D2.3 - Large Storage Systems for DHC Networks

Fifth generation, low temperature, high exergy district heating and cooling networks

FLEXYNETS

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Executive summary

In this report, the potential role of large-scale thermal energy storages (TES) in the FLEXYNETS concept has been analyzed. The report focuses on four storage types; tank, pit, aquifer and borehole storage (TTES, PTES, ATES and BTES respectively). The storage time scales, temperatures, volume, storage medium and investment costs have been described and quantified in the context of FLEXYNETS. The required storage volume and investment costs are highly dependent on the temperature difference in the storage. As the FLEXYNETS concept works with very low temperature differences between forward and return temperatures (approx. 5-15 K difference), this would require any TESthat work at the FLEXYNETS network temperature to be larger and more expensive than storages of the same energy storage capacity working at conventional district heating temperatures. However, if the amount of surplus heat is significantly higher at low temperature, it may be more feasible to choose a connection to this low temperature heat source. Also in this case it may be feasible to include a storage. The description of TES technologies also includes sections on spatial requirements and considerations on heat losses.

The utilization of surplus heat is an important aspect of the FLEXYNETS concept. Transmission pipeline costs for the utilization of surplus heat have been analyzed in connection with the thermal storages. The results suggest that sourcing surplus heat at even several kilometres away from the FLEXYNETS network can be economically feasible, as long as the surplus heat source is sufficiently large compared to the network demand and as long as the assumptions of the model are applicable. In reality the actual feasible transmission distance depends on local conditions and boundary conditions and must be evaluated individually in each case.

Situations have been identified in which large-scale TES could be most relevant in the FLEXYNETS concept. This is in case surplus heat is available at temperatures higher than the FLEXYNETS network temperature, and this heat is directly transferred, via a transmission pipeline, to a TES. The storage can in that case take advantage of the larger temperature difference between the surplus heat temperature and the FLEXYNETS cold pipe temperature, which lowers the required storage volume and investment compared to operating only at FLEXYNETS temperatures.

This system has been modelled in the simulation software *TRNSYS*. The simulations have been carried out for all four TES types and for three reference cities; Rome, London and Stuttgart. The simulations have been performed for different operating temperatures and for different amounts of surplus heat availability. The results of the simulations have been evaluated based on two indicators: the average thermal energy generation cost in the system (in €/MWh) and the annual CO_2 emissions arising from satisfying the heating and cooling demand in the system (in kton/year). Additionally, the Sankey diagrams of the energy flows for different locations and different TES technologies are shown, to quantitively describe how the energy is transferred between the different components of the system.

A storage can in general balance fluctuations in surplus heat supply and network heating and cooling demands, thereby facilitating more efficient usage of the incoming surplus heat and reducing the required auxiliary energy supply to the network (and any associated CO_2 emissions).

The results of the simulations show that especially ATES but also PTES and BTES can be very relevant as seasonal storage in the FLEXYNETS concept, in case surplus heat at temperatures above the FLEXYNETS operating temperature is available. Investing in such large-scale TES can significantly lower the system's annual CO_2 emissions associated with heating and cooling (by up to 95% in investigated scenarios), and either lower the thermal energy price (in investigated scenarios up to 50%) in the system or at least keeping it at a similar level compared to a system without the storage. The storage types all have different benefits and drawbacks depending on the system they are a part of. The conclusion is therefore that although large-scale thermal energy storages are not always relevant for

the FLEXYNETS concept, they can be very beneficial to the system in certain cases, in particular if surplus heat above the network temperature is available in large quantities, and are therefore worth considering when evaluating specific cases in more detail.

Table of Contents

1 Introduction

This report describes how large thermal storage systems (TES) can be used not only in general for district heating and cooling (DHC) networks, but also in the context of the lower temperature levels of a FLEXYNET. The aim is to provide answers to the question if and in what contexts large-scale thermal storages could be beneficial for the FLEXYNETS concept. The analysis includes both spatial requirements, energy performance (temperature dependency) and economic aspects of such storages.

Four types of large TES are considered in this report. These are tank storage (TTES), pit storage (PTES), aquifer storage (ATES) and borehole storage (BTES). These storages are considered to be relevant in the content of FLEXYNETS grids and/or DHC networks in general. In all analysed cases the energy storage medium is assumed to be liquid water, since water has a relative high heat capacity. A short section in the following chapter describes this choice.

In chapter 2 of this report, some general principles of TES are introduced and discussed in terms of the FLEXYNETS concept. These are principles related to storage time scale, categorization, temperature, volume, storage medium and economics of scale. In chapter 3, a more detailed description of the physical and economical parameters for each storage type is given and discussed in terms of storage temperature levels as well as spatial requirements and considerations on heat losses. In chapter 4, the utilization of surplus heat e.g. from industrial sources is discussed, with a focus on the transmission pipeline costs related to this (i.e. how long a transmission pipeline could be feasible to connect the heat source and the storage). In chapter 5, a model system with surplus heat and large-scale thermal energy storages is described and modelled using the *TRNSYS* simulation software. Data from chapter 3 and 4 are used as inputs for the model. The performance of the different thermal energy storage technologies in the modelled system is evaluated economically (in terms of the resulting energy price in the network) and technically (in terms of the CO_2 emissions reduction). In chapter 6, the main findings of the report are summarized, which results in guidelines for use of large-scale TES in the FLEXYNETS concept.

2 General principles of thermal storages

2.1 Storage time scale, categorization, temperature and volume

2.1.1 Time scale for storing

The idea of a TES is to utilize energy being generated while the production conditions are as effective and favourable as possible. Examples include the production of solar thermal during the day, heating or cooling generation in heat pumps while electricity prices are low, and the production of electricity and heat in a CHP plant while electricity prices are high.

Energy storage helps decoupling the production from the demand, which is useful in systems where it is difficult to regulate the production profiles. This is the case in systems with high shares of fluctuating renewable energy such as solar thermal. This can also be the case for systems with a constant inflow of surplus heat from industrial processes, which does not necessarily match the daily or seasonal variations in the heating and/or cooling demand. The storage thereby increases the flexibility to utilize sources of energy that cannot be regulated to fit the demand profile.

The basic principle of separating the production and demand in time can be either on a short-term basis or on a seasonal time scale. While small-scale storages for very short periods (e.g. only on hourly basis) may be useful on local level, the term "short-term storages" is used in this report for storages from daily variations up to weekly storage capacity. "Long-term storages" refer to storage capacities that can account for seasonal variations. The capacity of short-term and long-term storages in this regard, depends on the system properties (including production technologies and specific demand) to which the storage is connected.

2.1.2 State of the storage medium

Thermal energy storages can be divided into four physically different technologies according to the state of the storage medium:

Sensible storage: Use the heat capacity of the storage material. The storage material is most often water due to its favourable properties e.g. having a high specific heat per volume, a low cost and being a non-toxic medium (see next section).

Latent storages: Make use of the storage material's latent heat during a solid/liquid phase change at a constant temperature.

Chemical storages: Utilize the heat stored in a reversible chemical reaction.

Sorption storages: Use the heat of ad- or absorption of a pair of materials such as zeolite-water (adsorption) or water-lithium bromide (absorption).

This report focuses on sensible heat storages only, since the typical use of storages in DHC networks does not involve latent, chemical or sorption heat storages. Furthermore, the aim of the FLEXYNETS concept is to use existing and proven technology if possible, and latent, chemical and sorption heat storages are still being developed and have not been widely demonstrated or adopted for large-scale heat storage.

2.1.3 Temperature level and volume requirements

The temperature level in storages can range from cold storages used for cooling purposes to hot storages, where the temperature in the top of the storage corresponds to the supply temperature of the DH network. The heat storage capacity depends on the temperature levels in the storage. The energy storage capacity for sensible heat storage is

$$Q = m \cdot c_p \cdot \Delta T \qquad \text{(Equation 1)}$$

where m is the mass of the storage medium, c_p is the specific heat capacity of the storage medium and ΔT is the difference between the maximum and minimum operating temperature of the storage. The larger the temperature difference, the higher the heat storage capacity is for a fixed mass of the storage medium. Using Equation 1, the volume V required for storing one unit of energy Q (i.e. the specific volume) can be written as

$$\frac{V}{Q} = \frac{V}{m \cdot c_p \cdot \Delta T} = \frac{1}{\rho \cdot c_p \cdot \Delta T} \qquad \text{(Equation 2)}$$

where ρ is the density of the storage medium ($\rho = m/V$). The absolute volume required for storing the energy content Q with a temperature difference of ΔT is thus

$$V = \frac{Q}{\rho \cdot c_p \cdot \Delta T} \qquad \text{(Equation 3)}$$

These results apply to a storage medium at ambient pressure, regardless of the storage technology, and excludes any additional volume required for containing the storage medium (i.e. storage walls and insulation).

2.2 Water as a storage medium

Existing Danish heat storages for DH systems are usually with water as the storage medium. The reasons include that water is non-toxic, allows for temperature layering (stratification), can provide large effects when charging and discharging, has good heat transfer properties, has a high specific heat capacity and is relatively cheap. The specific heat capacity of water is approximately 4.18 kJ/(kg·K), which is higher than that of most other low-cost, abundant materials such as sand, iron and concrete. Some examples of specific heat capacities are given in Table 2.1.

Table 2.1 – The volumetric specific heat capacities of a few inexpensive, abundant materials (PlanEnergi, 2013).

Material	Capacity ($kWh/m^3/K$)
Water	1.16
Steel	1.07
Concrete	0.58
Soil	0.8 - 0.9

In some systems, a mix of glycol is used in order to avoid freezing. That is for instance seen in solar thermal fields, cooling systems and (shallow) geothermal systems. However, the use of glycol is not without drawbacks; the heat capacity is lower than water and the viscosity and density is higher than water, which results in a need for higher pumping energy in the system, compared to water. Properties of water and different mixes of propylene glycol is seen in the following table for comparison.

Table 2.2 – Properties of water and different mixes of propylene glycol.

	Density				**Constant pressure heat capacity**				**Kinematic viscosity**			
	Water	30% Propylene glycol	40% Propylene glycol	50% Propylene glycol	Water	30% Propylene glycol	40% Propylene glycol	50% Propylene glycol	Water	30% Propylene glycol	40% Propylene glycol	50% Propylene glycol
T	ρ	ρ	ρ	ρ	cp	cp	cp	cp	ν	ν	ν	ν
[° C]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kJ/kg K]	[kJ/kg K]	[kJ/kg K]	[kJ/kg K]	10^6 m^2/s	10^6 m^2/s	10^6 m^2/s	10^6 m^2/s
-30				1.074				3,26				180,00
-20			1.056	1.069			3,54	3,31			48,00	75,00
-10		1.040	1.053	1.064		3,75	3,57	3,35		13,00	23,00	35,00
0	1.000	1.037	1.049	1.058	4,22	3,78	3,61	3,39	1,75	7,40	12,00	17,50
10	1.000	1.033	1.044	1.053	4,19	3,81	3,65	3,43	1,30	4,80	6,30	10,00
20	998	1.029	1.038	1.046	4,18	3,84	3,68	3,47	1,00	3,30	4,30	7,20
30	996	1.024	1.033	1.040	4,18	3,88	3,72	3,52	0,80	2,40	3,00	4,30
40	992	1.018	1.027	1.033	4,18	3,91	3,76	3,56	0,66	1,75	2,20	3,10
50	988	1.013	1.020	1.026	4,18	3,94	3,80	3,60	0,55	1,40	1,75	2,20
60	983	1.007	1.013	1.019	4,18	3,97	3,83	3,64	0,47	1,10	1,40	1,75
70	978	1.000	1.006	1.012	4,19	4,00	3,87	3,68	0,41	0,90	1,10	1,40
80	972	993	999	1.005	4,20	4,04	3,91	3,73	0,36	0,78	0,95	1,20
90	965	986	992	997	4,21	4,07	3,94	3,77	0,32	0,70	0,81	0,99
100	958	979	985	989	4,22	4,10	3,98	3,81	0,29	0,60	0,72	0,88

Due to its advantages, water is the most widely used storage medium for storing heat at temperatures below 100 °C. If pressurized, water can also be used for storing heat at temperatures above 100 °C. In Figure 1, Equation 2 has been used to plot the dependence of the specific energy storage volume on ΔT for the case of water as the storage medium. Due to the inverse proportionality of the specific volume and the temperature difference between the storage inlet and outlet (ΔT), it is considerably more "bulky" to store heat in the form of water for small values of ΔT than for large values of ΔT.

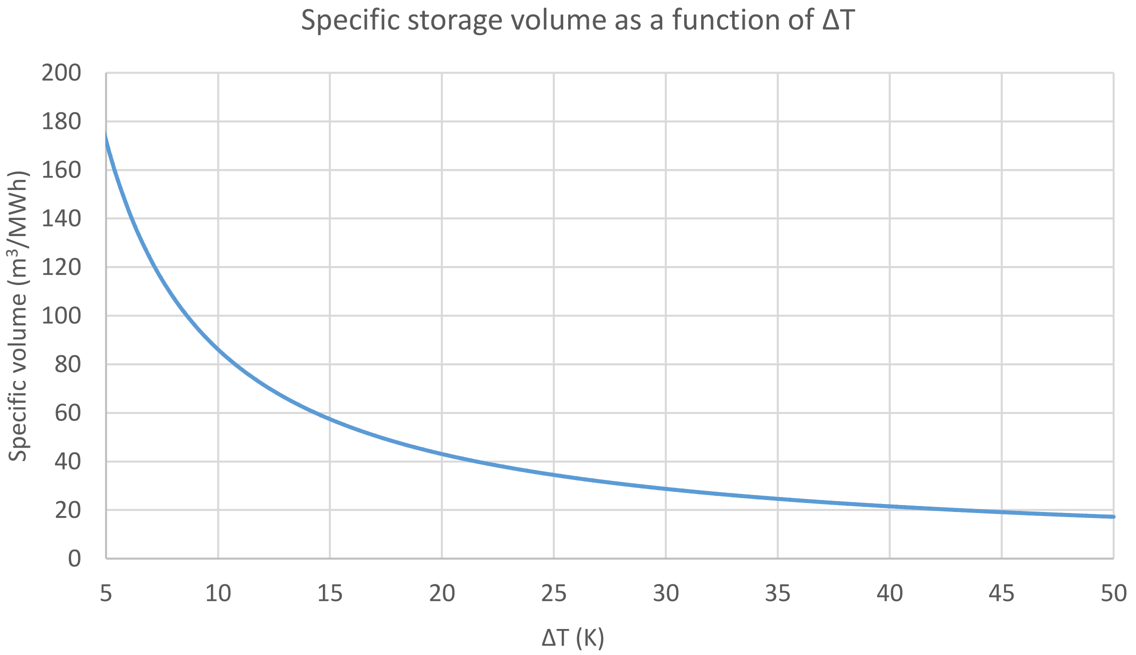


Figure 1 – The required volume for sensible storage of one MWh of heat as hot water shown as a function of the temperature difference between the maximum and the minimum storage temperatures.

