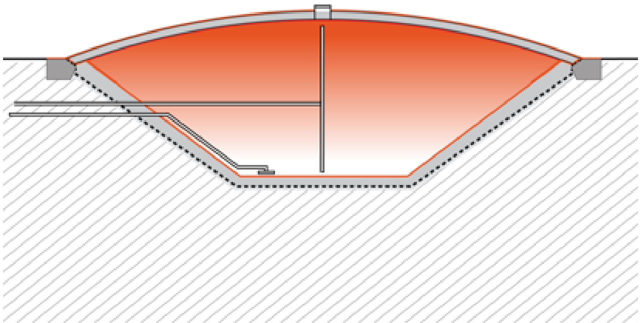
International Energy Agency Technology Collaboration Programme on
District Heating and Cooling including Combined Heat and Power

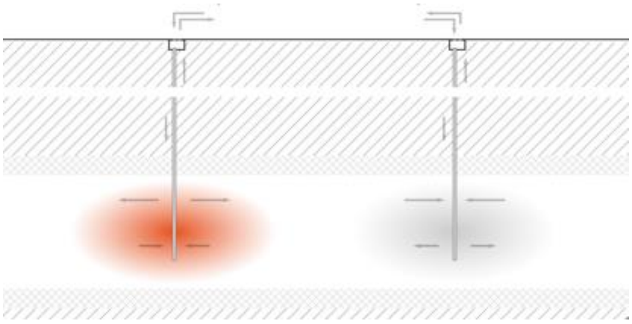
Integrated Cost-effective Large-scale Thermal Energy Storage
for Smart District Heating and Cooling

Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling

Draft, September 2018

(Please visit again the IEA-DHC website for final draft)





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About the International Energy Agency

The International Energy Agency (IEA) is an intergovernmental organisation that serves as energy policy advisor to 28 member countries in their effort to ensure reliable, affordable and clean energy for their citizens. Founded during the oil crisis of 1973-1974, the IEA was initially established to coordinate measures in times of oil supply emergencies. As energy markets have changed, so has the IEA. Its mandate has broadened to incorporate the “Three E’s” of balanced energy policy making: energy security, economic development and environmental protection. Current work focuses on climate change policies, market reform, energy technology collaboration and outreach to the rest of the world, especially major consumers and producers of energy like China, India, Russia and the OPEC countries.

With a staff of over 240 who are mainly energy experts and statisticians from its 30 member countries, the IEA conducts a broad program of energy research, data compilation, publications and public dissemination of the latest energy policy analysis and recommendations on good practices.

About IEA DHC

The Energy Technology Initiative on District Heating and Cooling including Combined Heat and Power was founded in 1983. It organizes and funds international research which deals with the design, performance, operation and deployment of district heating and cooling systems. The initiative is dedicated to helping to make district heating and cooling and combined heat and power effective tools for energy conservation and the reduction of environmental impacts caused by supplying heating and cooling.

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Abbreviations

ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
CHP	Combined heat and power
DH	District heating
DHC	District heating and cooling
GSHP	Ground source heat pump
HDPE	High density polyethylene
IEA	International Energy Agency
PCM	Phase change material
PE	Polyethylene
PEX	Cross-linked polyethylene
PP	Polypropylene
PUR	Polyurethane
PTES	Pit thermal energy storage
RES	Renewable energy sources
TES	Thermal energy storage
SDH	Solar District Heating
STES	Seasonal thermal energy storage
TTES	Tank thermal energy storage
UTES	Underground thermal energy storage
XPS	Extruded polystyrene

Executive Summary

Modern district heating and cooling (DHC) systems are a key technology for the energy transition to a green economy. They enable at a large scale to couple the heat and electricity sector and hence to increase the flexibility of the overall energy system. In smart DHC systems, large-scale thermal energy storages (TES) in DHC systems allow the integration of high shares of renewable energy sources (RES), to integrate excess electricity from RES and to optimize combined heat and power plants (CHP).

The IEA in its Heating and Cooling Roadmap [IEA, 2011] and the District Heating and Cooling Technology Platform in its strategic research agenda [DHC+ 2012] include large-scale TES as central elements of future modern DHC systems.

The research in the IEA project ‘Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and Cooling’ (IEA DHC Annex XII Project 3, Contract No. XII-03) contributes towards the development of data, information and analysis tools to encourage the use of cost-effective large-scale underground thermal energy storage (UTES) in DHC systems.

Four main concepts for large-scale UTES have been developed and demonstrated in the last decades (see Figure). Each of these concepts has different capabilities with respect to storage capacity, storage efficiency, possible capacity rates for charging and discharging, requirements on local ground conditions and on system boundary conditions.

The TES technologies of interest for this international collaboration are aquifer and pit thermal energy storage (ATES and PTES), where ATES use naturally occurring self-contained layers of ground water, so called aquifers, for heat storage and PTES are made of an artificial pool filled with storage material and closed by a lid. These TES types offer cost-effective solutions for large-scale applications. Where applicable, these TES types have a significant cost advantage compared to conventional heat stores. Cost levels of less than 50 €/m³ have been reached and are particularly interesting for DHC applications with a low number of storage cycles (e.g. long-term or seasonal storage of cold or heat).

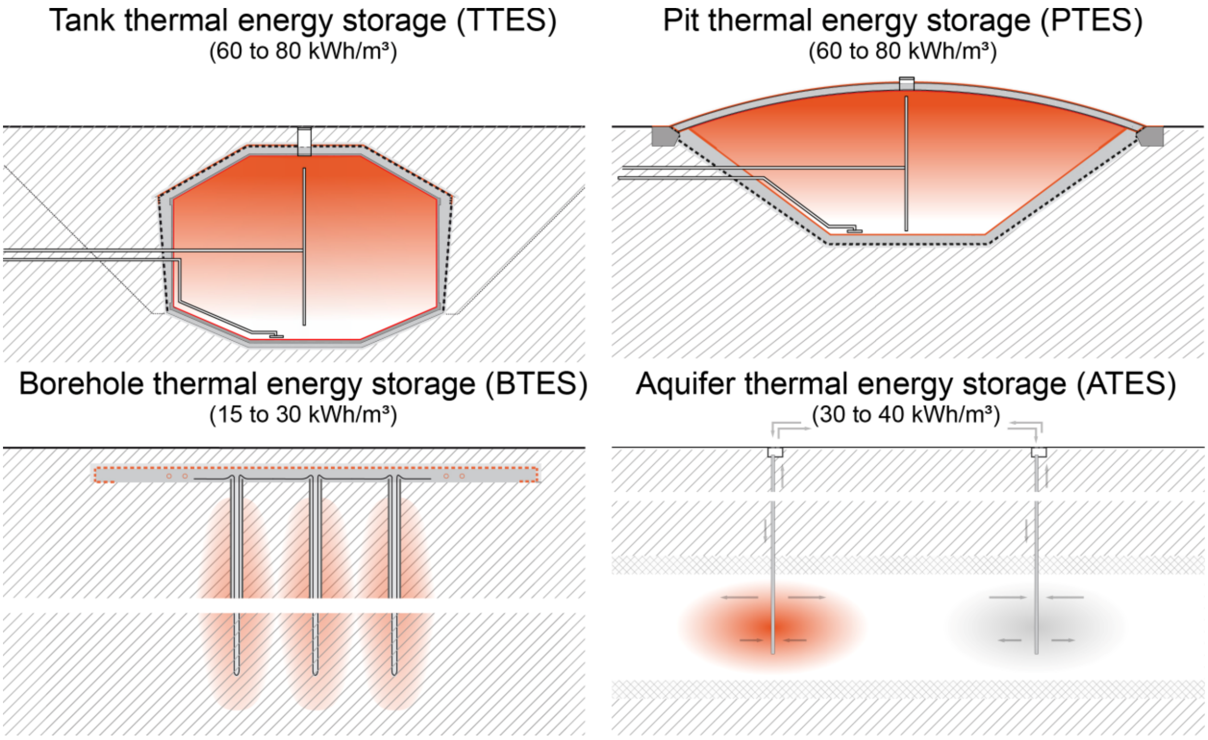


Figure: Overview of available underground thermal energy storage concepts (Solites)

In the participating countries in this IEA funded project (Canada, Denmark, Germany, The Netherlands and the USA) cost-effective concepts for large scale underground thermal energy storage, including ATES and PTES, have been developed in the last decades and realized in numerous concrete projects. In this report the authors' knowledge is compiled and summarized as follows:

- Design concepts for ATES and PTES; discussion of material aspects and lessons learned
- Description of typical application cases for these concepts, including design criteria and restrictions
- Overview of recently built projects with ATES and PTES in the partner countries, including concepts and integration details of the heat and cold sources or functionalities
- Cost analysis of realized projects
- List of technology suppliers and service providers at an international level

Large-scale underground thermal energy storage in DHC systems can serve for various purposes: short-term heat storage or peak shifting, long-term or seasonal storage of e.g. solar thermal or surplus heat, energy management of multiple heat producers or cold storage of e.g. ambient cold or evaporator cold from heat pumps. In realized projects, the typical applications include:

- Seasonal thermal energy storage for solar district heating
- CHP optimization
- Integration of power-to-heat applications
- Storage of industrial waste heat
- Combined heating and cooling applications

Each of these applications has specific considerations regarding temperature levels, heat losses, charging capacities and cost and thus each requires a thorough identification of the suitable storage concept. Further, a deliberated integration into the overall energy supply system is essential for an efficient operation of a large-scale TES. This includes a suitable hydraulic system layout as well as a careful design of not only the storage but also other system components such as additional heat or cold producers, DH network, heat transfer substations and, in particular the process control system.

Chapter 3 of this report discusses design concepts and implementation experiences of aquifer thermal energy storage. The ideal ATES application in terms of economic and technical viability is in energy systems where both cooling and heating are required. In summer, groundwater is extracted from the cold wells and used for cooling purposes, preferably for direct cooling. The warmed return water is injected in the warm wells to recharge the warm store. In winter the process is reversed: water is pumped from the warm wells and applied as a low temperature heat source for heat pumps. After the exchange of heat, the chilled water from the heat pumps is injected into the cold wells, recharging the cold store for use in the following summer. There are many examples of local DHC systems applying ATES according to this principle. In these systems, groundwater is either transported to a centralized heat pump plant room (centralized ATES system) or distributed directly to the building plant rooms (decentralized ATES system). The ATES capacity in these systems typically is in the range of 1-5 MW, with some ATES systems having a capacity exceeding 10 MW.

Since full scale PTES are mainly developed and implemented in Denmark, development of Danish design concepts and Danish implementation experiences are the main content in Chapter 4. The design of gravel/water PTES developed in Germany is also described.

Cost reduction has been the main driver for developing the Danish PTES concept. This has resulted in PTES concepts with soil balance shaped as a truncated pyramid placed upside down. Chapter 4 describes the development from the first pilot storage in 1994 until 2018. The status for the development is, that water is used as storage medium, welded polymer liners are used for tightening, the lid is floating on the water, and insulation materials in the lid are expanded clay or polyethylene/cross-linked polyethylene (PE/PEX) mats. Maximum temperatures are 90 °C for storing solar energy and 80-85 °C if the storage is not cooled down in the winter period. Five full scale storages have been implemented in Denmark. This report describes the implementation experiences from two of them.

Construction cost of the storage concepts vary significantly, however, all types show a significant effect of economy of scale, i.e. the cost decreases with increasing storage volume. Tank thermal energy storages (TTES) have higher specific investment cost than other UTES types. On the other hand, they offer advantages regarding the thermodynamical behavior and they can be built almost independently from the local ground conditions. The lowest cost can be reached with aquifer (ATES) and borehole (BTES). However, they often need additional equipment for operation such as buffer storages or water treatment and they have the highest requirements on the local ground conditions. In the last decade a number of large-scale PTES were built in Denmark with investment cost of 20 – 40 €/m³. For assessing the economy of a storage system not only the storage cost need to be considered, but the investment, maintenance and operational cost have to be related to its thermal performance in the overall system.

Realized example projects with their key performance indicators are presented in Chapter 5.

Chapter 6 of this report presents design and analysis tools which allow detailed modelling of TES in DHC systems in order to assess the thermal and economic performance of the storage systems, and also investigate complex cases with transient storage temperature behavior and possible long-term heat build-up impact in the surrounding soil.

1 Introduction and scope

Modern district heating and cooling (DHC) systems are a key technology for the energy transition to a green economy, because they enable at a large scale to couple the heat and electricity sector and hence to increase the flexibility of the overall energy system. In so-called smart DHC systems, large-scale thermal energy storages (TES) in DHC systems render possible the integration of high shares of renewable energy sources (RES), to integrate excess electricity from RES and to optimize combined heat and power plants (CHP).

The research in the IEA project 'Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and Cooling' (IEA DHC Annex XII Project 3, Contract No. XII-03) contributes towards the development of data, information and analysis tools to encourage the use of cost-effective large-scale underground thermal energy storage (UTES) in DHC systems. The TES technologies of interest for this international collaboration are aquifer and pit thermal energy storage (ATES and PTES), where ATES use naturally occurring self-contained layers of ground water, so called aquifers, for heat storage and PTES are made of an artificial pool filled with storage material and closed by a lid. These TES types offer cost-effective solutions for large-scale applications. Where applicable, these TES types have a significant cost advantage compared to conventional heat stores. Cost levels of less than 50 €/m³ have been reached and are particularly interesting for DHC applications with a low number of storage cycles (e.g. long-term or seasonal storage of cold or heat).

In the countries participating in the project (Canada, Denmark, Germany, The Netherlands and the USA) cost-effective concepts for large scale underground thermal energy storage, including ATES and PTES, have been developed in the last decades and realized in numerous concrete projects. These TES technologies have been demonstrated within the frame of national research and demonstration programs and more recently as non-subsidized projects by industry. In this report the following knowledge is compiled and summarized:

- Design concepts for ATES and PTES; discussion of material aspects and lessons learned
- Description of typical application cases for these concepts, including design criteria and restrictions

- Overview of built projects with ATES and PTES in the partner countries, including concepts and integration details of the heat and cold sources or functionalities
- Cost analysis of realized projects
- List of technology suppliers and service providers at an international level

This knowledge is made available and will be hopefully useful for operators of DHC systems and other stakeholders interested in transforming their systems to smart DHC systems.

2 Large-scale underground thermal energy storage types

2.1 Historical Context

The technology of large-scale underground thermal energy storage has been investigated in Europe since the middle of the 1970’s, initially with the main intention to develop cost-effective seasonal thermal energy storage (STES) for district heating systems with solar heat production. The first demonstration plants were realized in Sweden in 1978 and 1979 based on results of a national research program. Thanks to an international collaboration via the IEA SHC Program Task 7, STES found their way through part of Europe: Denmark, the Netherlands, Switzerland, Italy, Greece and Germany. While most of these countries stopped their research programs for seasonal thermal energy storage, Germany, Denmark and the Netherlands continued the development. Several technologies for STES have been improved and demonstrated. In Germany, the four basic storage concepts (tank (TTES), pit (PTES), borehole (BTES), and aquifer (ATES)), were demonstrated in a number of pilot plants. In Denmark mainly the PTES concept was further developed and in the Netherlands the ATES concept. Outside Europe, the interest for STES started with the realization of the “Drake Landing” demonstration plant in Okotoks, Alberta, Canada in 2007, which includes BTES.

In parallel to the IEA SHC program, many international collaborations within the frame of the IEA ECES program during the 1980s and 1990s have focused their activities on studying the potential of UTES concepts for building heating and cooling. The very first Annex of the IEA ECES program has resulted in completing a technical and economic evaluation of various UTES concepts presented by the participating countries. The final report of Annex 1 was published in 1981. Results of this pioneer work formed the basis for many subsequent Annexes under this IEA program addressing the technical and economic feasibility of various types of UTES technologies of that time.

In the last years, an important development for large-scale TES took place with the “multi-purpose” use of TES in DHC systems, which was mainly driven by the changes in the European electricity markets and the need to increase the flexibility for district heat and electricity production. Once more Danish utilities have been the forerunners in this development of so called “smart district heating” systems (see Figure 2.1). As a reaction to high shares of RES in the electricity production and consequently decreasing and fluctuating electricity prices, large-scale TES were introduced into DHC systems with the aim to enable:

- a flexible and electricity price controlled operation of CHP plants
- a flexible and electricity price controlled operation of electric boilers and heat pumps for grid balancing, in particular with excess RES electricity
- the integration of high shares of RES heat, e.g. from solar thermal, and surplus heat

Presently, largest UTES for this type of application, a pit storage with a water volume of 203,000 m³, has been constructed in the year 2015 for a smart district heating system for the Danish city of Vojens.

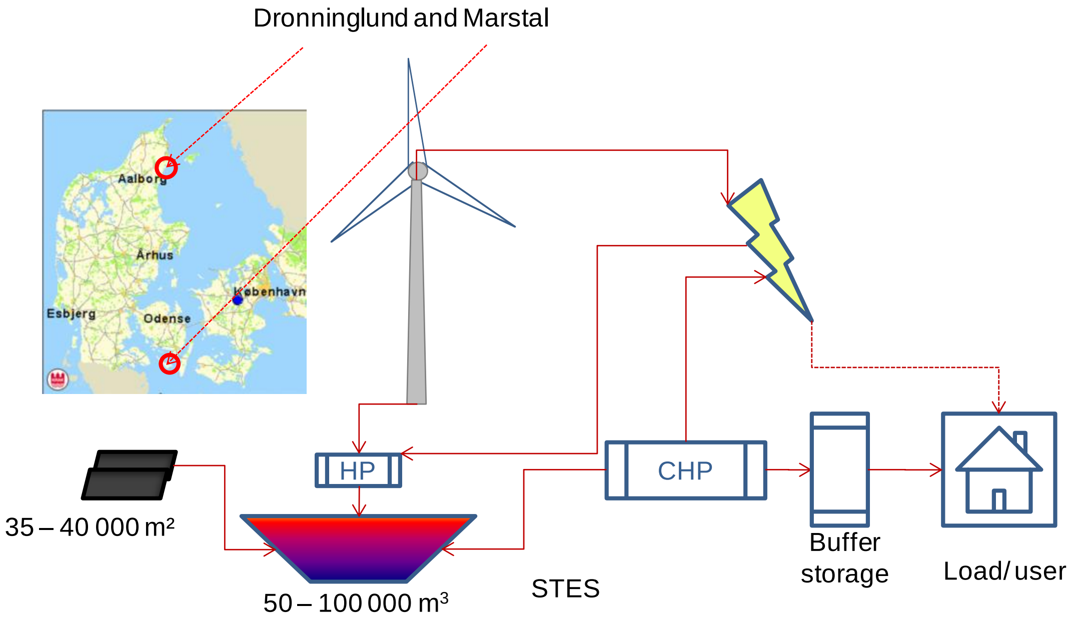


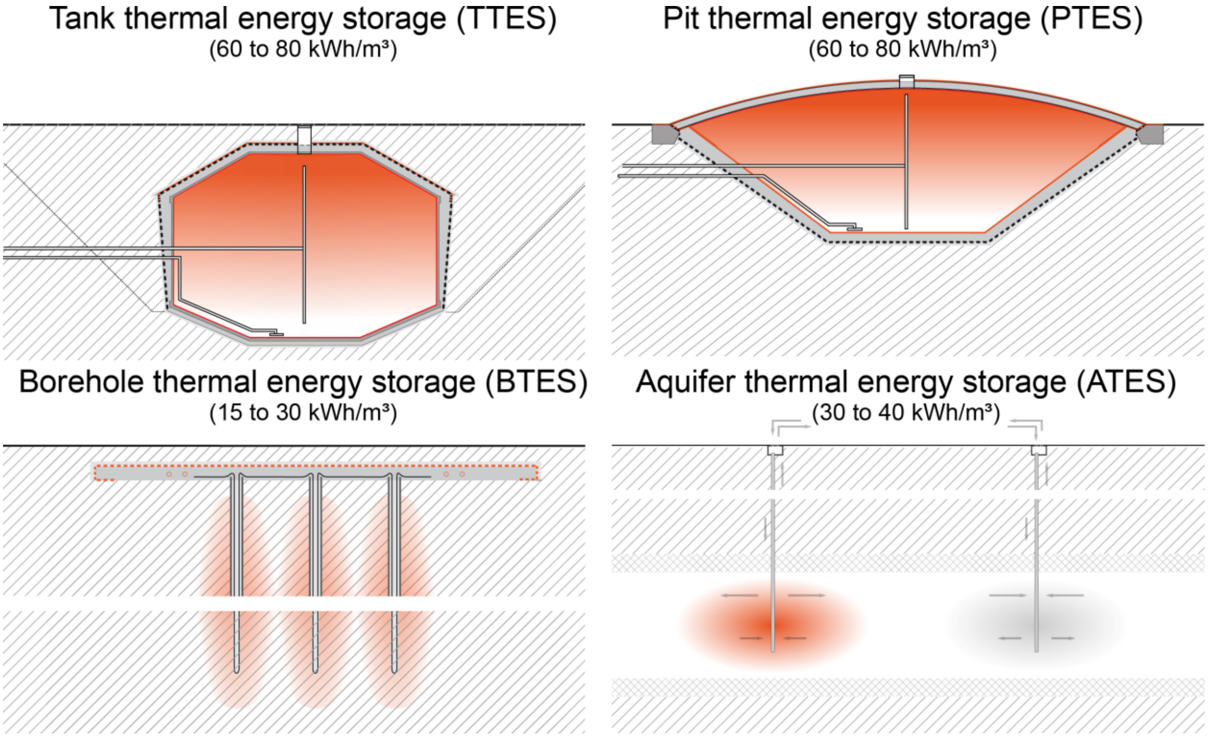
Figure 2.1: Example of smart district heating system in Denmark (PlanEnergi)

The IEA in its Heating and Cooling Roadmap [IEA, 2011] and the District Heating and Cooling Technology Platform in its strategic research agenda [DHC+ 2012] include large-scale TES as central elements of future modern DHC systems.

2.2 Types of large-scale underground thermal energy storage

Four main concepts for large-scale UTES have been developed and demonstrated in the last decades as depicted in Figure 2.2. Each of these concepts has different capabilities with respect to storage capacity, storage efficiency, possible capacity rates for charging and discharging, requirements on local ground conditions and on system boundary conditions (e.g. temperature levels), etc. (see Table 2.2).

The most suitable TES concept for a specific project has always to be found by a technical-economical assessment for the specific boundary conditions. In the following subsections the TES concepts are briefly introduced. The ATES and PTES concepts are treated in more detail in Chapters 3 and 4 of this report.



Tank thermal energy storage (TTES)
(60 to 80 kWh/m^3)

Pit thermal energy storage (PTES)
(60 to 80 kWh/m^3)

Borehole thermal energy storage (BTES)
(15 to 30 kWh/m^3)

Aquifer thermal energy storage (ATES)
(30 to 40 kWh/m^3)

Figure 2.2: Overview of available underground thermal energy storage concepts (Solites)

Table 2.1: Comparison of storage concepts regarding heat capacity and geological requirements (Solites)

TTES	PTES		BTES	ATES
Storage Medium				
water	water*	gravel-water*	soil/rock	sand-water rock-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 - 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 layer on top - no or low natural groundwater flow - suitable water chemistry at high temperatures - aquifer thickness of 20 – 100 m
Storage Temperature Range				
5 - 95 °C	5 - 95 °C		-5 - 90 °C	2 - 20 °C for shallow and 2 - 80 °C for deep systems

* Water is more favorable 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.)

2.2.1 Tank thermal energy storage

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

Large-scale steel tanks, insulated and non insulated, mounted above ground are state of the art. Because of the high investment cost they are in general usually used as buffer tanks with small and medium-sized volumes or for storage applications with a high number of cycles.

Figure 2.3 shows an example for a pilot TTES with 5,700 m³ of water volume, built in Munich, Germany in 2007. The storage bottom is made of in-situ concrete on top of a foam glass gravel layer for insulation. The walls and the roof are made of pre-fabricated concrete elements. The elements were assembled and pre-stressed by steel cables. They are insulated from the outside with expanded glass granules in a membrane formwork. The insulation thickness is 30 cm at the bottom and rises up to 70 cm on the roof. A stainless steel liner is added to protect the heat insulation from water vapour diffusion. To improve the thermal stratification a stratification device is installed inside the storage volume.

The storage is integrated in a local district heating system delivering heat to 300 apartments. The storage is charged by 3,000 m² of solar thermal collector field covering around 45 % of the total yearly heat demand.

Figure 2.3: Tank thermal energy storage with 5,700 m³ of water volume built from prefabricated concrete elements in Munich, Germany (in construction and finalized, Solites)

2.2.2 Pit thermal energy storage

Pit thermal energy storages are built without static constructions by means of mounting a liner with or without insulation material in an excavation pit. The design of the lid depends on the storage medium and geometry. In the case of using water along with gravel, soil or sand as storage medium the lid may be constructed with a liner and insulation material, often identical to the walls. The lid construction of a water filled 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. Temperatures in the storage are normally limited by the liner material to 80 – 90 °C. 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.

2.2.3 Borehole thermal energy storage

In a borehole thermal energy storage the underground geology is used as storage material. There is no exactly separated storage volume. Suitable geological formations are rock or water-saturated soils with negligible 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 2.4).

BTES do not have a vertical but a horizontal temperature stratification from the center to the boundaries, 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 surrounding ground. The horizontal stratification in the ground is supported by connecting the supply pipes in the center of the storage and the return pipes at the boundaries. A certain number of BHEs are hydraulically connected in series to a row and certain rows are connected in parallel. During charging the flow direction is from the center to the boundaries of the storage to obtain high temperatures in the center and lower ones at the boundaries of the storage. During discharging the flow direction is reversed.

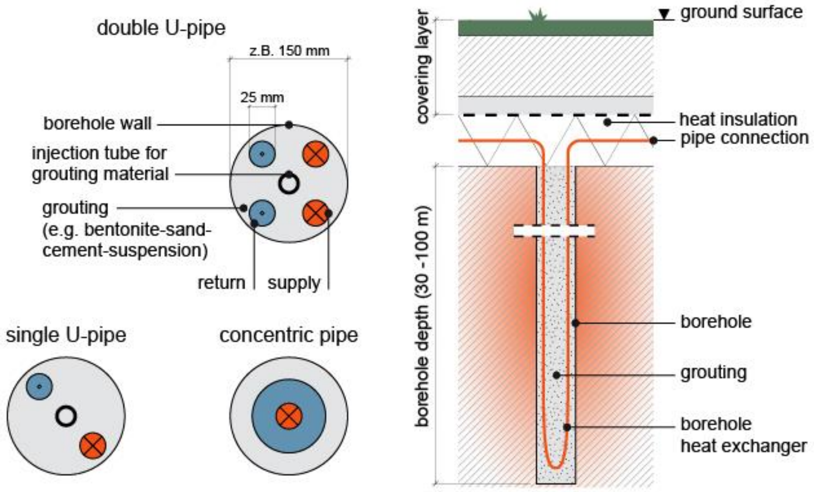


Figure 2.4: Common types and vertical section of borehole heat exchangers (Solites)

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

One of the advantages of this storage concept is the expandability. By adding additional BHEs next to the existing ones the affected ground storage volume can be increased easily. The connection of the new BHEs to the existing one should however consider the horizontal stratification as described above.

