developing a cost competitive innovative system that will allow for energy management, storage and dispatchable supply of many different renewable energy sources through the combination of electricity and heat sector. The system is expected to be site-independent (unlike pumped hydro), cyclically stable (unlike batteries), able to convert power into heat, able to convert renewable low temperature heat into power and able to store and deliver independently from each other upon request both, heat and power.

The CHEST system concept, as described first in [10] and [11], is a specific pumped TES variant based on Rankine cycles (organic or water-based) combined with a latent heat storage unit. "*In such systems, when excess electricity is available from a grid (usually from renewable sources), a thermal cycle is used to transform low temperature heat into high temperature heat, which is stored in a high temperature thermal storage during charging. During periods of high electricity demand, the thermal energy stored is used to operate a power cycle to produce electricity. By thermal energy integration, the system can also act as an energy hub, providing thermal energy for the district heating sector.*" [12]

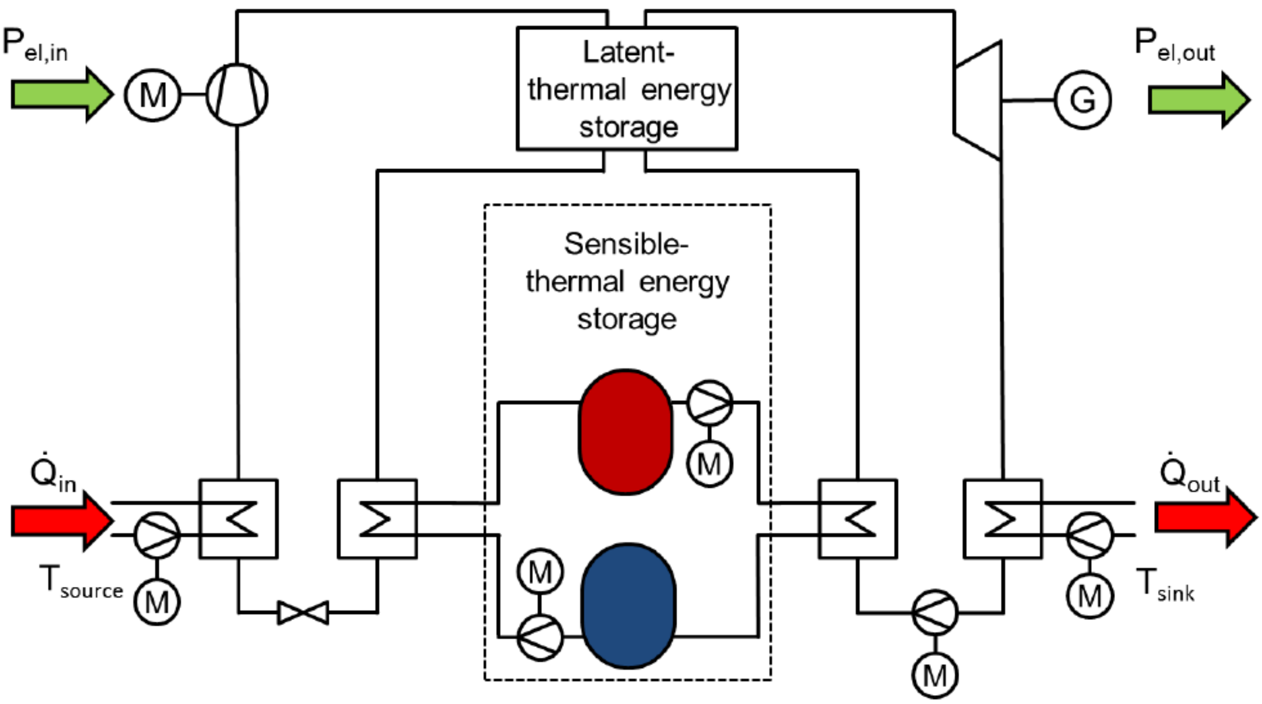

Figure 5. Basic scheme of the CHEST system (Source: [12])

Following technologies are integrated in CHESTER project (Figure 5):

- One high-temperature heat pump;
- One high-temperature TES (HT-TES);
- One Organic Rankine Cycle (ORC).

The heat pump consumes the electricity surplus from the grid to transfer heat from a low-temperature source to a high-temperature level (130-180°C), at which heat is stored in a HT-TES. The HT-TES is based on phase-changing materials and needs to follow the temperatures of the heat transfer fluids of the heat pump (condenser) and the ORC (evaporator), so to lose as little exergy as possible. When electricity is needed, the HT-TES can be discharged, working as heat source for an ORC cycle.

Although heat pump, ORC, and TES technologies already exist, ground-breaking advancements are necessary to ensure highefficiency and cost-competitiveness.

"*Connected to a smart DH system, the CHEST system uses the seasonal TES as low-temperature heat source for the HP. In addition, the waste heat of the ORC is fed back to the seasonal TES. In the power range up to about 10 MW a high technological potential is ascribed to simple ORC engines and corresponding temperature levels between 130 °C and 180 °C in the high temperature storage. The integration of the CHEST concept into an application with two different temperature levels in the low-temperature heat source or sink (here: approx. 90 °C and 40 °C) theoretically compensates for any irreversibility within the energy conversion. This is done by extracting of exergy from the seasonal TES which gives the possibility of achieving a real round-trip efficiency for the electric energy storage of 100% or higher.*" [13] The principle scheme of a CHEST system, using the TES of a DH network as source for the HP and heat sink for the ORC, is illustrated in Figure 6.