Large volumes are required to store large amounts of heat with a small difference between the maximum and minimum storage temperature. In Figure 2, Equation 3 has been used for plotting the required storage volume as a function of the required storage capacity for different values of ΔT. As can be seen in the figure, the difference in the required absolute volume can be very large when storing large amounts of heat in the form of water at different ΔT values. The benefit of an increased temperature difference becomes less pronounced at higher values (e.g. changing from 40 K to 50 K) compared to the lower examples (e.g. changing from 10 K to 20 K). In other words, at the low operating temperatures of FLEXYNETS, a slight increase in ΔT can have a big impact when it comes to storages.

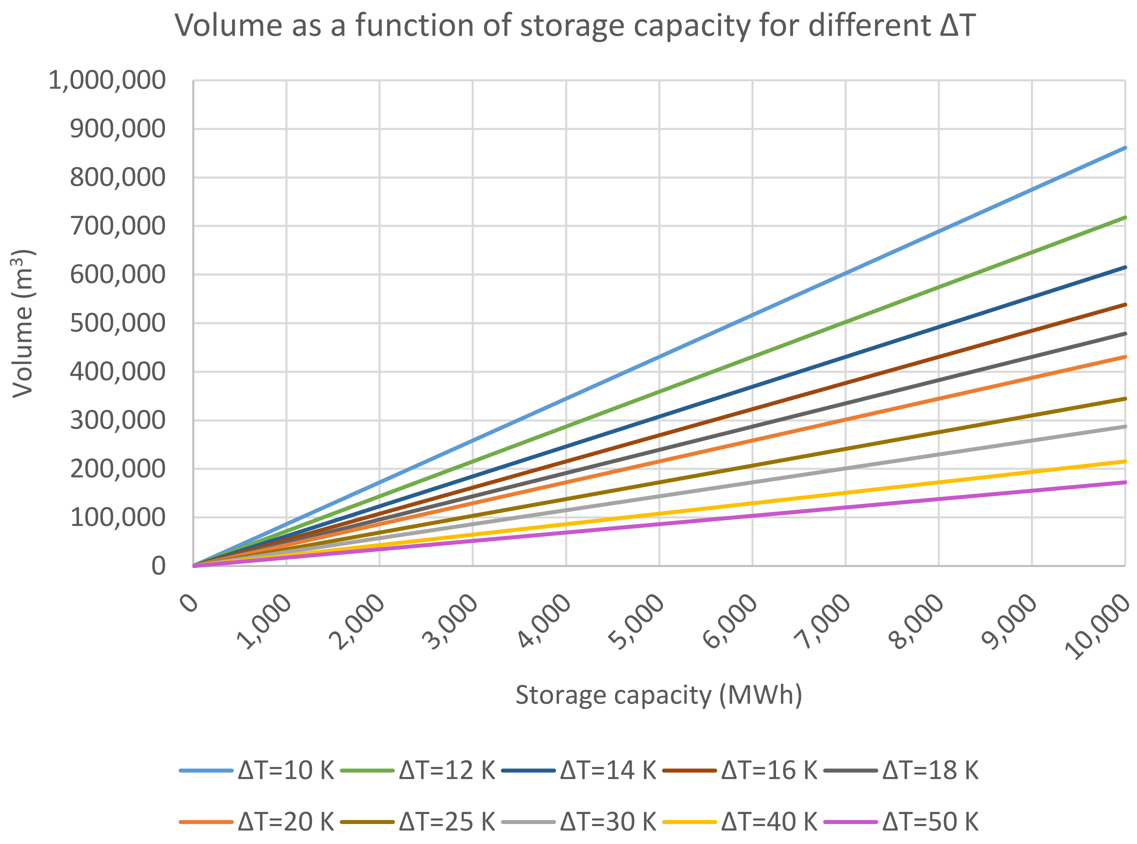


Figure 2 – The required storage volume as a function of the heat storage capacity when storing heat in the form of hot water, shown for a few different values of ΔT.

2.2.1 Network as storage

As shown in the previous section, water can be used to store large rather large amounts of energy. However, the stored capacity is dependent on the temperature difference. A DHC network can in itself contain large amounts of heated or cooled water. This section serves to look into the potential of using the network as a storage.

For this purpose some basic assumptions have been made using the same amount of heat demand, as the TRNSYS calculations later in this report (see Section 5 and forward). The heat demand is in these calculations 100 GWh. Based on rough assumptions, like an average pipe dimension of 168.3 mm (corresponding to a DN150 pipe), the network volume has been estimated to around 2,000 m^3. In the following, the total heat capacity of the network has been estimated based on the properties of water and mixes of propyle glycol, showed in Table 2. The mix of propylene glycol depends on the specific system, normally more than 30 % mix is not necessary, but higher percentages is included here for demonstration. From the numbers in Table 2 it is evidence, that water has the highest storage capacity. If the 50 % propylene glycol mix should have the same capacity as water at a difference temperature of 45 K, the difference temperature should be between 48-49 K.

It is also clear that the temperature difference is of highest significance, and not the supply and return temperature.

Table 2.3 – Estimated storage capacity of a network supplying 100 GWh.

Storage capacity [MWh]						
T_{supply} [°C]	T_{return} [°C]	$T_{diff.}$ [K]	Water	30% propylene glycol	40% propylene glycol	50% propylene glycol
20	10	10	24	23	22	21
30	15	15	36	34	33	31
40	20	20	47	45	44	42
50	25	25	59	57	55	53
60	30	30	70	69	66	64
70	35	35	82	80	78	74
80	40	40	93	92	89	86
90	45	45	104	103	100	97

In some DH systems, the temperature differences in the network are used to reduce peaks. This method is forinstance seen in Denmark, where the DH plants use the method to reduce morning peak loads by raising the supply temperature well in advance to supply in the morning peak. In relation to the FLEXYNETS project – it may not be possible to raise the supply temperature due to drawbacks such as increased heat los by use of minimum pipe insulation – instead the return temperature can be lowered to increase the temperature difference. In this case, a mix with propylene glycol may be necessary, if the temperature is lowered to below the freezing point of water.

In the following example it is shown that a change in the temperature difference can increase the capacity of a network. As illustration for a FLEXYNETS system a supply temperature of 20 °C isused, and the temperature difference is varied from 5 to 15 K. The demand of 100 GWh is still used and the network storage volume is the 2,000 m^3. The results of the network storage capacity is seen in the following figure.

It is seen that it is possible to dubble or triple the capacity in the network in this example. However, as it is also the case for DH plants in Denmark, there is not sufficient capacity to use the network as storage capacity in the purpose of optimizing production from for instance solar thermal plants, heat pumps, etc. Volume capacities used for the same heat demand in the TRNSYS calculations later on is for instance up to 1,0 mio. m^3 water equivalent PTES.

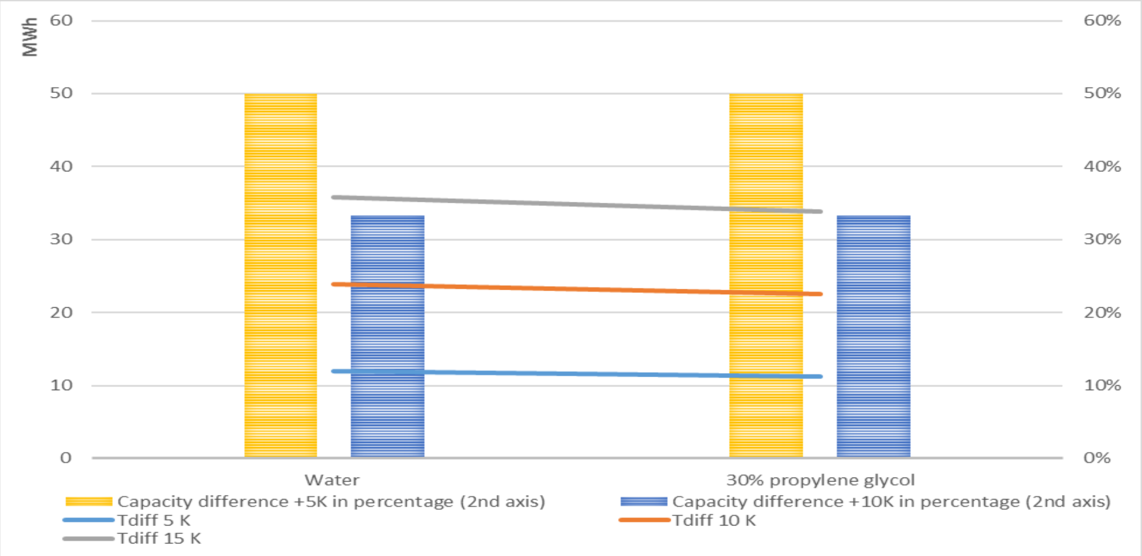


Figure 3 – Network storage capacities at different temperature differences for a supply temperature of 20 °C.

A general remark on utilizing the network as storage is that, it seems to be necessary to have rather large dimensions in the network and the temperature difference is of significance to the network storage capacity. The network volume in itself is not considered sufficient to have the necessary capacityto be used as storage for optimization, but can be used for peak shaving in some peak loads period (e.g. morning peak load). It should however be kept in mind, that the network should not be dimensioned for this purpose. Other things to keep in mind, is the possible higher heat loss – especially in the FLEXYNETS and similar concepts, where the pipe insulation is kept to a minimum, the thermal stress of the pipes if the temperature is varied too much and the higher use of pumping energy if a mix of propylene glycol is used due to high viscosity of the fluid.

2.3 Energy storage economics of scale

Similar to most other energy conversion and/or storage facilities, the specific investment costs of heat storages (defined as costs *C* per unit of volume) are dependent on its dimensions in the form of a power law:

$$\frac{C}{V} = a \cdot V^b \Longrightarrow C = a \cdot V^{b+1} \qquad \text{(Equation 4)}$$

For a given type of storage, the constants a and b can be found by fitting a power-law to a data set containing investment cost data for an array of differently sized storages.

By combining Equation 4 and the expression for the required storage volume from Equation 3, the following expression for the economics of scale as a function of the energy storage capacity and the temperature difference can be obtained:

$$C = a \cdot \left(\frac{Q}{\rho \cdot c_p \cdot \Delta T}\right)^{b+1} \qquad \text{(Equation 5)}$$

This method of evaluating the economics of scale is used later in this report for the investigated storage types.

3 Physical and economical properties of selected storage types

3.1 Investigated storage types

The following large-scale storages are investigated:

- Steel tanks (centralized “daily” water storages)
- Water pit storages (centralized “daily” to “seasonal” storages)
- Borehole storages (centralized “daily” to “seasonal” storages)
- Aquifer storages (centralized “daily” to “seasonal” storages)

These storage types are analyzed and described in terms of energy density, costs etc. depending on the temperature levels. A thing to consider in a given context is whether it is more feasible to store at

a) low temperatures (because the investment in insulation can be reduced and/or more surplus heat may be available at low temperatures)

or

b) high temperatures (because this will mean higher energy density and thereby a smaller storage volume for the same energy content).

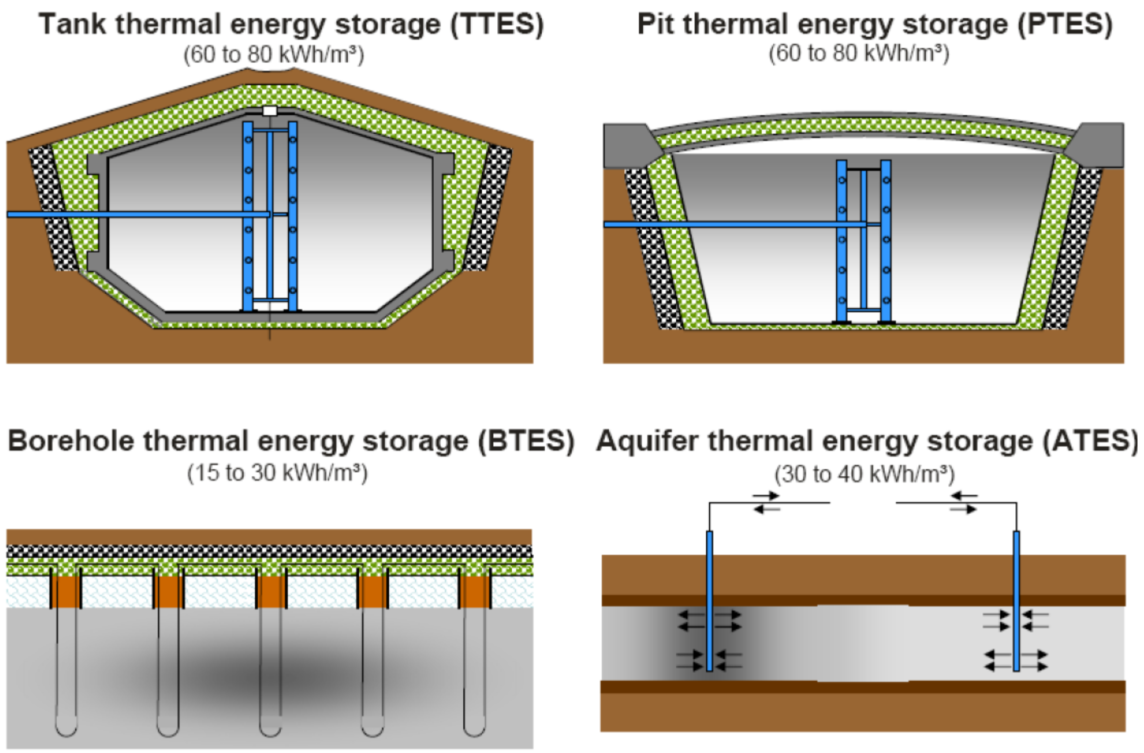


Figure 4 – Concepts of four different thermal energy storages. Figure reproduced from (Mangold, 2007).

Figure 3 from (Mangold, 2007) is reproduced to illustrate the principles of tank storage, water pit storage, borehole storage and aquifer storage.

Storing at low temperatures will imply a limited ΔT and thereby a limited energy density in the storage. This will also depend on the available heat supply (i.e. if high temperature heat is directly available or not).

Some large-scale storages occupy free space whereas others can be integrated with recreational areas. In case the storages must be located in the outskirts of (or outside) the city, transmission pipes have to be included. See more on spatial requirements of the different TES in section 3.7.

3.2 Tank Thermal Energy Storages (TTES)

3.2.1 TTES technology description

Cylindrical steel tanks are also known as TTES, which is an abbreviation of tank thermal energy storage. This type of storage can be located above ground level, which is the most common case, but it can also be located below ground level. This is for instance seen in Germany, where tanks are sometimes used even as seasonal storages in connection to e.g. solar thermal, supplying smaller residential areas. If the storage is placed as steel tank above ground, it can be dominant in the landscape. If the storage is below ground level, it may be possible to use the area for other purposes. See more information on spatial requirements of TTES in section 3.7.