Figure 2.5 shows an example for a BTES part of the Drake Landing Solar Community located in Okotoks, Alberta, Canada (www.dlsc.ca). The solar district heating (SDH) system with integrated seasonal BTES storage is designed to provide over 90% of the space heating for 52 single family homes from solar. The system was commissioned in the summer of 2007, reaching its 11th year of operation in 2018. The BTES is installed under a corner of a neighborhood park adjacent to the energy center building shown on the bottom right corner of the aerial view on Figure 2.5. The BTES is covered with a 200 mm layer of extruded polystyrene (XPS) insulation beneath the topsoil. The BHE is composed of 144 single U-pipe boreholes, each 35 m deep and radially plumbed in 24 parallel circuits, each with a string of 6 boreholes in series, see Figures 2.6. Each series string is connected in such a way that the water flows from the centre to the outer edge of the BTES when storing heat, and from the edge towards the centre when recovering heat, so that the highest temperatures will always be at the centre. The boreholes are laid out in a grid pattern (2.25 m on centre) within a 35 m diameter circle. The resulting cylinder of earth has a volume of about 34,700 m^3. Figure 2.6 shows the borehole field under construction and currently, as a landscaped park. The BTES is charged by 2,293 m^2 of flat plate solar thermal collectors.

Figure 2.5: Aerial view of Drake Landing Solar Community (NRCan)

Figure 2.6: Drake Landing borehole field under construction and currently, as a landscaped park (NRCan)

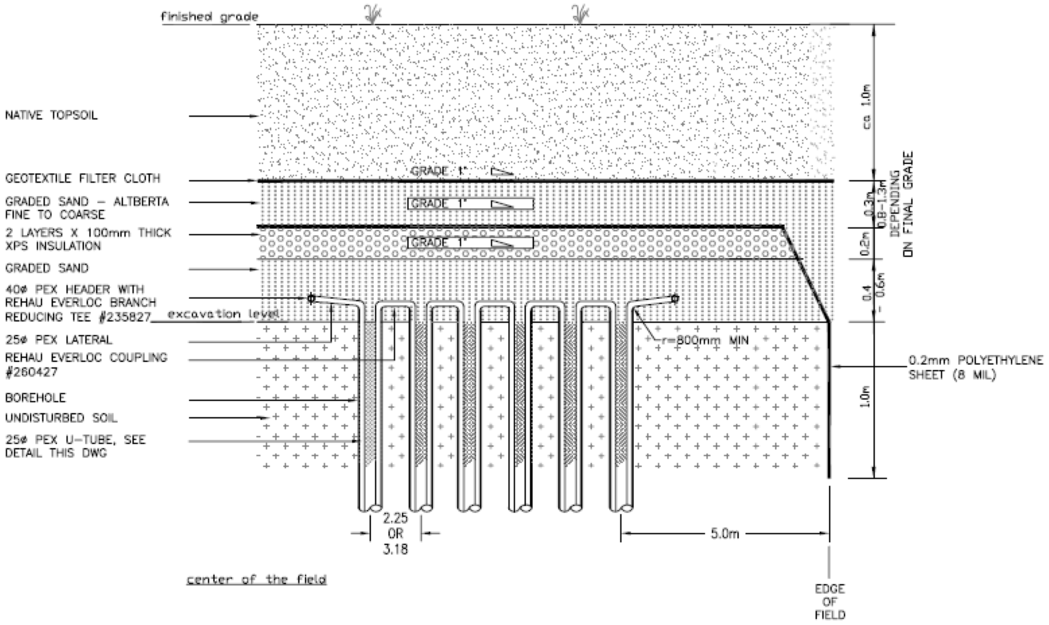


Figure 2.7: Cross section of the top portion of Drake Landing BTES (NRCan)

2.2.4 Aquifer thermal energy storage

Aquifers are water-filled bodies below ground comprised of permeable sand, gravel, sandstone or limestone layers with high hydraulic conductivity. Aquifers are suitable for thermal energy storage if impervious layers exist above and below and natural groundwater flow is negligible. In this case, two wells (or several groups of wells) are drilled into the aquifer layer and serve for extraction and injection of groundwater. During charging of heat, cold groundwater is extracted from the cold well, heated up either by a heat source or a cooling application and injected into the warm well. For discharging 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.

The storage volume of an ATES cannot be thermally insulated against the surroundings. Thus heat storage at higher temperatures (above 50 °C) is normally only efficient for large storage volumes greater than 50,000 m³ with a favorable surface-to-volume ratio. For low temperature or cooling applications, smaller storages can also be feasible.

ATES requires very specific geological and hydro-geological ground conditions that have to be determined by test drillings and a hydro-geological investigation at an early project stage.

2.3 System integration

Today ATES, PTES and other UTES can be applied in all application areas where large thermal storage capacities are required at moderate or low temperature levels below 100 °C. Large-scale TES can have different purposes in energy supply systems. The most common ones are:

- Buffer storage for short-term heat storage or peak shifting
- Long-term or seasonal storage of e.g. solar thermal or surplus heat
- Energy management of multiple heat producers such as CHP, solar thermal, heat pumps, and industrial surplus heat
- Cold storage of e.g. ambient cold (air, surface water) or evaporator cold from heat pumps

A deliberated integration into the overall energy supply system is essential for an efficient operation of a large-scale TES. This includes a suitable hydraulic system layout as well as a careful design of not only the storage but also other system components like additional heat or cold producers, DH network, heat transfer substations up to the point of building installations. In particular, the process control system must be configured to ensure the storage services achieve greatest benefit, depending upon specific project objectives such as maximization of renewable energy share or CHP electricity production.

Storage temperature levels, quality of stratification and return temperatures of the heating network strongly influence the efficiency of a TES. Those parameters not only depend on the storage, but also to a large extent on the connected energy system. Hence, during storage design an accurate prediction of the entire system characteristics is needed. Operation temperatures of the storage throughout the year and charging and discharging power rates have to be predicted, along with the DH network return temperatures, as they have a key role for the performances of the storage. Together with the maximum charging temperatures, they define the usable temperature difference and accordingly the thermal capacity of a TES. For some storage concepts, additional components such as short-term buffer tanks or heat pumps can also be economically reasonable supplements.

A key advantage of large-scale TES are low specific heat losses. Most of the common storages accumulate thermal energy as sensible heat in a water volume. In general, the water is heated up to temperatures below 100 °C. The thermal losses of the storage are mainly influenced by the surface-to-volume ratio of the storage volume and the quality of the installed insulation material. Large storages have much lower surface-to-volume ratios than small storages, which is an important advantage in particular for long-term storage. For example, a small storage with a volume of 20 m³ has a surface-to-volume ratio that is eight times higher than the ratio of a storage with 10,000 m³. Hence, the specific heat losses of the large store are a factor of eight lower (see Figure 2.8).

The thermal quality of the insulation material is defined by its thermal conductivity. In practical application, significant differences between theoretical and measured thermal conductivity values at high temperatures can be observed due to the influence of absorbed moisture as well as other factors such as the presence of thermal bridges.

The energy efficiency of a storage device is further strongly influenced by the so-called number of storage cycles. This is an indicator for how often the storage is charged and discharged in a certain time period and for the energy turnover.

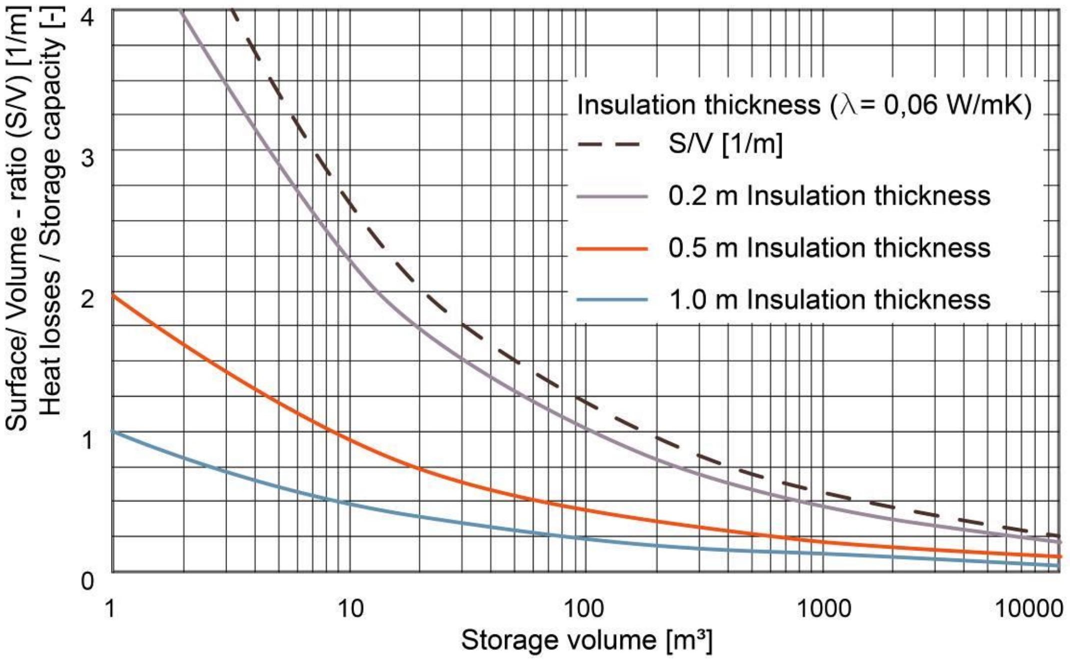


Figure 2.8: Ratio of heat losses to storage capacity ratio versus storage volume in m³ for a storage duration of 6 months and a storage temperature of 40 K above ambient temperature (Solites)

2.4 Application cases

Large-scale underground thermal energy storages are most common in the following applications.

- In **solar district heating** (SDH) systems with seasonal thermal energy storage, large solar thermal collector areas produce heat mostly in the summer period. Solar heat that is not used directly is charged into the seasonal storage for a heat supply in the following heating season. STES enables SDH systems to supply more than 50% of the annual DH heat demand by solar energy. Examples for this application are the Danish PTES systems in Marstal, Dronninglund and Eggenstein-Leopoldshafen described in Chapter 5.

- Large-scale TES used for the **optimization of CHP plants** allow for a separation of the electricity from the heat production. The CHP units can operate independently of the actual heat demand when economic conditions in the electricity grid are favorable. Surplus heat can be charged into the TES for later use when electricity prices are low and the CHP is switched off. In these periods no expensive backup boilers have to be operated.

- In **power-to-heat applications**, surplus renewable electricity can be transferred into heat with direct electrical heaters or central heat pumps. In connection to large-scale TES more heat than is actually needed can be produced and stored. In larger applications, regulation services can be offered to the electricity market, which offer additional business opportunities.

- **Smart district heating systems** combine the three application cases described above and have been implemented in a number of Danish district heating systems in the past years. They often consist of the four main components: large-scale solar thermal system, CHP plant, electrical heat pump and / or direct electrical heater, and large-scale TES. In the summer period solar heat is produced by the solar thermal collectors. Surplus solar heat is stored into the TES. In the winter period the solar heat is discharged. In addition, the heat pump produces heat in periods with low electricity prices and uses the colder parts of the TES as heat source. The CHP plant produces heat in periods with high electricity prices, independently from the actual heat demand. The Smart District Heating concept also allows for selling regulation services to the electricity market. Examples for this application are the Danish PTES systems in Marstal and Dronninglund described in Chapter 5.

- **Industrial waste heat** is often available on a rather constant power level throughout the year, whereas heat demand usually follows the seasonal weather variations. TES can level out this discrepancy and offers the possibility for much higher amounts of waste heat to be used compared to a direct waste heat usage only.
- In **cooling applications**, ambient cold from ambient air, surface or sea water can be charged into a TES in the winter period for cold supply in the summer period. From the economical point of view these systems are often very interesting, as no cold has to be produced by a cooling machine but only freely available ambient cold is used. Besides the electricity for some circulation pumps, no further operational cost is incurred.
- **Combined heating and cooling** applications work similarly for the cooling part, besides the fact that the cold source is the evaporator side of a heat pump in this case. The heat that is charged into the TES during the cooling season is used as a heat source for the heat pump in the following heating season. Because of the favorable economics, quite some local DHC systems with heat pumps and UTES are in operation already. Examples for this application are the ATES systems implemented in the Eindhoven University of Technology, Stockholm Arlanda Airport and in the London Riverlight project all described in Chapter 5.

Table 2.2 presents the specific requirements and recommended UTES types for the application cases described above.

Table 2.2: Specific requirements and thermal energy storage types versus application cases

Application case	Specific requirements	Possible types	Comments
Seasonal thermal energy storage for solar district heating	Low heat losses, Low cost	All UTES types	Typically the number of storage cycles per year is below 2. Therefore, low storage heat losses and storage cost are crucial.
CHP optimization	High charge and discharge capacities, High temperatures	TTES, PTES	Main purpose is short term peek shifting.
Power-to-heat applications	High charge and discharge capacities, Low heat losses, Low cost	TTES, PTES	Normally a short term storage is sufficient. Long term storage of heat is possible if heat production prices are very low from power to heat production
Smart district heating	Dependent upon the single applications to be integrated	TTES, PTES, BTES	Thermal energy storage for smart district heating applications need to combine the requirements of the single applications in an optimized way.
Industrial waste heat	Low cost	All UTES types	Thermal energy storage is often needed for adapting constant waste heat availability to a daily heat load profile, for weekend load covering or, in some cases, for seasonal storage of waste heat
Cooling applications, combined heating and cooling applications	Annually balanced charge and discharge heat amounts, Low cost	ATES, BTES, PTES, TTES	Often ATES and BTES offer cost efficient solutions when combining direct building cooling in summer with heat pump heating in winter.

2.5 Cost of large-scale underground thermal energy storage

Construction cost of the four storage concepts vary significantly. Figure 2.9 presents the investment cost data of realized large-scale TES pilot and demonstration plants. For comparing different storage concepts and storage materials, the specific storage cost are related to the water equivalent storage volume. The listed storages are operated at maximum storage temperatures between 50 °C and 95 °C and are integrated into solar district heating plants with seasonal storage. Six of them are additionally used for CHP optimization and/or power-to-heat applications.

The graph illustrates the cost decrease with increasing storage volumes. Appropriate sizes for large-scale UTES are above 2000 m³ water equivalent. Generally, TTES have higher specific investment cost than other UTES types. On the other hand, they offer advantages regarding the thermodynamical behavior and they can be built almost independently from the local ground conditions.

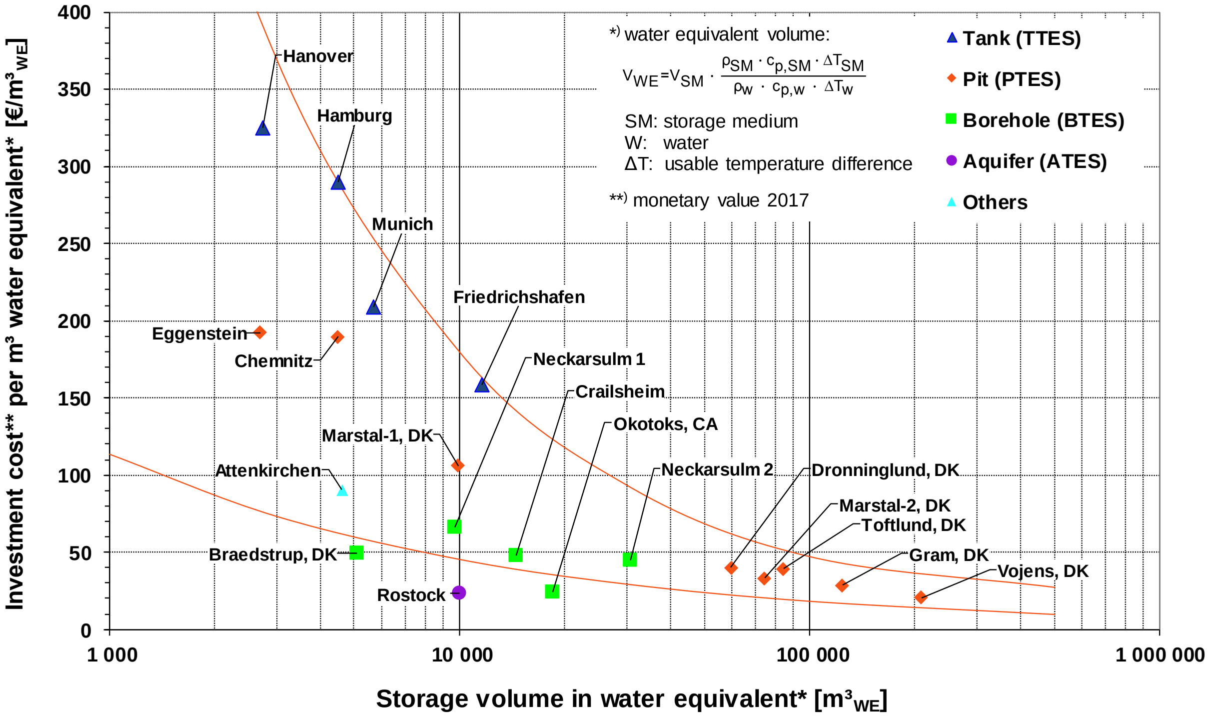


Figure 2.9: Specific investment cost for large-scale thermal energy storages (including all necessary cost for building the storage device, without design, without connecting pipes and equipment in the heating plant, without VAT, Solites)

**Others- refers to a combination of TTES and BTES*

The lowest cost can be reached with ATES and BTES. However, they often need additional equipment for operation such as buffer storages or water treatment, and they have the highest requirements on the local ground conditions. In the last decade a number of large-scale PTES were built in Denmark with investment cost in the order of 20 – 40 €/m³.

The economic viability of a storage system depends not only on the storage cost, but also on the thermal performance of the storage and the connected system. Hence each system has to be evaluated separately. To determine the economy of a storage system, the investment, maintenance and operational cost have to be related to its thermal performance in the overall system.

3 ATES design concepts

3.1 Introduction to ATES

An aquifer is a subsurface geologic feature that is capable of yielding large quantities of water (e.g. a layer of sand, gravel, sandstone or fractured rock). The technology of storing thermal energy in aquifers was first applied more than fifty years ago in the Peoples Republic of China. The projects were abandoned in the 1990's [Tian 1980 and Sun 1986]. Independently, Aquifer Thermal Energy Storage (ATES) was developed in the western countries. The first ATES demonstration/pilot projects were installed in the early 1980s in the US, Switzerland, and Denmark. The International Energy Agency's Implementing Agreement on Energy Conservation through Energy Storage (ECES) supported several research and development activities on ATES commencing in the early 1980s. Cold storage for cooling buildings with "cold" stored in the winter proved the most promising in temperate and northern climates: the natural underground temperature is typically only 0 to 10 K warmer than the required storage temperature for cooling. This allows sizing an ATES system to meet (part of) the cooling demand with direct cooling, i.e. without running a chiller.

An ATES system can be defined as a large open-loop geothermal system optimized and operated to realize seasonal thermal energy storage by reversing extraction and injection wells seasonally.

Figure 3.1 displays the basic principle of an ATES system that is used for both cooling and heating. In summer, groundwater is extracted from the cold well(s) and used for cooling purposes, depleting the cold store over the cooling season. The warmed return water is injected in the warm well(s) to recharge the warm store. In winter the process is reversed: water is pumped from the warm well(s) and applied as a low temperature heat source for a heat pump. After the exchange of heat the chilled water from the heat pump is injected into the cold well(s), recharging the cold store for use the following summer.

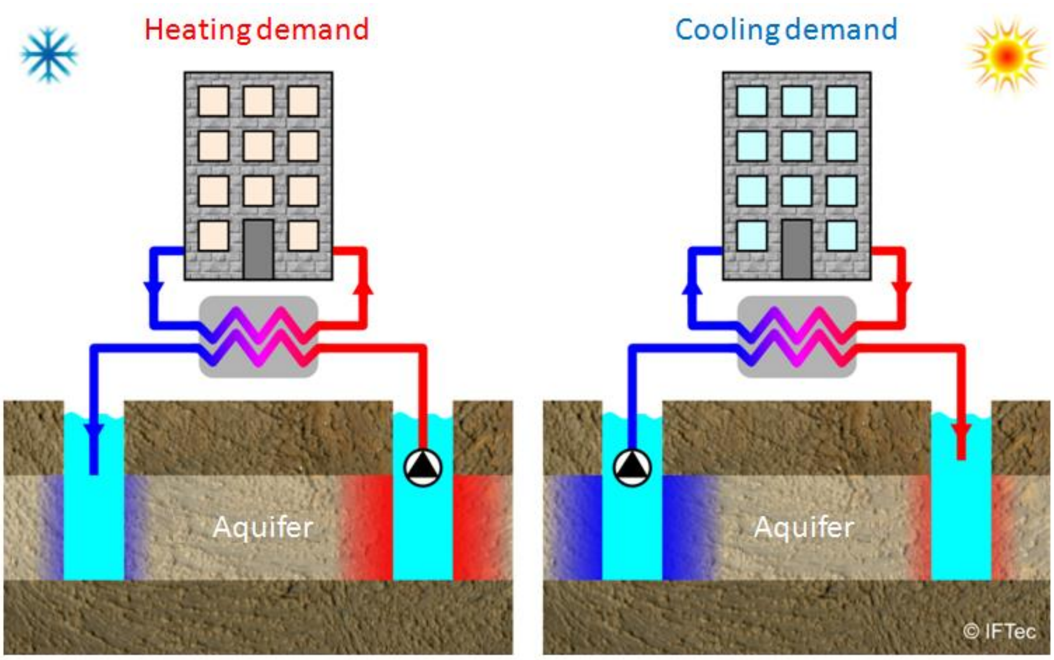


Figure 3.1: Principle of ATES in heating (winter) and cooling (summer) mode (IFTec GeoEnergia).

All the water extracted from the cold store is re-injected into the warm store. There is no net extraction of groundwater, so despite the fact that ATES systems operate at high flow rates, there is no consumptive use of groundwater. ATES systems are carefully designed and operated so that temperature is the only characteristic of the water that is modified; no chemicals or additives are injected into the aquifer. Balance is a key characteristic of ATES systems: the injection and withdrawal rates are balanced, and the systems are typically designed so that a net thermal balance on the aquifer is maintained.

ATES systems require a minimum distance between warm and cold wells, depending on site conditions and thermal capacity of the system. ATES systems require three primary site-specific physical characteristics:

1. An aquifer capable of yielding high flow rates to wells
2. Seasonally variable (and preferably, relatively balanced) heating and cooling requirements
3. Relatively large thermal loads, typically greater than 250 kW heating and cooling load

As of the end of 2017, an estimated 3,000 ATES projects were in operation in Europe. The majority of these projects can be found in (ranking by number of projects) The Netherlands, Sweden, Belgium, Denmark and the UK. This estimate includes both small and large scale projects. Figure 3.2 shows a subdivision of the ATES projects by market sector. From this figure it can be concluded that the number of ATES projects integrated in a local DHC network already has exceeded 100. These are larger scale ATES projects with a distribution network serving two or more buildings or industries.

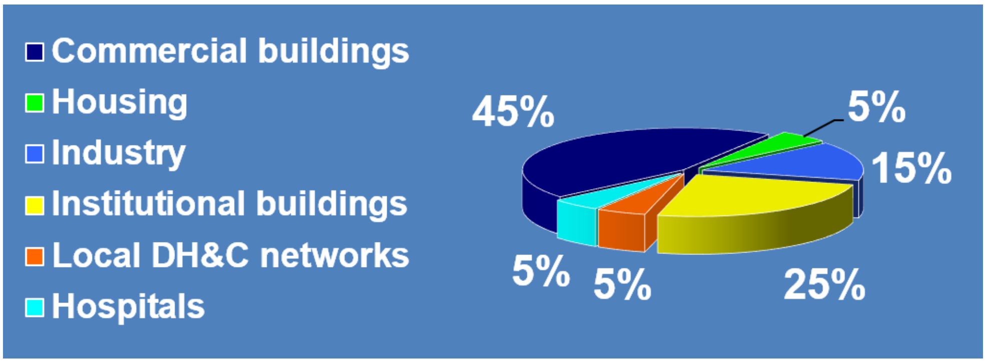


Figure 3.2: Subdivision of ATES projects in Europe by market sector (IFTech)

3.2 ATES design concepts

3.2.1 Aquifer characteristics

The application of ATES for cold and low temperature heat storage in local DHC systems implies larger scale ATES systems (storage capacity 1 MW or more). Aquifers that are suitable for high well yields are limited to sands and gravels, sandstones and highly fractured or karstified carbonate rocks. While aquifers are geographically limited in area around the world, they are typically located under large population areas such as the east coast of the US and river deltas such as the Netherlands.

For an economically feasible project, the aquifer must have a relatively large thickness and high hydraulic conductivity, and the top of the aquifer is preferably within 300 m from the surface.

Furthermore, the groundwater flow and groundwater composition are important factors. For ATES systems, the regional groundwater flow velocity should be limited in order to prevent significant losses of heat and/or cold from the thermal store. Due to different geochemical processes in combination with groundwater flow, the groundwater composition in an aquifer can vary both in vertical and in horizontal directions. The most common zoning occurs in the vertical direction and is caused by redox processes. An ATES well extracts water from a certain vertical depth interval and can also attract groundwater from other depths in the aquifer. When different types of groundwater are mixed, this can cause chemical reactions that lead to well clogging. This is a particular risk where mixing of groundwater that contains oxygen and/or nitrate with groundwater that contains dissolved iron can cause serious well clogging problems by iron(hydr)oxide precipitates. This type of well clogging is well known in water wells used for extraction [e.g. Houben et al. 2007]. In comparison to extraction wells, injection wells are even more vulnerable to this type of well clogging, because the injection of water with solid particles (consisting of the reaction products that are formed in the mixed water) is notoriously problematic.