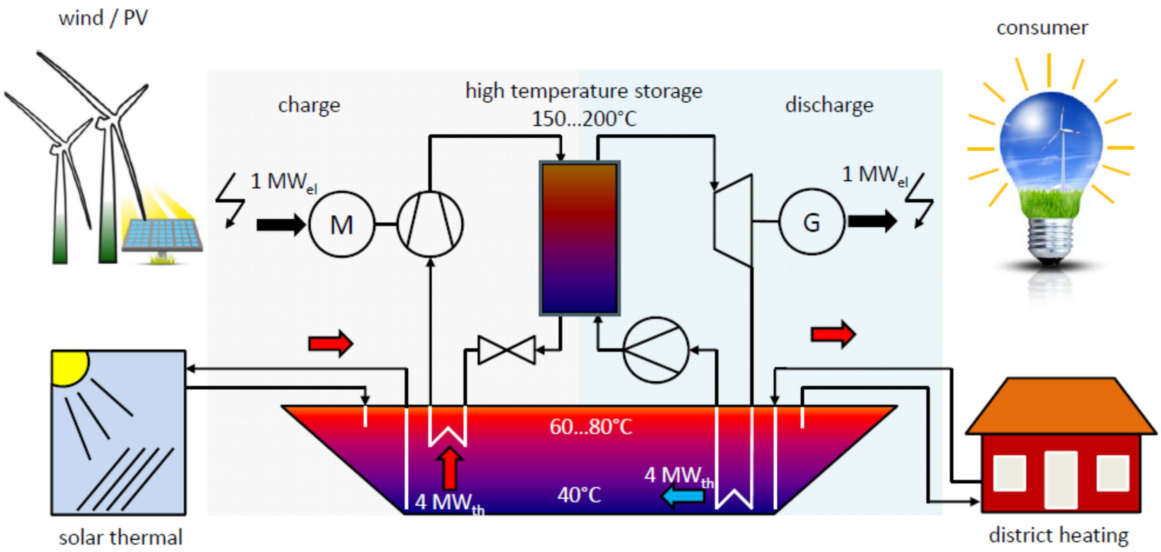

Figure 6. Principle scheme of a CHEST system integrated in DH system equipped with PTES (Source: [14])

The first experimental tests of the CHESTER concept are expected to start late 2020. The component prototypes have been developed based on the results of thermodynamics simulations and so far separately tested:

- ORC (Organic Rankine Cycle), developed by Ghent University (Belgium)
- High-temperature heat pump, developed by Tecnalia (Spain)
- High-temperature TES, which in CHESTER concept is charged by the heat pump and provides thermal energy for the ORC. "*DLR (Germany) manages the development of this component, consisting of 2 parts: a latent (LH-TES) and a sensible heat (SH-TES) thermal energy storage for an optimal adaption to the heat pump and the power cycle. As the two cycles use different working fluids, DLR developed a novel double-tube LH-TES design, which allows for a heat exchange between the two fluids as well as between each fluid and the storage material at the same time. The testing phase will provide charging and discharging characteristics as well as the limits of the operation range*." [15]

SANBA

The project SANBA (Smart Anergy Quarter Baden) is an interdisciplinary demonstration project of the Austrian program NEFI (New Energy for Industry). The scope is developing a low-temperature heating and cooling (LTHC) network for the former military camp "Martinek-Kaserne" in the City of Baden, south of Vienna, which is out of use since 2014 and for which there are plans to develop a new urban mixed-use quarter. Key elements are the use of industrial low-temperature waste heat from processes in the neighbouring NÖM dairy plant as well as the development of refurbishment and conversion concepts for the protected buildings.

The concept for the LTHC network is illustrated in Figure 7 and consists of following components:

- Heat recovery from the wastewater, cooling units and compressed air of the neighbouring NÖM dairy plant;
- Integration of locally available renewable energy sources;
- Energy storage aspects with a focus on seasonal BTES;
- The special challenge of different building standards of the old protected buildings vs. newly built buildings with different usages (living, commercial, education), and therefore different supply temperatures and demand characteristics;
- Moderate cooling via Free Cooling.

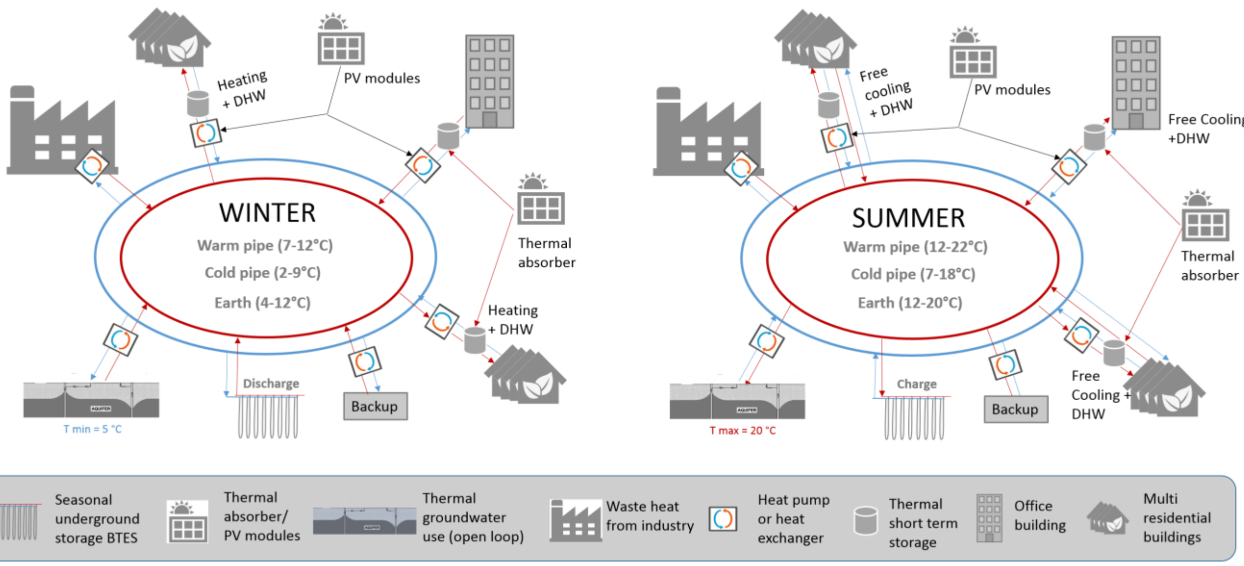

Figure 7. Concept of the low-temperature heating and cooling network in the SANBA project (SANBA consortium)

The project is currently in development and the technical and economic feasibility for three scenarios will be finished in early 2021.

ATES Vienna

ATES Vienna aims to develop high-temperature (>40 °C) and large-capacity (>10 GWh) deep ATES systems, including integration options for the Austrian district heating sector. The project will address the identification and characterization of available aquifer resources, and provide assessment tools to estimate their suitability for ATES applications. Based on this analysis, a detailed technical concept for the first pilot ATES in the Vienna area will be developed, considering the utilization of existing hydrocarbon wells and new drilled wells. The feasibility study will be completed by a holistic socio-economic and regulatory impact analysis. ATES Vienna will therefore support the development of a roadmap for the future implementation of ATES technologies in Austria in line with the National Energy and Climate Plan (NECP) 2021-2030.

Additionally to sustainable investment costs, essential to the economic feasibility of the ATES will be the possibility of sufficiently high charge and discharge rates and operating hours.

Heat Harvest

The Austrian project Heat Harvest investigates an innovative solution for ST production and integration in the urban space as well as for avoiding urban heat islands. The typical measures already implemented in several places (greening as well as green and/or water surfaces) are not always effective enough, approvable or desirable, such as in old, historic or listed buildings.