Nearly 300 Danish DH plants have heat accumulation tanks. These are not buried underground, but are made as insulated freestanding cylindrical steel tanks located next to the DH plant. The average size is approx. 3,000 m^3 (PlanEnergi, 2013). The cumulated storage capacity of all these tanks is approximately 50 GWh. The tanks were initially installed together with CHP-plants to enable flexible production, optimizing the revenues from the electricity production. Due to the increased electricity production from wind turbines in Denmark, the annual operation hours of the CHP plants are decreasing. Now these tanks are in many cases utilized for solar heating plants, where they are sometimes supplemented by additional tank capacity.

The tank is typically made of stainless steel, concrete or glass-fiber reinforced plastic and contains water as storage material. Insulation of the storages is determined according to the environment and application. For steel tanks, 30 – 45 cm of mineral wool is typically used to keep heat losses at an acceptable level.

In most installations the temperature supplied to the storage is chosen to make it able to provide the supply temperature in the DH network. The temperature distribution in the storage is managed by a pipe system, shown in Figure 4 by the blue pipes. This system strives to keep the efficiency of the storage as high as possible. A vertical temperature distribution is seen in the steel tank, where the hot water is in the top. This is referred to as thermal stratification. It is possible for some tanks (with several outlets, even though they are not as many as shown in Figure 4) to extract heat at different heights. In such tanks water at the desired demand temperature level can be used (e.g. from the middle part of the tank) while maintaining high temperature water in the top of the tank if the temperature in the top of the tank is higher than what is needed. This is especially useful when operating with very large storages, where it is important to maintain a good thermal stratification, meaning a high temperature difference in the tank from top to bottom, in order to avoid having a large volume of too low temperature to be utilized directly in the network.

3.2.2 TTES economics of scale

Figure 5 shows the specific investment costs for cylindrical TTES as a function of their volume. This storage technology shows very good economics of scale for tanks in the size of 0 – 5,000 m^3, but for much larger tank sizes the cost curve is quite flat. The data in the figure is for TTES in Denmark. No data is shown for TTES larger than 10,000 m^3 since this is quite uncommon although tanks up to 60,000 m^3 exist in Germany. The heat losses depend on the volume and the surface area of the tank, and are estimated to be in the order of 2% per week for 500 m^3 storages and 1% per week for 5,000 m^3 storages (PlanEnergi, 2013).

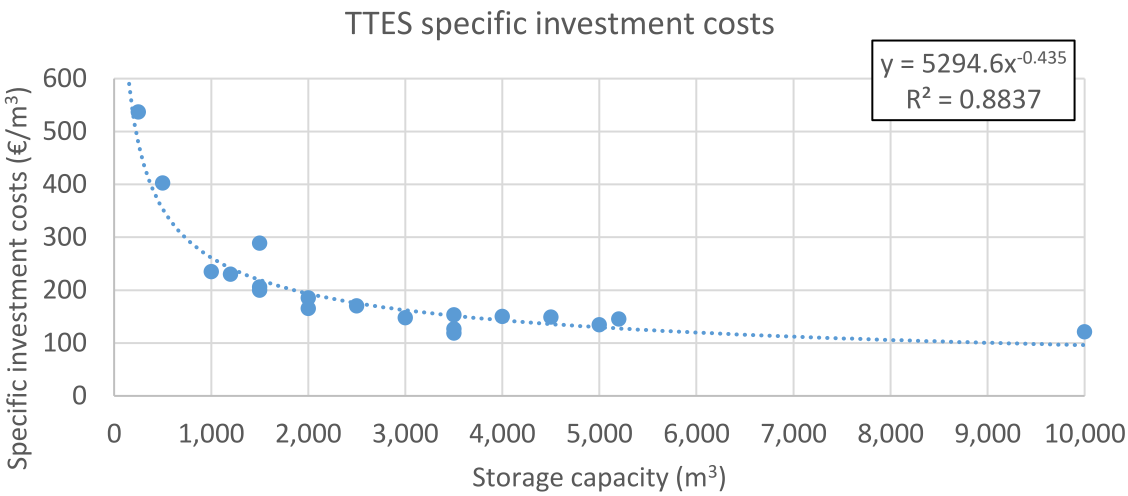


Figure 5 – Economics of scale for a few TTES storages in Denmark. Data from (Danish Energy Agency, 2014) and (PlanEnergi, 2013). The data was fitted using a power curve (see Equation 4). The fit shows good agreement with the data points.

3.3 Pit Thermal Energy Storage (PTES)

There are different technical concepts for seasonal heat storage. One of the concepts is the pit thermal energy storage (PTES), which has been developed since the 1980s at The Technical University of Denmark where a test storage was built. The first pilot demonstration storage was established in Ottrupgård, Denmark in 1995 (1,500 m^3) and the second pilot demonstration storage was constructed in Marstal, Denmark in 2003 (10,000 m^3). The first full scale storage was built in Marstal 2011 - 2012 (75,000 m^3), and the second full scale storage in Dronninglund, Denmark during 2013 - 2014 (60,000 m^3) – both in connection to large solar collector fields, covering around 40 - 50% of the DH demand in each network. PTES is a rather inexpensive storage form per m^3, developed in conjunction with solar heating. In Denmark 6 PTES are already in place and more are expected to follow.

3.3.1 PTES Technology description

A PTES is a large pit dug in the ground fitted with a membrane, typically of plastic, on the bottom and walls of the pit to keep the storage from leaking. Like for the TTES, the PTES also uses water as the storage medium. The pit is covered with an insulating lid, which floats on the surface of the water, to reduce the energy losses. The side walls and bottom of the storage are often not insulated because the ground soil has an insulating effect itself and the additional costs for improving the insulation are not feasible considering the reduced energy losses. See more on heat losses in section 3.8.

Figure 6 shows a cross section of the PTES and details of the construction. Liners are applied both as part of the lid and in the top of the PTES. The slope of the sides is relatively low, but depends on the local soil conditions.

Similar to TTES, PTES also have a vertical temperature distribution in the storage to increase the total efficiency of the storage. The same kind of system to manage this temperature distribution is also fitted here, and indicated in the blue pipes in Figure 3. The PTES requires a relatively large amount of area, compared to other thermal storage technologies. See more on spatial requirements of PTES in section 3.7.

For large-scale thermal storages this is the most common technology in Denmark, though not a large number of them have been established yet. PTES is currently used and planned for use as seasonal storage, primarily (but not only) in conjunction to solar thermal DH production. In Marstal there is in total 85,000 m^3 of PTES installed where the first 10,000 m^3 have been operated for more than a decade and the additional 75,000 m^3 was constructed in 2012. In the case of Marstal the solar fraction (i.e. the share of solar thermal energy for the district heating supply) is around 41% (Marstal District Heating).

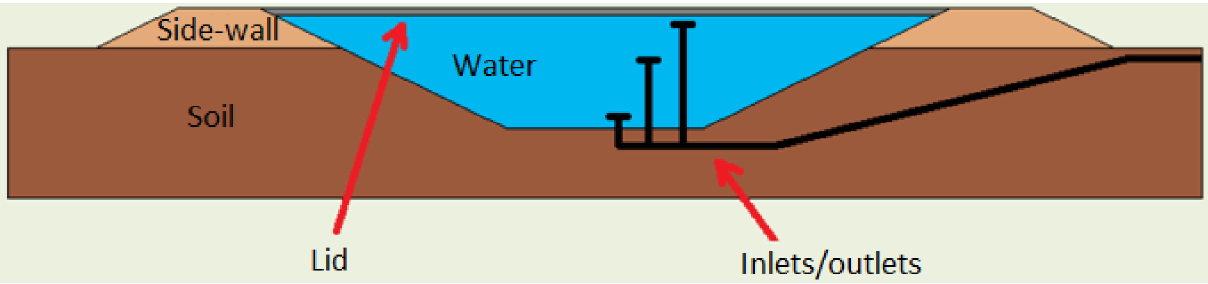


Figure 6 – The principle of pit thermal energy storage (PTES). Figure by PlanEnergi (PlanEnergi, 2013).

A PTES of 60,000 m^3 has been constructed in Dronninglund and in Gram a large PTES storage of 122,000 m^3 is constructed recently. Today the largest PTES is constructed in Vojens, with more than 200,000 m^3 capacity in connection to a solar heating system with a total collector area of 70,000 m^2. The seasonal storage ensures that around 40% of the annual DH demand can be covered by solar heat.

For conventional DH temperature levels, the specific capacity of the storage is 60 - 80 kWh/m^3 similar to TTES. The heat losses depend on the temperature level in the storage, the insulation of the lid and the volume/surface-ratio, and whether a heat pump is used to discharge the storage. In general, the dimensioning of insulation is subject to economical optimisation, i.e. does it make more sense to invest in insulation or more solar collectors. See more on heat loss considerations in section 3.8. Examples of storage efficiencies in the range of 80% to 95% have been seen.

Key points for PTES are choice of material and water chemistry. Water treatment – removal of salts and calcium, raise of pH to 9.8 – is important to reduce/avoid corrosion. In addition, choice of steel quality of the pipes is crucial to ensure long technical lifetime. The insulation material in the lid should be resistant to water in case of a leakage, so that the insulation effect is not lost. Leakages can be found and repaired by divers. A key component of the pit thermal energy storage is the liner. The technical lifetime of the liner depends on the temperature of the water – the higher the temperature the shorter the lifetime.

3.3.2 PTES Geometry – Considerations regarding design, soil balances etc.

When establishing a very large pit heat storage, for instance of 1 million m^3, it can be beneficial to consider establishing two pit heat storages of 0.5 million m^3 each and located just next to each other. In this case, the two storages are connected in series, which will correspond to having the two storages on top of each other. Typically, once a year, the connection is reversed. The benefits of this include

- Redundancy

- The two storages can be established and commissioned separately
- One storage can be taken out of service in case of maintenance
- The lifetime of the topliner increases
- Improved stratification

PTES are normally constructed as excavations designed as an inverted truncated pyramid, see Figure 7. The excavated land is laid in a bank around the excavation, thus achieving soil balance, and the volume of the storage is partly below and above the original terrain.

The sides and bottom of the storage are planned to avoid sharp stones, which can damage the liner. Then Geotextile lanes are laid to further protect the liner and eventually lanes off HDPE liner are welded together to provide a watertight surface. The lanes typically have a width of 6 - 7 m. The length of the lanes must be large enough to reach from the top to the bottom of the storage to avoid welding along the sides of the storage. The liner is held in drains/banks around the bearing as shown in Figure 7.

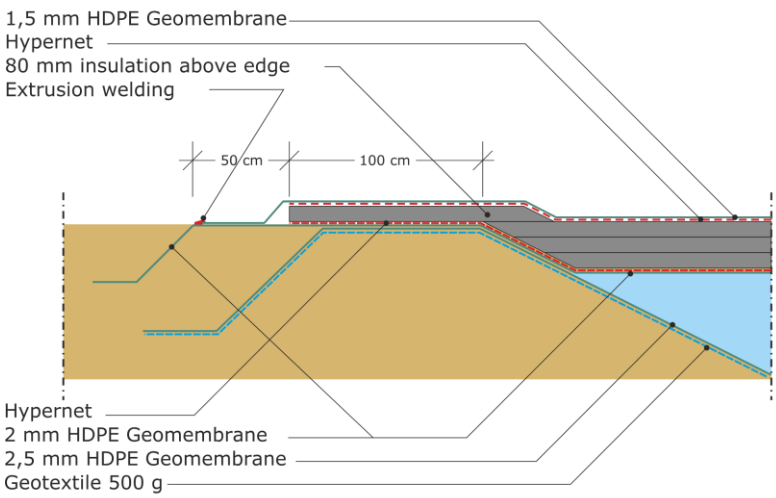


Figure 7 – Cut through the lid and lockers. The locking gates are channels dug free around the storage. In these channels, the ends of the liners are placed and then filled with soil that locks the liner (PlanEnergi).

Depending on the size of the storage, typically three tubes are introduced through the bottom or side of the storage to three diffusers placed in respectively the top, middle and bottom of the storage in order to move the water to and from the storage.

When the storage is filled with water, the work with the top is initiated, which typically consists of an HDPE liner floating on top of the water that is welded and pulled over the water surface so that the entire surface is covered. The bottom cover of the lid is locked as the sideliner fixed in the soil banks. At the top of the bottom line of the lid, a drain line is placed, then insulation, and at the top another drain line before closing the lid with an HDPE top liner. The top liner is welded to the bottom of the lid along the edge of the bearing. A number of vacuum valves are attached to the top line, which secures the liners against wind impact and, in combination with the drainage valves, ventilates the lower structure. An HDPE liner is not steam diffusion proof, and ventilation is therefore necessary to avoid build-up of moisture in the lid that destroys the insulation properties.

The lid is a major part of both the investment and the heat loss. The lid should therefore be as small as possible, which is achieved by making the (inner) slope as large as possible, as well as making the storage as deep as possible. Figure 8 shows the relative lid area (compared to a reference with a depth of 40 - 45 m and a slope of 1:2) as a function of water depth for a rectangular 0.5 million m^3 pit storage, for two different slopes of the storage sides. It is apparent that the higher the slope, the smaller the area (the red curve is below the blue curve). This means that for a given volume and a certain depth, a significant share of the lid area can be saved if the slope can be increased. The maximum slope is limited in practice by geotechnical conditions and/or working conditions in connection to establishment of the bottom/sideliner. It is difficult to have a steeper side than 1:2 (as ratio between height and width of the sides). It is also apparent that the greater the depth of water, the smaller the area (the curves fall to the right). However, the curves eventually flat out, so the gain is limited for water depths greater than respectively 30 m and 45 m approximately for the two slopes shown. However, the maximum water depth will usually also be limited by the groundwater level and the desired level of soil balance. Figure 9 shows possible shapes for PTES of two different depths.

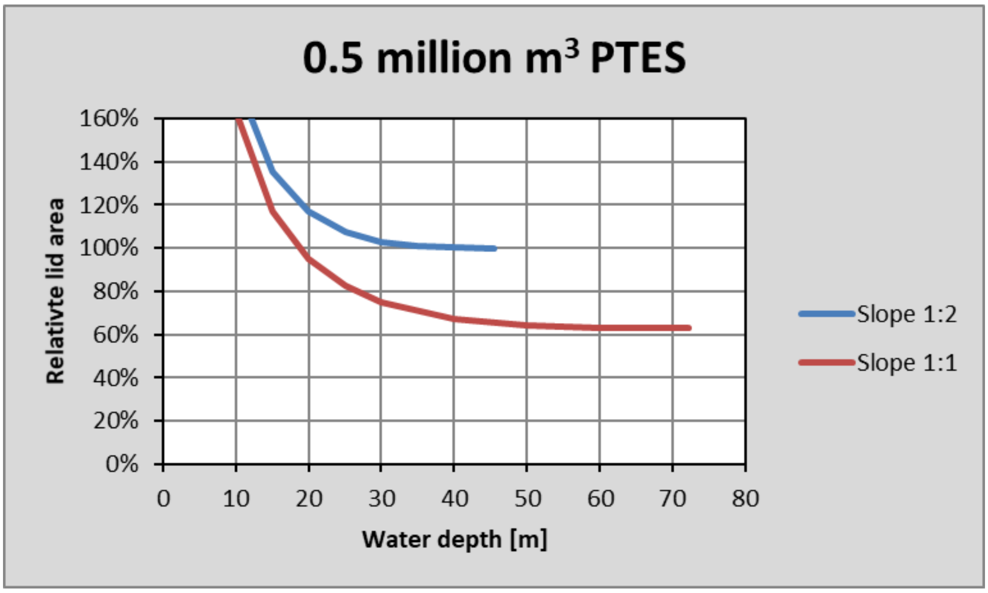


Figure 8 – Lid area relative to the area of a PTES with a depth of 45 m and a slope of 1:2 as function of water depth for a 0.5 million m^3 PTES. The figure shows that for depths larger than approx. 35 m (1:2 slope) and approx. 50 m (1:1 slope), no reduction of the lid area is obtained.