Other factors affecting ATES design are: stratigraphy, grain size distribution, degree of consolidation, natural temperature, static head, groundwater flow direction, geological structures and fracture distribution, aquifer geometry, storativity and leakage factor of confining layers. Table 3.1 summarizes the range of parameters normally required for successful application of a larger scale ATES system in an unconsolidated aquifer.

Table 3.1: Criteria for larger scale ATES systems in unconsolidated aquifers

	Lower Limit	**Upper Limit**
Depth of the well(s) (top of productive zone) [m]	25 (injection pressure)	300 (economic feasibility)
Aquifer thickness [m]	20	none
Hydraulic conductivity [m/s]	1 x 10^{-4} (thick aquifer) 5 x 10^{-4} (thin aquifer)	1 x 10^{-3} *
Groundwater flow velocity [m/d]	0	0.3 *
Static head [m below ground surface]	50	- 5

* For ATES, a high value usually results in a high groundwater flow velocity and a low storage efficiency as a consequence.

Proper insight into the aquifer characteristics is needed for a realistic assessment of the feasibility, design and environmental impact of an ATES system. Investigating a site usually starts with an inventory of existing information. When existing information is not sufficient, the missing information will have to be gathered on site. The method depends on the type of information that is missing.

A test boring is performed to the depth of interest and provides information on the hydrogeological sequence that is present. By installing piezometers at different depths in the borehole, the groundwater composition at different depths can be investigated. When the aquifer hydraulic properties are needed, a well screen can be installed that enables a single well test or a pumping test. For the interpretation of these tests, analytical solutions [Kruseman et al. 1994] and specialized software (e.g. MLU for Windows or AQTESOLV) are available.

Sampling existing piezometers can be useful when the information on the groundwater composition or groundwater flow rate and direction is insufficient, provided that existing piezometers are present at the right depth and distance from the location.

In order to obtain reliable ground samples, reverse rotary, percussion and sonic drilling are good options. A borehole log is sometimes used to acquire more accurate information on the soil sequence and on the depth of the fresh to salt water transition zone, if any.

3.2.2 Well design

Since ATES systems are meant to operate over several decades, it is very important that the performance of the wells can be sustained over a long period of time. Therefore, the design of the well should enable a long lifetime with limited maintenance. Much of the knowledge on well design has been derived from research in the drinking water industry.

ATES wells differ from conventional water-supply wells because they are designed to operate as withdrawal wells during the heating or cooling season and as injection wells during the opposite season. Because injection wells are subject to plugging from fines, colloids and mineral precipitates in the recharge water, typical practice in the US has been to double the well screen length, if possible, or operate them at one half or less of the maximum flow rate of a similarly constructed groundwater withdrawal well [Driscoll 1986].

The basic design criterion is to keep the flow velocity of the water around the production and infiltration well low enough for fines to stay in the aquifer (production well) and to collect fines that moved from the production well to the infiltration well in the gravel pack, if any. Thus, wells can be back-flushed readily at the end of each season to maintain low injection resistance. These design criteria result in much larger diameter wells than would normally be expected for a standard water extraction water supply well. For production wells a maximum approach velocity is used. Several equations have been developed over time to relate the maximum approach velocity to aquifer characteristics [Pyne 2005].

A measurement technique to determine the suitability of water for infiltration in unconsolidated aquifers is the Membrane Filter Index (MFI) measurement, giving a measure for the “plugging capacity” of the water. The technique has been developed during research on clogging of infiltration wells in The Netherlands. It is used to check the water quality of wells for ATES systems and it has been applied for the ASR systems in the USA. The clogging rate of an injection well can be estimated based on the MFI value, the approach velocity in the well and the aquifer characteristics [Pyne 2005]. A smaller diameter well (higher approach velocity) will result in a higher clogging rate and thus higher maintenance cost. This implies the economic criteria, such as total cost of ownership, determine the design of infiltration wells.

Apart from the maximum flow velocity during extraction and injection, the maximum injection pressure is the third criterion that has to be met. When the injection pressure is too high, hydraulic fracturing may occur and (part of) the water that is injected into the well may find a path to the surface instead of going into the aquifer. Since the maximum allowable injection pressure increases with the depth of the aquifer, this criterion is especially relevant for shallow aquifers.

In *rock aquifers* (sandstones, carbonate rocks) the grains are cemented and can therefore not easily be mobilized. When the cementation is fully developed, the production of fines will be limited. In that case there is no need to limit the flow velocity in the formation like in unconsolidated aquifers. Furthermore, the rock will have extra strength in comparison to unconsolidated sediments, which means that the maximum allowable injection pressure increases significantly. In competent rock aquifers, well design is therefore based on limitations to the drawdown in the production well or the energy efficiency of the groundwater loop, i.e. the ratio between thermal energy transported and pump electricity required. In friable sandstone aquifers, prevention of the production of fines becomes more important and the design standards shift towards those of unconsolidated aquifers.

3.2.3 Well field design

The optimal well field layout depends on many issues, and in real life the well field layout is often determined by the possibilities the site offers. Well field design is meant to minimize (1) thermal interference between the production and infiltration wells and (2) undesirable hydraulic and thermal impact in the surrounding area.

Thermal interference will lead to an unfavourable impact on the extraction temperature of the extraction well. For ATES systems that are applied to store cold and low temperature heat and are thermally balanced, design guidelines (NVOE-guidelines 2006) state that a minimum distance between a warm and a cold well of 3 times the thermal radius of the stored cold or heat is sufficient to minimize thermal interference (Figure 3.3). The thermal radius r_{th} can be calculated as follows:

$$r_{th} = \sqrt{\frac{c_w Q}{c_a H \pi}}$$

where:

r_{th} = Thermal radius of the stored cold or heat [m]

c_w, c_a = Heat capacity of water and aquifer (water and solid part) [J/(m³ K)]

Q = Amount of pumped/injected water per season [m³]

H = Length of the productive zone (well screen) [m]

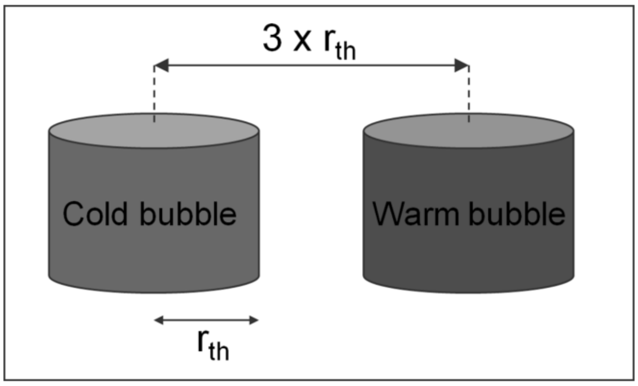


Figure 3.3: According to the design guidelines, the distance between a warm and a cold well should be three times the thermal radius (IF Technology).

In case the temperatures of both the warm and cold wells are on one side of the natural groundwater temperature (both above or below the natural temperature), some short-circuiting will increase the thermal efficiency. In that case, the distance between the wells can be decreased to around 1 to 2 times the thermal radius [Pyne, 2005]. For ATES systems that do not have a thermal balance, either the warm or the cold “bubble” will increase in size year after year. To prevent thermal breakthrough in the long run (e.g. over a twenty-year period), the distance between the warm and cold wells has to be increased. The extra distance that is needed will depend on the degree of energy imbalance, the groundwater flow velocity and the orientation of the wells with respect to the direction of groundwater flow.

According to the superposition principle, the *hydraulic impact* of production wells (decrease in hydraulic head) and injection wells (increase in hydraulic head) of a well field will partly compensate each other. The smaller the distance between the production and injection wells, the stronger the compensation will be. This principle can be used to minimize the area of hydraulic influence during well field design. Figure 3.4 shows the hydraulic impact for three well field layout options of a system consisting of 4 extraction and 4 injection wells. In Option A all production wells are grouped in one cluster (left-hand side) and all injection wells in the other cluster. This option results in a relatively large hydraulic impact in the surrounding area in comparison to Option B (alternating single wells) and Option C (2 clusters of 2 production wells and 2 clusters of 2 injection wells). Option A has the lowest investment cost due to the limited length of the piping that connects the wells. In Options B and C the length of the connecting piping increases (higher investment cost). These options can be used when the hydraulic impact of Option A is unacceptable or undesirable.

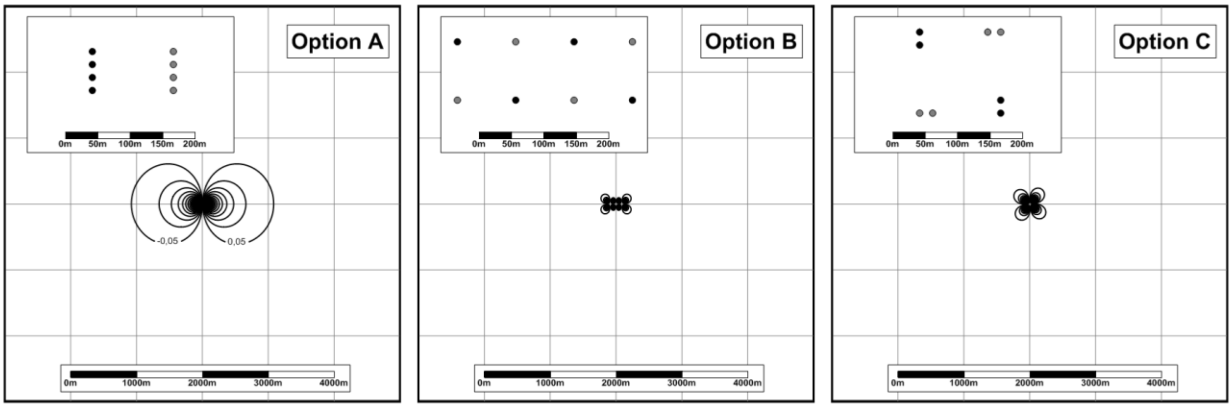


Figure 3.4: Calculated drawdown in the aquifer (0.05 m contours) for three different options of the well field layout. Groundwater extraction 330 m³/h [Rees 2016]

The *thermal impact* of an ATES system in the surrounding area can be relevant for existing groundwater users, especially for other ATES and open-loop GSHP systems. Minimizing thermal impacts is not only relevant on the scale of one project, but also on the scale of an area with several projects. Also the thermal impact of an ATES project can be influenced (reduced) by the well field lay-out. Figure 3.5 shows the hydraulic impact for two well field layout options of an ATES based DHC system consisting of 24 warm and 24 cold wells. In option A both the warm wells and cold wells are grouped in two clusters of 12 wells each. This option results in a larger thermal impact in the surrounding area in comparison to option B with 3 clusters of 8 warm wells and 3 clusters of 8 cold wells. The down side of increasing the number of well clusters, apart from the increasing piping cost, is the reduction of the thermal efficiency of the ATES system.

When the energy demand and the underground (aquifers and aquitards) have been characterized, hydro-geological and hydro-thermal modelling tools are used for the design of the ATES system and for calculating the environmental impact. Such modelling tools enable assessment of the injection pressures (relevant for well design), distance between the wells and well field layout (well field design) and the hydraulic and thermal impact of the ATES system on the underground (environmental impact).

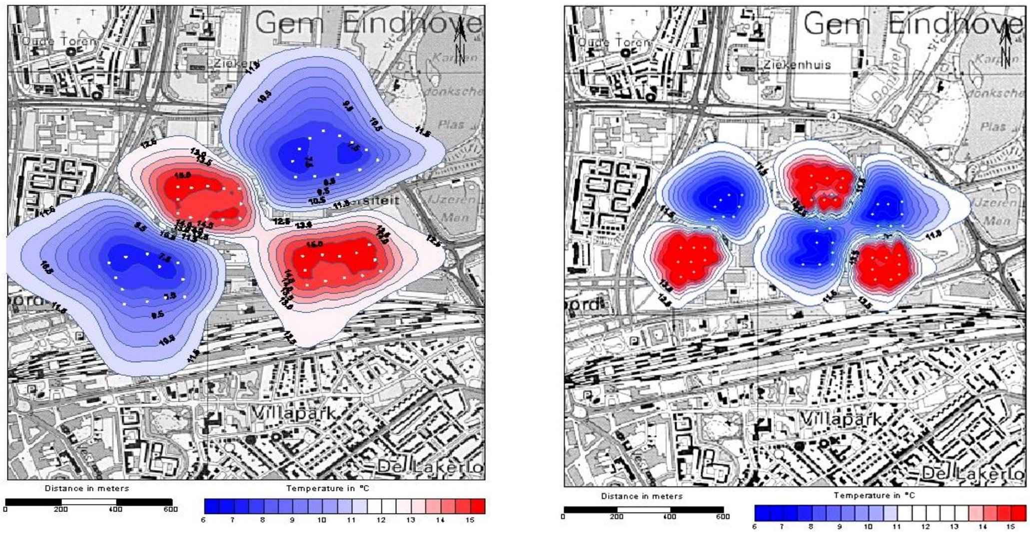


Figure 3.5: Calculated isotherms in the aquifer (0.5 °C contours) for two different options of the well field layout (IF Technology). Groundwater extraction 3.000 m³/h.

For modelling of the hydraulic and thermal impact of ATES systems, well established numerical groundwater modelling software is available, see Chapter 6.3. Figure 3.5 is a result from modelling with a hydro-thermal model.

3.2.4 Well equipment

In most wells, a well screen and well riser is installed and the well screen is gravel packed. In stable rock aquifers, a casing can be installed that reaches the top of the aquifer and the rest of the borehole can be left open. The thickness of the gravel pack varies between a minimum of 100 mm to a maximum of 300 mm. The grain size of the gravel and the size of the screen slots have to be adjusted to the grain size of the screened aquifer, or (the other way around) the layers that are selected for screening should not be too fine considering the grain size of the gravel pack. To prevent mixing of different types of groundwater and to be sure the water is extracted and injected at the depth selected, low permeability layers (e.g. clay, loam) that were perforated have to be sealed during backfilling.

When well development is completed (see hereafter), a number of components have to be installed in the well (Figure 3.6) and the wells have to be connected to the plant room, typically located in the building. In the plant room, the heat and cold is transferred from the groundwater loop to the building loop.

If groundwater contains high concentrations of dissolved gas, the pressure reduction that occurs during upward transport of the water can result in the formation of gas bubbles that can rapidly clog the infiltration well. Maintaining sufficient overpressure will prevent degassing and the associated risk of this type of well clogging. This is achieved with a pressure controlled automatic valve located in the infiltration well. Variable speed submersible pumps located in the well are used to match load conditions and to maximize the temperature drop between abstraction and infiltration. In this way, the pumping energy is minimized and the amount of thermal energy produced from a given volume of water pumped is maximized. However, maintaining sufficient overpressure in the groundwater loop will be a greater challenge with variable speed pumps than with fixed flow pumps.

To prevent corrosion, the material selection has to take into account the groundwater composition. The main aspects that influence the required corrosion resistance are salinity and the presence of oxygen. Many ATES systems that apply low injection temperatures (below 30˚C), use PVC for the well screens and well risers and plastic (mainly PE) for the connecting piping from wells to plant room and vice versa. In general stainless steel is used for the wellheads and for the piping in the well housing and around the heat exchanger. In fresh water without oxygen, stainless steel grade SS304 is generally applied, also for the heat exchanger. In case the groundwater is salt or brackish (and contains no oxygen), grade SS316 is used. In case of salt/brackish groundwater also containing oxygen, plastic is the preferred choice in combination with a titanium alloy for the heat exchanger. Use of other metals like carbon steel has led to corrosion problems [Pyne, 2005].

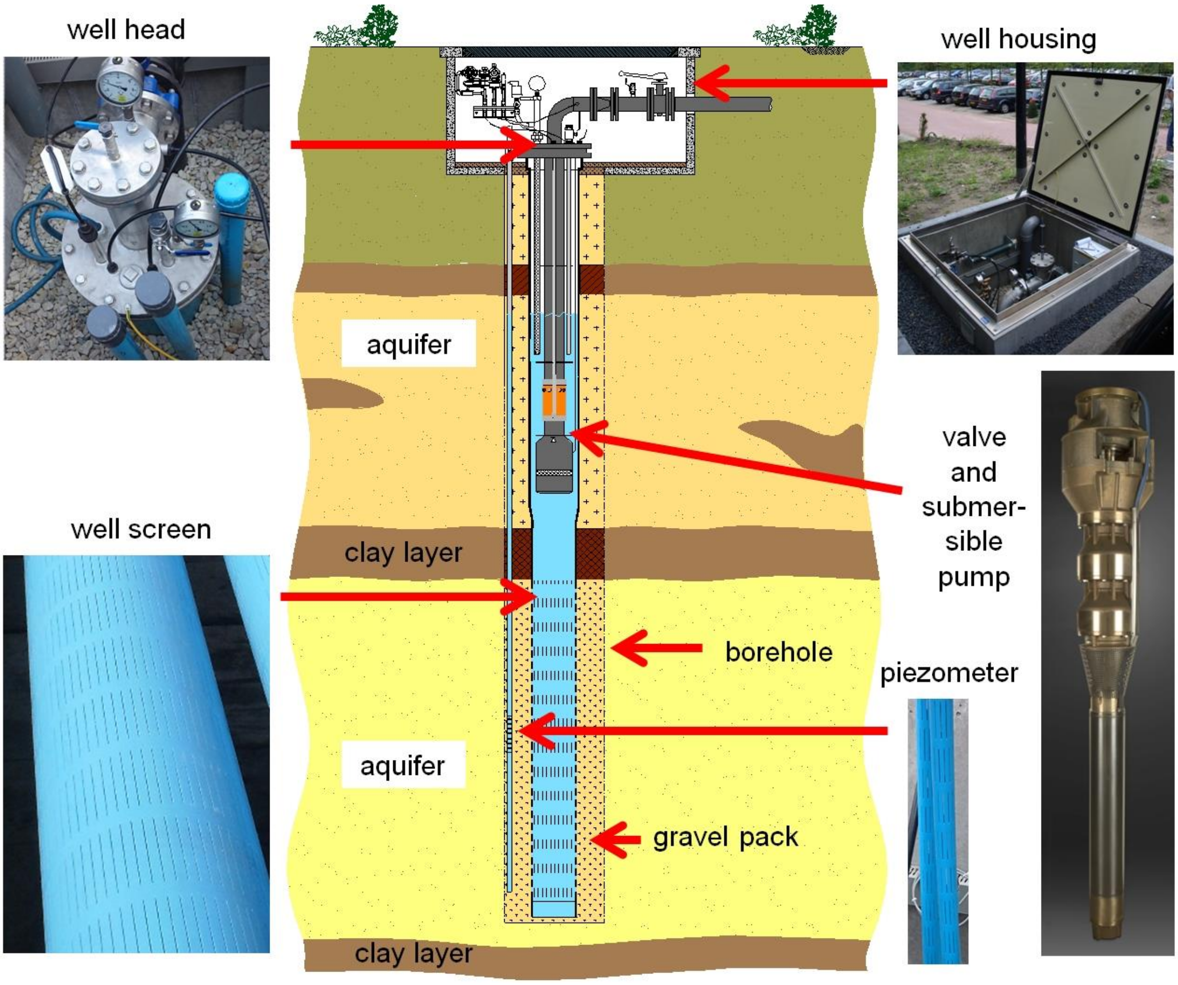


Figure 3.6: Schematic of a well in an unconsolidated aquifer and the associated components [Rees 2016]

3.2.5 ATES integration in DHC systems

Utility scale ATES projects consist of a well field with several groundwater production/ recharge wells, groundwater transport/distribution piping, heat pumps as well as warm and chilled water distribution piping. The system is providing heating or cooling, or simultaneous heating and cooling to several buildings. The groundwater circuit is hydraulically separated from the heating and cooling circuits inside the buildings by plate heat exchangers.

From the thermal energy distribution perspective, several system configurations can be distinguished (Table 3.2).

Table 3.2: Distribution system configurations

Heat pump location	**Distribution groundwater**	**Distribution chilled and warm water**
1. In centralized plant room for all buildings together.	Between well field and central plant room. Single, uninsulated piping (water is flowing either from warm to cold wells or from cold to warm wells).	Supply and return piping for warm and chilled water between central plant room and buildings, and inside buildings. Four-pipe system, insulated. Remark: DHW supply requires special attention.
2. In central plant room per building (also group of houses/apartment block). Remark: Best suited for ATES application.	Between well field and buildings. Two- or four-pipe system, piping not insulated.	Supply and return piping for warm and chilled water inside buildings. Four-pipe system, insulated. Remark: DHW make-up might be integrated in building plant room.
3. Distributed heat pumps in the buildings. Remark: Central heat exchanger per building is recommended for hydraulic separation ATES and building circuit.	Between well field and buildings. Two pipe system (supply and return), piping not insulated.	Two-pipe system (supply and return) inside buildings between heat exchanger and distributed heat pumps. Piping insulated. Supply and return piping for warm and chilled water after heat pumps. Two- or four-pipe system.

The majority of the utility scale ATES projects in Europe provide heating and cooling and most of these projects have a plant room per building (configuration according to Option 2 in Table 3.2.). For this configuration of an ATES based DHC system, the selection of the distribution system between the wells and the building plant rooms is summarized as a flowchart in Figure 3.7. If there is no simultaneous demand for heating and cooling (all buildings are either demanding cooling or heating), a two-pipe groundwater system (supply and return) will suffice. The two-pipe system provides either warm water or chilled water to the building plant rooms.

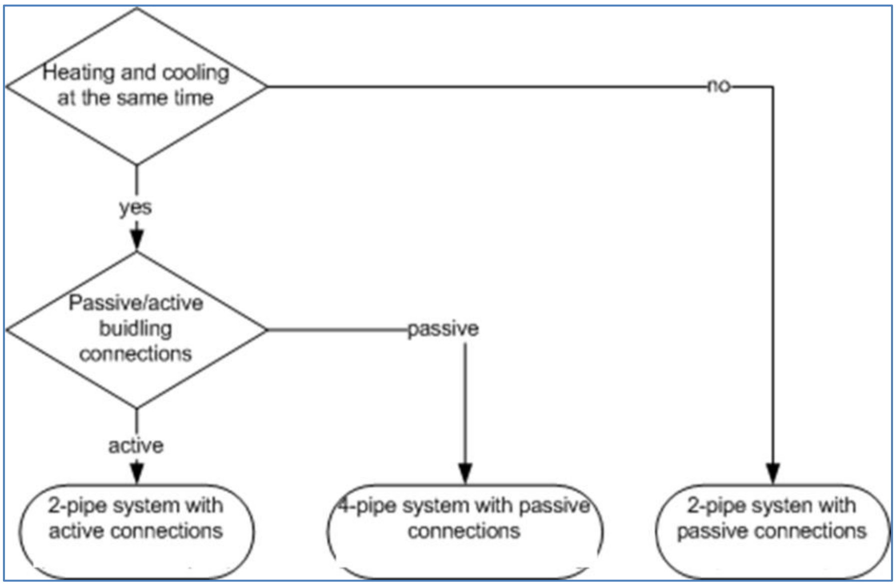


Figure 3.7: Groundwater distribution system selection flowchart (IFTech).

In the case of simultaneous heating and cooling demand, which is the most common situation for ATES-based DHC systems, both a two-pipe and a four-pipe groundwater distribution layout are possible. Figures 3.8 and 3.9 show a schematic representation of the four-pipe and two-pipe configuration.

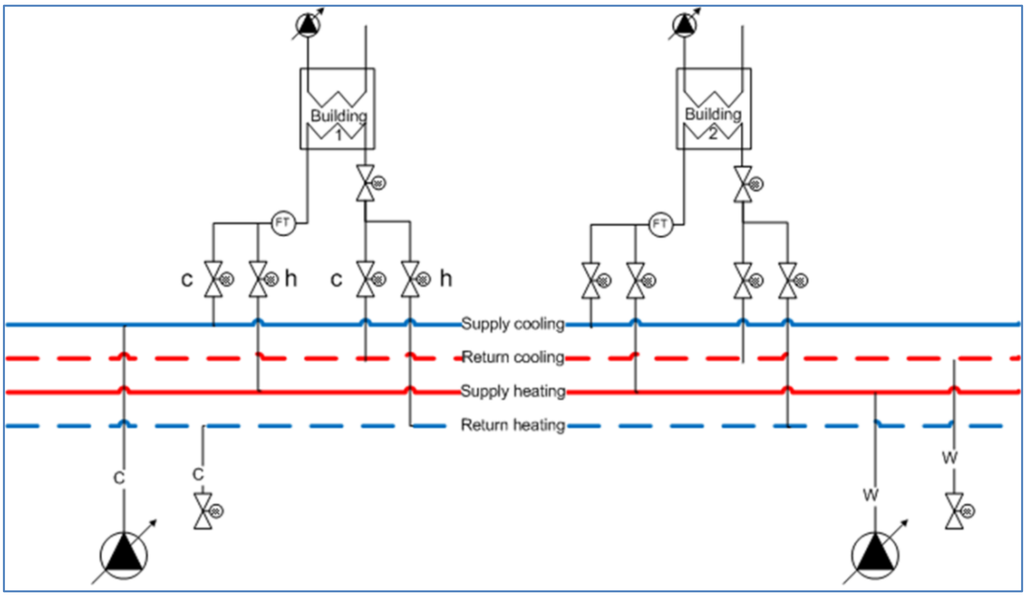


Figure 3.8: Four-pipe groundwater distribution, passive building connections (IFTech).