Heat Harvest proposes a simple, invisible, and seasonal solution, i.e. the "harvesting" of solar urban excess heat from building surfaces, sidewalks, roads and squares through shallow absorber ducts, which are then used in borehole heat exchanger (BHE) fields (illustrated in Figure 8) for later use as heat source for the buildings or the DH network. The project investigates and tries to predict also the thermal behavior of the subsoil in the densely built sensitive urban space with high area competition, which is a very important aspects to consider for feasibility evaluations. In fact, temperatures in urban surfaces are sometimes very high (up to 50 °C) and cannot easily be introduced into BHE fields.

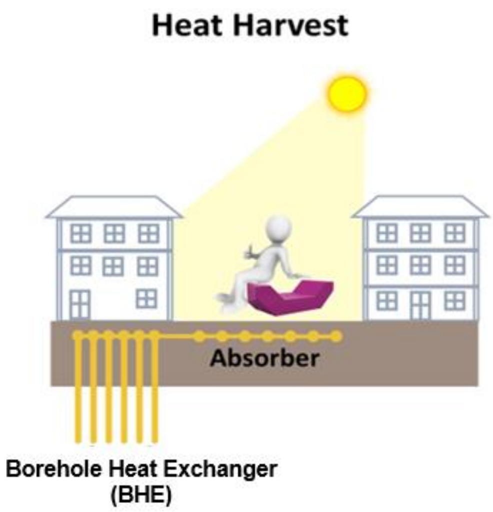

Figure 8. Vision of Heat Harvest illustrated with the "Enzis" at the Museumsquartier in Vienna (Source: AIT)

German subproject of HEATSTORE

The GEOTHERMICA and ERA-NET co-funded project HEATSTORE consists of nine national projects. Aim of the German subproject is to create a technically and fully functional seasonal mine TES pilot plant for the energetic reuse of the abandoned coal mine Markgraf II in Bochum, with the emphasis on a two year operating and monitoring phase during the project lifetime. The conceptual idea is based on storage of seasonal unutilized surplus heat during the summer from ST collectors within the mine layout and to use the stored heat during the winter for heating purposes of the institute buildings of the International Geothermal Centre (GZB).

The mine has a depth of about 63 m below the ground. The void volume is assessed with 10% approximation to be about 27.400 m^3. With a ΔT of 50 °C, the heat capacity results about 165 MWh, which resembles the yearly heat demand of the GZB compound. Hence, it is expected that the yearly GZB heat demand can be entirely met by ST energy. After the two-year pilot phase is concluded, the integration of the Markgraf II TES into the DH network of the "unique Wärme GmbH" could be tackled [9].

Modeling of seasonal TES systems

General aspects

Modeling and simulation of large TES systems is necessary for an accurate investigation of the thermo-hydraulics affecting the storage performance. In particular, simulations can help in quantifying the heat losses over a certain storage operating period and in investigating the TES behaviour and the temperature stratification, as well as the temperature field for the surroundings, so that the feasibility of an investment plan or of an integration concept as well as optimization margins for design or operation can be assessed with good reliability. Expected benefits are then a reliable support in investment decisions as well as in the identification of measures or load management strategies to improve the thermodynamic efficiency and the planning security, increase the share of renewables, and decrease the TES costs. These aspects are highly important for energy systems hosting large-scale TES technologies, since they are characterized by large investment costs and typically not neglectable risks.

However, while numerical modeling of hot water tanks has been widely investigated in the literature, "*there was little efforts made for modeling large-scale hot water tanks numerically, especially in the case of underground tanks*" [16]. Modeling tools for TES systems can be classified as follows:

- Tools for energy system simulation (ESS), such as Modelica/Dymola, TRNSYS, Matlab/Simulink;
- Building envelope heat and mass transfer tools, such as WUFI Pro and Delphin;
- Tools for computational fluid dynamics (CFD), such as ANSYS Fluent, OpenFOAM and COMSOL Multiphysics (which is also used for building envelope heat and mass transfer).

A list of advantages and disadvantages of existing models and simulation environments was set up by the University of Innsbruck and is reported in Table 5. In general, CFD models give the most detailed outcomes, but the computation efforts required for large-scale seasonal TES for (multi-)annual system simulations "*is currently not feasible and probably not in the near future. Furthermore, another drawback of CFD models is that any slight change in geometry is related with a complex numerical mesh generation. Hence, assumptions are typically made in geometry, material properties and boundary conditions for the simulation, which yields in return a significant reduction of the computational efforts producing the so-called "coarse models".*" [16]

Among the ESS tools, "*TRNSYS is the most broadly used when modeling buried water stores because of XST and ICEPIT models that can be easily coupled to buildings, heating plants and other components in a system level and also its modular nature for adding further new components. Nevertheless, there exist attempts to seek the modeling of buried tank TES in other environments*" [16], such as the dynamic model presented in [17] for underground hot-water TES of different shapes (cylinder, cone) in Matlab/Simulink.

Table 5. Overview of advantages and disadvantages of existing models and simulation environments (Source: University of Innsbruck)

Software	Approach	Advantages	Disadvantages	Publications
COMSOL	Finite element	3D, multiphysics analysis, different modules	Models from up-to-date versions are hard to open in earlier versions	Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer Techno-economic planning and construction of cost-effective large-scale hot water thermal energy storage for Renewable District heating systems Toward efficient numerical modeling and analysis of large-scale thermal energy storage for renewable district heating Numerical Analysis and Evaluation of Large-Scale Hot Water Tanks and Pits in District Heating Systems
ANSYS Fluent	Finite volume	3D, detailed heat transfer and fluid flow analysis, CFD		Comparative study of the transient natural convection in an underground water pit thermal storage
AQUA3D	Finite element	3D, groundwater flow, heat and mass transfer		Numerical scheme to simulate flow through anisotropic rocks in TOUGH2
DuMuX	Finite element, cell centered finite volume	Multi-{Phase, Component, Scale, Physics, ...} flow and transport in porous media, free and open-source simulator	C++ based	Matching Pressure Measurements and Observed CO2Arrival Times with Static and Dynamic Modelling at the Ketzin Storage site
FlowHeat	Finite element	3D, suitable for heat and fluid transfer in areas of which water head and temperature are affected by well flow	Requires another tool HST3D	-
HST3D	Finite difference	Saturated porous media; allowing for differing groundwater properties, such as fresh and salt water	Quantities for only one type of boundary condition per zone of boundary facial area can be summed.	Geothermal Response Tests with Heat Extraction and Heat Injection: Example of Application in Research and Design of Geothermal
CONFLOW	Analytical code	2D, for hydraulic and thermal processes, a thermal front tracking model;	Doesn't count for energy transport in these processes Assuming only homogeneous and isotropic layer with constant thickness Quite old fashioned	Gas evolution in eruptive conduits: combining insights from high temperature and pressure decompression experiments with steady-state flow modeling
FEHM	Control volume finite element	3D, for multiphase flow of heat and mass with air, water and CO2, methane hydrate, plus multicomponent reactive chemistry and both thermal and mechanical stress.	Quite old fashioned Complex	Model study of the thermal storage system by FEHM code