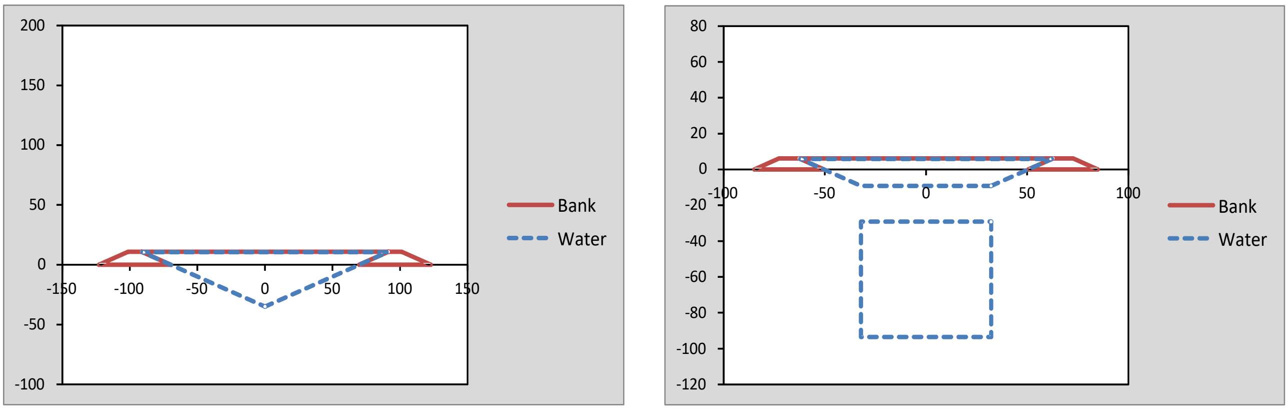
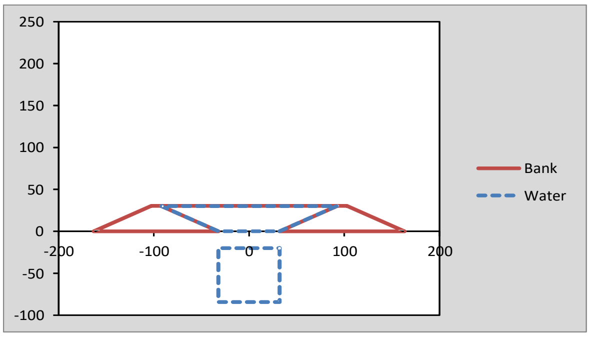


Figure 9 – PTES of water depths of approx. 45 (left) and 15 m (right). Notice the different scales on the secondary axis (sketch by PlanEnergi).

3.3.3 Soil balance

It will often be expensive for a PTES if the excavated material is to be disposed of (if the storage is placed only under ground level) or if external material is to be supplied (if the storage is located above ground level). The surplus soil / soil deflection is shown as a function of the vertical position of the storage for a storage of 0.5 million m^3 in Figure 10. If the storage is buried completely (the sketch to the right in



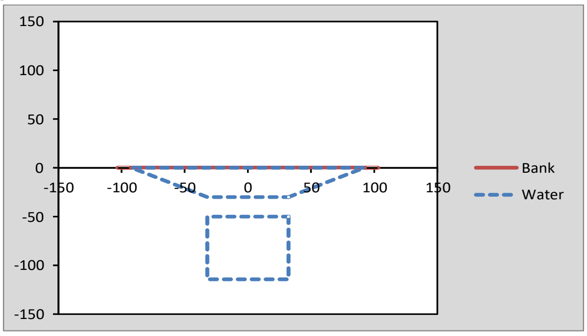


Figure 11) the soil surplus is obviously approximately 0.5 million m^3 (the complete water volume). If the storage is reversed across the terrain (the sketch on the left in Figure 10), approximately 1 million m^3 material needs to be added. The storage must be buried approximately 19 - 20 m down to achieve soil balance (where the red curve intersects the blue in Figure 10). The depth of the PTES has a rather large impact on the soil balance. In the given case, a change of depth by ±1 m changes the soil balance by around ±50,000 m^3 of material.

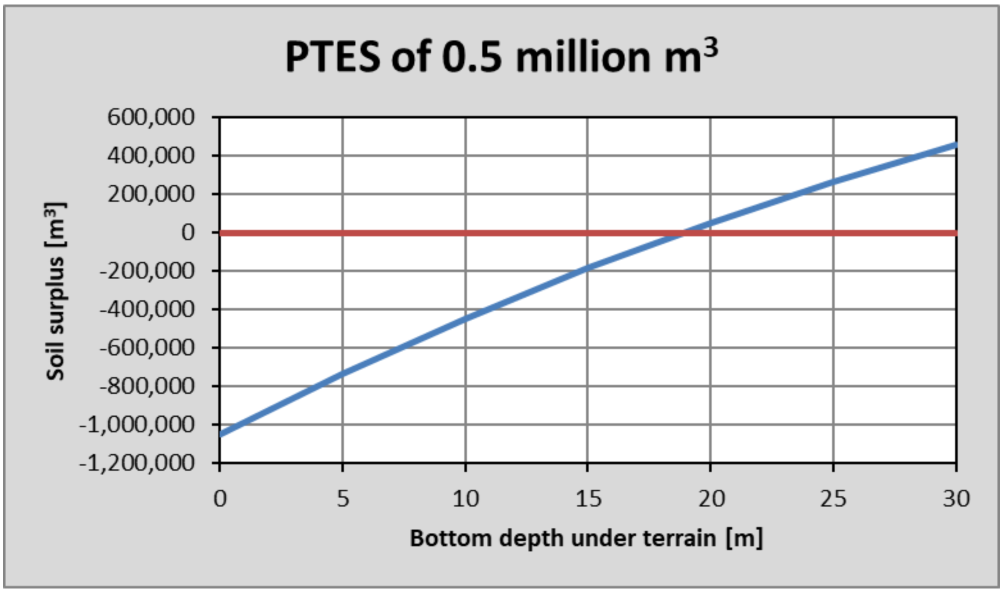


Figure 10 – Soil surplus as function of the bottom depth under terrain.

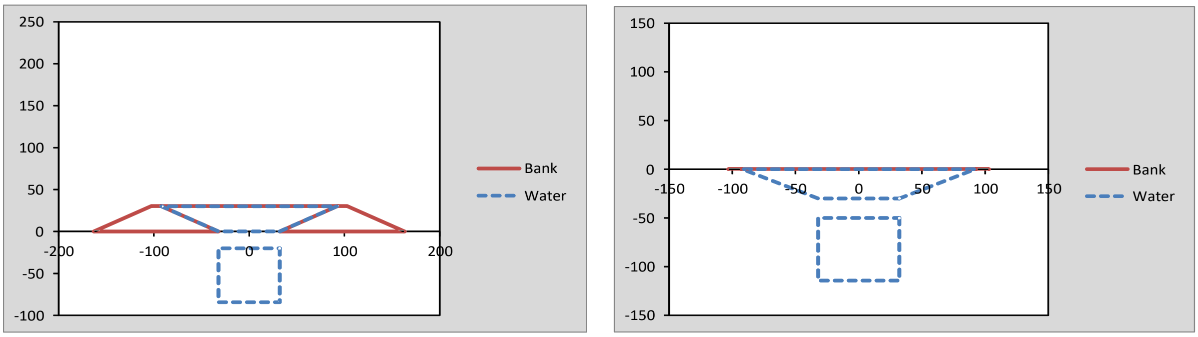


Figure 11 – PTES of the same volume above and under terrain. The water depth is 30 m in each case and the slope is 1:2 Notice the different scales on the secondary axis (sketch by PlanEnergi).

3.3.4 Storage depth

It is often the groundwater level that determines how deep the excavation can go. In addition, it is desirable that the storage is cooled as little as possible by flowing groundwater. Figure 12 shows that a hole depth below 19.7 m gives a water depth of 30 m, see sketch on the left on

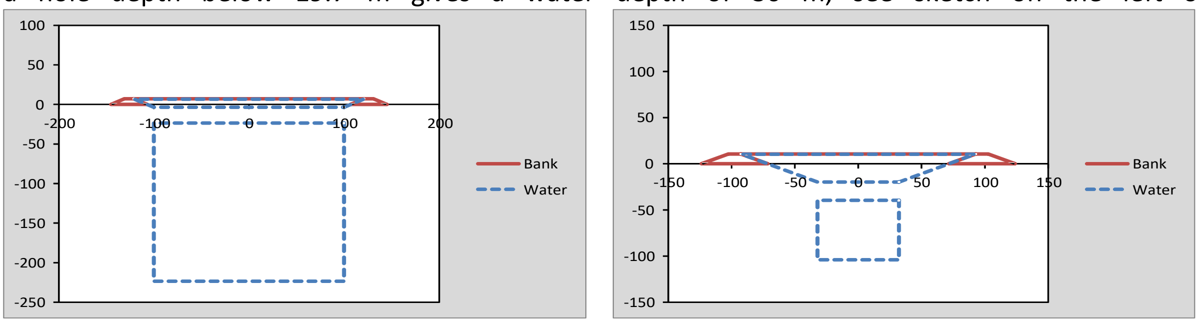


Figure 13. Similarly, a hole depth of 10 m gives a water depth of 19.3 m, and a hole depth of 5 m gives a water depth of 12.7 m. At the same time, it can be seen that the deeper buried underground, the

smaller the lid area. As mentioned previously, it will often be the conditions of the soil or the groundwater that will determine the depth under terrain.

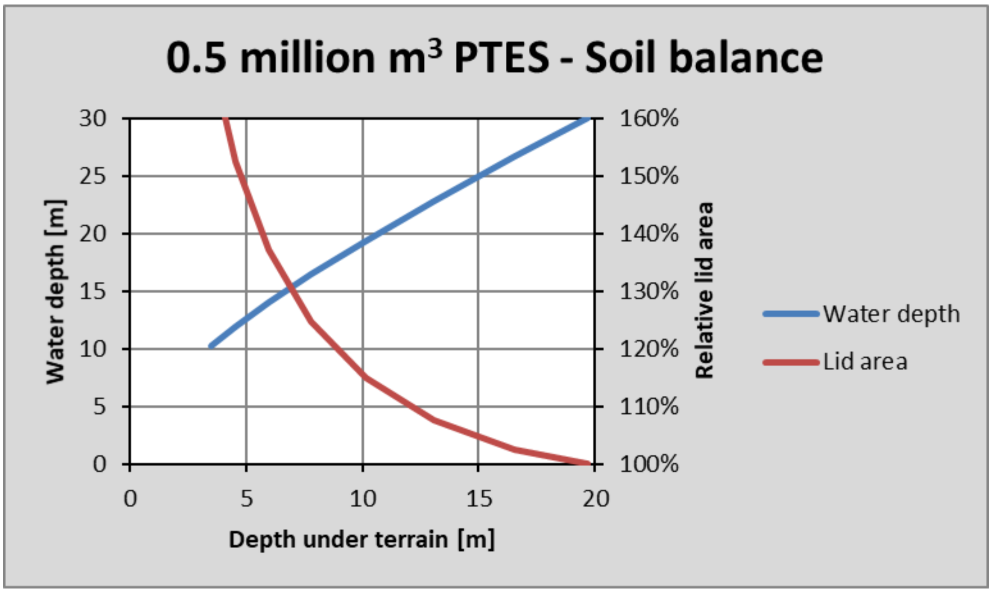


Figure 12 – Water depth and relative lid area as function of hole depth for PTES with soil balance.

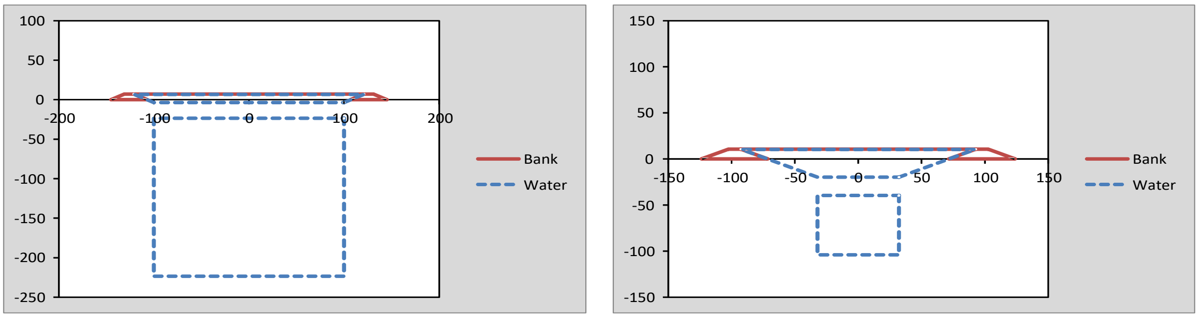


Figure 13 – PTES with water depths of approximately 10 and 30 m. Notice the different scales on the secondary axis (sketch by PlanEnergi).

3.3.5 PTES economics of scale and investments

Pit thermal energy storages have significant economics of scale benefits as shown in Figure 14. They are primarily suitable as large-scale facilities and the tendency has been that every new PTES that is constructed is larger than those already existing. For large-scale heat storage, PTES has considerably lower specific investment costs than TTES.

The total investment of a storage solution depends strongly on the geometry of the storage, which is shown in the previous sections but also factors as location and work salary. Especially the lid has a high price per area. Some estimated costs are shown in Table 3.1. The costs were collected in connection with a project by PlanEnergi for two storages of 0.5 million m³ each.

Table 3.1 The specific investment costs for the main components of PTES systems.