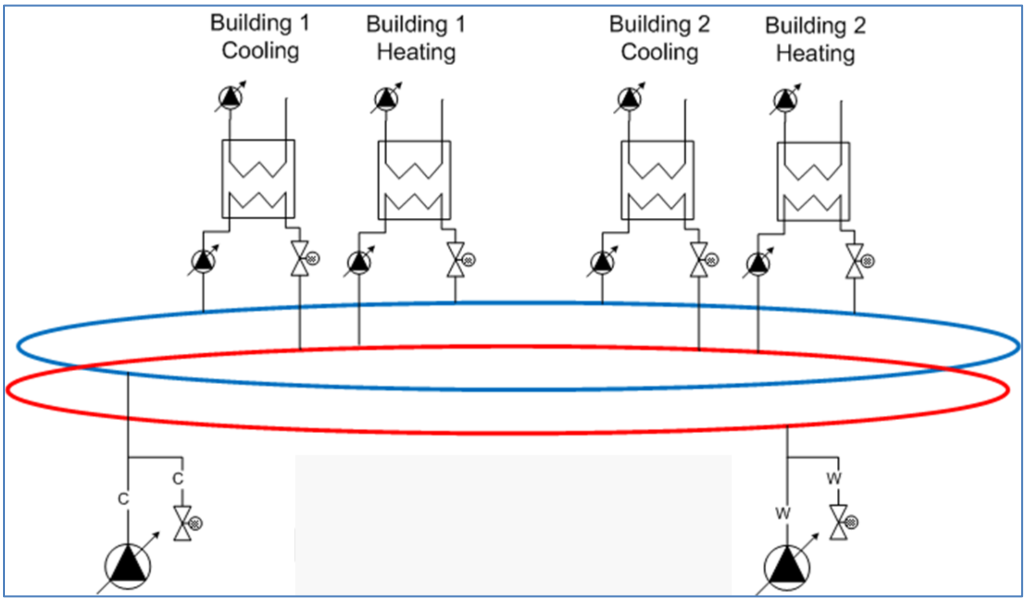


Figure 3.9: Two-pipe groundwater distribution, active building connections (IFTech)

In both the four-pipe system and the two-pipe system the flow of the groundwater in the ATES system is driven by the well pumps. In the four-pipe system, these well pumps also provide the pressure drop over the heat exchangers in the central building plant rooms. This is realized by maintaining a constant pressure difference between supply and return pipes of the groundwater loop. This building connection is defined as a passive building connection, see also Figure 3.8. By opening/closing valves, the building is connected to either warm water supply and return or chilled water supply and return. A separate control valve in the building connection controls the flow over the building heat exchanger by maintaining a pre-set return temperature or temperature difference between supply and return.

In the two-pipe system, the well pumps in combination with the valves in the injection wells maintain an equal pressure in the warm and chilled groundwater loop. Each building has its own pump to take water from the chilled water loop and return it to the warm water loop and vice versa (active building connection). The flow rates of the building connection pumps are controlled by the temperature of the return water, see Figure 3.9. In this example schematic the building is taking water from the chilled water pipe and returning it to the warm water pipe at a minimum temperature of 15 °C. It is important that this pre-set temperature condition is met, because a neighboring building might be taking water from the warm water pipe at the same time and the minimum supply temperature has to be guaranteed by the energy supply entity.

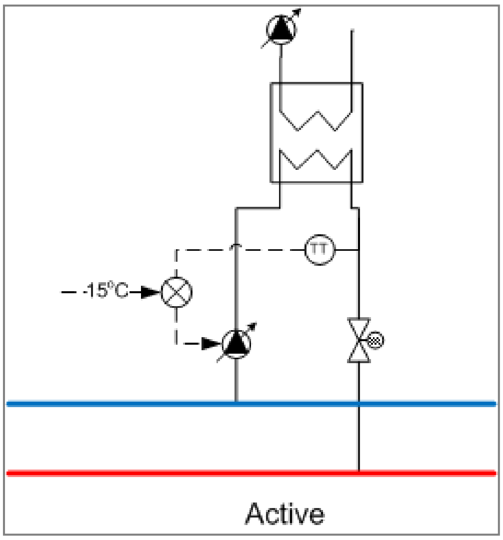


Figure 3.10: Active building connection (IFTech)

The two-pipe configuration is more complex regarding building connections and controls. The piping cost, however, is significantly lower than for the four-pipe groundwater distribution system.

Figures 3.11 and 3.12 depict the conceptual design of an ATES integrated with a local DHC network. A two-pipe groundwater loop with active building connections is applied in this example. The principle of operation for a building in winter mode and the ATES system in winter mode (ATES system heating mode and charging operation for the cold ATES wells) is displayed in Figure 3.11. In winter mode, groundwater is pumped from the warm wells to the cold wells and the warm water is used by heat pumps as a low temperature heat source. The water that is cooled down by the heat pumps is discharged into the cold wells. The heat pumps provide heating for the buildings in winter operation. Note that with this winter mode configuration:

- Some buildings can still be in cooling mode while the remainder are in heating mode. In heating mode of the ATES system, the net flow in the groundwater loop will be from the warm wells into the cold wells.
- The warm well discharge temperature indicated in Figure 3.11 is resulting from the summer operation.

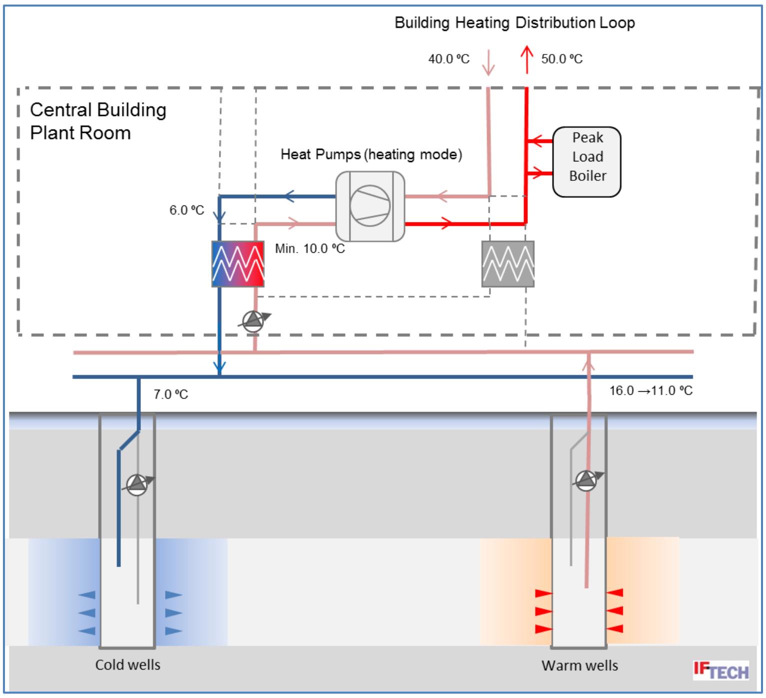


Figure 3.11: Principle of ATES system in heating mode - winter operation (IFTech)

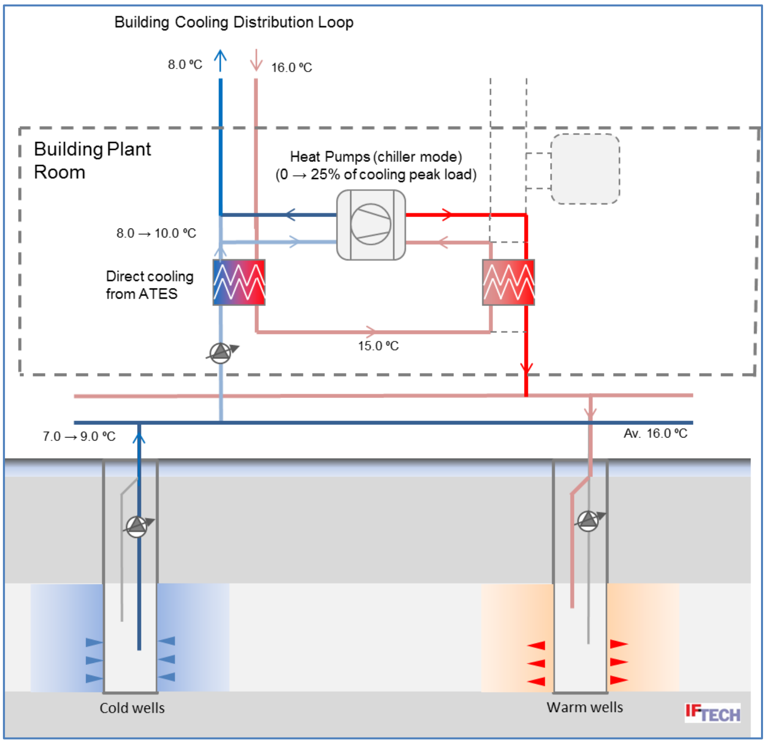


Figure 3.12: Principle of ATES system in cooling mode - summer operation (IFTech)

The principle of operation for a building in summer mode and the ATES system in summer mode (cooling operation) is displayed in Figure 3.12. In cooling mode (discharging operation for the cold ATES wells) groundwater is pumped from the cold wells to the warm wells. Direct cooling to a building in cooling mode is supplied by thermal energy exchange over a plate heat exchanger.

At the start of the cooling season, when the cold wells are fully charged, the extraction temperature from the cold wells will be close to the charging temperature. As a result of the temperature drop over the plate heat exchanger (in this example 1.0 K) both during charging and discharging, the temperature supplied to the building distribution loop will be 8.0 °C. During summer operation the extraction temperature from the ATES wells will gradually rise.

The heat pump(s) in the building plant room are utilized in chiller mode for additional cooling in order to have a guaranteed cooling capacity and temperature. In this example it is assumed the annual heating demand of the building is significantly larger than the annual cooling demand. In order to maintain a thermal energy balance for the aquifer and to avoid low abstraction temperatures in heating mode, part of the heating is not supplied by heat pumps but by a peak load gas boiler, located in the plant rooms of the buildings with the largest annual heating demands.

3.3 Implementation experiences

3.3.1 Construction

The aim of well drilling, completion and development (cleaning) is creating a well with a good specific capacity that produces a minimum amount of fines and is not prone to clogging.

The first step is to use a *drilling technique* that minimizes the intrusion of drilling mud into the aquifer and enables obtaining reliable soil samples, needed for careful selection of the depth interval to use. In the Netherlands, reverse rotary drilling is the industry standard for well drilling in unconfined aquifers to meet this requirement. Since the drilling phase determines the chance of success and the effort needed for well development, it is important to minimize the amount of drilling mud used and avoid the use of a type of mud that is hard to remove afterwards (for that reason, the use of bentonite as a drilling mud additive should be avoided). Similarly in rock drilling, care is required to prevent closing off of the pores or fractures. For drilling a larger diameter well, a working space is required of about 400 m^2. Figure 3.13 gives an impression of the working area.

During well drilling, drilling mud (or fines from overlying ground layers) can penetrate the part of the formation adjacent to the borehole. A variety of well development techniques is used to remove these mud remnants and the fines present in the aquifer. An overview of well development techniques is available in literature [e.g. Houben et al. 2007]. Since water has to be infiltrated and extracted for many years without significant clogging, there are a number of strict requirements that the drilling company has to meet: a specific well capacity of at least 80% of the theoretical value, a membrane filtration index (MFI) value below 1 to 2 s/l^2 and less than 0.01 to 0.1 mg/l of suspended solids (fines) in the produced water. The effort required for the development of wells for ATES systems (and the associated cost), is considerably higher than for wells that are only used for production. A couple of weeks of development time is not exceptional. Even after this effort, there are many examples of wells that show improvement of the specific capacity after some time of use. Apparently, part of the drilling mud remnants was not removed during well development and was mobilized during the operational phase. During preventive maintenance in the operational phase, these mobilized fines can be removed by extracting groundwater at maximum capacity from the injection well for a short period of time and disposal of the extracted water and the suspended fines.

In coarse grained, poorly sorted unconfined aquifers, the development of a natural gravel pack may be the best option [Misstear et al. 2006]. A natural gravel pack is created by removing the fine fraction from the formation close to the well during well development. The remaining course fraction of the formation is left behind, creating a natural gravel pack around the well screen. In this type of wells it may be needed to repeat well development actions several times during the operational phase when the amount of fines in the extracted water increases too much.

Figure 3.13: Overview well drilling site (IF Technology)

3.3.2 Operation and maintenance

The well pump is by far the major electricity consumer in the groundwater loop of an ATES system. Due to construction limitations, the efficiency of an in-line submersible pump is relatively low (in the range 0.60-0.70) as compared to a high efficiency circulation pump. To improve the overall energy efficiency of the groundwater loop, it is accordingly necessary to minimize the pressure difference provided by the pump. However, the possibilities to realize this are rather limited because part of the pump pressure required is more or less fixed by the static head from groundwater level to surface and the draw-down in the production well.

The other important factor influencing the pump electricity demand is the loop flow rate. The groundwater flow rate can be reduced significantly by:

- increasing the temperature difference between groundwater extracted and groundwater injected. This is not only a groundwater loop issue, but also a function of the temperatures and flow rates in the building loop. So the groundwater loop efficiency cannot be fully optimized without taking into account the interaction with the building system.

- maintaining the temperature difference in the groundwater loop for building partial load conditions. This can be achieved by applying variable speed well pumps in combination with pressure maintaining valves in the infiltration wells.

To have only little effect on the overall DHC system energy efficiency, the ratio between thermal energy provided by (or absorbed by) the groundwater loop and the electricity required by the well pump(s) should be in the range to 30-40. This implies that providing 30-40 kWh of thermal energy requires one kWh of electricity.

To optimize the energy performance of a DHC system with ATES and heat pumps, the interaction between groundwater loop and building loop is even more important. This is illustrated in Figure 3.14, showing the relevant temperatures for an ATES-HP system in cooling mode. For this example it is assumed that:

- The natural ambient groundwater temperature in the aquifer is 14.0 °C.
- The supply temperature of the building cooling system is 8.0 °C and constant.
- The return temperature of the building cooling system is 16.0 °C and constant.
- Charging the cold wells in winter is at a constant temperature of 7.0 °C.
- The temperature difference over the heat exchanger between groundwater loop and building loop is 1.0 °C.

The extraction temperature (discharging temperature) from the cold wells will increase slowly during the summer season as a result of conductive and convective thermal transport in the underground and eventually go to the ambient groundwater temperature. As long as this temperature is well below the building return temperature, part of the cooling can be provided directly from the groundwater loop (dashed area in the Figure), which is very energy efficient due to the low electricity consumption involved. The remainder of the cooling should be provided by the heat pumps in cooling mode.

Figure 3.14 shows that direct cooling is stopped when the abstraction temperature exceeds 13.0 °C (the so-called cut-off temperature). This implies that the return water in the building system still might be cooled down 2.0 °C, taking into account the 1.0 °C temperature drop over the heat exchanger, but continuing abstraction will reduce the ratio between thermal energy provided by (or absorbed by) the groundwater loop and the electricity required by the well pumps to an unacceptable level.

As can be seen from this example, the optimization of the *integral ATES heat pump system* is important for the performance of the ATES loop. In particular the charging temperature of the cold wells in winter and the building loop return temperature in summer are strongly influencing the system thermal efficiency in cooling mode by influencing the ratio between direct ATES cooling and heat pump cooling.

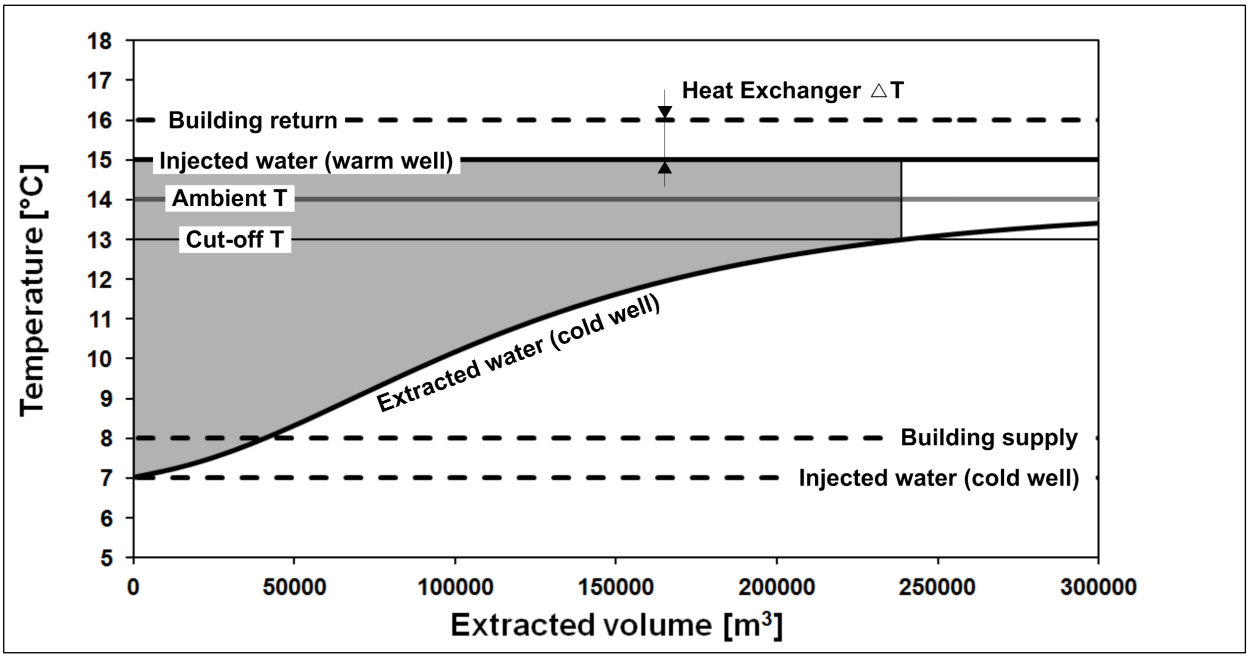


Figure 3.14: Example of the interaction between the building chilled water supply and return temperatures and the discharge temperature from the cold wells [Rees 2016]

Monitoring an ATES system as part of a DHC network may have various objectives. Firstly, monitoring may be required as part of the *groundwater abstraction and discharge license or consent*. In general, this monitoring is restricted to drawdowns in the wells and the water and energy flows in the groundwater loop (e.g. m^3/month and MWh/month) and focused on the impacts of the ATES system on the aquifer (and via the aquifer on nearby interests).

Monitoring and maintaining the thermal balance in the underground has become the most important operational and permit condition for an ATES system. For example, in the Dutch legislation on the use of the underground for shallow geothermal purposes, it is stated that “the total amounts of heat and cold, expressed in MWht, which after commissioning are added to the ground by an open loop ground energy system have to be equal at least once in the first period of five years and after this period at least once in the following periods of three years [Ministry IenM 2010]”. Figure 3.15 illustrates the way how monitoring might be set up to show whether this condition is met or not.

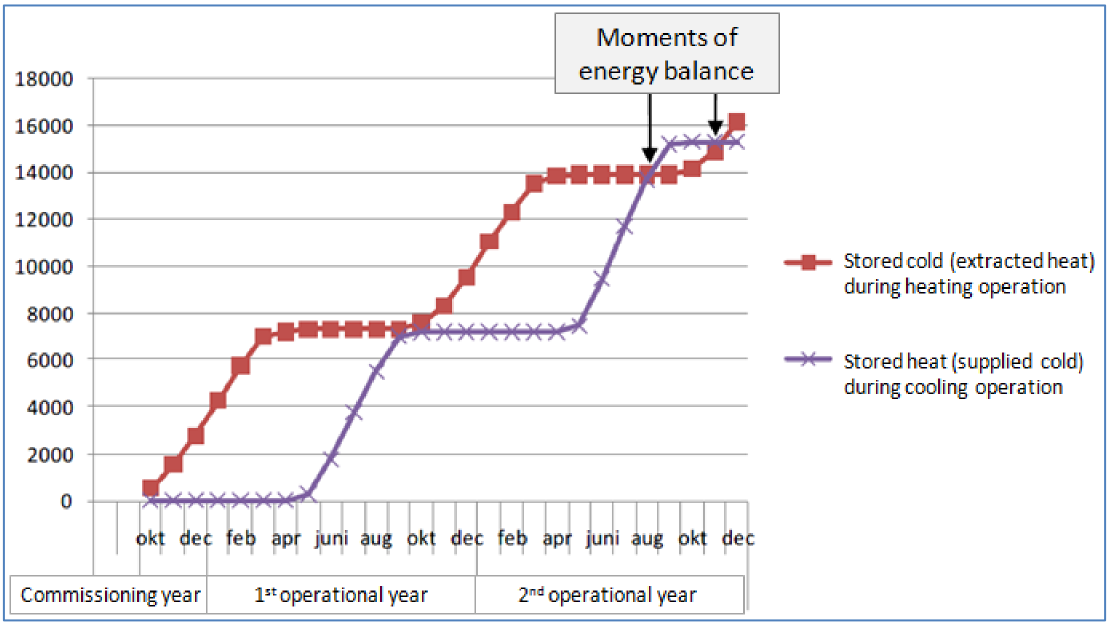


Figure 3.15: Monitoring the energy balance in the underground [SIKB 2012]

Secondly, monitoring can be focused on *preventing/scheduling maintenance*. For the groundwater loop, the major issues are detecting a leakage in the loop and deterioration of a well at an early stage. A leakage is detected from pressure loss in the loop during stand-still periods. A good way to monitor the well quality is by trending the specific well capacity, i.e. yield in m^3/h divided by drawdown in m, as derived from monitoring results of the groundwater flow rate and the water level in the well. An early warning system of potential well clogging is important, since the clogging process accelerates over time. When a clogged well is redeveloped in time, it can be used for at least several decades. However, when a well has been severely clogged once, it will keep clogging rapidly after each cleaning action.

Last but not least, monitoring data can be used to determine and *optimize the energy performance* of the open-loop system. Because of the interaction with the building part of the system, this will require monitoring data from the building system also. For this purpose, the energy flow, the supply and return temperatures, as well as the electricity consumption of the heat pumps and circulation pumps need to be monitored with a five or ten minute interval for the groundwater loop and the building heating and cooling loops.

In practice, the actual load and/or energy demand of buildings often turn out to be (significantly) different from the values available in the design stage. This may negatively influence the thermal efficiency of the ATES system:

- when the actual thermal load is lower than designed for, the ATES system will have more part load operation, resulting in a higher electricity consumption and increased thermal losses from transport piping per MWh delivered;

- when the thermal balance in the underground is significantly changed due to the different annual heating and/or cooling demand of the buildings, provisions might be required to restore the balance in order to avoid interference between extraction and injection wells or undesired environmental impacts.

Furthermore, the return temperature from the building loop might turn out to be higher (heating mode) or lower (cooling mode) than designed for. This will result in additional electricity consumption for transportation pumps (including well pumps) and in a reduction of the direct cooling contribution.

Performance monitoring and optimization of larger ATES systems, at least during the warranty period, is consequently important to be able to deliver the energy efficiency that the system was designed for.

In order to guarantee trouble-free operation of the ATES system for many years, preventive maintenance will be required. This preventive maintenance will require one to two site visits a year, depending on the level of remote monitoring. The focus of the preventive maintenance is on avoiding well deterioration and well pump failure.

The preventive maintenance of the ATES system includes:

- visual inspection of well heads, valves, transmitters and heat exchangers on leakage and corrosion. Removing dirt from well housings;
- checking the state (deterioration) of the well pumps by measuring the electrical resistance between the phases;
- twice a year back-flushing of each of the injection wells at maximal capacity for about one hour per well to remove collected fines. Back-flushing is scheduled preferably near the end of the winter season and the end of the summer season. To remove the fines from the system, the groundwater extracted during back-flushing is not returned to the aquifer, but discharged to (e.g.) the sewer. During back-flushing the specific capacity of the wells is also assessed. This action can be performed automatically or from remote using the ATES control system.
- assessment of the proper functioning of the well pump frequency drives, the valves, the sensors and indicators (temperature, pressure and flow), the safeguards, as well as the control unit.

3.4 Cost analysis of large-scale ATES systems

The investment cost for design, construction and commissioning of a number of ATES systems applied in a DHC network has been analyzed. Because of site specific circumstances, as well as the fact that these projects are in various countries, each with its own construction industry and regulations, the spread in the cost is rather large.

Some additional remarks:

- All costs provided below are in Euro’s, 2017 price level. The cost data from older projects has been adjusted based on the price index for civil construction works from the Netherlands.
- The battery limit between ATES system and building systems is behind the heat exchangers that separate the groundwater circuit from the building circuits. So, the heat pumps etc. are not included in the cost of the ATES system.
- The control and montoring provisions for the ATES system are included, not the same for the building systems nor the BMS.
- Plant room space is not included in the cost of the ATES system.

Figure 3.16 shows the overall cost of the ATES systems as a function of the design cooling capacity (kW) of the system. The rationale for this is that most of the ATES cost components are flow rate, and thus kW, related and far less seasonal storage capacity, and thus MWh, related. Increasing the number of full load hours of an ATES system only slightly influences the investment cost of the system.

The breakdown of the investment cost by the main cost components is shown in Figure 3.17 as a percentage of the overall investment cost. Note: these percentages are averaged for the projects considered.