Task 55 Towards the Integration of Large SHC Systems into DHC Networks

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Solar DH – network hydraulics and supply points

Software	Approach	Advnntages	Disadvantages	Publications
TOUGH2	Integeral finite differences	3D, variably saturated porous and fractured media coupled transport of water, vapor, non-condensable gas and heat. TOUGH2 can be applied to a wider range of problems in heat and moisture transfer. For problems involving strongly heat-driven flow	Mainly for geothermal reservoirs	A fast and robust TOUGH2 module to simulate geological CO2 storage in saline aquifers
HSTWin	Finite difference	3D, viscosity and density are dependent on temperature and concentration changes	Modified version of HST3D	-
FEFLOW	Finite element	3D, able to incorporate spatially variable properties, geologic layering	Expensive (even new FEFLOW Essentials is ~$5K/license), takes longer to learn and setup	Thermal convection of viscous fluids in a faulted system: 3D benchmark for numerical codes
MODFLOW	Finite difference	3D, easy to set up and pre/post process files, industry standard, free to use and GUIs are inexpensive to run/view/process model, modular (new packages added frequently)	Currently cannot simulate complex features, such as angled faults and simulate steep hydraulic gradients such as rewetting/drying cells using the same code; have to choose either USG or NWT/SURFACT capabilities	Reduced order modeling of the Newton formulation of MODFLOW to solve unconfined groundwater flow
MT3DMS	Finite difference	3D, simulating heat transport due to the analogy between heat and mass transfer processes	Always coupled with MODFLOW	Modeling hydrology, groundwater recharge and non-point nitrate loadings in the Himalayan Upper Yamuna basin
SEAWAT	Finite difference	3D, variable-density variable-viscosity saturated groundwater flow	A coupled version of MODFLOW and MT3DMS	Heat transport and temperature distribution during managed artificial recharge with surface ponds
SHEMAT	Finite differences	3D, simulate coupled fluid, heat and reactive transport in a saturated porous medium	NOT MENTIONED	Modeling anisotropic flow and heat transport by using mimetic finite differences
VS2DH	Finite difference	2D, constant density fluid, variably saturated porous media, single phase fluid flow	NOT MENTIONED	Bank thermal storage as a sink of temperature surges in urbanized streams
Matlab	Coding	Easy to implement equations, equation-based modeling	Time intensive for detailed models	Energy analysis and modeling of a solar assisted house heating system with a heat pump and an underground energy storage tank
Matlab/Simulink	Object-oriented	Drag and drop components, Customized blocks.	Time intensive for detailed models, Algebraic loops	Store4Grid
Matlab/Simscape	Object-oriented physical modeling	Drag and drop components, Customized blocks, Thermo-hydraulic analysis.	Need to build a model and some customized components, Might also need to define a domain, No given models for storage systems, Few papers about Simscape library	NONE

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SOLAR HEATING & COOLING PROGRAMME
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Solar DH – network hydraulics and supply points

Software	Approach	Advantages	Disadvantages	Publications
Modelica/Dymola	Object-oriented modeling	Easy to adapt, Drag and drop components, Equation-based modeling, Mostly used for physical modeling of energy systems in a wide range of domains, Wide variety of published and valid libraries that are open-source and free.	No valid model for underground TES systems The model is detailed --> high computational efforts but still less than Matlab	Storage from Building Library Storage from ISE Library Storage from AixLib Library Storage configuration from AIT-UIBK
TRNSYS	Modular approach, dynamic modeling	Easy to adapt, Equation-modified, Mostly used for solar energy modeling	No valid model for underground tank TES systems	Model type 534 Model type 60f Model type 1322/1301/1302 Model type 342/type 343 Check Literature Survey.xlsx
Python	Coding	Easy to implement equations, equation-based modeling Requires some time to adapt		
Advanced System for Process Engineering ASPEN Plus	Flow-sheet simulation	Dynamic modeling of chemical processes with energy transport Integertation of mathemtical tool for economic analysis Different working fluid can be applied in a layer from the built-in library	Mainly used for techno-economic analysis where you have to adjust the system Intensively used for chemical engineering and CSP Plants for two tank TES A bit complex	Techno-economic assessment of technological improvements in thermal energy storage of concentrated solar power
Polysun	Object-oriented	Pre-design simulation tool GUI (Graphical user interface) Moslty used for building systems Detailed hydraulics modelling Time-saving simulations	Quite expensive	Optimization Design of Solar Heating System for Public Bathrooms in the Countryside
IDA ICE	Modular structure, dynamic modeling	Open-source models Interactive 3D with visualization for input as well as results Modular structure, access to model source code	(Nothing found up to now)	On the performance of LCC optimization software OPERA-MILP by comparison with building energy simulation software IDA ICE
Matlab/INSEL	Add-on to Matlab	Similar to Simulink, Simscape and Dymola (block-diagram modelling) Eady-made simulation models for a quick start Dynamic building simulation Component databases Wide variety of solar systems applications (e.g. solarthermal, PV) For engineering and for large complex energy systems Development and extension of components and libraries	In-house tool Mainly for electrical system and buildings Not widely used Might be expensive Time-consuming simulations	Energy and Economic Performance of Solar Cooling Systems World Wide

Review of the tools available in open-source Dymola/Modelica libraries (AIT)

In the dynamic simulation of DHC networks, Modelica/Dymola is a widely used tool. Therefore, the possibility to model seasonal TES systems in Modelica/Dymola is recognized to be highly beneficial. However, while from the one side Modelica/Dymola offers multiple open-source libraries allowing the simulation of several system components, it lacks from the other side of valid models for seasonal storages easy to adapt to different geometries. In fact, the available models for hot-water storage systems have following main limitations:

- They consider the typical cylindrical geometry of the storage tanks, which is suitable to model large-scale TTES but not different storages;
- Models for thermal exchange with the ground (in case of underground systems) are not implemented.