Component	Value	Unit
Digging and rebuilding (chalk)	13	€/m^3
Bottom and sides	27	€/m^2
Lid (insulated with 300 mm Nomalén) (insulation 51 €/m^2)	111	€/m^2
Water (raw water 0.8 €/m^3 + water treatment 1.9 €/m^3)	3	€/m^3

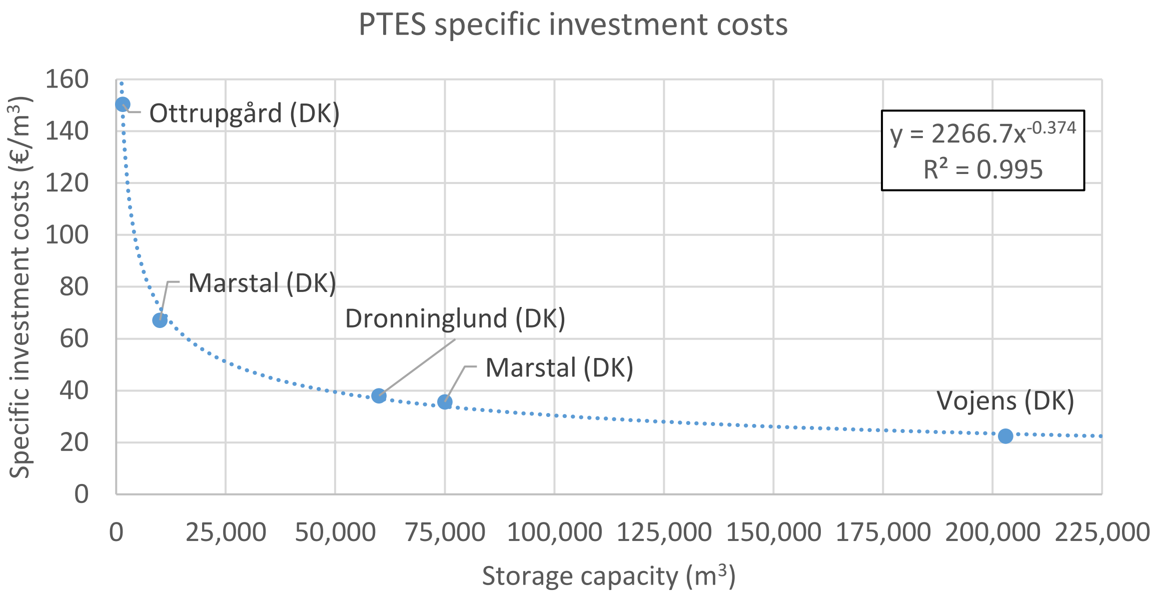


Figure 14 – Economics of scale for PTES systems. Data from (PlanEnergi, 2013) and (PlanEnergi, 2015). The data was fitted using a power curve (see Equation 4). The fit shows an excellent correlation with the data points.

3.4 Borehole Thermal Energy Storage (BTES)

3.4.1 BTES technology description

A borehole thermal energy storage (BTES) consists of a number of boreholes in the ground in which pipes are placed. The storage is charged by pumping hot water through the pipes in the boreholes, which then transmits heat to the ground surrounding the boreholes. The storage medium here is the soil surrounding the boreholes and not the water in the pipes which is just a transfer medium. There is usually a layer of insulation on top of the boreholes to reduce heat losses. See more on considerations on heat losses in section 3.8.

Figure 15 shows a cross-sectional and a three-dimensional drawing illustrating how the BTES is located in the ground. When discharging, cold water is pumped through the pipes in the boreholes and the stored energy in the ground is absorbed in the water.

A number of BTES facilities exist today in a number of countries, including Germany, Sweden, Canada, USA and Denmark. The first BTES in Denmark was constructed in 2012 and put in operation in

Brædstrup for district heating supply in conjunction with a large solar thermal capacity. The facility consists of 48 boreholes of 45 m in depth with a total storage volume of 19,000 m^3 soil. At the time of construction, the Brædstrup BTES was the largest BTES facility for district heating in Europe.

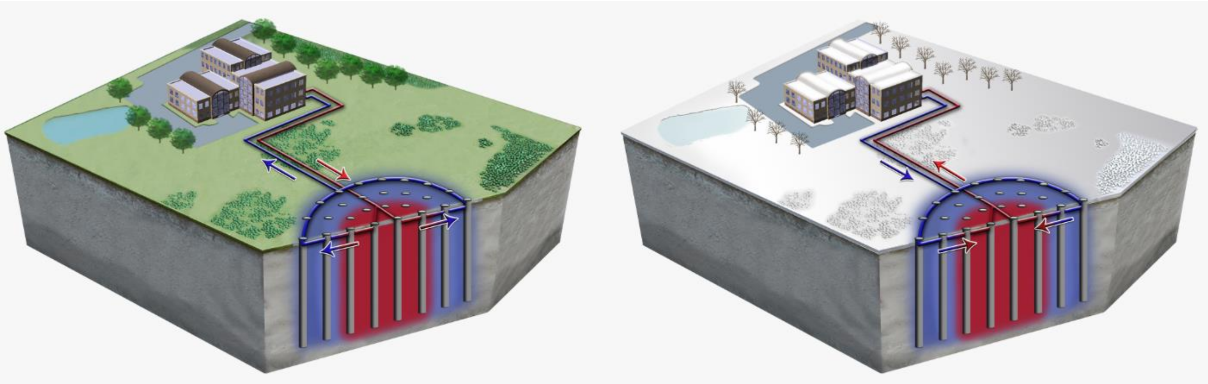


Figure 15 – Three-dimensional drawing of BTES; left: BTES summer operation (cooling), right: BTES winter operation (heating) (http://underground-energy.com/our-technology/btes/).

The capacity of BTES can be anything between one borehole for the use of one single household to large-scale storages of several hundred boreholes. However, a single borehole for a single household is typically not used as a storage, but simply as ground heat source. In this case, energy can be extracted from the ground to supply heat pump evaporators at higher temperature levels than ambient air in winter and thus improve the seasonal performance factor (SPF) of the heat pump. Vice versa, the geothermal heat exchangers can be used for heat rejection of the chiller condensation energy at lower temperature levels than ambient air or cooling towers, which again improves the chiller energy efficiency ratio. The boreholes can also be directly used.

Direct use of thermal energy from the underground for building cooling or heating is a very efficient way to use underground heat exchangers (e.g. boreholes), as only electricity for energy distribution (pumps and fans) is required. The heat carrier media can be air or water brine. A specific cooling power in the range of 45 W/m was reached with an air-geothermal heat exchanger in an office building in Weilheim in Germany, whereas only 25 W/m were recorded in a brine-based system. Data for the power as a function of ambient temperature for this system is shown in Figure 16. Data for the power as a function of the brine temperature for a brine-based system is shown in Figure 17

In (Biermayr, 2013), a 2 year simulation of a U-shape ground heat exchanger designed for seasonal storage of solar heat shows that specific charging powers of over 130 W/m are reached, because of the high temperature difference between the ground temperature (12 °C in average) and the outlet temperature of the solar field of 70 °C. With a discharge temperature of -2 °C (heat pump evaporator), the specific discharge power of only 40 W/m are reached. The storage efficiency can be increased with geometrical distribution of several ground heat exchangers. The results can be found in Figure 18.

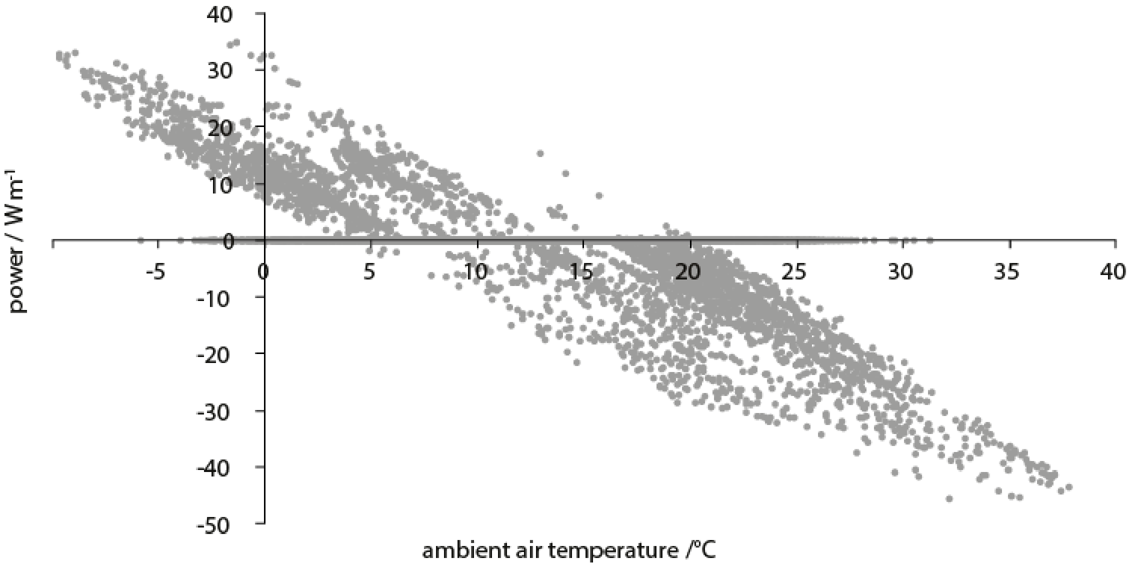


Figure 16 - Power of the earth-to-air geothermal heat exchanger in the Weilheim office building as a function of ambient air temperature, which corresponds to the inlet temperature to the ground heat exchanger.

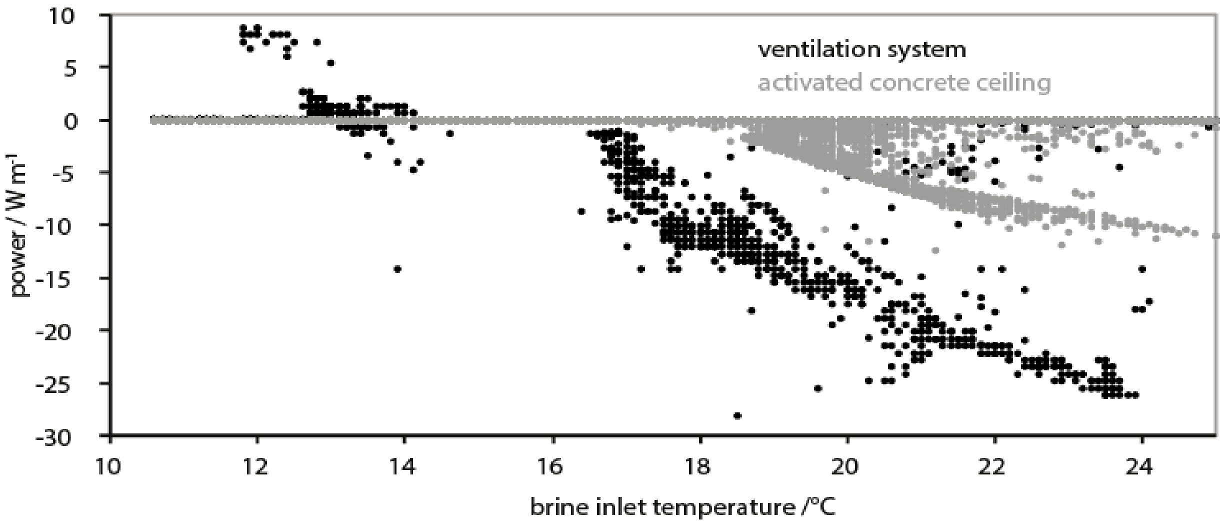


Figure 17 - Measured geothermal power in 2006 as a function of brine inlet temperature to the ground (office building in Freiburg).

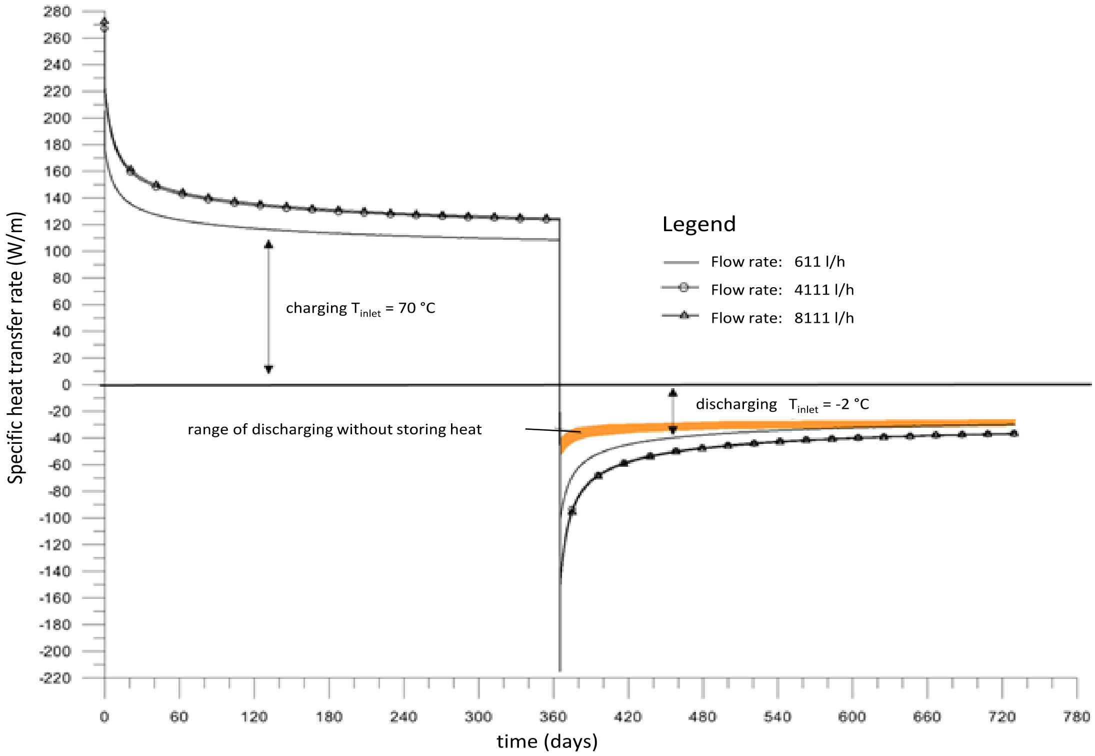


Figure 18 - Specific heat transfer rate per metre of borehole length of a common U shape double pipe ground heat exchanger for 2 years. Year 1: charging period with a temperature level of 70 °C; year 2: discharge with a temperature level of -2 °C. The orange line represents the discharge specific power without storing heat previously (Biermayr, 2013).

(Biermayr, 2013) shows that the combination of a BTES with a short term TTES can be financially interesting by increasing the direct use of solar heat. The TTES can act as a buffer between variations in solar heat production (varies from day to night) and the BTES (which cannot be charged as fast as the solar heat is produced). Also for large-scale installations, experience shows that the best economical performances of BTES are achieved when a buffer tank is included in the system.

The most suitable geology for BTES is saturated soils with no or very limited groundwater flow and a high heat capacity. The specific capacity of the systems is estimated to being 15 - 30 kWh/m^3 of storage material for conventional DHtemperature levels (PlanEnergi, 2013). The efficiency depends on the size of the storage. For small systems, the efficiency can be as low as 60% where for large systems of above 100,000 m^3 the efficiency can reach 85 - 90%.

The charge and discharge effect is limited by the convection from or to the storage material in the ground and the transferring medium in the ground pipes. This is why BTES mainly is used for base load capacity. The investment costs are sensitive to the ground properties of the location where the storage is to be constructed. Since it requires many boreholes for large facilities, any difficulty in drilling the boreholes can increase the investment costs significantly. Compared with other storage options (e.g. PTES) examples of pro and con arguments for BTES are: BTES does not take up a large area (since the top surface can be used for other purposes). The heat cannot be extracted at a sufficiently high temperature level to supply conventional district heating directly. Hence a heat pump is needed even if the heat is injected at higher temperatures, and an exergy loss is thereby introduced. The outlet temperature issue becomes less important in the context of the (lower) FLEXYNETS network temperatures.