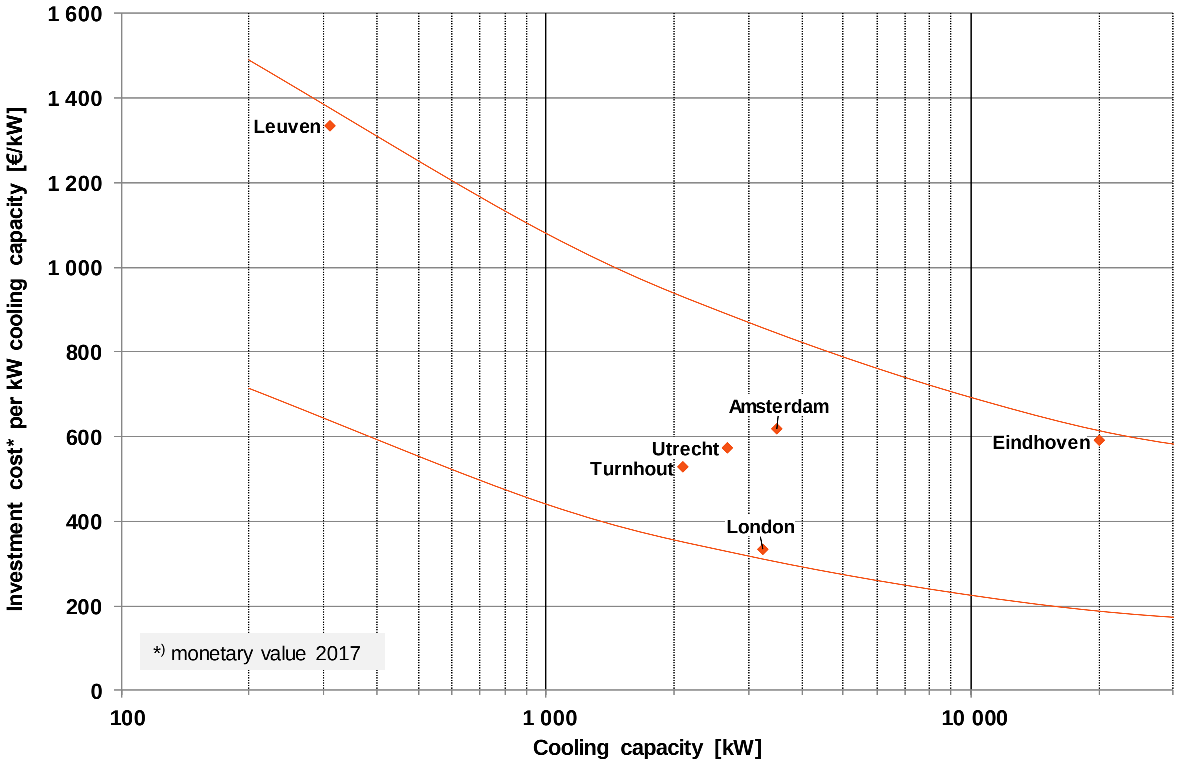


Figure 3.16: Overall investment cost large-scale ATES systems (data source: IFTech)

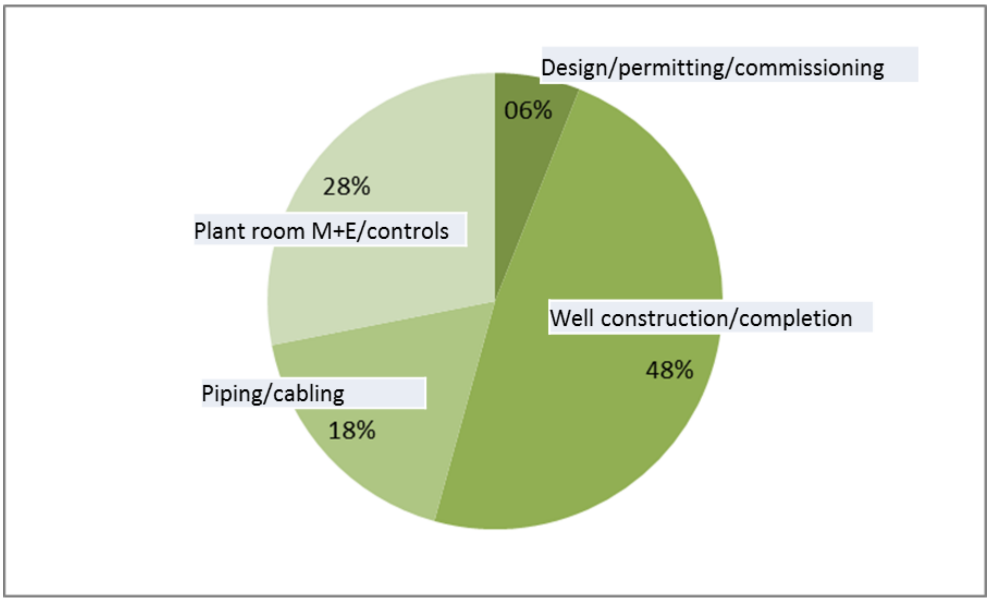


Figure 3.17: Breakdown of ATES investment cost (IFTech)

4 PTES design concepts

4.1 Introduction to PTES

In Pit Thermal Energy Storage (PTES) systems, large, shallow dug, lined pits with insulated covers are used to hold the thermal storage medium. PTES has mainly been developed with the purpose to extend the solar fraction in solar thermal district heating systems to 50% or more. The development of PTES has mainly taken place in Sweden, Germany and Denmark. The Swedish and Danish systems incorporate floating lids and use water as storage medium.. The German systems have been designed with fixed lids and use of gravel, soil or sand and water as storage medium. Most of the content in this chapter deals with the Danish PTES development.

In Denmark, the development of PTES took place at Danish Technical University (DTU) in the 1980s. The driving force was to lower the price of solar heat, and the researchers developed a design applying the concept of a truncated pyramid placed upside down in the ground and with a floating insulated lid. The original design used clay for tightening of the banks and bottom. A pilot project having a 1,500 m^3 storage following this concept was built in Ottrupgård in Northern Jutland in 1994-95.

Since the first pilot storage in 1994, the Danish PTES concept has been further developed with the construction of a 10,000 m^3 pilot storage in Marstal on the island Ærø in 2003, a 75,000 m^3 full scale storage in Marstal in 2011-12, a 60,000 m^3 full scale storage in Dronninglund in Northern Jutland in 2013 and three full scale storages in Gram (122,000 m^3), Vojens (203,000 m^3) and Toftlund (85,000 m^3) in Southern Jutland from 2014 to 2017. At present a 70,000 m^3 storage is planned in Høje Taastrup near Copenhagen.

Advantages and disadvantages for the Danish PTES concept are:

Advantages:

- Quick charging and discharging
- Can be utilized also as short time storage
- A closed construction
- Water as storage medium means good stratification and high thermal capacity/m^3
- The same storage can be used as hot water and cold water storage at the same time due to the inherent stratification

- Relatively low cost construction where suitable ground conditions exist

Disadvantages

- Large land area required can be difficult to find in urban centres
- Lifetime of liner material and lid construction still being demonstrated
- Higher construction costs in areas having high ground water levels and where excavated soil is not suitable for use in the bank construction
- Maximum temperature 90 °C, due to liner material properties.

4.2 Design concepts

4.2.1 Overall design

The main driver in the development of the Danish PTES concept has been the price for stored solar heat. In the 1990s, the overall objective was to construct long term thermal storages for a price below 200 DKK/m^3 (27€/m^3) including inlet and outlet, connection pipes, heat exchangers and pumps, valves, etc. in the storage loop.

To reach this objective the total construction and the different parts of the construction have to be economically optimized.

The total construction cost for large long term pit storages (>50,000 m^3 water equivalent) is minimized if the construction can utilize the soil excavated with a soil balance such that no material has to be added or to be removed from the building site.

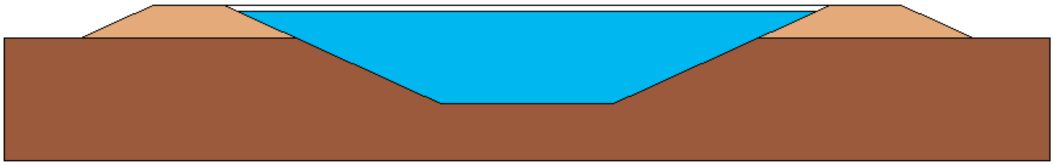


Figure 4.1. Principle sketch of a pit heat storage cross section (PlanEnergi)

To make this possible, the excavated soil has to be of a quality that can be utilized as banks. Too much silt in the soil can be a problem and a geotechnical investigation has to confirm that the excavated soil can be utilized as banks.

Insulation is one of the most expensive elements of PTES designs. As such, the use of insulation material must be optimized. Analysis carried out by DTU in the 1990s for an example of a 100,000 m^3 PTES [Wesenberg et al. 1991] showed that insulation on the banks and on the bottom of the pit is not economically feasible, nor is it economically feasible to extend the lid insulation to cover the top of the banks. It should be noted that this result is dependent on the temperatures in the storage, local cost of insulation materials and other boundary conditions, and needs to be confirmed when conditions are changed.

The **storage medium** used in Danish PTES is water since water is inexpensive, is environmentally safe, has high thermal capacity and allows stratification pumping and high charge and discharge capacity. Since the thermal capacity for water is approximately 1.16 kWh/m^3/K compared to 0.8-0.9 kWh/m^3/K for soil and rock, filling the storage with gravel or stones will reduce the thermal capacity. However, water can be corrosive due to the presence of oxygen and bacteria. Therefore the water in the Danish PTES storages is treated similarly to water in the district heating network (pH 9.8, removal of lime and removal of salts).

For tightening the storage polymer liners are generally used with high thermal resistance. Metal liners can also be used, although they have been found to be cost prohibitive. Polymer liners as polypropylene (PP) and polyethylene (PE) are relatively inexpensive and easy to install with well documented welding and testing techniques. Therefore they are widely used for geomembranes. The welding process is shown in figure .

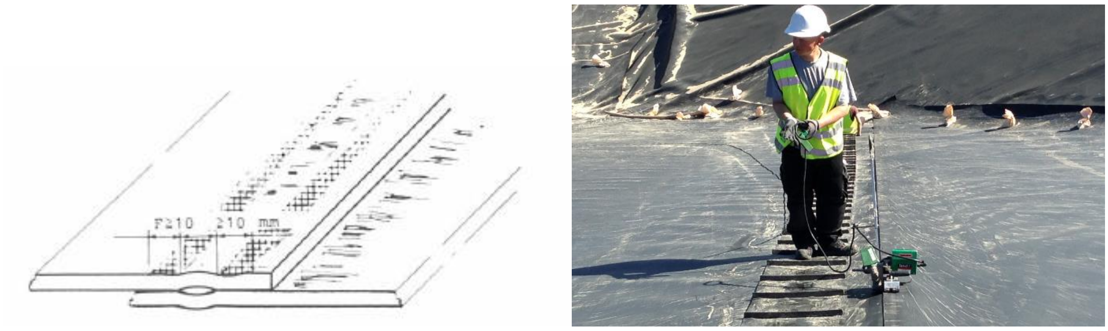


Figure 4.2: Double welding of a HDPE liner. The welding can be tested by applying pressurized air to the air channel between the welding seams. (PlanEnergi)

Water vapour permeability of polymer liners can impose issues in PTES design, as the permeability rate is strongly temperature dependent. This issue is not a factor for metal liners. As such, the selected liner material for the PTES design requires careful consideration based upon expected operating temperature and acceptable leakage rate. High density polyethylene (HDPE) liners have the lowest water vapour permeability compared to other geomembranes. At 20°C the water vapour permeability is around 0.03 g/m^2/day for a 1 mm liner. Supplier data is limited for temperatures above 60°C but experiments have shown a water vapour permeability for a 2.5 mm liner of approximately 1.5 g/m^2/day at 80°C [Vang Jensen 2014]. For PP the water vapour permeability is approximately 4 times higher than HDPE. For comparison, low density polyethylene (LDPE) has a water vapour permeability 45 times higher and PVC 115 times higher than HDPE.

Having a floating **PTES lid,** as used in Danish designs, avoids an expensive structural system and prevents the need to use steam or nitrogen as corrosion protection between lid and water, otherwise required if an air gap was present. The lid is described in detail in the next section.

4.2.2 Lid construction and tightening

The lid construction and tightening of PTES in Denmark has been continuously developed since the first 1,500 m^3 pilot storage in Ottrupgård. In the 1994-1995 pilot storage in Ottrupgård the lid was made from prefabricated cold store panels with tongue and groove construction. The insulation material was polyurethane (PUR) foam with stainless steel sheeting on the water side and galvanized iron plates coated with plastic on the upper side. The elements were joined with silicone from beneath (see Figure 4.3) and joints were sealed with a bitumen tape.

Figure 4.3. Mounting of cold store elements in Ottrupgård (PlanEnergi)

As previously noted, clay was used to water-tighten the Ottrupgård pilot storage. An EPDM liner (not welded, since it had not to be tight) was also included with drainage bands below the 85 cm compressed clay, geotextile and flag tiles.

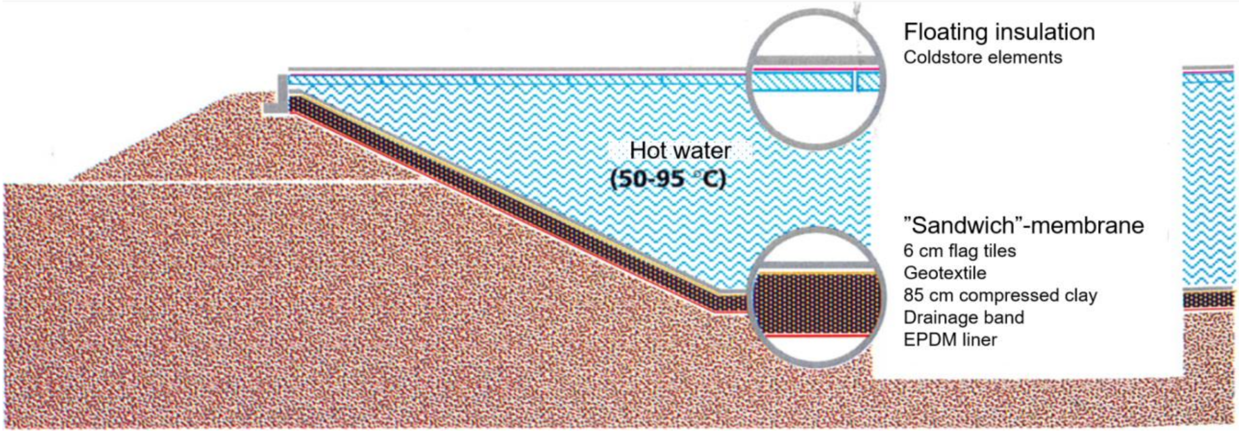


Figure 4.4. The storage construction in Ottrupgård (PlanEnergi)

The storage in Ottrupgård is still in operation, but the construction was not replicable for larger storages for the following reasons:

- Extensive rain experienced at the site during construction caused significant delay, with this step taking several months to complete. As such, construction with clay for tightening was found to be very weather dependent and expensive.
- Installation of the lid panels was found to be complicated and labour intensive, resulting in higher than expected costs.

To find a lower cost tightening methodology, polymer liner materials (PP and HDPE) were tested at Danish Technological Institute in Copenhagen. Testing was completed under temperatures of 100, 107 and 115 °C. The lifetime was mainly defined as the point of time when the extension that causes break was reduced to 50 %. The lifetime of the liners tested is shown in Table 4.1.

Table 4.1: Lifetime of HDPE liners

Temp ºC	Liner 1	Liner 2
100	400 days	530 days
107	200 days	330 days
115	120 days	180 days

The lifetime for the same liners under the temperature conditions expected at that time (<70 °C) in the top meter of a storage was calculated as 22.6 years (liner 1) and 24.3 years (liner 2) [PlanEnergi 2005]. Furthermore, the water tightness might be preserved for an even longer period of time provided the liner is not submitted to physical load. Therefore, it was decided to use HDPE for the side and bottom liners in any future PTES designs.

To find a new cover solution several constructions were investigated. One proposal was to use PP-modules with insulation inside, but test results showed inadequate lifetimes for the PP-modules. Another solution was to use stainless steel, but it was found to be cost prohibitive and also difficult to implement.

Since the HDPE-liner could withstand the storage water temperatures, the investigations ended up with a “roof construction” where a HDPE liner is placed on the surface of the water and the roof is built up with the following layers (from the bottom).

- 2.5 mm HDPE
- Vapour barrier (vapour diffusion through the HDPE-liner would cause condensation in the insulation of the lid).
- Geotextile (for protection of the vapour barrier and liner).
- Steel grid (to maintain the shape of the cover during extensions due to temperature).
- 75 mm mineral wool.
- 125-335 mm EPS formed as a roof
- Roof foil with ventilation caps.

The construction was implemented in Marstal in 2003 for a pilot that is referred to as the SUNSTORE 2 project. The design is shown in Figure 4.5.

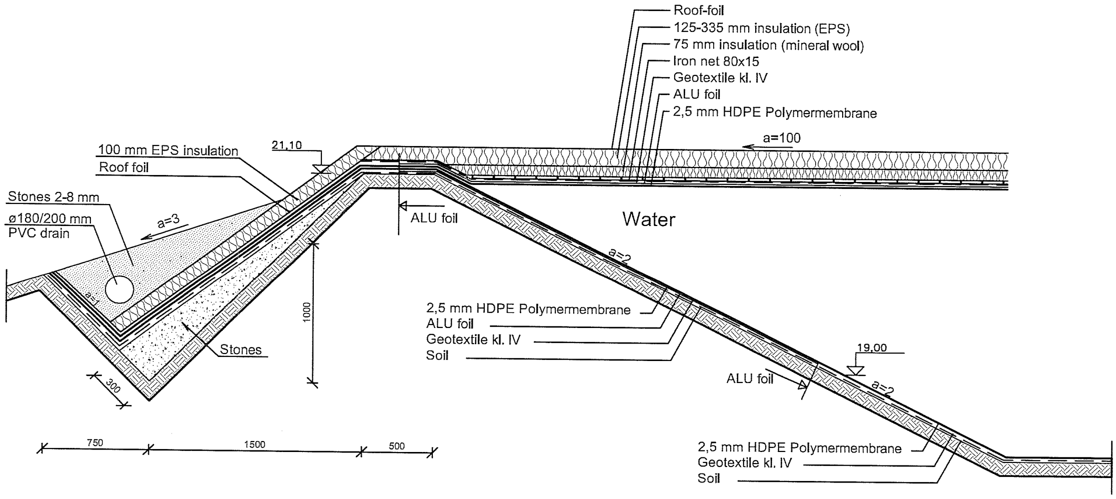


Figure 4.5. PTES construction in Marstal (SUNSTORE 2) (PlanEnergi)

The SUNSTORE 2 design did solve the cost challenge for both tightening and lid construction compared to the Ottrupgård design. However, the SUNSTORE 2 design was not free of operational issues. After two years of operation a leakage developed in the manhole, due to the presence of improper HDPE material, and caused water infiltration into the lid insulation. Additional problems were also experienced, including:

- Air bubbles formed as the storage water was heated creating an air gap that caused the lid to lift by up to ½ meter.
- Inadequate drainage of rain water resulted in water pooling around the ventilation caps.
- The vapour barrier failed due to the temperature of the water.

The original goal for the SUNSTORE 2 project included achieving the following design criteria:

- Lifetime: >20 years
- Heat loss from cover: <0.15 W/m^2/K (corresponding to 300 mm mineral wool)
- Price level for >50,000 m^3: <30 €/m^3

The objective was now for future storages to still meet these criteria and at the same time solve the problems experienced in the Marstal pilot. This resulted in new investigations of materials and constructions of the lid.

Insulation materials considered included mineral wool, EPS, PUR, Perlite, Leca (expanded clay), Poraver or Mussel shells. Having the experiences from SUNSTORE 2 in mind, mineral wool and EPS were eliminated as viable options as they were found to be too vulnerable if water infiltration into the lid occurred. Perlite was expected to be too difficult to control during implementation. Poraver was too expensive (three times more expensive than Leca). Mussel shells are heavier than water, and therefore must be combined with additional materials to be effective, and will sink to the bottom of the PTES if the lid breaks [PlanEnergi 2011].

The remaining viable options were PUR and Leca. Later, Nomalén, a PE/PEX product sold in mats was found to also be suitable.

Liner materials being considered include polymer liners (HDPE or PE) and metal liners. Two additional HDPE-liners were tested for expected service life under varying conditions in 2010-11 and 2012-13. The result can be seen in Table 4.2 compared with liner 1 and 2 earlier tested. A fifth HDPE liner that is better than the four already tested is still being tested as of 2018. In general, testing results indicate that HDPE liner materials have improved in terms of expected service life under high temperatures.

Table 4.2: Service life for HDPE-liners

	Service life (years)			
Temperature (° C)	**Liner 1**	**Liner 2**	**Liner 3**	**Liner 4**
90	2.5	3.2	2.9	4.3
80	6.1	7.2	10.0	10.0
70	25.9	17.0	15.6	23.0
60	43.7	42.4	35.9	52.9

Metal liners could solve the problems with moisture infiltration into the insulation. Steel and aluminum have been investigated [PlanEnergi 2015]. Aluminum liners are not appropriate since the pH in the storage water can be as high as 9.8 in district heating systems, which can result in corrosion of the aluminum. Stainless steel liners can stand the temperatures and are tight. But the price for the stainless steel liner material is a factor of 3 higher than for the polymer liner. Furthermore, welding is complicated, as induction welding is required to avoid deformations. As well, and the metal liner coils are just 145 cm in width, compared to 700 cm for HDPE, meaning many more seams and higher implementation cost.

Lid constructions: Two different lid constructions were developed taken the above mentioned design conditions, problems and material conditions into account [PlanEnergi 2015]. The first solution is based on Leca as insulation material. For the **Leca solution** the problems in the SUNSTORE 2 concept were expected to be solved as follows:

The construction: Despite the use of automatic floatvents, practical use of the SUNSTORE 2 storage demonstrates that air pockets are formed below the floating lid containing up to several m^3 of air. This happens because the water in the storage is not contained in a hermetically closed system, causing air to be released when the storage is charged at the relatively high temperatures for this process. For the Leca solution more efficient air vents are used. For security reasons ventilation hoses will also be added in ten spots of the foil. These hoses will be made of HDPE material of the same temperature resistance as the liner and the feed through will be secured with double welding. They will lead into ten inspection wells in which moisture in insulation can be surveyed and eventually pumped out and dried.

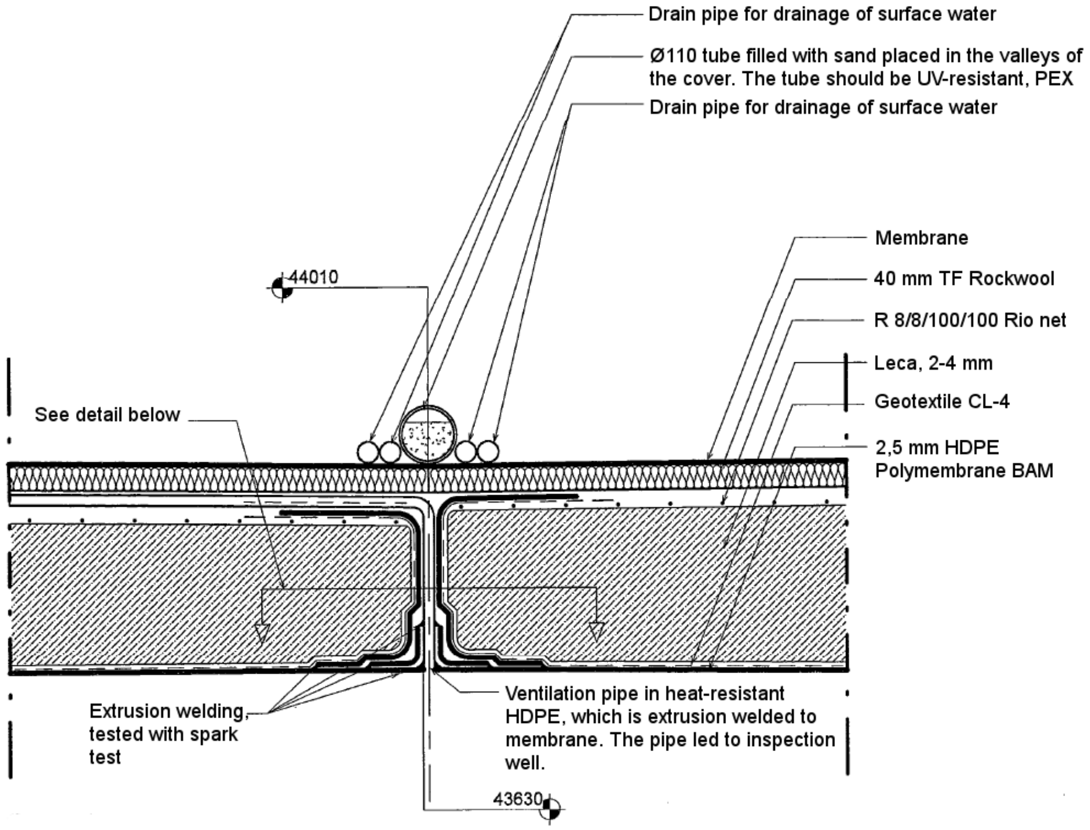


Figure 4.6: Section of lid, bottom and ventilation in the Leca solution (PlanEnergi)

Contrary to the floor constructions in which Leca is normally used, in this case, the highest temperatures are found in the bottom. Hence, there is a risk of convection.

Shown in Figure 4.6 is the construction of the insulation. On top of the floating liner is a layer of geotextile to protect the liner mechanically. Then follows the Leca layer which is approximately 375 mm thick in the section shown. On the top of this layer is a steel grid to make the Leca strong enough for treading on. Supporting the roof liner will be a hard mineral wool plate, here named by the Danish trade name, Rockwool, (20 mm). The thickness of the Leca layer will vary in order to create the slope for rainwater to be conducted off the lid.

Water inside the lid: As shown in Figure 4.8 the lid will be constructed in five lengthwise sections to allow the man holes and the inspection wells to be placed where the sections are thickest (approximately 675 mm Leca) and the bottom of the lining is at its deepest. Any water inside the lid will collect there and thus be detected.

Air pockets: Ventilation holes and sectional borders will be placed in the four ‘valleys’ where the lid is thinnest and any air pockets under the lid will occur as shown in Figure 4.8.

Rain water: A sand-filled pipe is positioned so as to weigh down the roof lining into the ‘valleys’ in situations where there is little wind, when the vacuum valves will not be able to secure the correct position of the lining in this place. Through this construction a slope of approximately 2% occurs on the top of the lid to conduct the rain water into the ‘valley’ and off the lid whereas an equivalent rise of approximately 1% will be obtained on the inside of the lid to allow the air to run into the ventilation holes.

Formation of larger puddles of water on roof foil near the edge: This will be executed by constructing the lid with an extra slope of the edge zone as indicated below in Figure 4.7.

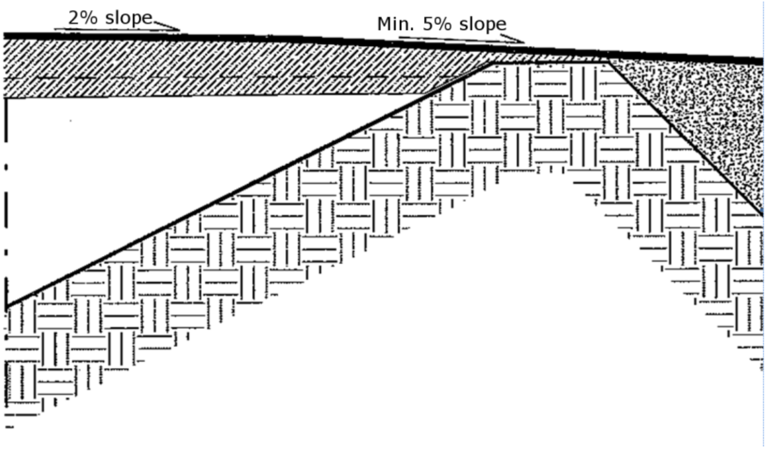


Figure 4.7: Section near PTES edge (PlanEnergi)

Decomposition of vapour barrier: No vapour barrier will be used in the bottom of the floating lid, partly because the advanced vapour barrier used in the SUNSTORE 2 storage (3 layers of aluminum plus 2 layers of polyethylene) appear not to be able to resist the temperatures in the long run and partly because calculations have shown that it is possible through ventilation to get rid of the small amounts of water that diffuse through the liner.