A review of the tools available in open-source libraries of Dymola/Modelica is summarized in Table 6. The review covers following libraries: IBPSA, Buildings, IDEAS, Aix, Soltermica, BuildingsSystems, ThermoCycle. Focus of Table 6 is on following aspects:

- Possibility of fluid injection/subtraction at any intermediate level (i.e. not only at the storage top and bottom);
- Possibility of setting different outside temperatures for tank top, side, bottom;
- Possibility of heat supply/subtraction in the stored mass (e.g. to simulate electric rods), and of specification of the heat supply/subtraction point;
- Possibility of modelling internal heat exchangers and relevant modelling details;
- Adopted buoyancy model to account for effective thermal conductivity when inverse thermocline takes place;
- Accuracy of the model for calculating the heat losses (conduction through walls and/or insulation, possibility of considering internal and/or external convection and/or heat capacity of solid components);
- Pressure calculations across the storage.

In general, all the available models are 1-dimensional and consider the storage as a series of layers; the implemented equations for the heat exchange between two adjacent layers and with the environment are derived assuming a cylindrical geometry. The external temperature at the storage side is uniform, i.e. gradients cannot be defined unless modifying the source code. Furthermore, none of the models consider the effects of layer mixing caused by inflows or outflows.

Table 6. Review of the tools for TES modelling available in open-source libraries of Dymola/Modelica (Source: AIT)

Library	Model	Fluid injection/withdrawal in the single layers	Heat port(s) for internal supply/subtraction	Heat ports at single-layer detail	Diversified ext. temperature top/bottom/side	Possible internal coil(s)	User-defined location of internal coil(s)	Coil(s): internal convection	Coil(s): external convection	Coil(s): conduction	Capacitive coil(s)	Buoyancy model	Capacitive walls and insulation	Conduction through walls	Conduction through insulation	Convection at the internal and external side	User-friendly hydraulic integration	User-friendly stratified input
IBPSA - Buildings - IDEAS	Stratified	X	X	X	X	0						kdT^2			X			
	StratifiedEnhanced		X	X	X	0						"third order" kdT^2			X			
	StratifiecEnhancedHex		X	X	X	max 1	X	calculated	calculated		X	"third order" kdT^2			X			
DisHeatLib	StorageTank		X	X		0						"third order" kdT^2			X		X	
	StorageTankHex		X	X		max 1	X	calculated	calculated		X	"third order" kdT^2			X		X	
Aix	BufferStorage		X			max 2	X		user-defined	X	X	5 different	X	X	X	user-defined coefficients	X	
	Storage					pass-through	automatic			X		$kdT^{1.5}$			X		X	
Soltermica	HotWaterTank				adiabatic							hydraulic		adiabatic			X	
	HotWaterTankInternalHeatExchanger				adiabatic	X	input required but not used	user-defined global coefficient				kdT interface interpolated		adiabatic			X	
BuildingSystems	FluidStorage	X				max 2	X	user-defined global coefficient				$GdTn^a$		as insulation (under-estimated!)	X	user-defined coefficients	X	X
ThermoCycle	HeatStorage		(X)		X	(max1)	X	user-defined global coefficient			X	none	user-defined global coefficient				X	

giga_TES (Austria)

Numerical simulations in COMSOL Multiphysics® have been used by the University of Innsbruck in the Austrian FFG Flagship project giga_TES (Giga-Scale Thermal Energy Storage for Renewable Districts) to evaluate the energetic performances of large-scale hot water TES for DH systems. The considered TES volumes range from 100,000 to 2,000,000 m^3. The simulation results have been used for a techno-economic analysis based on (simplified) cost calculations. The analysis, reported in detail in the paper [18], considers tank and pit TESs with and without insulation, with trafficable and non-trafficable cover, with polymer or stainless liner. The simulations included also the ground around the storage and the evolution of its temperature (example in Figure 9), which affects the heat losses. The evolution of the TES efficiency over the first 10 years of operation for different volumes and designs is reported in Figure 10, while Figure 11 represents the breakdown of the thermal losses in the last year. The economic analysis bases on a breakdown of the costs considering excavation, construction, site facilities and components: diaphragm wall, cut-off wall, insulation, liner, cover. Some results are summarized in terms of specific costs in Figure 12.

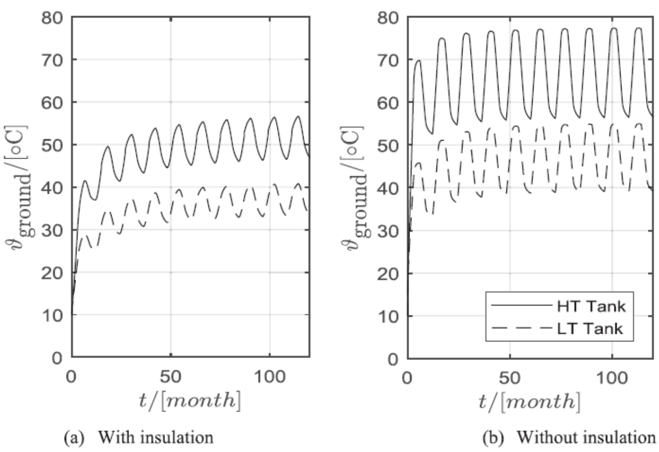


Figure 9. Example of simulated evolution of ground temperature over the first 10 operation years (Source: [18])