3.4.2 BTES economics of scale

The storage volume of BTES is not as well defined as for TTES and PTES. It is often assumed that 3 m^3 of soil volume BTES are equivalent to 1 m^3 of water storage volume because the soil has a lower specific heat capacity than water (Mangold, 2015), though in practice this will depend on the local conditions. After making this conversion from soil volume to water equivalents, BTES storage volume can be compared directly with the volumes of TTES and PTES.

As shown in Figure 19, BTES does not have as well-defined economics of scale as TTES and PTES. The specific investment cost is around 40 €/m^3 water equivalent for four out of the five systems in the examples used. An increased amount of data points would provide a more reliable estimate of the economics of scale of BTES. The investment cost for such systems is also location-specific, as it relies on the geological suitability of the soil for drilling the holes and on the composition and permeability of the soil with regard to heat exchange and storage.

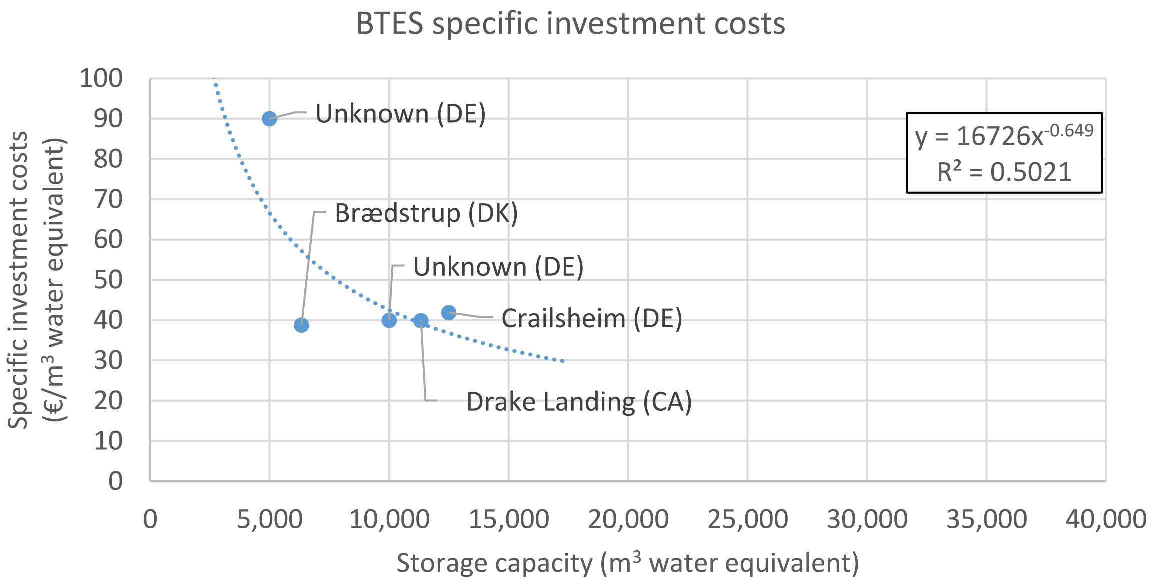


Figure 19 – Economics of scale for BTES systems. Data from (PlanEnergi, 2013) and (CIT Energy Management, 2011). The data was fitted using a power curve (see Equation 4). Note that the fit is somewhat unreliable due to the large scattering of the data points.

Detailed capital costs were available for the two 134 m boreholes of the heat pump system in Ostfildern in Germany, shown in

drilling:	17 903 €	52%
legal certification:	1 553 €	4%
4 double U-tubes:	3 076 €	9%
brine package:	3 809 €	11%
2 pumps + membrane expansion:	966 €	3%
connection tubes:	2 496 €	7%
brine distribution:	928 €	3%
connections/ valves:	3 875 €	11%

Figure 20. The investment costs correspond to 129 €/m of earth heat exchanger with the drilling

costs accounting for about 50 % of the total costs. Other project examples (e.g. systems from Spain) have significantly lower specific investment costs (about 50 - 60 €/m).

A study of the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg from 2011 showed a linear correlation between investments and ground heat exchanger length with a slope of 58 Euros per metre, shown in Figure 21. The specific cost, reported for Austria in (Biermayr, 2013), for boreholes under 150 m deep is around 40 to 50 €/m by using hydraulics drilling technic. This price does not include taxes nor equipment such as pipes.

drilling:	17 903 €	52%
legal certification:	1 553 €	4%
4 double U-tubes:	3 076 €	9%
brine package:	3 809 €	11%
2 pumps + membrane expansion:	966 €	3%
connection tubes:	2 496 €	7%
brine distribution:	928 €	3%
connections/ valves:	3 875 €	11%

Figure 20 - Investment costs of the vertical heat exchangers at the youth centre installation in Ostfildern.

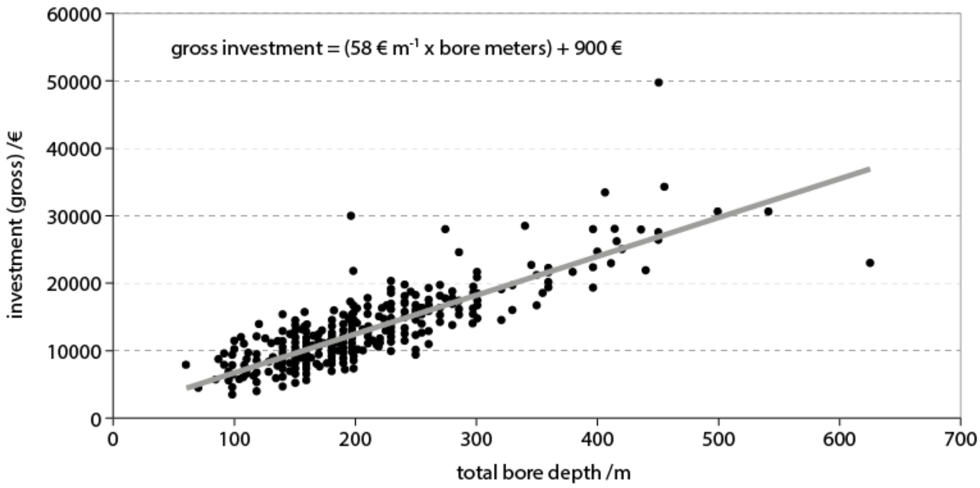


Figure 21 - Gross investment costs for vertical earth heat exchangers (examples of investment in boreholes only).

3.5 Aquifer Thermal Energy Storage (ATES)

3.5.1 ATES technology description

In aquifer thermal energy storage (ATES) systems, two (or multiples of two) separate wells are drilled into an underground groundwater reservoir (aquifer) for seasonal TES. One of the wells is used for heat storage and the other for cold storage. Favourable geological conditions are a prerequisite for ATES systems, which require a high yielding aquifer. The working principle of the storage system is as follows: In winter, water is pumped from the warm well for use as a heat source for a heat exchanger or a heat pump. Cooled water from the heat exchanger or heat pump is pumped into the cold well. In summer, the process is reversed. Water from the cold well is pumped up for cooling and heated water from a heat exchanger or heat pump is pumped into the warm well. In this way, the ATES is a closed system as the water from the aquifer circulates in a loop without any net consumption of groundwater. The operation principle of ATES during summer and winter is illustrated in Figure 22.

ATES systems are low-temperature storages. In fact, it is most often the demand for cooling (rather than heating) that motivates the investment in ATES systems and the systems can be economically feasible even without being used for heat supply (Pedersen, 2014). Typical temperature ranges for the reservoirs are 7-16 °C for the cold well and 10-18 °C for the warm well, with the temperature depending on the seasonal state of charge of each well. In most countries, there are regulations on how warm the water that is pumped into the underground may be; in Denmark it is e.g. not allowed to pump water that is warmer than 25 °C into the ground, with the monthly average not exceeding 20 °C.

The typical storage capacity of one well is 500 MWh and the typical injection and extraction power of one well is 1 MW. The investment costs for the system is largely power related and not storage capacity related. The storage efficiency can be as high as 90% (Snijders, 2017). The ATES technology is rather mature and has been widely used in the Netherlands, Belgium, Sweden and Germany since the 1990s. In the Netherlands alone, there are over 1,500 ATES systems in operation.

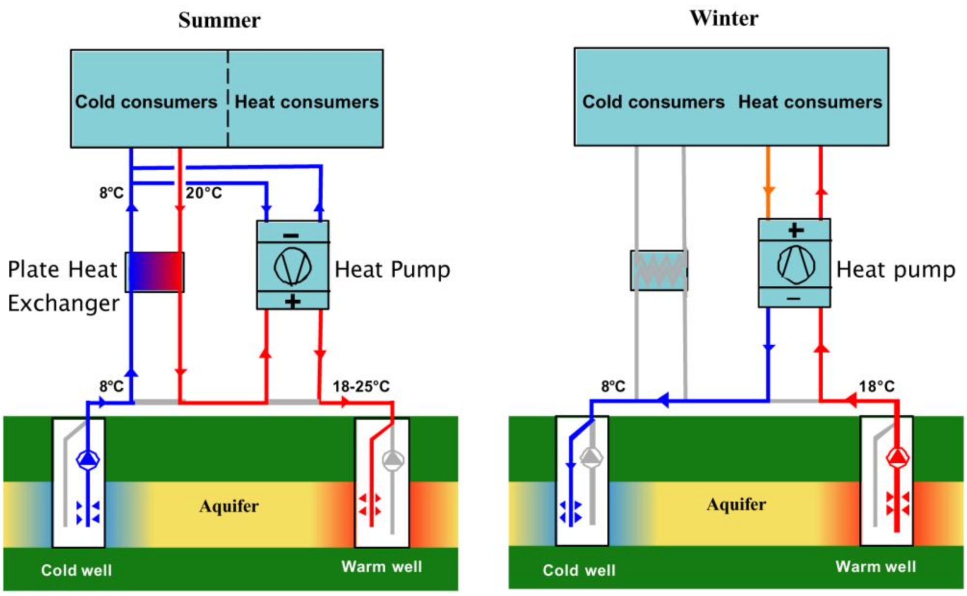


Figure 22 – Principle drawing of ATES (Pedersen, 2014).

3.5.2 ATES economics of scale

The economics of ATES systems are highly dependent on the geological conditions at each specific site, in particular on the water yield from each well and on the ΔT of the storage. As shown in Figure 23, the specific investment cost remains almost constant for different storage capacities. The economics of scale for ATES systems are not particularly attractive, because ATES systems are modular in nature, with each borehole pair yielding similar power and storage capacity. A doubling of power therefore requires a doubling of the number of wells.

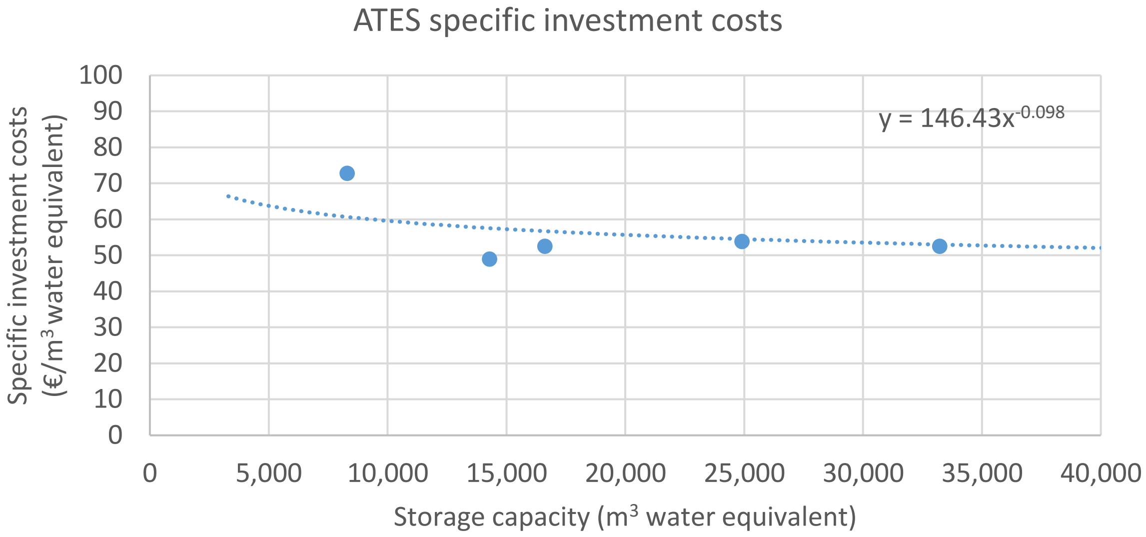


Figure 23 – Economics of scale for ATES systems. (Data from PlanEnergi, 2013) and (IFTech, 2017). Here, an aquifer with an average yield (50 m^3/h per well) and a ΔT of 10 K are assumed. The data was fitted using a power curve (see Equation 4). Due to the small number of available data points the fit is associated with some uncertainty.

3.6 Investment costs depending on storage temperature levels

One thing to consider is whether it is more feasible to store at low temperatures (e.g. because the investment in insulation can be reduced) or to store at high temperatures because this will mean higher energy density and thereby a smaller storage volume for the same energy content. This will of course depend on the available heat supply (i.e. high temperature directly available or not).

The specific investment costs for TTES, PTES, BTES and ATES as a function of the temperature difference ΔT are plotted in Figures 24, 25, 26 and 27, respectively. The plots are produced using Equation 5 with the fit parameters a and b from Figure 5, Figure 14, Figure 19 and Figure 23 for each respective storage technology. In each figure, the costs are plotted for four different storage capacity examples.

The temperature difference has a large impact on the specific investment costs, and more so as the value of ΔT decreases. For example, in the case of TTES, the specific investment costs roughly double when going from ΔT = 50 K to ΔT = 15 K, and double again when going from ΔT = 15 K to ΔT = 5 K. It is therefore clear that thermal storage quickly becomes expensive when the difference between maximum and minimum storage temperature is lower than 15 - 20 K. Large-scale thermal storages may be feasible at such low values for ΔT, as envisioned in the FLEXYNETS concept, if the increase in investment costs (compared to conventional district heating networks) can be accepted. In case such higher storage investment costs are unacceptable, large-scale storage may still be viable if inexpensive surplus heat is available at higher temperatures (and within a reasonable distance from the storage).