Based on properties for the vapour diffusion in the liners used, a calculation has been carried out for the Leca solution, concerning the amount of vapour steam that will diffuse through the floating liner as a result of high temperatures. It amounts to approximately 0.15 g/s (or app. 0.5 l/h) for a total surface of 10,000 m^2. Assumed that the ventilation air temperature rises 10 K from intake to outlet it will be able to absorb approximately 0.015 kg/m^3. This results in a ventilation need of 36 m^3/h for the complete lid.

Because of the small amount of air (it corresponds to an air change of 1% per hour), the ventilation may be executed at a very low counter pressure at app. 1 Pa.

In practice it is expected that the ventilation can be secured by means of the vacuum valves as shown in Figure 4.8. Controlled air intakes may be introduced at the inspection wells in case they do not on their own provide sufficient change of air. If this is not sufficient either, then there must be established mechanical ventilation (suction) in connection with an inspection well in each section.

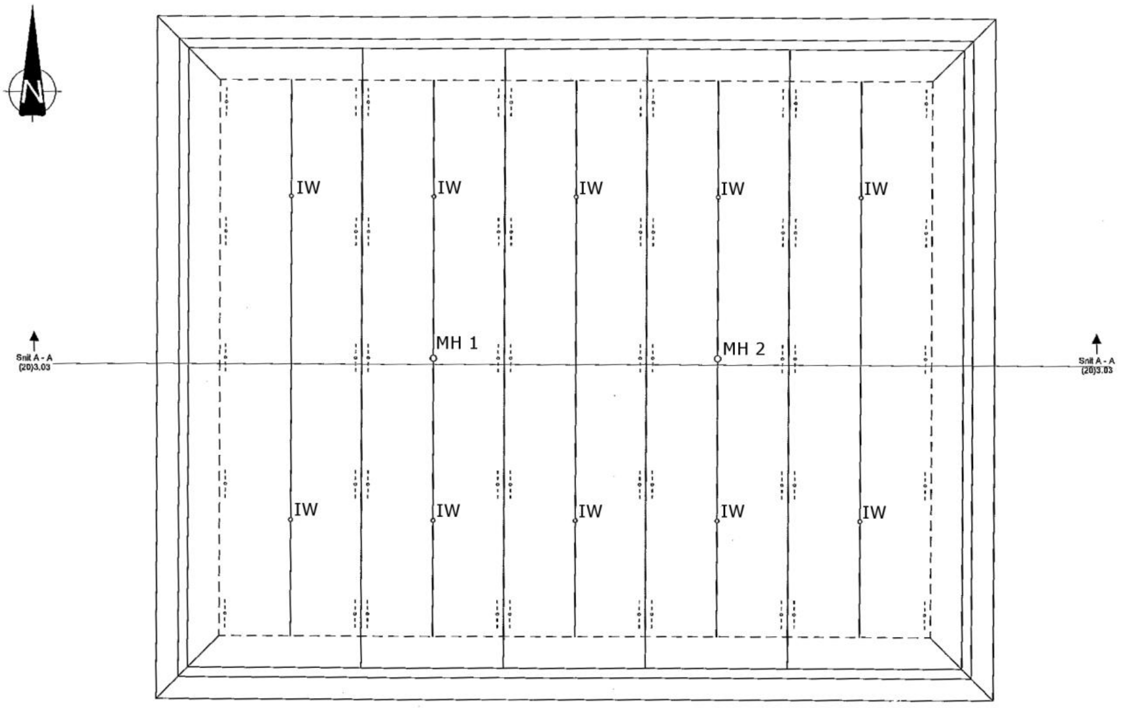


Figure 4.8: Top view, MH=Manhole, IW=inspection well, --o-- = vacuum valve w. perforated tubes into the Leca layer (PlanEnergi)

The second lid design solution is based on Nomalén as insulation material (the Nomalén solution). The lid design is based on experience from storages in the US, where the company GSE has built several storages with floating covers. Rain water is in the Nomalén solution is collected in the middle of the storage lid and pumped away.

Air pockets under the lid are avoided by laying weight pipes on the floating lid liner as illustrated in Figure 4.9 and 4.10.

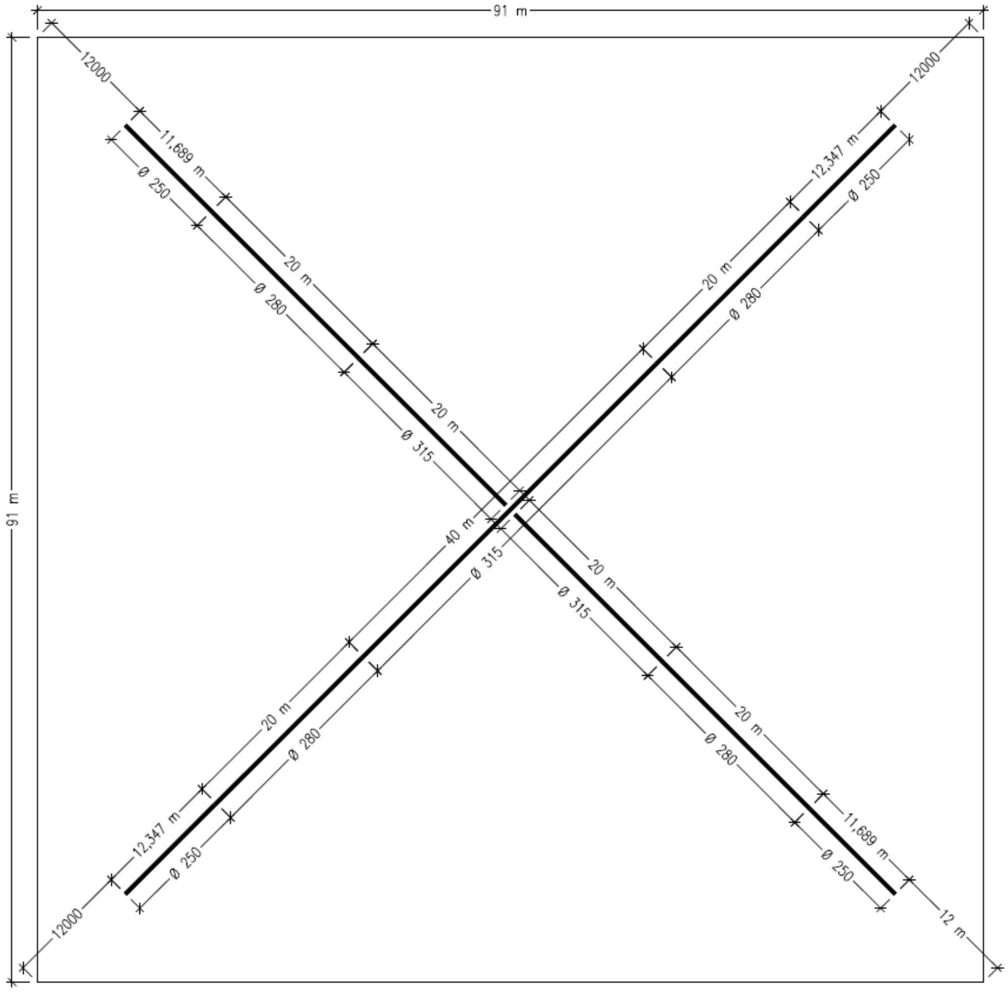


Figure 4.9: Example of a layout of the weight pipes on the floating liner (PlanEnergi)

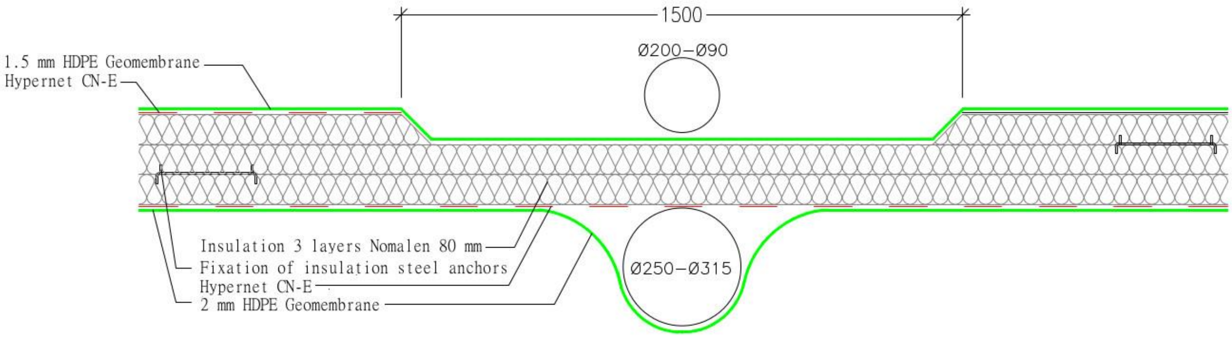


Figure 4.10: Section drawing of the weight pipe on the floating liner (PlanEnergi)

Water inside the lid will flow to the weigh pipe ducts and to the pumping area in the middle of the storage.

Vapour in the construction: As for the Leca design it is expected that the ventilation can be secured by means of vacuum valves (see Figure 4.11). 50 vacuum valves will be placed along the edge of the lid. Controlled air intakes may be introduced at the inspection wells in case the vacuum valves do not on their own provide sufficient air change. If this is not sufficient either, then there must be established mechanical ventilation.

Because of the low permeability of the insulation it has been decided to install ‘hypernets’ as seen in Figure 4.11 as well between the floating liner and the insulation as between the insulation and the top liner. It is assumed that the small slots between the mats of insulation and the direct connection with a pipe to the vacuum valve will cause sufficient opportunity for the hot humid air in the bottom hypernet to move to the top hypernet, where the main part of the ventilation will take place. If this proves not to be the case openings through the insulation can be made in connection with the vacuum valves.

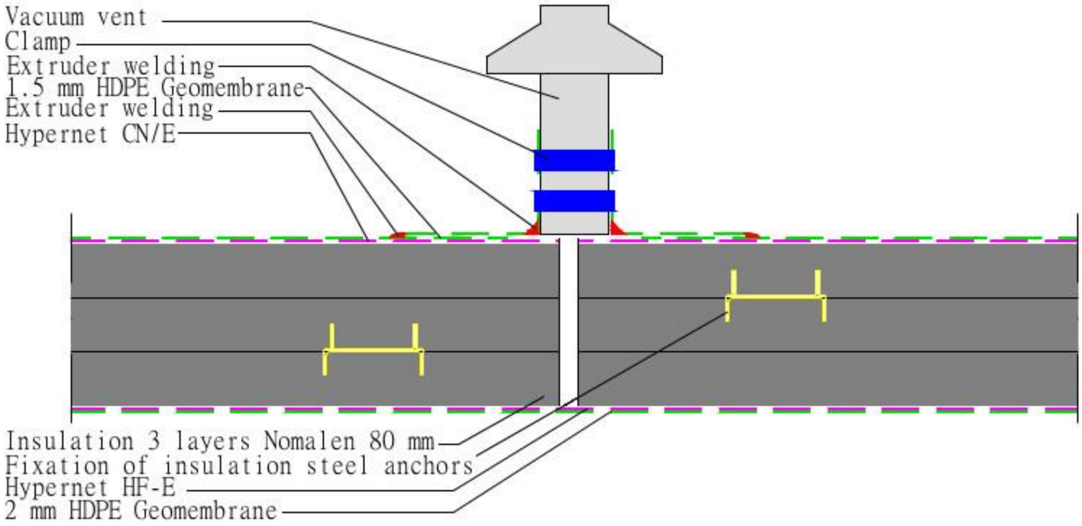


Figure 4.11: Section view of the cover (PlanEnergi)

Water pooling on roof foil is avoided by laying weight pipes on the roof foil leading the rain water to the pumping area. See Figure 4.12.

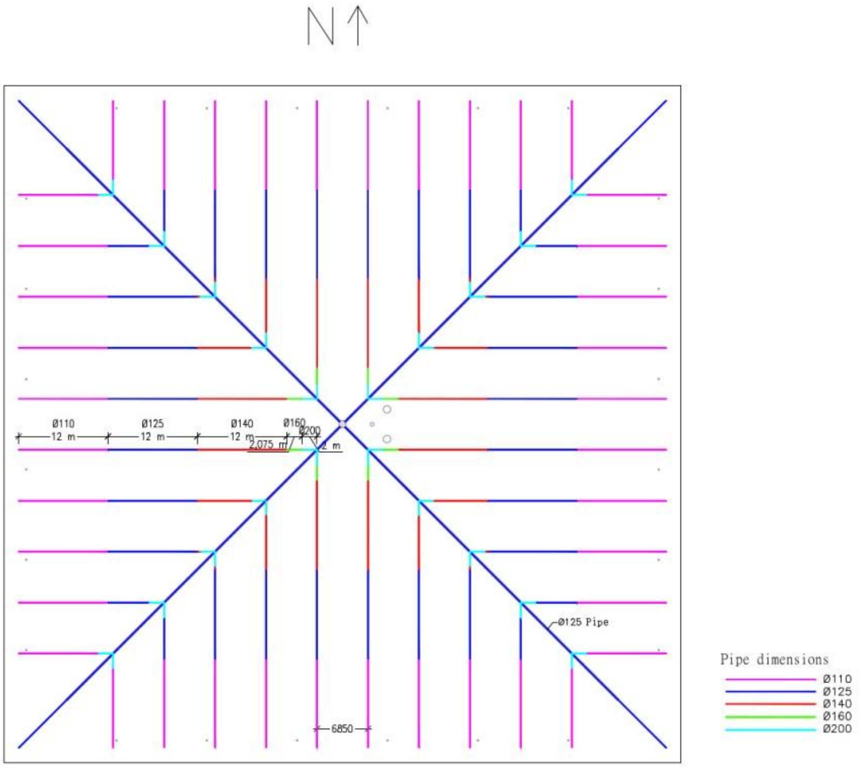


Figure 4.12. Example of a weight pipe layout on top of the cover (PlanEnergi)

Comparison of tender results and price calculations from suppliers showed that the cost of the two lid solutions were similar. “Marstal Fjernvarm”e, the SUNSTORE 4 PTES system owner, decided in the to implement the Nomalén solution. The same design was implemented by “Dronninglund Fjernvarme”, the SUNSTORE 3 PTES system owner.

4.2.3 Charge and Discharge

To be able to get energy to and from the storage an in-/outlet arrangement is used. The in-/outlet arrangement consists of at least two pipe connections: One pipe connection at the bottom of the storage and one pipe connection at the top of the storage. Depending upon the operating conditions of the system connected to the storage and the flexibility wanted, including three or more pipe connections at different depth levels may be advised, to help eliminate layers with unusable water temperatures.

The pipe connections can be led through the top cover, the side, or the bottom of the storage. In the SUNSTORE 3 PTES the pipe connections are led through the bottom of the storage. The SUNSTORE 4 PTES has pipe connections through the side of the storage. Pipe connection through the cover has not been implemented in the Danish storages. The pipe connection through the side or bottom liner has to be sealed very carefully to avoid leakage. This can be done by welding a flange to the pipes and clamp the liner between the flange and a collar by a bolt connection. A temperature and moisture resistant gasket is placed between the steel flange and the liner. Directly outside the storage the pipes are kept in place by a concrete construction.

The advantage of letting the pipes enter in the bottom of the storage is that the pipes enter the storage perpendicular to the liner. This makes the concrete construction below the liner and the flange connection simpler. The disadvantage compared to a pipe connection through the sides is that the pipes have to be buried deeper in the ground (below the storage).

The diffusors for in- and outlet has to be so large that the velocity of the water is less than 0.2 m/s at the edge of the diffusor to avoid spoiling the temperature stratification.

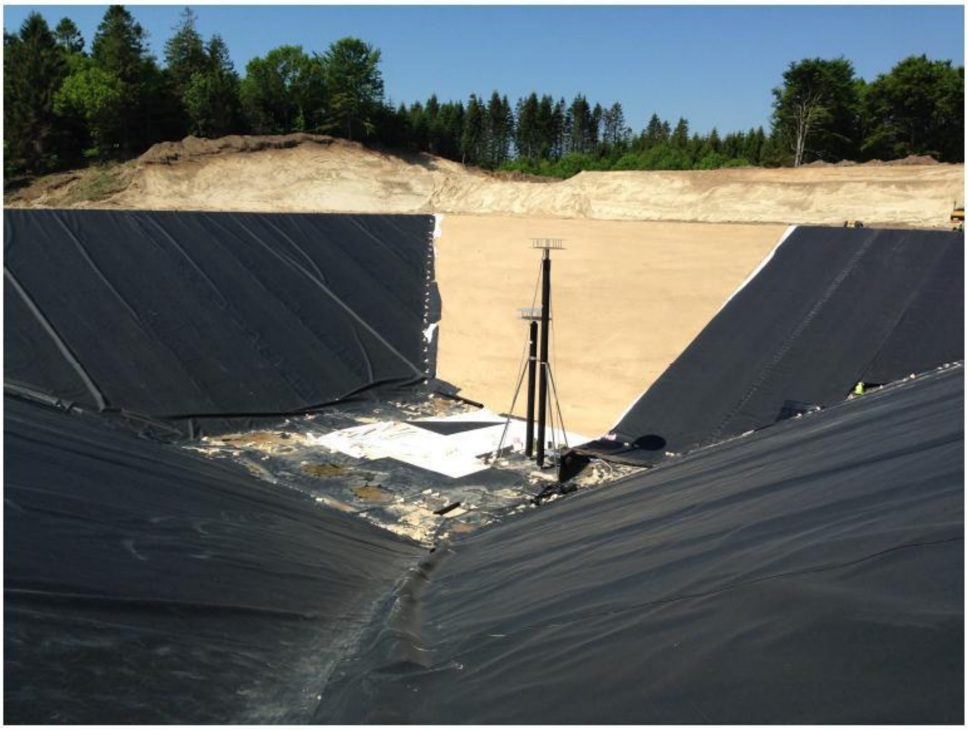


Figure 4.13: In-/outlet arrangement led through the bottom of the storage. Three pipes ending in a diffusor in the top, the bottom and the volume middle of the storage. Photo from the implementation of the SUNSTORE 3 storage in Dronninglund. (Dronninglund Fjernvarme)

Figure 4.14: In-/outlet arrangement led through the side of the storage. Photo from the implementation of the SUNSTORE 4 storage in Marstal (Marstal Fjernvarme)

The in/-outlet arrangement can be made of stainless steel or mild steel with or without surface coating. Regardless of the steel type it is important to maintain a water chemistry in the storage that will not cause corrosion of the steel parts. Corrosion can happen very fast because of the high temperature of the water. When using stainless steel the water chemistry is naturally not as critical as when using mild steel but in both cases a corrosion specialist should be consulted to secure a long lasting combination of materials and water chemistry.

4.2.4 Thermal losses

The annual thermal loss from PTES depends on the temperature in the storage, the shape of the storage, and the insulation level, if the storage is placed at least 3 m above the ground water level.

Since about 2/3 of the heat loss goes through the lid, it is important to minimize as much as possible the lid surface area. This is also important because the lid is the most expensive part of the construction.

In the 1980s, the Danish Technical University calculated the expected heat loss for PTES as a percentage of the storage capacity for storages having a slope of 1:2 for the banks and with one storage cycle per year. Calculations were based upon Copenhagen climate. The results are shown in Figure 4.15.

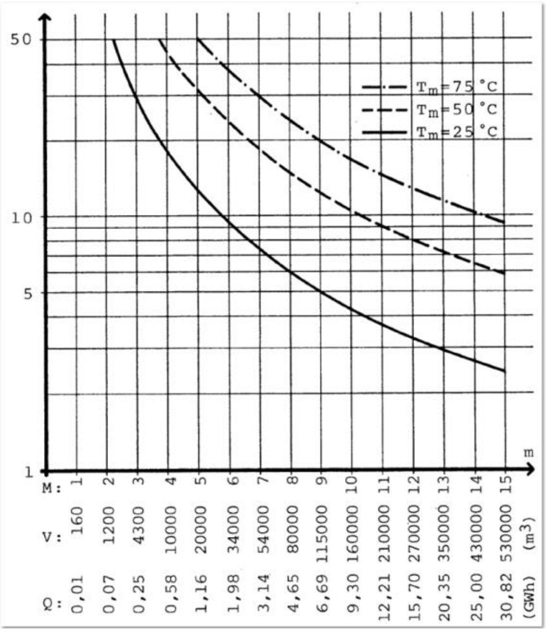


Figure 4.15: Percentage of heat loss for storages from 160 m^3 to 540,000 m^3 after 4 years of operation (Danish Technical University)

To determine the storage temperatures and heat expected heat losses it is normally necessary to carry out a system simulation. Figure 4.16 shows the results of an example simulation analysis completed by PlanEnergi to compare the heat loss of two 500,000 m^3 storages in Aalborg to a single storage with a volume of 1million m^3.

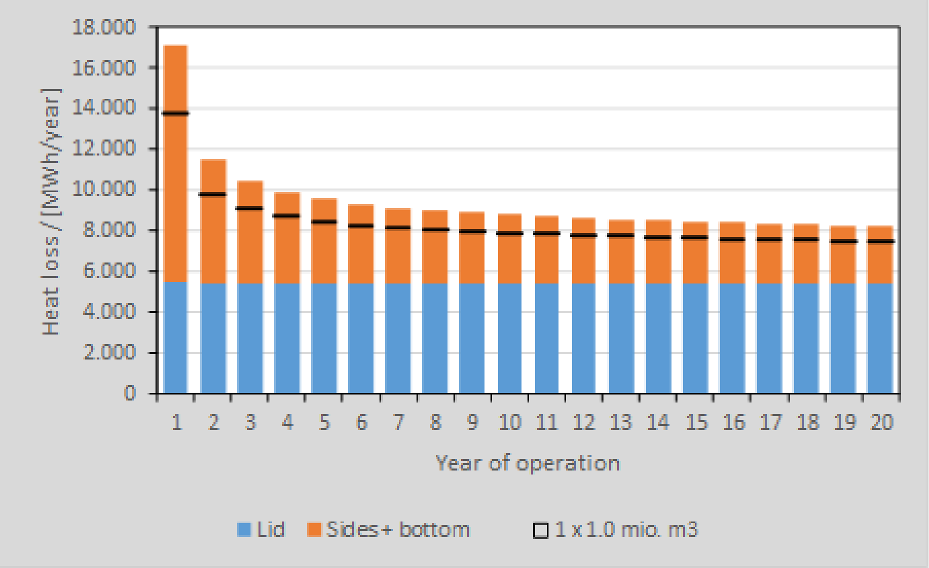


Figure 4.16. Yearly heat loss from a 0.5million m^3 PTES compared with 1million m^3 PTES in the DH system in Aalborg (PlanEnergi)

Heat losses have been monitored for the storages in Marstal and Dronninglund.. Results can be seen in Sections 5.5 and 5.6.

4.2.5 Gravel-Water PTES

Despite the fact that from the thermodynamic point of view, water is a more favorable storage medium compared to a gravel-, sand- or soil-water mixture, there are still good arguments for the latter ones in some cases. This especially applies if the surface of the storage is intended to be used e.g. as a parking lot, school yard, park area, etc. A floating lid on a water surface becomes very costly in these cases due to the demand on static load rating. In the example of a gravel-water PTES, the gravel transfers the load from the lid to the ground without any need for further supporting structures.

Because of the different specific heat capacity values gravel-, sand- or soil-water PTES have to be approximately 30 – 100 % larger than water-filled PTES to be able to provide the same storage capacity, as was shown on Table 2.1. Furthermore it must be noted that, due the higher thermal conductivity of gravel compared to water, temperature stratification in the store is also reduced. The high temperature amplitude between supply and return flow (as the underlying objective) is lower due to the additional heat transfer from water to gravel (and back) and the reduced temperature stratification, which in turn adversely affects the efficiency of the connected plant.

The pit thermal energy store is charged and discharged by means of water-filled pipes. To discharge the heat during the heating season, water is extracted from the hottest part of the store. A distinction is made between direct and indirect charging:

- With **direct charging**, the heated water is conducted directly into the store and likewise extracted from it, see left Figure 4.17. Possible contamination by the storage material (e.g. sand and gravel) could cause clogging of the charging and discharge pipes, which must be prevented by means of filters.

- Indirectly charged stores are crisscrossed by waterproof plastic pipelines which supply heat to the storage material, i.e. the load water circuit does not come into contact with the storage material, see right Figure 4.17. Indirect discharge is also carried out via the water-carrying pipes, with the difference that the storage material transfers the heat to the heat transfer medium (opposite heat flow). With indirect charging and discharging, additional temperature losses can be expected through the heat transfer process.

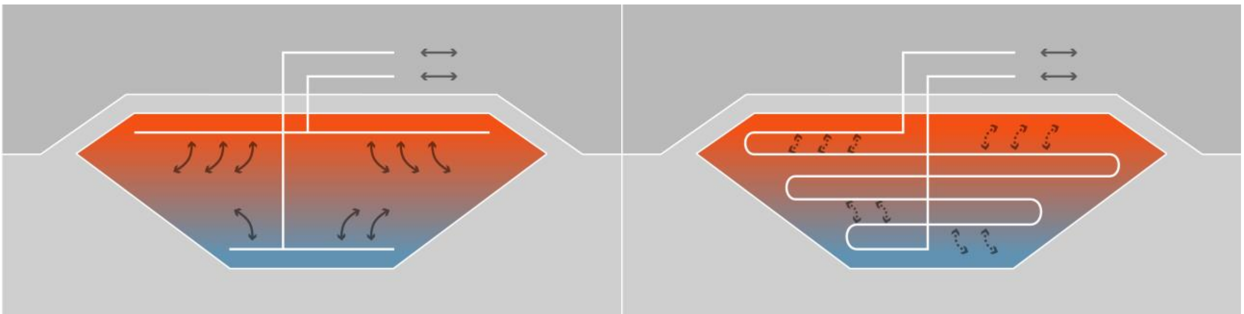


Figure 4.17: Possible charging and discharging designs of PTES with gravel-, sand- or soil-water mixtures as storage medium; left: direct charging and discharging, right: indirect charging and discharging (Solites)

4.3 Implementation experiences

4.3.1 Construction

During the implementation phase for PTES designed as the Nomalén solution it is important to be aware of the following topics:

Secondary ground water levels: Careful geotechnical investigations will localize the ground water level and secondary ground water levels. If secondary ground water levels are localized it is important to get a precise price from the excavating entrepreneur for drainage measures.