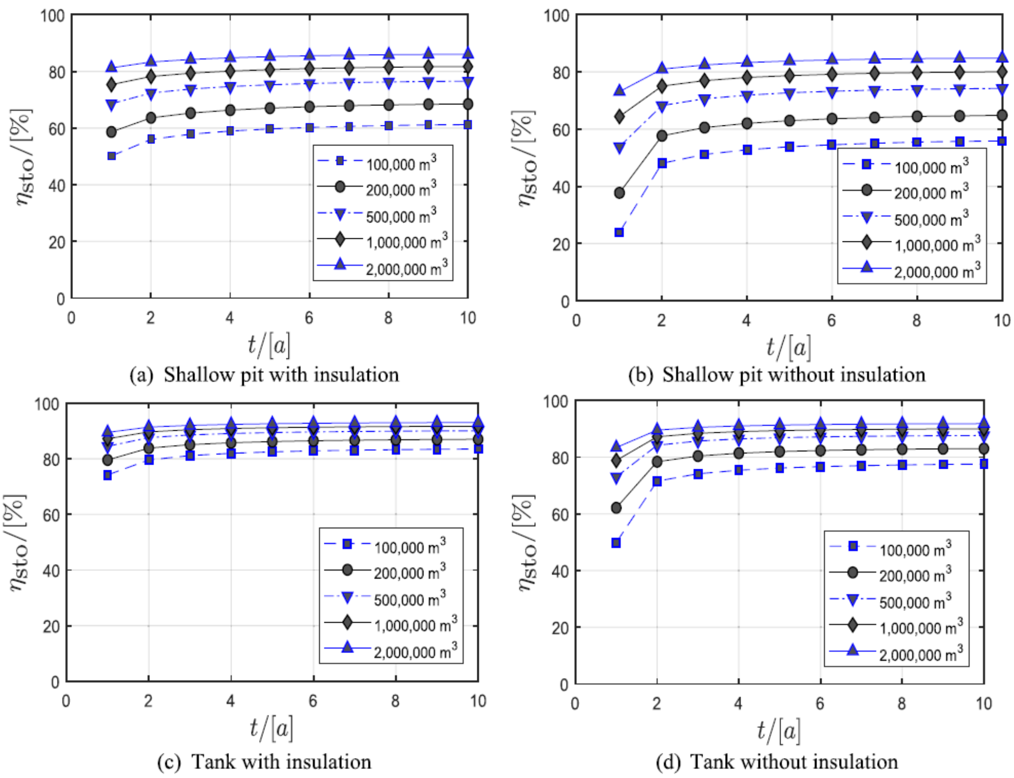


Figure 10. Simulated evolution of the TES efficiency over the first 10 operation years (Source: [18])

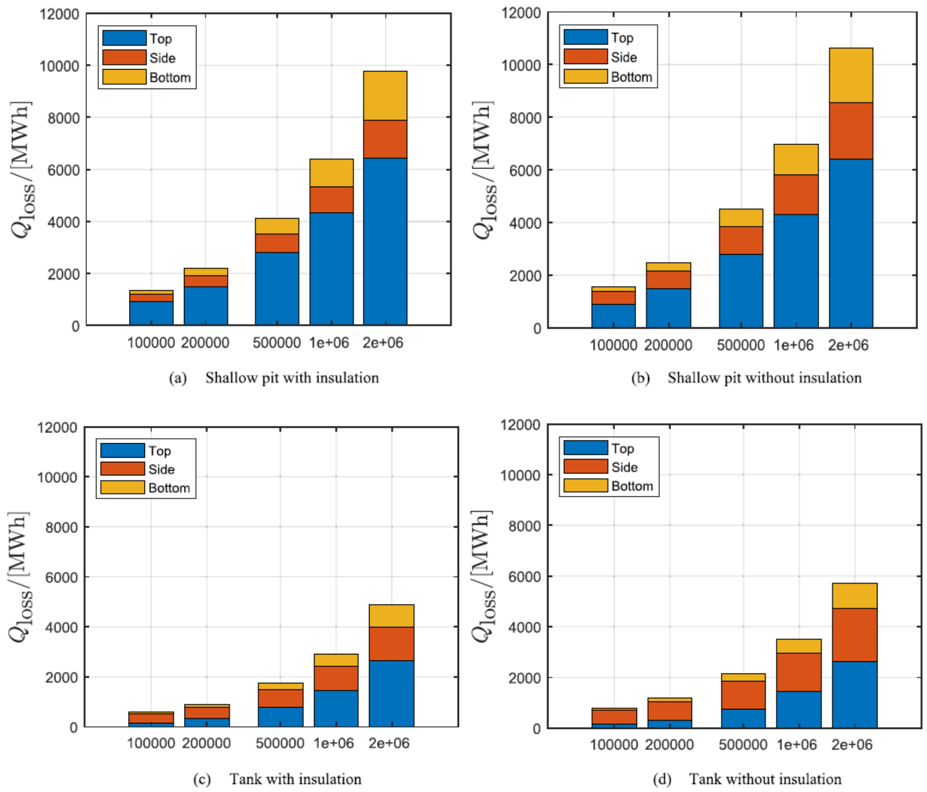


Figure 11. Breakdown of the thermal losses in the 10th operation year vs. storage volume (Source: [18])

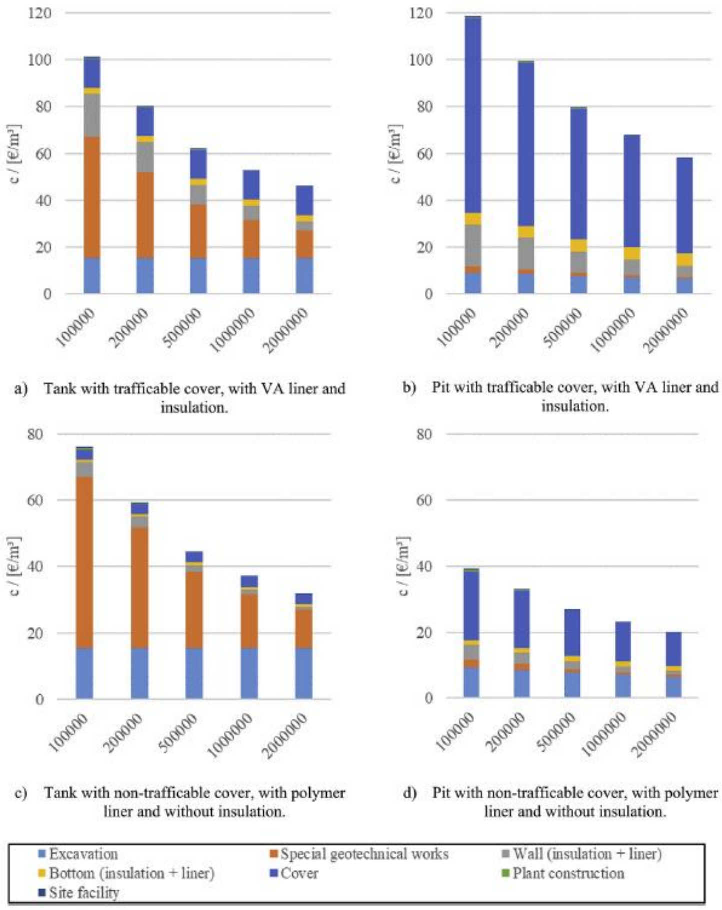
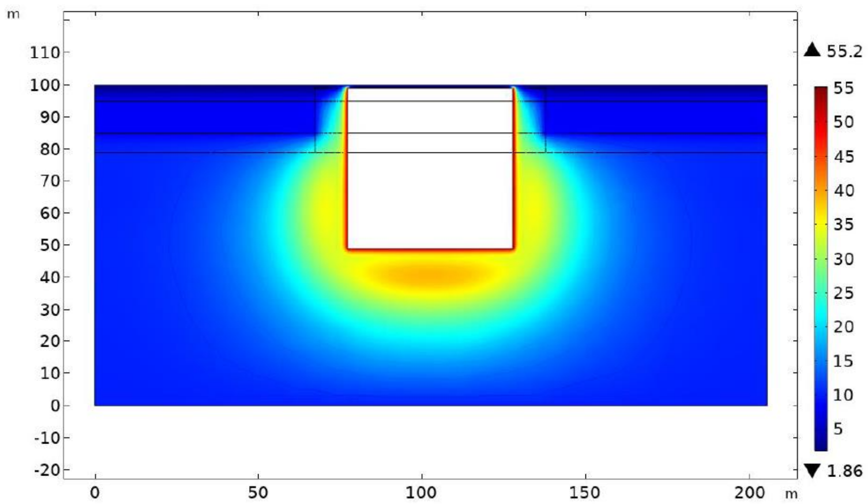