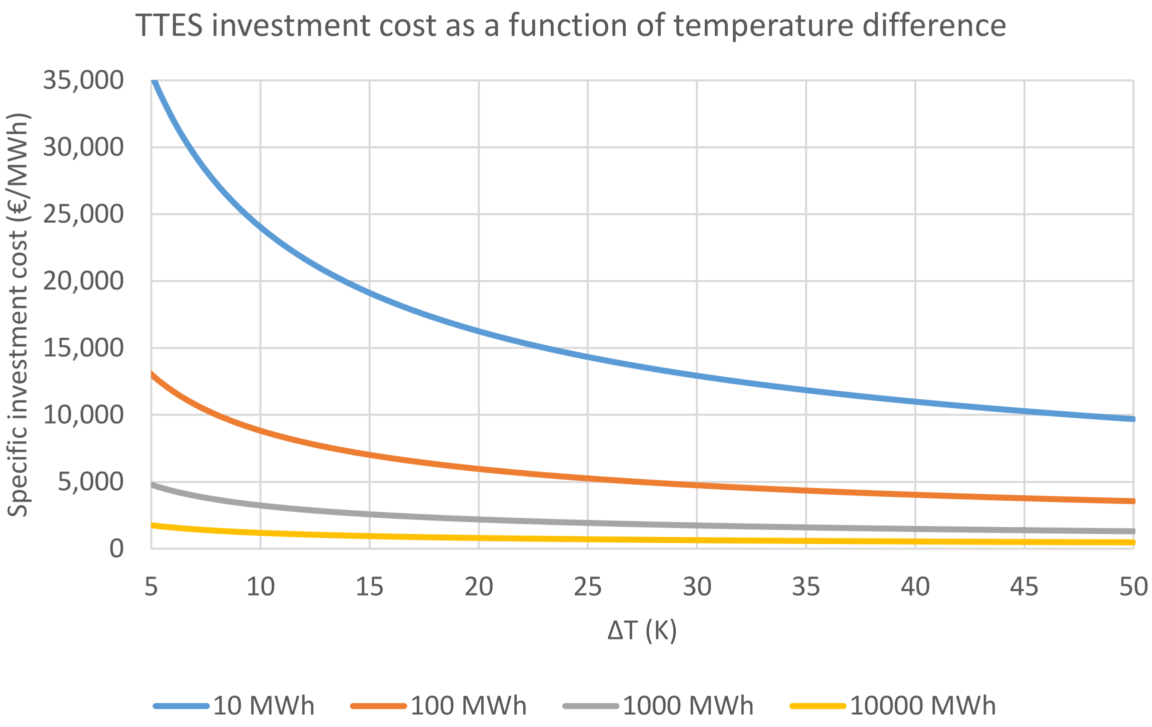


Figure 24 – The specific investments costs for TTES systems as a function of the maximum temperature difference in the storage, plotted for four different storage capacities.

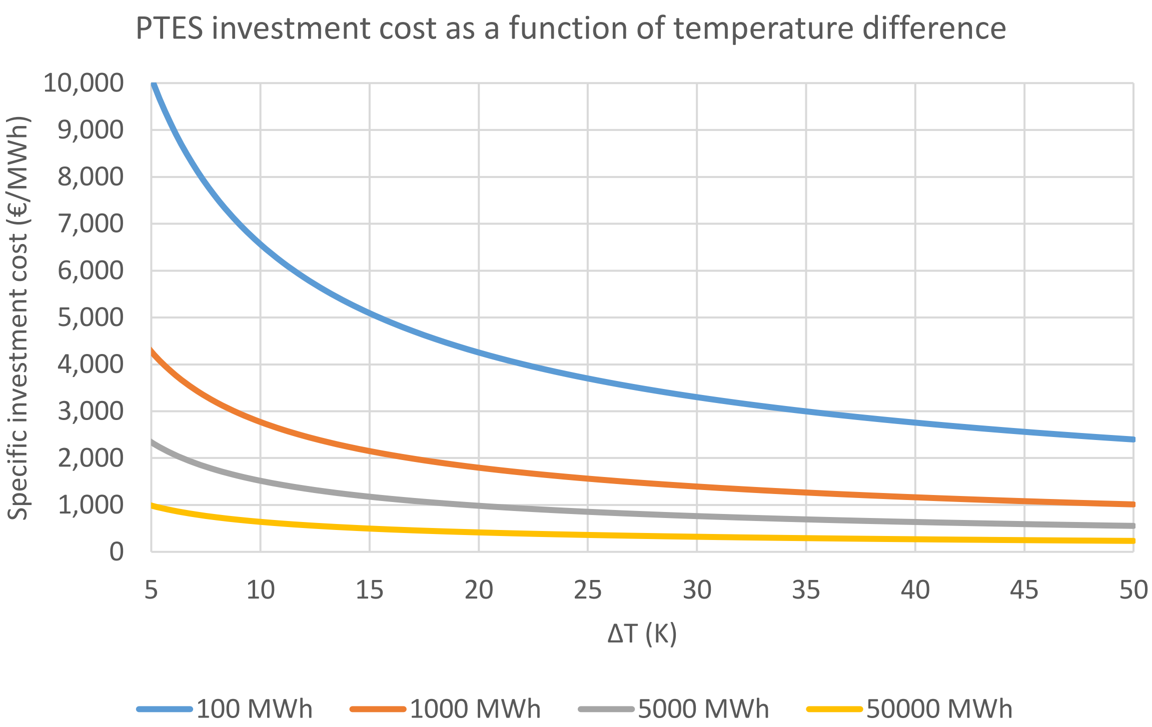


Figure 25 – The specific investments costs for PTES systems as a function of the maximum temperature difference in the storage, plotted for four different storage capacities.

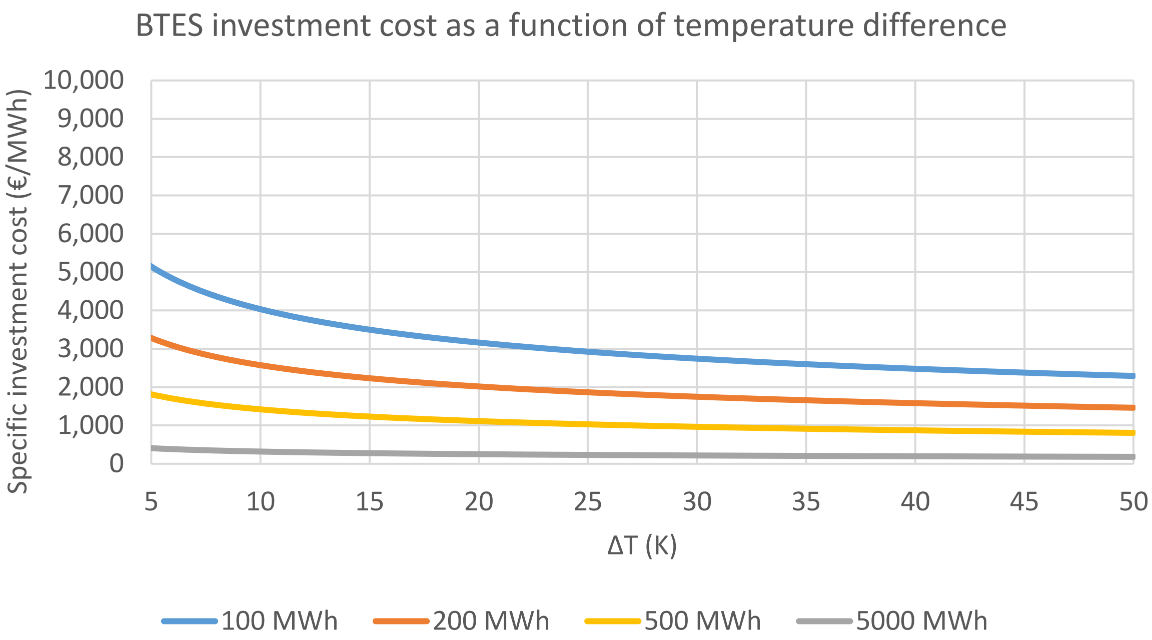


Figure 26 – The specific investments costs for BTES systems as a function of the maximum temperature difference in the storage, plotted for four different storage capacities.

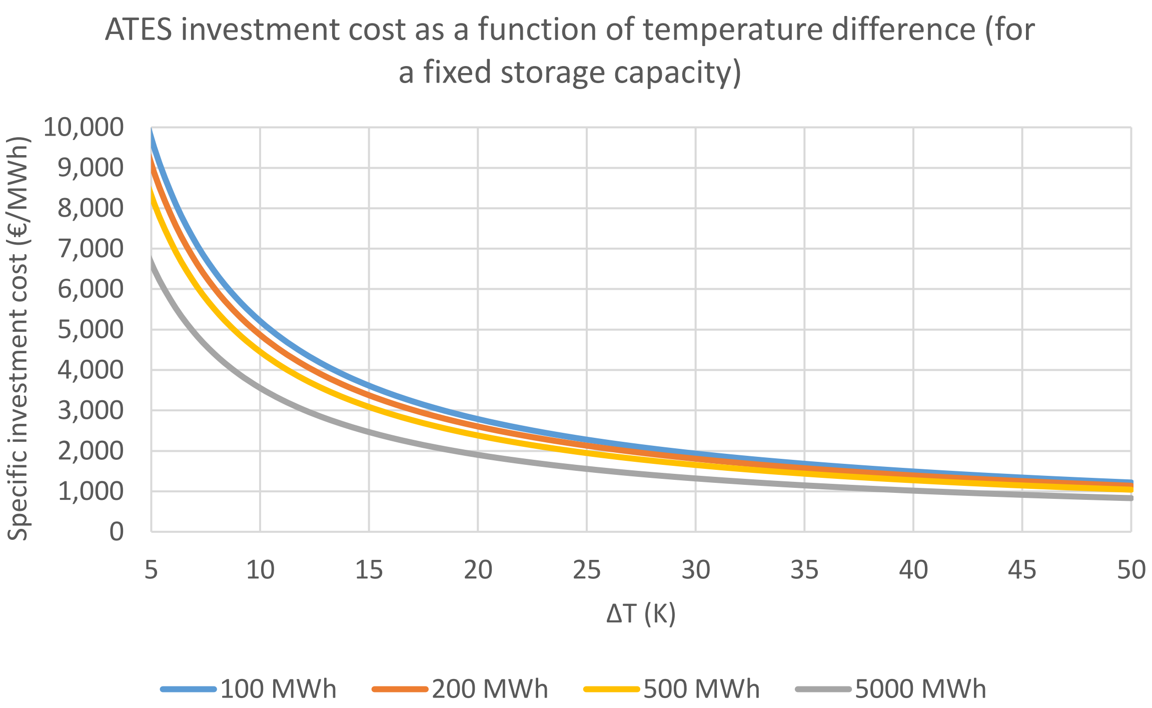


Figure 27 – The specific investments costs for ATES systems as a function of the maximum temperature difference in the storage, plotted for four different storage capacities.

3.7 Spatial requirements

The spatial requirements for each type of thermal storage depend on a series of conditions, such as storage application, volume, temperature levels, ground conditions and design. TTES and PTES occupies areas above gound as well as volume below ground level (PTES mainly), while BTES and ATES have the main area/volume below ground level. It is therefore difficult to give some general formulas on how much ground area the different storage types occupies per storage volume, but from data collected for different examples of TES, the following figure show some order of magnitude estimated in m^2/MWh for the four different types of TES.

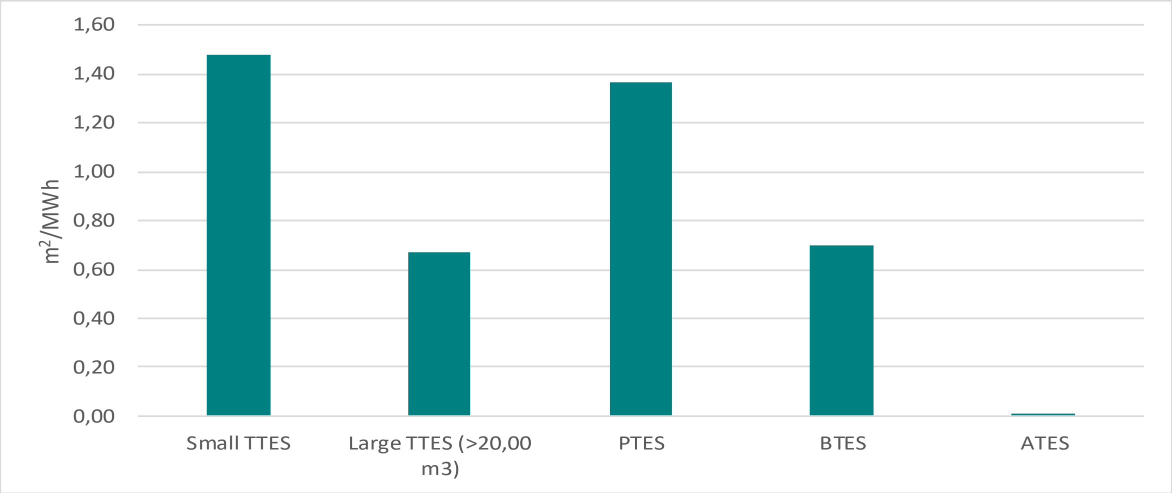


Figure 28 – Estimated spatial requirements for different types of TES. Numbers are based on examples; small TTES from Hjallerup of 3,000 m³, Large TTES from different volume capacities ranging from 20,000 – 60,000 m³, PTES is an average of Marstal and Vojens, BTES is from the BTES in Emmaboda, ATES is from average values for IFTech's installations.

In the following sections some examples are given in order to provide an idea of the spatial requirements for the different types of storages.

3.7.1 Spatial requirements for TTES

The TTES technology is as described mainly a cylindrical steel tank placed above ground – and in some applications the TTES has been seen to be placed below ground level – or built in the landscape. The spatial requirement for this type of storage is therefore limited and often placed next to the DH plant. The TTES will often be visible, but will in most cases be placed in connection to other technical facilities. An example of this is seen on the following figure where a TTES of 3,000 m^3 is placed in connection to a solarfield of 21,500 m^2 and a straw boiler of 1,8 MWt. The TTES is 19 m heigh (above ground level) and has a diameter of 16 m. An example of a TTES built into the landscape is seen in Figure 30.

Figure 29 – TTES of 3,000 m³ in Hjallerup, Denmark in connection to a solarfield of 21,500 m² and a straw boiler of 1.8 MWt (Hjallerup Fjernvarme).

Figure 30 - TTES with 5,700 m³ of water volume built from prefabricated concrete elements in Munich, Germany (in construction and finalized, Solites).

3.7.2 Spatial reguirements for PTES

Some considerations regarding the geometry of a PTES are previously described in Section 3.3.2 PTES Geometry – Considerations regarding design, soil balances etc. The lid area – and hence also the spatial requirements of the PTES depends on the slope of the sides of the PTES and the water depth, see more details in the mentioned section.

The relative lid area as a function of the slope is showed in Figure 8. This figure shows that the higher the slope, the smaller the area. This means that for a given volume and a certain depth, a significant share of the lid area can be saved if the slope can be increased. It is important to keep in mind, that there are boundaries to how steep the slope can be. As mentioned, also the water depth has impact on the lid area – for the same storage volume – i.e. the more depth the smaller the lid area. This is illustrated in Figure 12 – Water depth and relative lid area as function of hole depth for PTES with soil balance. The depth of the storage is often limited by soil conditions, especially in the present of ground water of the specific site.