Compression of excavated soil: When soil is rebuilt in the banks it has to be compressed to a certain standard defined in the tender documents. This standard has to be proved by taking out samples for laboratory testing.

Stones on the banks: Before the liner contractor begins the liner installation, stones have to be removed from the banks and a geotextile with high penetration resistance must be placed to protect the polymer liner.

Rain water under excavation: Rain will drain from the banks and collect at the bottom areas. This can cause problems, especially if there is clay. A drain in the bottom with drainage pumps is necessary during the construction until the liner work is finalized.

Test of welds: The liner welds must be properly pressure tested. But not all weldings are double. Electrical tracer detection of the total area of liner and welds is recommended after the liner work has been completed.

The top of the banks have to be in the same level: Since the water level is 100 % equal it is important that the elevation of the banks are level. A maximum deviation of 2 cm is tolerated so as not to lose storage capacity.

Water in the lid: When the liner for the lid construction is floated on the water, waves can easily cause water on the liner. This must be avoided. Rain during the lid construction cannot be avoided but must be removed before the roof foil is implemented.

4.3.2 Operation and Maintenance

During operation and maintenance it is important to:

- Clean filters protecting heat exchangers.
- Check the water quality at least yearly (pH, oxygen content..)
- Check the construction under the water yearly (diver inspection)
- Be aware of how much water that has to be added and control expected level of the water in the PTES continuously.
- Be aware of spoiled stratification if PTES is connected to solar thermal because a too hot bottom temperature might cause boiling in the solar system.
- Control daily that everything works normally (rain water pumps functions, water puddles on the lid etc.)

Normally the stratification in the storage only has to be monitored in one place since the temperatures are the same everywhere in the storage in the same height.

Leakages in liners can be repaired under water. Marstal Fjernvarme had for instance a 7 cm leakage (missing welding) in the bottom liner, that was repaired by a diver.

4.4 Cost analysis of large-scale PTES

The Marstal SUNSTORE 2 pilot storage was designed with a total volume of 10,000 m^3 and construction took 3 months to complete, excluding excavation. As this was a pilot project, the overall cost per unit of storage volume was understandably higher that would be expected for a larger storage. However, the expected price for a larger, 100,000 m^3 storage following the same design was calculated as 31 €/m^3 (see Table 4.3).

Table 4.3. Calculation of cost for a full scale PTES with SUNSTORE 2 design.

	Cost (1000 €)	**Cost (€/m^3)**
Excavating	761	7.6
Side- and Bottom liners	184	1.8
Cover	1,516	15.2
Draining	26	0.3
Intake and outlet	268	2.7
Control system	67	0.8
Other cost 10%	282	2.8
Total	**3,104**	**31**

For the SUNSTORE 4 project in Marstal the actual cost are shown in Table 4.4.

Table 4.4: Cost of the storage in Marstal (adjusted 2018 costing)

	Marstal (75,000 m^3)	
	1000 €	**€/m^3**
Excavation	601	8.0
Side and bottom liners	180	2.4
Lid	1069	14.3
In- and outlet	172	2.3
Water and water treatment	195	2.6
Pipes and heat exchanger	413	5.5
Total	2630	35.1

PTES are characterized by a significant effect of economy of scale (see Figure 4.18).

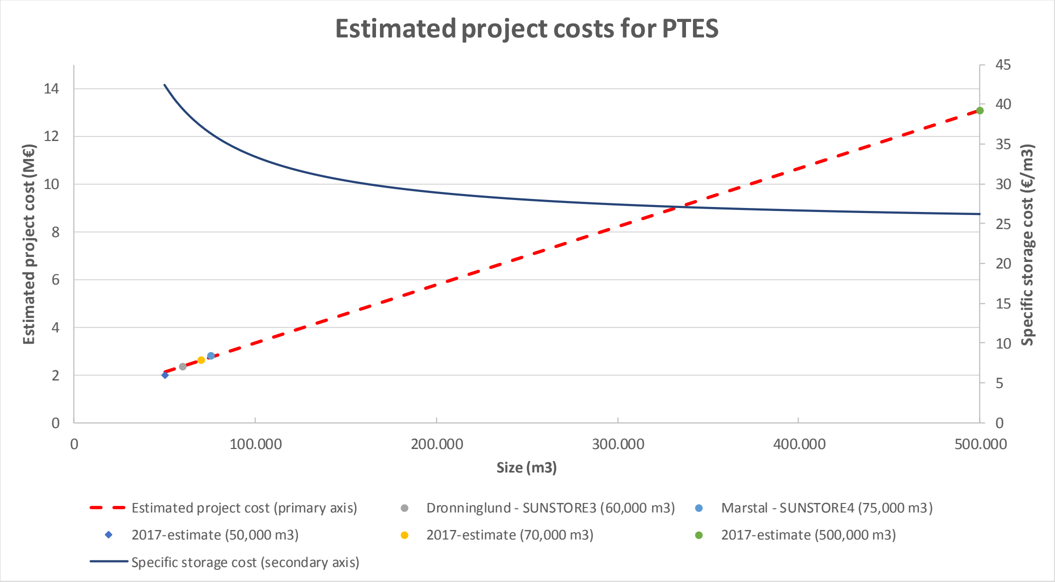


Figure 4.18: Project cost for PTES with the Nomalén solution (PlanEnergi)

5 Project examples

5.1 Overview of some ATES and PTES integrated in DHC systems

In this chapter, several real life ATES and PTES projects integrated into district heating and cooling networks are discussed. The following table provides an overview.

Table 5.1: Select ATES project examples, with storage used for combined heating and cooling

Project	Operation start	Owner	System type	Storage medium	Storage size [m³]
Eindhoven University of Technology	2001	Eindhoven University, Eindhoven, The Netherlands	DHC system for 20 university buildings	Aquifer	1,700,000
Arlanda Airport Stockholm	2011	Swedish Civil Aviation Administration, Stockholm, Sweden	DHC system for the Stockholm Airport	Aquifer	1,000,000
Riverlight London	2014	SSE Plc (EsCo), London, United Kingdom	DHC system for a new residential and mixed use complex	Aquifer	180,000

Table 5.2 – Select PTES district heating project examples, with solar seasonal heat storage

Project	Operation start	Owner	System type	Storage medium	Storage size [m³]
Marstal-2 (Sunstore 4)	2012	Marstal Fjernvarme, Marstal, Denmark	DH system for a village of 2,200 inhabitants	Water	75,000
Dronninglund (Sunstore 3)	2014	Dronninglund Fjernvarme, Dronninglund, Denmark	DH system for a village of 3,300 inhabitants	Water	60,000
Eggenstein-Leopoldshafen	2009	Municipality of Eggenstein-Leopoldshafen, Eggenstein-Leopoldshafen, Germany	DH system for municipal buildings	Gravel/sand-water	4,500

5.2 ATES Eindhoven University of Technology, The Netherlands

General information

Name of the project:	ATES based DHC system at Eindhoven University Campus
In operation since:	2001
Location:	Eindhoven, The Netherlands
Owner:	Eindhoven University

Context

Eindhoven University of Technology was established in 1956. In size, it is the second largest university of technology in the Netherlands and hosting about 7,000 students and 3,000 employees (as per 2010 statistics).

In the early 1990s, the university committed itself to improve its energy efficiency by 20% over the period 1996 - 2006. This commitment and the fact that many of the forty-year old buildings had to be refurbished over the next decades, resulted in several studies on the future energy infrastructure of the campus site. As a result of these studies, in 1998 the decision was made by the Board of Directors of the University to establish heating and cooling infrastructure based on large-scale aquifer thermal energy storage (ATES based district heating and cooling system).

The ATES-DHC system on the campus of Eindhoven University of Technology was completed in 2001 and can serve approximately 20 buildings with a total floor space of about 250,000 m^2.

Technical concept and system integration

The ATES system supplies direct cooling in summer as well as low-temperature heating in winter for the evaporators of the heat pumps. The heat pumps are located in the plant rooms of the buildings and can provide peak load cooling in summer as well. In order to be able to charge enough cold in winter, cooling towers are used to charge additional cold.

The ATES based DHC system consists of a main distribution network with two distribution rings (one warm and one cold) to which the cold wells and warm wells, as well as the buildings, are connected. By means of this main distribution network, cold and low temperature heat are available all year round.

Every building connected to the network has an energy transfer station (ETS), including a heat exchanger and several mechanical and electrical components to exchange cold and heat between the building and the distribution network. The ATES based DHC system also enables the users to exchange cold and/or heat by means of the distribution network. In this case the groundwater is functioning as energy transport medium between the buildings. In case of a net cooling or heating demand after the energy trade-off between users, groundwater is extracted from the cold or warm wells respectively and transported to the users by means of the distribution network. As a result of this energy exchange between the buildings, the energy efficiency is further improved.

Figure 5.1 – Construction of main distribution loop (Eindhoven University)

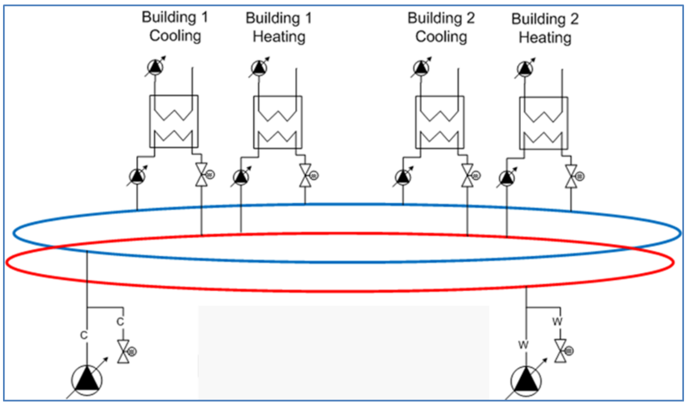


Figure 5.2: Two-pipe ground-water distribution, active building connections (IF Technology)

An overview of the key features of the ATES system at Eindhoven University of Technology is given in Table 5.2.

Table 5.2: Main storage parameters

Storage type:		ATES
Storage capacity (heating and cooling)	MW	17
Max. energy delivery (heating and cooling)	GWh/y	15-30
Maximum flow rate (heating and cooling)	m^3/h	2,000
Max. amount of pumped water (heating)	m^3/y	3,500,000

Max. amount of pumped water (cooling)	m^3/y	3,000,000
Average infiltration temperature (heating)	°C	6
Average infiltration temperature (cooling)	°C	16
Number of warm wells	-	16
Number of cold wells	-	16
Number of wells per cluster	-	5 or 6
Diameter of borehole	mm	700
Maximum flow rate per well	m^3/h	125
Diameter of main field piping	mm	450
Total length of main field piping	m	1,500

The soil conditions on the campus show a top layer of approximately 28 m in which a shallow phreatic aquifer is present. At a depth between 28 m and 80 m below surface the ‘first aquifer’ is found with a transmissivity in the range of 1,600 to 2,000 m^2/day. Below this aquifer an aquitard is found of 60 m thickness with a hydraulic resistance of 20,000 days. Deeper aquifers are present and protected by the government as drinking water reserves and therefore these aquifers are not available to be used for ATES. The natural temperature of the groundwater in the first aquifer is 11.8 °C and the groundwater flow of 15 to 20 m/a is directed north/north-west. The groundwater is fresh with a chloride content of 10 to 40 mg/l.

Operational experience

A characteristic of ATES based DHC systems is that a major part of investment in infrastructure has to be made up front, i.e. at the moment when the first building requires heating and/or cooling from the system. The major part of the ATES-DHC infrastructure at Eindhoven University of Technology was realized by 2002. Ten years later, about 70% of the building area on the campus was connected to the system. Due to changes of the refurbishment and building program, this took more time than envisaged.

New buildings in the framework of the so-called Campus 2020 program are heated and cooled completely by the ATES/HP DHC system.

Economics

The total investment in the ATES-DHC infrastructure, including the building connections and the controls, but excluding the cooling towers to thermally balance the system, has been about € 8.5 million, excluding VAT (price level 2002).

It is expected that the annual energy savings will increase from about 3 M kWh_e and 600 000 m^3 natural gas in 2012 to about 4 million kWh_e and 1 million m^3 natural gas when all buildings will be connected.

Partnership

The partners in the project realization are shown in Figure 5.3.

Figure 5.3 – Project partners of the ATES Eindhoven University of Technology project (Eindhoven University)

5.3 ATES Arlanda Airport Stockholm, Sweden

General information

Name of the project:	Arlanda Airport ATES system
In operation since:	2011
Location:	Stockholm, Sweden
Owner:	Swedish Civil Aviation Administration

Context

Stockholm Arlanda airport handles 20 million passengers per year. About 15,000 people are working at the airport which makes it the largest work place in Sweden (2012 values). The airport is owned and operated by the Swedish Civil Aviation Administration (LFV), a governmental company that is operating 16 Swedish airports.

Stockholm Arlanda has a cap for carbon dioxide emissions included in its environmental permit. This emission cap includes emissions from starting and landing of aircraft, ground transports to, from and at the airport and heating and cooling of airport buildings. It states that the net CO_2 emissions from these activities shall not be higher in year 2016 than they were in 1990, regardless of any expansion. Another goal for the airport was a considerable reduction of its energy consumption and also that it should use 100% renewable energy as from 2010 [Andersson 2009].

A feasibility study to apply an ATES system was made in 2006, followed by hydro-geological site investigations. The Swedish Environmental Court gave the necessary permits in August 2008.

Technical concept and system integration

Heat and “cold” is seasonally stored in an aquifer. This aquifer is situated in an esker approximately 2 km away from the terminals. The ATES based DHC system consists of a main groundwater network connecting the ATES wells to the central plant room where the heat exchangers are located. From the plant room warm and chilled water is distributed to the buildings and the ramps. The general principle of the ATES-DHC system is shown in Figure 5.4.

In winter the ATES is used for preheating of the ventilation air in the terminal buildings and for melting snow using ground heating coils at the gates. This way the water of the aquifer water is cooled down during the winter.

In summertime the flow through the ATES system is reversed as it supplies cooling to the terminals where the need of cooling is large. This way the ATES system replaces the old conventional chillers which had an annual electricity consumption of 4 GWh. The return temperature to the ATES wells is about +15 °C, but this temperature can be increased to approximately +25 °C by using the ground heating coils at the gates as solar collectors during sunny days.

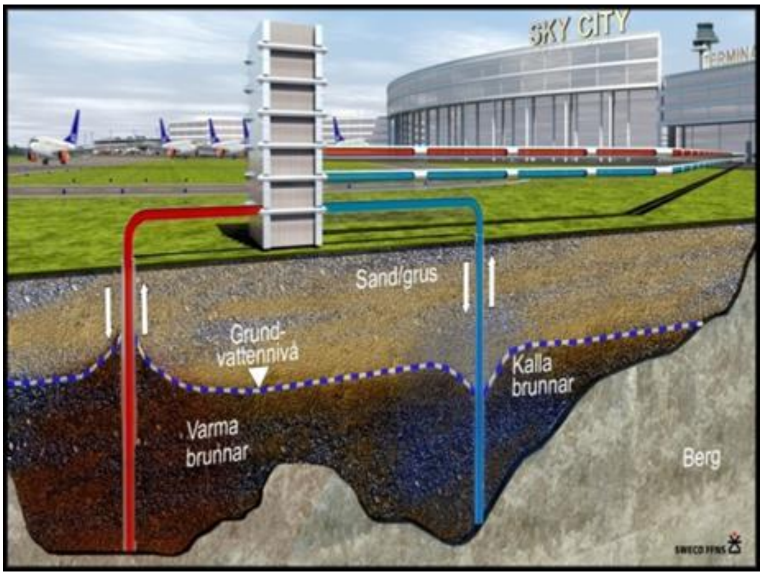


Figure 5.4: Principle of ATES-DHC system (Sweco)

Table 5.3: Main storage parameters

Storage type:		ATES
Storage capacity (heating and cooling)	MW	10
Max. energy delivery (heating and cooling)	GWh/y	20
Maximum flow rate (heating and cooling)	m^3/h	720
Infiltration temperature (heating)	°C	2-3
Infiltration temperature (cooling)	°C	20-25
Number of warm wells	-	6
Number of cold wells	-	5
Diameter of borehole	mm	270-400
Maximum flow rate per well	m^3/h	100-200
Diameter of main groundwater field piping	mm	450
Total length of groundwater field piping	m	2,700

An overview of the most important features of the ATES system at Arlanda Airport is given in Table 5.2 [Andersson 2009 and Gehlin et al. 2016]

The soil conditions vary significantly over the esker. Depending on these conditions the well depth varies between 15-30 m. For the same reason the well capacities and the well dimensions vary, as indicated in Table 5.3.

In the north the groundwater level is approx. 7-8 m below the surface, while in the south, the distance is somewhat smaller, around 4-5 m. The smaller distance in the south is a limiting factor for the uplift of the groundwater level during infiltration. For this reason there are five wells in the north and six wells in the south, in order to spread the infiltration points over a larger area.

Economics

The ATES plant at Stockholm Arlanda Airport has considerably lowered the energy consumption: electricity use for cooling reduced by 4GWh/year and heat use from district heating by 20 GWh/year. As a result, the cost of energy has been reduced by at least € 1,000,000 annually for an investment of approximately € 5,000,000 (price level 2011).

5.4 ATES Riverlight London, United Kingdom

General information

Name of the project:	Riverlight London
In operation since:	2014
Location:	London, United Kingdom
Owner:	SSE Plc (EsCo)

Context

The Riverlight project along the River Thames in London comprises the construction of 806 residential apartments along with a number of retail spaces, restaurants, bars and a crèche. On the re-development site six apartment buildings have been constructed, ranging from 12 to 20 storeys. The overall floor area of the private apartments is approximately 55,000 m².

The first building was commissioned in 2014. To meet the energy performance criteria for new buildings in London, as they were at the time of project planning, a local ATES-DHC system turned out to be one of the most cost-effective options.

Figure 5.5: Artist impression Riverlight project and impression construction site in 2013 (picture IFTech)

Technical concept and system integration

The ATES and heat pump system has been designed to completely provide the cooling demand of 2.9 MW at a chilled water design flow and return temperature of 10-18 °C, the major part of the annual cooling demand being provided as direct ATES cooling. The system has three heat pumps, located in a central plant room in one of the buildings.

In winter, the ATES system provides low-temperature heat to the evaporators of the heat pumps. The ATES-HP system has been designed to provide a significant part of the annual heating demand of the Riverlight development. The peak heating demand of the Riverlight development is 9.0 MW; a base load of 1.8 MW is provided by the three heat pumps of the ATES-HP system. The remainder of the heating demand is provided by a combined heat and power unit (CHP unit) and peak load boilers. The heating design flow and return temperature for the ATES-HP system are 45-35 °C, which is raised by the CHP unit and/or the boilers. The CHP unit as well as the peak load boilers for the entire development are located in the central plantroom also. Hot and chilled water are distributed from the central plant room to the apartment buildings.

An overview of the most important features of the ATES system at Riverlight is given in Table 5.4.

Table 5.4: Main storage parameters

Storage type:		ATES
Storage capacity cooling	MW	3.7
Storage capacity heating	MW	1.6
Max. energy delivery (heating and cooling)	GWh/y	1.4
Maximum flow rate (heating and cooling)	m^3/h	200
Average infiltration temperature (heating)	°C	8
Average infiltration temperature (cooling)	°C	24
Number of warm wells	-	4
Number of cold wells	-	4
Diameter of borehole	mm	300
Maximum flow rate per well	m^3/h	40-60
Diameter of groundwater field piping for each cluster of two wells	mm	160
Total length of groundwater field piping	m	450

The ATES system consists of 4 warm and 4 cold wells into the London chalk aquifer. The depth of the wells is about 100 m. The groundwater is pumped from and recharged into a fractured zone with a thickness of about 25 m in this aquifer.

Operational experience

Since the commissioning of the first building, the ATES-HP system has provided all of the cooling demand of the Riverlight development. However, due to the low heat abstraction from the aquifer (see hereafter), there is a thermal unbalance in the aquifer, resulting in a slowly increasing groundwater temperature.

The contribution of the heat pumps to the heating demand has been significantly lower than as per the design, resulting in a larger contribution from the CHP and the boilers. The reason for this lower heat pump contribution is the fact that the building heating flow and return temperatures are higher than the design temperatures (45-35 °C), resulting in inefficient use of the heat pumps. Measures will be taken to rectify this situation.

Partnership

The ATES-DHC system of the Riverlight development is owned and operated by Scottish Southern Electric (SSE Plc).

5.5 PTES Marstal-2, Denmark

General information

Name of the project:	Sunstore 4
Location:	5960 Marstal, Denmark
Owner:	Marstal Fjernvarme

Context

The district heating production plant in Marstal, as illustrated in below Figure 5.6, consists of the following main units:

- 33,365 m^2 solar collectors
- 10,000 m^2 pilot pit heat storage
- 75,000 m^3 pit heat storage
- 2,100 m^3 steel tank
- 4 MW biomass boiler with 750 kW ORC unit

- 1.5 MWth electrical heat pump
- Bio oil boilers

In June 2012, 15,000 m² of solar collectors, a 15,000 m³ PTES, a biomass boiler with ORC and a heat pump were put into operation as a part of the project "SUNSTORE 4", which is supported by EC 7th framework. The project enables Marstal District Heating to deliver heating to the consumers from 100 % renewable energy sources wherefrom approximately 50 % is solar heat. The energy balance is generated by the biomass boiler.

Technical concept

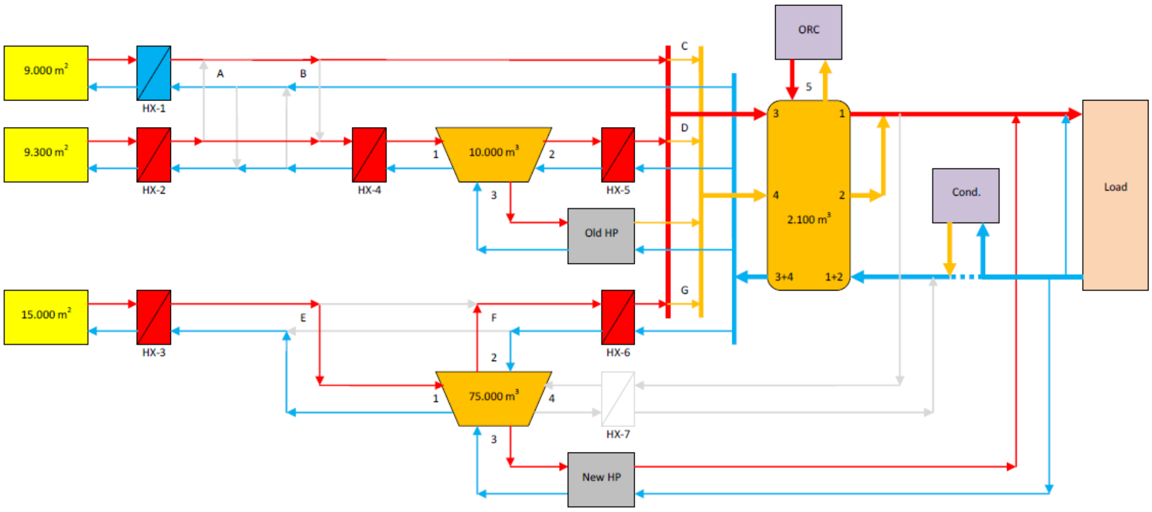


Figure 5.6: PTES system integration schematic in Marstal (PlanEnergi)

A technical economic analysis based on a TRNSYS analysis was completed in order to estimate and optimize the pit storage size . The geometry of the storage is defined as a truncated pyramid upside down. The excavated soil from the lower part of the storage is used as an embankment around the storage. To ensure stability of the storage during excavation and long-term stability, geotechnical investigations of the local conditions were made. The geotechnical investigations pointed out that the slope of the internal sides of the storage should not be steeper than 27°.

On top of the storage the water is covered by a floating insulated cover. The surface covered is approximately 10,000 m². Different designs of the cover have been investigated as a part of the project "SUNSTORE 4" and the final design consists of (from bottom to top): 2 mm HDPE liner on top of the water, drainage net, 240 mm insulation (Nomalén), drainage net and 1 mm HDPE liner as top liner (see Figure. 5.7).

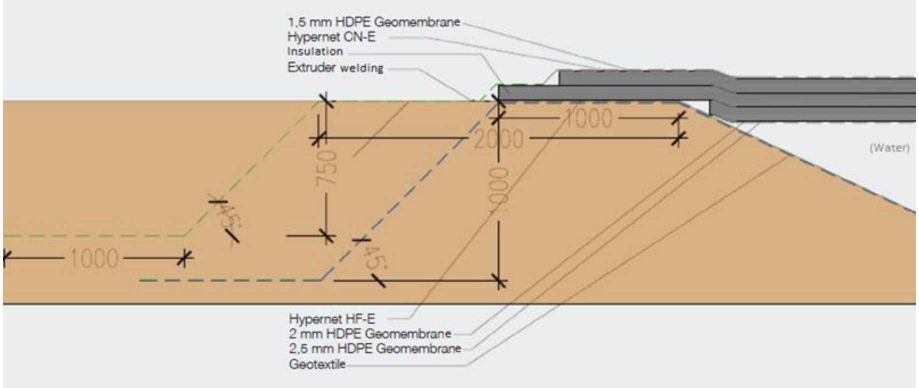


Figure 5.7: Cross section of the edge of the floating cover (PlanEnergi)

The intention of the drainage net is to allow ventilation between the insulation and the liner. This is necessary because of vapour diffusion through the liners. If the vapour is not removed there is a potential risk of condensate in the insulation that could damage the insulation over time. The base ventilation is handled by 30 roof vacuum valves mounted along the edges of the cover and if necessary a blower can be installed to force a higher ventilation rate through the cover.

The insulation is based on a cross bonded PE foam. As for the liner, the properties of the insulation regarding temperature and moisture stability is very critical.

The surface of the cover is exposed to a large amount of water during heavy rainfalls. Different solutions to ensure an efficient way to handle the water have been investigated. Two approaches were considered for this project, either to let the rainwater float across the edges of the storage or to collect it in the middle. The final design is based on collecting the rain water in the middle of the cover. This means that the rain water has to be pumped away, but the advantage is that it is easier to avoid puddles of water on the cover and air traps below the cover. To help guide the water in the right direction and to create tension in the liner several weight pipes are placed on top of the storage. The weight pipes consist of HDPE pipes filled with concrete.