Figure 12. Breakdown of the specific investment costs vs. storage volume (Source: [18])

The PTES model was recently validated against measured data from Dronninglund [19]. Additionally, it was possible to include in the model a groundwater system to evaluate the TES performance in locations with groundwater (Figure 13). Different scenarios have been compared considering different TES typologies (cylinder, pit) with insulation (characterized by high costs, complex building physics and not guaranteed durability) and without insulation (just with a cut-off wall) [20]. Different velocities of groundwater have been also considered.



- Tank in LT system, d = 10 m
- 3D: Groundwater velocity = 0.002 m/s
- Ground thermal conductivity = 1.5 W/m/K

Figure 13. Simulated ground temperature with groundwater flow at 0.002 m/s (Source: University of Innsbruck)

The main conclusions are:

- The thermal losses can be significantly reduced with a cut-off wall;
- The cut-off wall is not enough to prevent the groundwater from overheating;
- With the insulation it is possible to prevent overheating; however, a cut-off wall is required to protect the insulation from groundwater penetration. Though, insulation is not feasible, it is important to prevent the ground from overheating.

Green Heat[3] (Germany)

In the German project Green Heat[3], the Technische Universität Dresden (Technical University of Dresden) evaluated the feasibility of large ST integration in the DH system of Dresden. The considered collector area is 70,000 m^2 and the large-scale TES is a pit of 500,000 m^3 with following characteristics:

- The maximum operating temperature is 90 °C and is defined by the long-term stability of the foils;
- The insulation is only in the cover area at the top.

The PTES performance was evaluated through simulations in COMSOL Multiphysics of the ground, while the charging and discharging strategy (Figure 14) were determined by the optimization tool BoFiT, precasting the temperature profile along the PTES flank with 1-hour resolution (Figure 15).

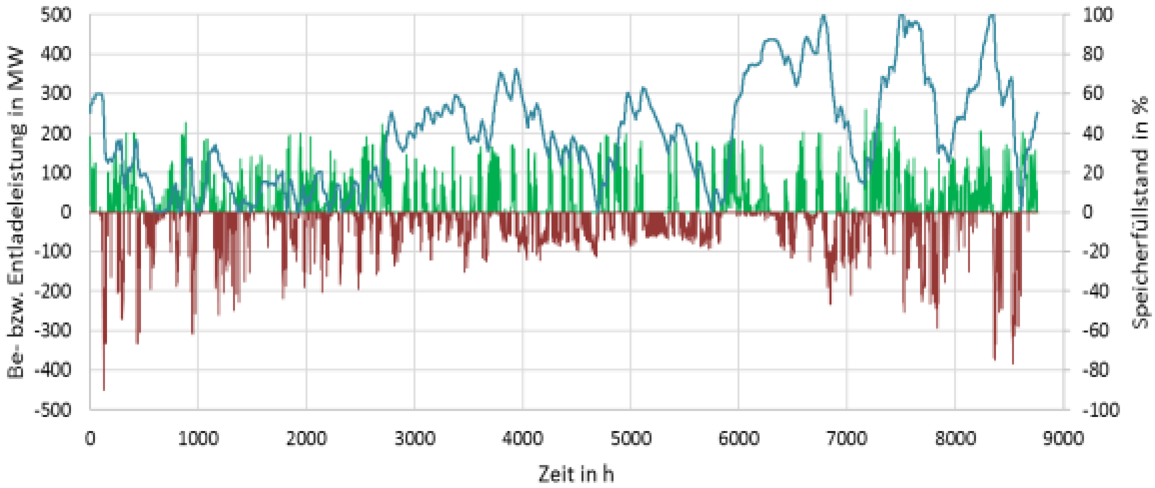


Figure 14. Optimal TES charging (green line), discharging (red line), and charge status (blue line) over 1 year and with 1-hour resolution (Source: [21])

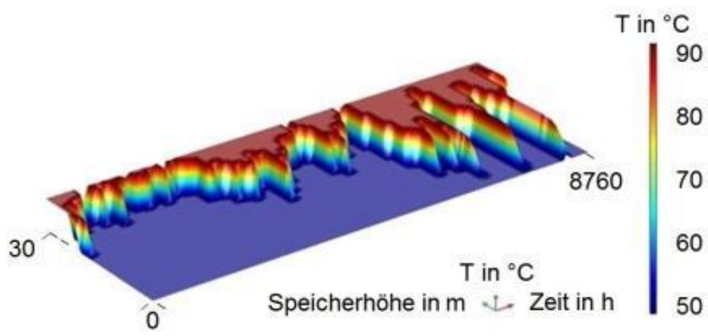


Figure 15. Temperature profile over 1 year (8760 hours) along the TES flank (30 m top, 0 m bottom) (Source: [21])