Table 5.5: Main storage parameters for Marstal-2 PTES system

Storage type:	PTES	**Storage material**	water
Storage size	75,000 m³	**Effective storage capacity**	6,000 MW_{th}
Max. allowed temperature	90 °C Up to 95 °C in short periods		

Implementation of the Marstal pit heat storage

The implementation of the storage was complicated because of bad weather conditions. Figure 5.8 shows pictures of the excavation process. In the first picture the excavators are preparing the slides for liner implementation. The second picture is a few days after a cloud burst. In the last picture a cable excavator is digging up mud from the bottom while the liner implementation has begun.

Figure 5.8: Pictures of the excavation process (PlanEnergi)

The excavation, liner work, water filling and lid construction were supposed to be implemented in the period from spring to autumn 2011 but were delayed because of rain. The liner work was finished end of November 2011 and water had to be filled in during winter. The lid was constructed in spring 2012. The floating liner was welded section by section on shore and continuously pulled out on the water surface until the entire surface was covered. The insulation and the top liner were installed at the same time in a continuous process.

System Operation

When deciding when the different production units in the system shall run, the units are prioritized depending on the production price at the moment of time. Solar thermal has the first priority, the biomass boiler and ORC has second priority unless the market price for electricity is so low in favor of the heat pump which is then triggered second ahead of the biomass boiler and ORC. Last unit is the bio oil boilers.

Investment cost of the PTES in Marstal-2

Table 5.6 presents the key economical figures of the project.

Table 5.6: Key economical figures of the Marstal-2 PTES

Total Investment:	2.63 M. € or 35 €/m^3 (see Section 4.4 for further details)
Operational cost:	App. 30,000 €/Year

Operational experience

The overall experience in the operation period from 2012 until 2017 is that the storage functions well, but some minor problems have turned up:

- After one year, corrosion was found by a diver inspection of the storage. The problem was that galvanized metal was mixed with iron and that organic material in the water gave possibilities for bacterial corrosion. The pH value has now been changed from 7.4 to 9.8 and galvanized metal was replaced.

- The heat exchanger between the storage and the energy system was very ineffective. The reason was sludge from the storage water. The heat exchanger was cleaned and a filter had to be implemented in the heat exchanger inlet.

- Two holes in the liner have been located in the yearly diver inspection. The holes have been patched by a diver.

The overall experience is that performance and operation of the storage is nearly as expected. The technology seems to be reliable, but lifetime for liner and insulation has to be further investigated. Table 5.7 shows the KPIs of the storage project.

Table 5.7: Key Performance Indicators (KPIs) of the Marstal-2 PTES

Volume:	75,000 m^3 water
Max capacity:	6,000 MWh (T_{max} 88 °C and T_{min} 17 ˚C monitored in 2014)
Thermal losses/capacity:	48 % (Thermal losses 2,908 MWh in 2014, capacity 6,000 MWh)
Investment/capacity:	0.44 €/kWh
Max charge/discharge capacity:	10 MW
Investment/max charge capacity:	263 €/kW

Partnership

Owner and operator:	Marstal Fjernvarme (consumer owned DH utility)
Design of TES and hydraulics:	PlanEnergi and Sunmark (Ramboll)
Financial support:	EU 7th Framework program and Danish Energy Agency

5.6 PTES Dronninglund, Denmark

General information

Name of the project:	Sunstore 3
Location:	9330 Dronninglund, Denmark
Owner:	Dronninglund Fjernvarme

Context

The district heating production plant in Dronninglund consists of the following main units:

- 37,573 m^2 solar collectors
- 60,000 m^3 pit heat storage
- 2.1 $MW_{cooling}$ absorption heat pump
- Bio oil boilers
- Gas boiler

The pit heat storage, the solar collectors and the absorption heat pump were in operation from March 2014 as part of the project “Sunstore 3”, supported by the national Danish EUDP-program. The project enables Dronninglund district heating to deliver heating to the consumers from 70 % renewable energy sources where approximately 40 % is solar heat.

Technical concept

The storage, the solar collectors and the absorption heat pump were recalculated in TRNSYS in order to find the most feasible combination covering 50 % of the heat production with solar energy.

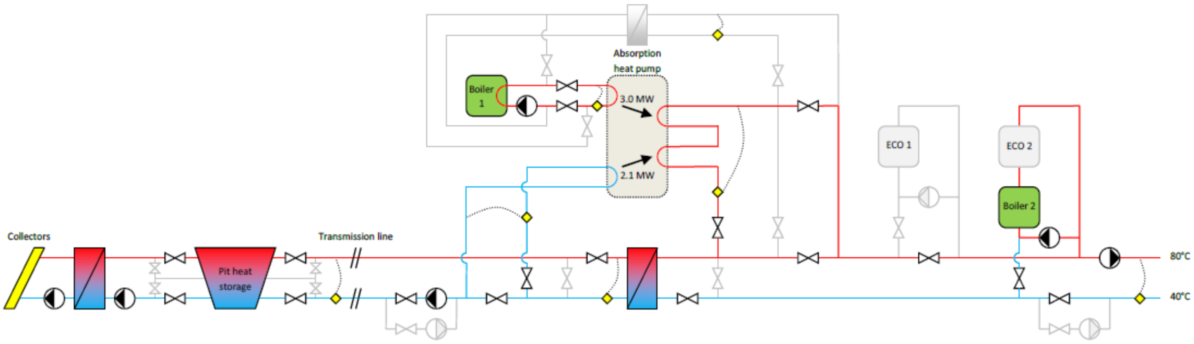


Figure 5.9: PTES system integration schematic in Dronninglund (PlanEnergi)

The design of the storage is similar to the Marstal design, but the excavation was easier because the storage is situated in an old gravel pit. Furthermore, a new HDPE liner was used. The supplier has given Dronninglund a 20-year performance guarantee if the liner temperature does not exceed 90 °C.

Further differences to Marstal are that stainless steel is used in in- and outlet pipes instead of normal steel, water for filling has been treated with reversal osmosis and pH is 9.8 as for water in district heating pipes to prevent corrosion. Additionally, less dirt was entering the storage during construction because the lid was implemented before winter. Filters were implemented at the storage side of the solar heat exchangers to prevent dirt from coming into the heat exchangers, and heavier weight pipes implemented to be sure, that air under the lid would be transported to the edges of the storage.

Table 5.8: Main storage parameters of the Dronninglund PTES

Storage type:	PTES	**Storage material**	water
Storage size	60,000 m³	**Effective storage capacity**	5,400 MW_{th}
Max. allowed temperature	90 °C Up to 95 °C in short periods		

Implementation of the Dronninglund PTES

The excavation, liner work, water filling and lid construction took place in the period from March 15th 2013 to October 2013. There were no major challenges during the construction period.

Figure 5.10: Pictures from implementation of the pit heat storage in Dronninglund (source Dronninglund Fjernvarme)

System Operation

When deciding when the different production units in the system shall run the units are prioritized after production price. Solar thermal has the first priority, the absorption heat pump using the storage as heat source has second priority unless the market price for electricity is high in comparison to that of the gas fired CHP than this later is given priority. The last unit is always natural gas boilers.

Investment cost

Table 5.9 presents the key economical figures of the project.

Table 5.9: Key economical figures of the Dronninglund PTES

Total Investment:	2.3 M. € or 38 €/m^3
Operational cost:	App. 30,000 €/Year

Operational experience

During the operation period from 2014 no major problems have turned up. Water ponds are regularly removed from the lid and water can occur in the insulation maybe because water from water puddles on the lid comes through the ventilation valves. A yearly diver inspection shows no corrosion signs and clear water.

Performance and operation of the storage is as expected. The technology seems to be reliable but life time for liner and insulation has to be further investigated. Table 5.10 shows the KPIs of the storage project.

Table 5.10: KPIs of the Dronninglund PTES

Volume:	60,000 m^3 water
Max capacity:	5,400 MWh (T_{max} 89 °C and T_{min} 12 °C)
Thermal losses/capacity:	19 % (Thermal losses 1020 MWh in 2016, capacity 5,400 MWh)
Investment/capacity:	0.43 €/kWh
Max charge/discharge capacity:	27 MW
Investment/max charge capacity:	85 €/kW

Partnership

Owner and operator:	Dronninglund Fjernvarme (consumer owned DH utility)
Design of TES and hydraulics:	PlanEnergi and Niras
Financial support:	EUDP (Danish development program for energy technologies)

5.7 PTES Eggenstein-Leopoldshafen

General information

Name of the project:	Pit thermal energy storage Eggenstein-Leopoldshafen
Location:	76344 Eggenstein-Leopoldshafen, Germany
Owner:	Municipality of Eggenstein-Leopoldshafen

Context

One part of the renovation of the Eggenstein-Leopoldshafen school and sport centre, which includes a school, gym, indoor swimming pool and municipal buildings totaling agross floor area of 12,000 m², was the replacement of an old leaky flat roof by a new pitched “solar roof” mounted on top of the school buildings (see Figure 5.11). The solar roof has a total collector area of 1,600 m² and feeds its heat in the local block heating system which supplies 1,150 MWh for heating all connected buildings. The gravel-water PTES with a storage volume of 4,500 m³ was integrated for rendering possible a high solar fraction of the total heat generation. The building renovation works started in the year 2004. The PTES was built in the years 2008 and 2009, when it was also taken in operation.

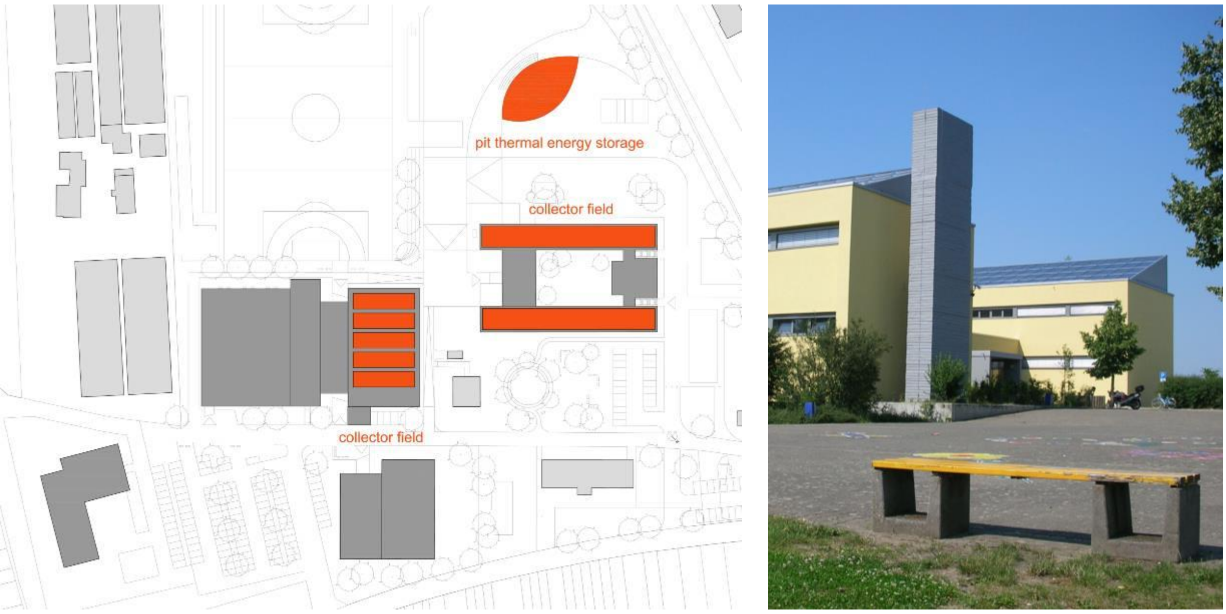


Figure 5.11: Areal view of the school and sport centre Eggenstein-Leopoldshafen (source PKI), renovated school buildings with solar roofs (Solites)

Technical concept

The storage walls are composed inside of a compound liner, the insulation material and a HDPE (high density polyethylene) liner outside. To avoid vapor diffusion from the inside of the storage to the insulation, the inside composite liner is made of three layers: an aluminum layer enclosed between two HDPE layers. The sealing band is segmented, creating compartments that are filled with expanded glass granules. The compartments were evacuated, which improved the tightness control during building of the storage, the long-term impermeability, the static and the protection against rain and humidity. The upper and lower parts of the storage were filled with gravel. The middle part was filled with sand from the excavation. The insulation material installed at the bottom (50 cm) and the side walls (50 to 70 cm) is expanded glass granules, for the lid foam glass gravel (100 cm) was used. Moreover, 30 cm of earth cover the storage, which renders the surface available as playground for the school. The storage is charged and discharged through two well-like in- and outlet devices in the upper and lower gravel layers.

Table 5.11: Main storage parameters

Storage type:	PTES	**Storage material**	gravel-water
Storage size	4,500 m³	**Effective storage heat capacity**	220 MWh_{th}
Max. allowed temperature	80 °C		

Figure 5.12: Construction phases of the PTES (Solites)

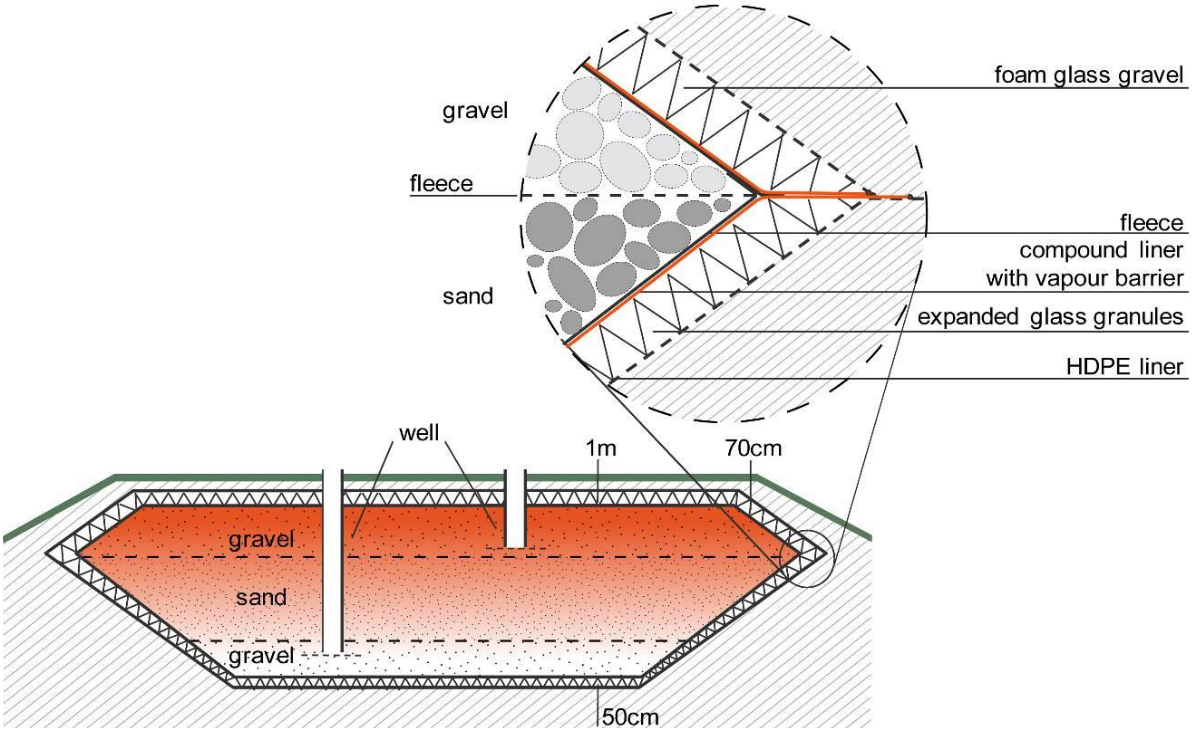


Figure 5.13: Construction details of the gravel-water PTES (Solites)

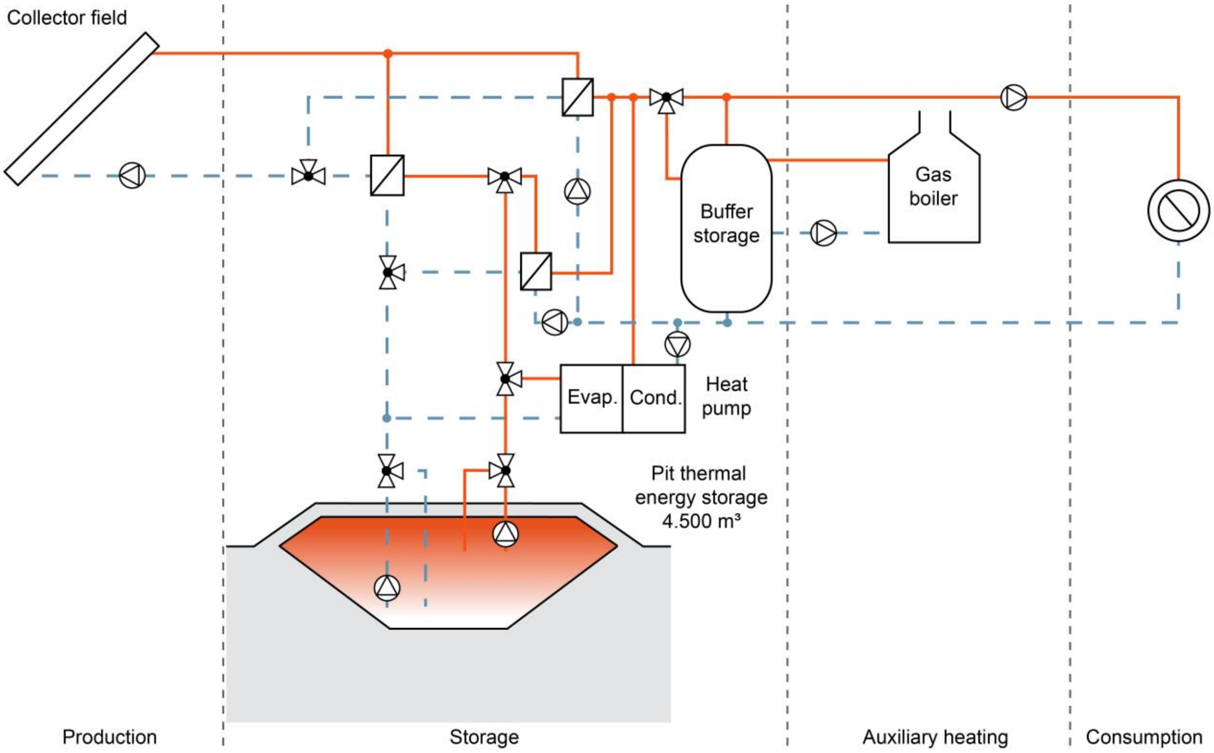


Figure 5.14: Construction details of the gravel-water PTES (Solites)

System integration

The integration of the PTES in the overall system is presented in Figure 5.14. The heat pump (60 kW_{th}) is an essential component of the system. It is used for discharging the PTES to low temperatures, when the temperature at the top of the PTES is no longer sufficient for a direct supply to the DH system. The integration of the heat pump leads to three advantages: low heat losses of the storage, a high usable thermal capacity of the storage due to the low storage temperatures in winter and high solar collector field yields due to low return temperatures.

Operational experience

Problems occurred with the water suctioning of the discharge pump and heat losses through the storage lid, that were higher than expected.

Economics

The total investment cost for the PTES amounted to 433,000 €.

Partnership

Owner and operator:	Stadt Eggenstein-Leopoldshafen
Design of TES and hydraulics:	PKI Ingenieurgesellschaft, Stuttgart
Storage construction:	Züblin Spezialtiefbau, Stuttgart
Storage concept and simulation:	Solites, PKI
Scientific support:	ITW University of Stuttgart, Solites
Financial support:	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit Wirtschaftsministerium Baden-Württemberg

6 Technology suppliers, service providers and design tools

6.1 Technology suppliers and service providers for ATES

To design, build and operate an ATES system as part of a DHC project, part of the services and components are widespread in the construction industry and part of the services and components are quite specific for ATES projects. The latter are:

1. Design, including modelling, of ATES wells and ATES well fields
2. Integration of a DHC network and ATES
3. Drilling, development and completion of ATES wells
4. Providing well screens
5. Providing submersible pumps
6. Providing in-line pressure sustaining valves

Table 6.1 gives an overview of the major technology providers for the ATES specific services and components.

Table 6.1: Major technology providers ATES systems

	Item	Providers	Remarks
1.	Design and modelling ATES systems	IF Technology, Netherlands Sweco, Sweden IFTech NV, Belgium EnopSol, Denmark GTN, Germany Underground Energy, USA	
2.	Integration DHC and ATES	Companies, e.g. consultancies and utilities, designing DHC and HP projects	Often lack of experience with ATES characteristics
3.	Construction of ATES wells	Water well drilling companies	Often lack of experience with ATES characteristics
4.	Well screens	Boode, Netherland (PVC) Stüwa, Germany	Distributed by local representatives

		Johnson Screens, USA (SS, PVC)	
5.	Submersible pumps	Grundfoss, Denmark Melotte, Netherlands Pleuger, Germany Xylem, USA	Distributed by local representatives
6.	In-line pressure sustaining valves	Cla-Val, Switzerland Melotte, Netherlands Grundfoss, Denmark	Distributed by local representatives

6.2 Technology suppliers and service providers for PTES

6.2.1 Liners

GSE Lining Tecnology - www.gseworld.com

AGRU Kunststofftechnik GmbH - www.agru.at

6.2.2 Insulation

NMC Termonova OY (Nomalén) - www.termonova.fi

Rockwool (mineral wool) - www.rockwool.com

Nordic Perlite Aps (perlite/vulcane rock) - www.perlite.dk

Sundolott (EPS/ekspandet polystyren) - www.sundolitt.dk

6.2.3 Geotextile

Propex (Geotex) - http://propexglobal.com/

6.3 Design and analysis tools

With their high capital cost, transient storage temperature behavior, and possible long-term heat build-up impact in the surrounding soil, proposed TES solutions often require detailed modelling to assess the thermal and economic performance of the design over the anticipated lifetime of the equipment. But it is often not enough to just study the TES system individually without also considering its impact on the balance of the system. For example, in a design where the TES system is being charged by a combined heat and power plant, being able to accurately predict the storage temperatures can be critical when deciding when and how to operate the power producing components (turbines, fuel cells etc.). A modelling platform that can accurately analyze the available TES technologies, as well as their interaction with power producing components, heat rejection devices, solar energy components, controllers and heat distribution networks, becomes a valuable tool to the designers, operators and investors. For this IEA task, the TRNSYS software package [SEL 2018] was chosen for the simulation engine.

TRNSYS is a transient system simulation package that has been developed and supported for over 40 years and features an extensive library of commercial and research grade component models covering a wide range of applications. TRNSYS is a powerful modelling platform that has been used extensively in IEA projects due to its inherent flexible nature and ability for users to easily add content to the package. For this IEA project, TRNSYS was chosen because it contains state-of-the-art component models for many of the TES technologies under consideration and it has the balance of system models required to integrate the TES models into real-world applications. A quick discussion of the available TES technologies in TRNSYS follows.

TTES: There are storage tank models in TRNSYS for spherical, cylindrical, rectangular parallelepiped, conical and inverted pyramid storage geometries. These models typically rely on 1-dimensional finite difference approaches using horizontal isothermal temperature nodes within the storage to solve the inter-dependent set of coupled differential equations. The models are well validated and are extremely flexible with where insulation is placed, where fluid enters and exits the tanks, where auxiliary energy can be added to the fluid, etc. These models usually assume constant volume storage but there are several versions with variable volume.

PTES: There are several options in TRNSYS for the analysis of pit thermal energy systems. Most of the TTES models described above also have a soil “wrapper” model that can be used to effectively bury the tank in the ground. These soil wrappers are typically either 2-dimensional (radial and vertical direction) or 3-dimensional (x, y and z directions) finite-difference conduction solution models. These models are used iteratively with the storage tank models to pass temperature and energy flow information back and forth between the models. In addition, a highly detailed model of an inverted, truncated pit storage system (tank + soil) has been developed by the authors and is being validated against a measured data set with very promising results.

ATES: There are two approaches being used to study ATES systems in TRNSYS currently. The first relies on a model developed by Solites called TRNAST [Schmidt 2005] that solves the case of two de-coupled wells (the wells do not interact thermally). This model has been used to study ATES systems for many years and usually does a nice job provided the injection and extraction wells are far enough apart that they do not interfere with each other. The second solution is relatively new and involves the pairing of the popular ModFlow groundwater modelling package [Langevin 2017] with TRNSYS. The user describes the detailed ATES sub-surface conditions and design using ModFlow and the balance of the system using TRNSYS (heat distribution system, heat generation equipment, controls etc.). Because the timescale for the balance of system components in TRNSYS can be on the order of minutes or seconds, and the timescale for the aquifer is often on the order of days, weeks, or even months, the solution methodology can be slightly de-coupled (if desired to help speed up the simulations) where the ModFlow program is only called every ‘n’ TRNSYS timesteps (where n is an integer ≥1). Between ModFlow calls, the TRNSYS balance of system components use the temperature of the aquifer from the previous ModFlow solution. This new approach using ModFlow/TRNSYS is currently being validated against two multi-year measured data sets from commercial ATES applications in Europe.

BTES: There are several BTES options in TRNSYS with the most popular being a modified version of the DST solution methodology from Lund University in Sweden [Hellström 1989]. This model is for U-tube and concentric tube borehole systems using a cylindrical approach and has been extensively validated over a wide range of commercial and residential applications. The DST model in TRNSYS has been recently updated to allow for fluid flow into different ‘rings’ of the stratified ground field.

For modelling the hydraulic impact of ATES systems, well established numerical groundwater modelling software are available including, FEFLOW, MicroFEM and MODFLOW can be used. In many cases, assuming constant hydrogeological properties in the area of influence is a reasonable assumption. This means that relatively simple analytical groundwater modelling software can be used (e.g. MLU for Windows).

A common limitation of groundwater modelling software is that the influence of temperature on the hydraulic conductivity (caused by the temperature dependency of the viscosity) is not included. For low temperature ATES systems (injection temperatures generally less than 10 K above or below the ambient groundwater temperature), the error of the calculated hydraulic impact is very small, but for high temperature ATES systems the error can be significant.

Hydro-thermal transport models do incorporate the temperature dependency of the hydraulic conductivity. These models are necessary to calculate the temperature and thermal energy of the water extracted, to ensure that thermal breakthrough does not occur and to assess the thermal impact of an ATES project. Examples of hydrothermal transport models are METROPOL, MOCDENSE, NAMMU, SUTRA, FEFLOW, SEAWAT and HST2D/3D.

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