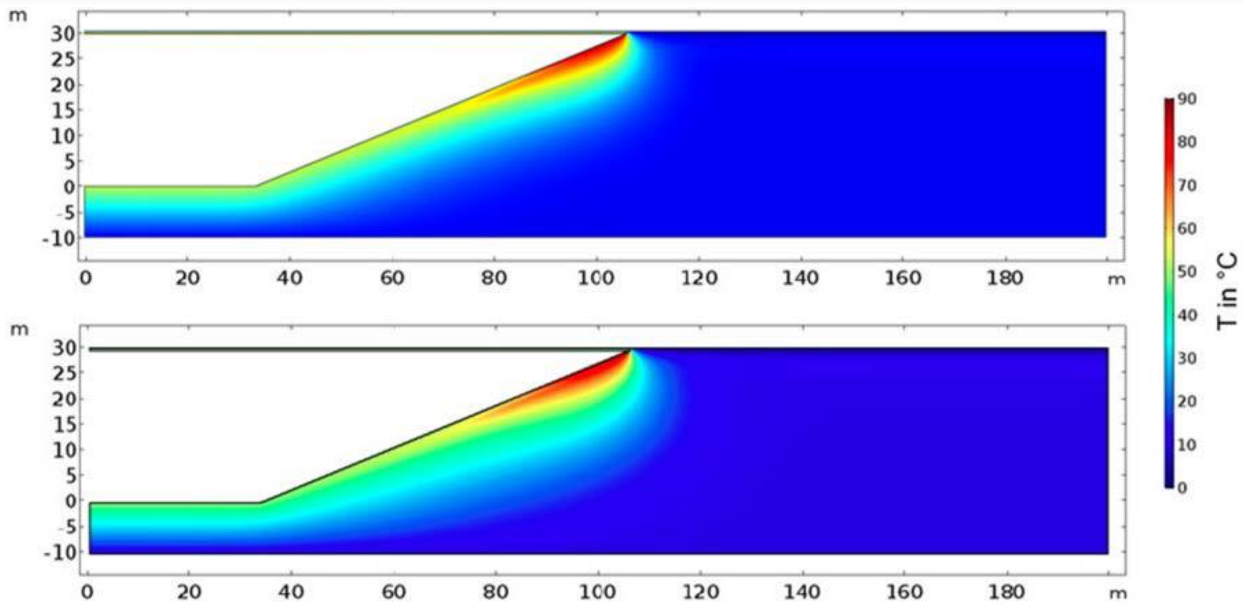


Figure 16. Simulated ground temperature profile after 5 and 10 years of PTES operation (upper and lower chart respectively) (Source: [21])

The numerical simulations allowed to estimate the effects on the TES performance over the years, indicating decreasing heat losses with the operating time (Figure 16 shows the ground temperature profile after 5 and 10 years of operation).

The resulting heat losses over the first 10 operating years are illustrated in Figure 18, which refers to the breakdown of Figure 17. The main outcomes are:

- The highest annual heat losses are in the first year and decrease to 30% in the fifth year;
- The dominating heat losses are through the cover and are constant over the years;
- The ground conditions are almost stabilized after 10 years;
- The effects of groundwater show an opposite trend.

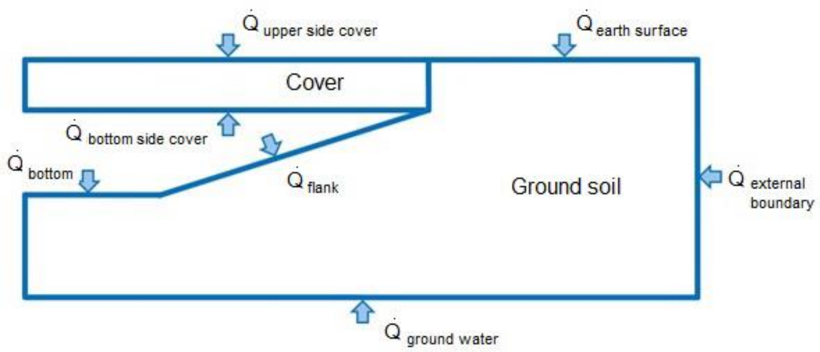


Figure 17. Scheme for the thermal loss breakdown (Source: [21])

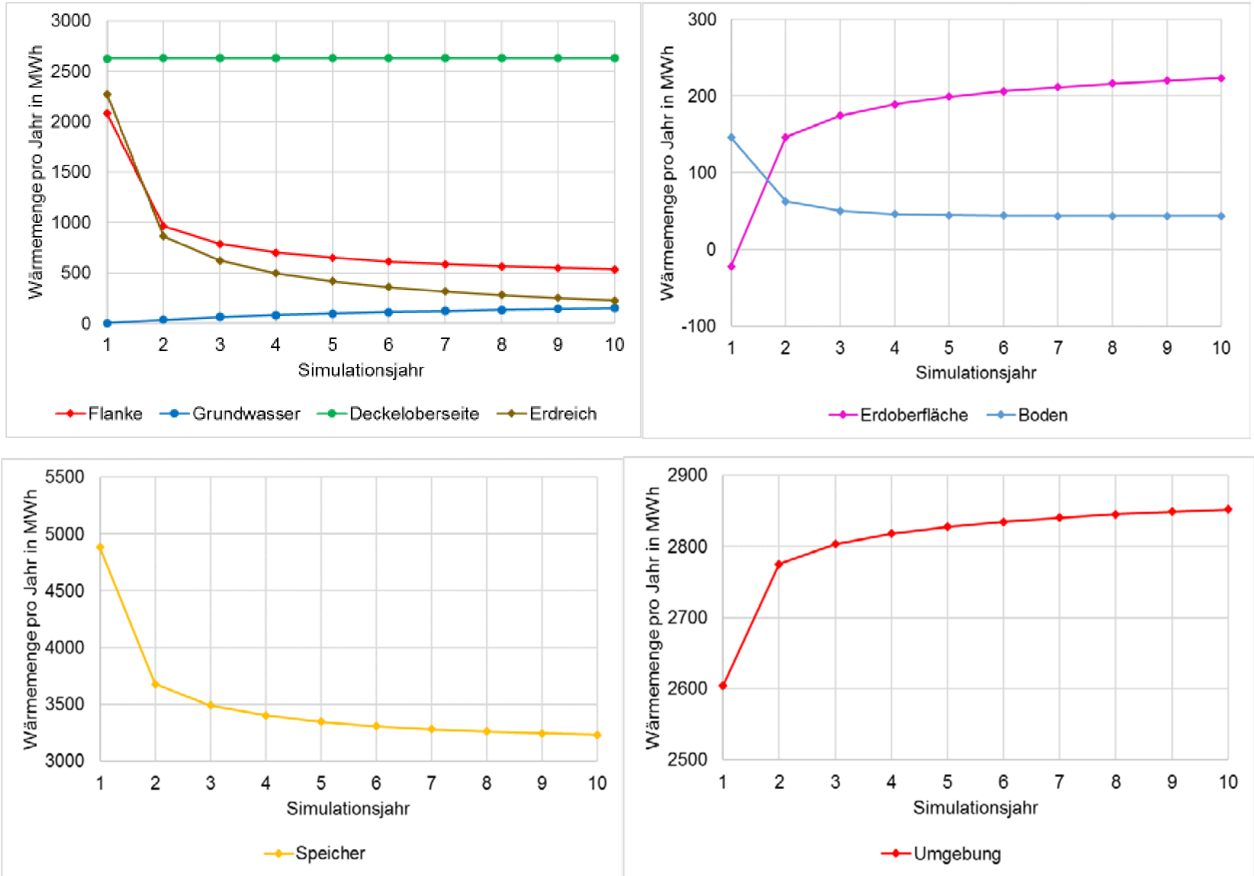


Figure 18. Simulated evolution of the heat losses over the first 10 operation years (Source: [21])

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