An arerial view of the PTES in Dronningslund is shown in Figure 31. The PTES has a volume of app. 60,000 m^3 and was built in 2014 in connection to 37,573 m^2 solar collectors and a bio oil boiler driven heat pump (2.1 MW cooling). These are additional facilities to the original plant from 1989, with an 8 MW natural gas boiler and 6 MW egines: η(heat) 60 %, η(el) 34.5 %.

Figure 31 – PTES in Dronninglund, Denmark (Dronninglund Fjernvarme).

3.7.3 Spatial requirements for BTES

In a BTES storage, the soil is the energy storage medium as the storage technology consists of a number of boreholes in the ground in which pipes are placed. The spatial requirement above ground level is therefore limited. An example of a BTES facility is seen in Brædstrup in Denmark. In connection to Brædstrup DH a pilot BTES is built in connection to the other facilities; a total of 8,000 m² of solar collectors were commissioned in 2007 in connection to the existing natural gas fired CHP. In 2008 Brædstrup DH decided to take the second step towards 100 % renewable energy. It was decided to implement another 10,600 m² of solar panels, 5,500 m^2 buffer tank, 1.2 MWth heat pump and a 10 MW electric boiler. The BTES consists of 48 bore holes. The probes are lowered to a depth of 45 meters and 5 times 60 m deep holes for temperature sensors. In the BTES 19,000 m³ of soil is heated (planenergi.dk).Some measurements of the pilot BTES can be seen at the following illustration showing how the boreholes are connected underground. In total the BTES is 24 m in diameter.

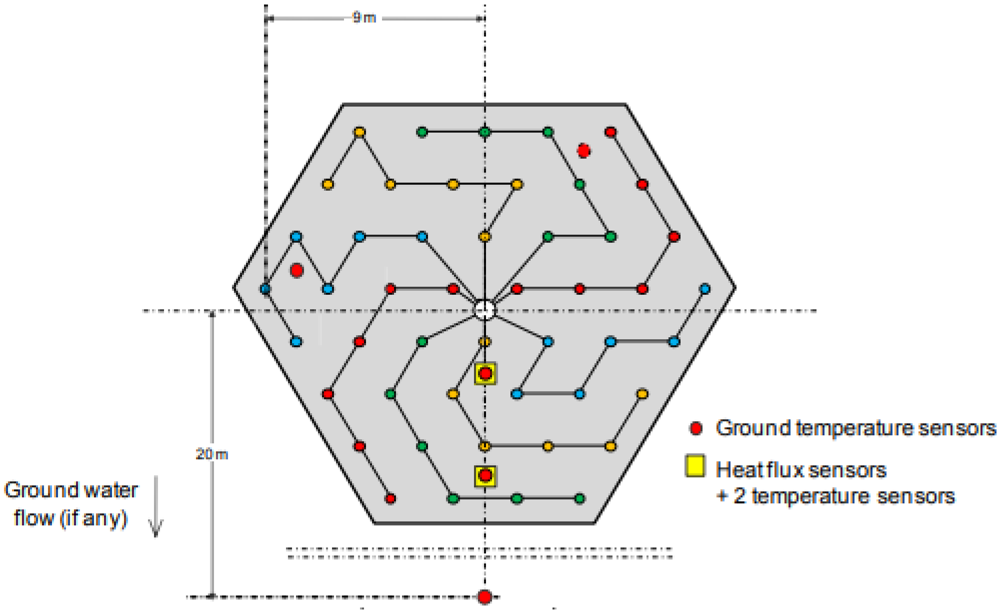


Figure 32 - Overview of the BTES design in Brædstrup, Denmark. The figure is reproduced from (Pedersen, 2014)

3.7.4 Spatial requiments for ATES

As described previously, ATES systems exist of two (or multiples of two) separate wells that are drilled into an underground groundwater reservoir (aquifer) for seasonal storage of thermal energy. The spatial and volume requirements for this type of storage are therefore mainly underground (therefore no picture to show of ATES equipment above ground). According to the IEA report (www.iea-dhc.org) the minimum depth of the wells is 25 m due to injection pressure, while the maximum depth is approximately 300 m, which is the limit for economic feasibility.

3.8 Considerations on heat losses

Low specific heat losses (or thermal losses) are considered as one of the key advantages of large-scale TES. The thermal losses of a TES type are mainly influenced by several parameters, but the surface-to-volume ratio of the storage volume and the quality of the installed insulation material is of significance. Large TES have much lower surface-to-volume ratios than small TES, which is an important advantage for long-term TES technologies. In the following figure, the ratio of heat losses to storage capacity ratio versus storage volume in m³ for a storage duration of 6 months is shown.

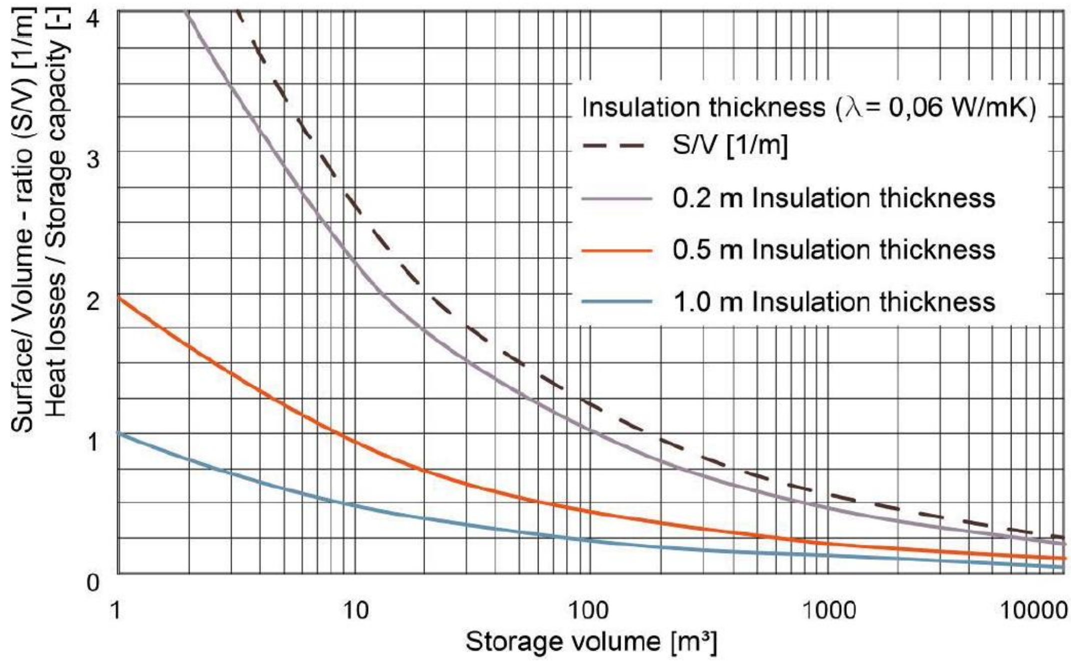


Figure 33 - Ratio of heat losses to storage capacity ratio versus storage volume in m³ for a storage duration of 6 months and a storage temperature 40 K higher than the average ambient temperature (Source: Solites).

An example; a small TES with a volume of 20 m³ has a surface-to-volume ratio that is eight times higher than the ratio of a TES with 10,000 m³. Hence, the specific heat losses of the large store are a factor of eight lower (www.iea-dhc.org).

To reduce losses, insulation is used where it is possible to apply. The thermal quality of the insulation material is defined by its thermal conductivity. The performance of a TES is further strongly influenced by the number of storage cycles. This is an indicator of how often the storage is charged and discharged in a certain time period.

The following sections include general considerations on the four types of TES. The heat losses are further handled in the TRNSYS simulations in Chapter 5.

3.8.1 Heat loss TTES

The temperature levels in TTES varies since the conditions are different from system to system and depend on the production units that produce the heat on the DH plant. In the case of solar heat and heat pumps the temperature is approx. 70 - 80 ° C, and if the heat is instead produced on CHP, the heat can be stored at a temperature of 90 - 100 ° C. The maximum and minimum temperature in the tank influences the energy capacity but also the heat loss of the tank. Other parameters that affects the heat loss is the ambient temperature, if the TTES is charge or discharged, wind conditions and insulation thickness and insulation material, as well as the shape of the tank.

Ideally the minimum heat loss is found if the TTES was shape like a globe. However, since stratification is more pronounced in a cylindrical tank – a rule of thumb, is that the TTES typically are dimensioned so the relation between diameter and height is about 1.5 – 2.5 (PlanEnergi, 2013). A simple calculation on heat loss variating with ambient temperature (T_a) for different volumes of TTES; cylindrical tanks with a relation between height and diameter of 1.5 is shown in the following figure. The calculations are for a full tank with a top temperature of 90 °C and 300 mm insulation.

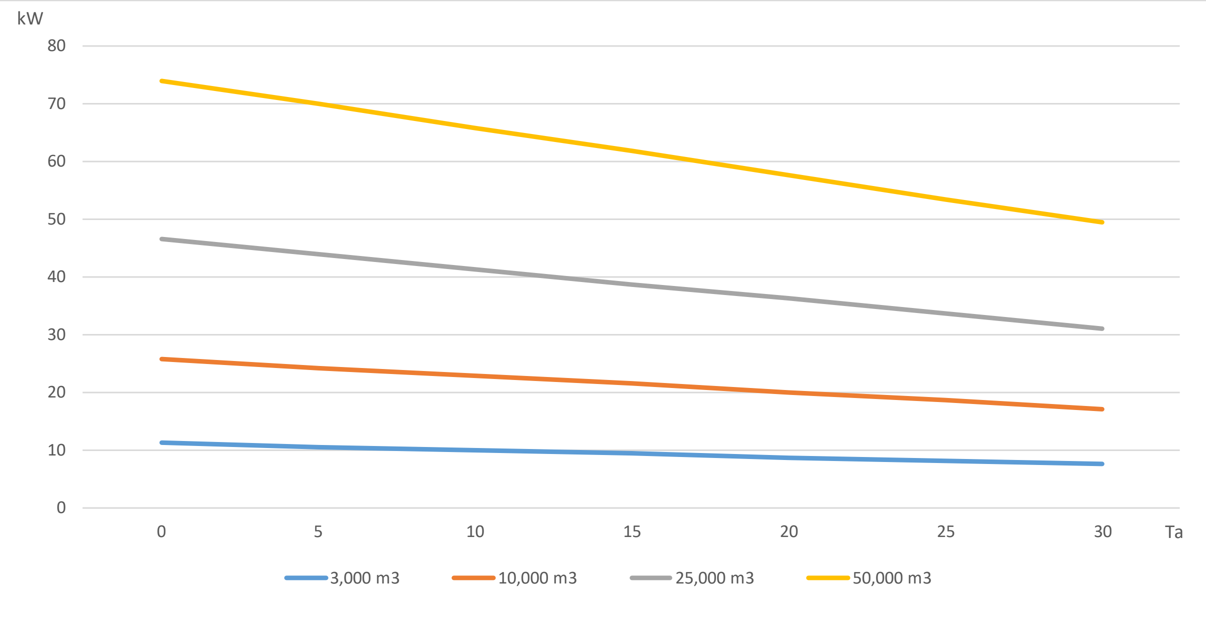


Figure 34 – Simple heat loss calculation with variating ambient temperatures and TTES volumes.

According to a study shown in (PlanEnergi, 2013), where all Danish DH plants provided information on the implemented TTES, if was found that the heat loss is relatively small and is approximately 3 – 4 %. The following tale provide some more detailed calculations on heat loss performed in (PlanEnergi, 2013) including wind at 10 m/s.

Table 2 – Calculated heat loss for different volumes of TTES at a wind of 10 m/s, insulation thickness at 300 mm mineral wool, the height-diamter relation is 1.8. The table is reproduced from (PlanEnergi, 2013).

Calculated heat loss at 300 mm insulation			
TTES volume	500 m3	1,000 m3	5,000 m3
Capacity at 90 - 40 °C	29 MWh	58 MWh	290 MWh
Heat loss [W/temp.diff.]	40 W/K	63.5 W/K	192 W/K
Heat loss at 90 / 0 °C	3.6 kW	5.7 kW	17.4 kW
% heat loss per week at 90 / 0 °C	2.1 %	1.7 %	1.0 %

The calculated heat losses are based on simple calculations and are found lower than the heat losses found in the before mentioned study. This is because the calculated heat loss is only through the insulation of the TTES – in the mentioned numbers from the study, the heat loss includes loss from pipes and installations in relation to the TTES. For use of TTES as longterm storage, the heat loss from installations is considered negligible. But at constant charge or discharge of the TTES, the heat loss in pipes and installations are considerable and should be included in system calculations (PlanEnergi, 2013).

3.8.2 Heat loss PTES

Heat loss in PTES, as for TES, also depends on parameters such as temperature levels, insulation type and thickness and the shape of the storage. It can be a clear advantage to minimize the lid area as much as possible – hence having af deeper storage. This is however not always possible due to limitations of the ground at the specific site. It is therefore important to find an optimum in the design phase of possible designs due to limitations and the calculated heat loss through the lid.

To provide an idea of the magnitude of calculated and minitores heat loss, numbers from (PlanEnergi, 2015) is presented in the two following figures. The numbers are from the SUNSTORE 3 project where the objective was to optimize, design and implement a full scale demonstration plant with 35,000 m^2 solar thermal collectors, 60,000 m^3 PTES and a heat pump that utilizes the storage as heat source. The demonstration plant opened in May 2014.

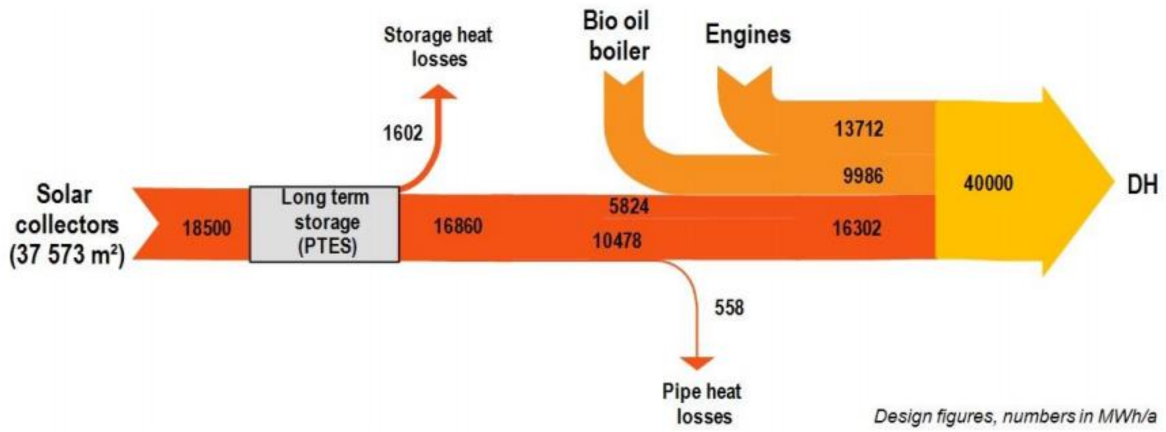


Figure 35 – Annual calculated energy flow of the SUNSTORE 3 project (PlanEnergi, 2015).

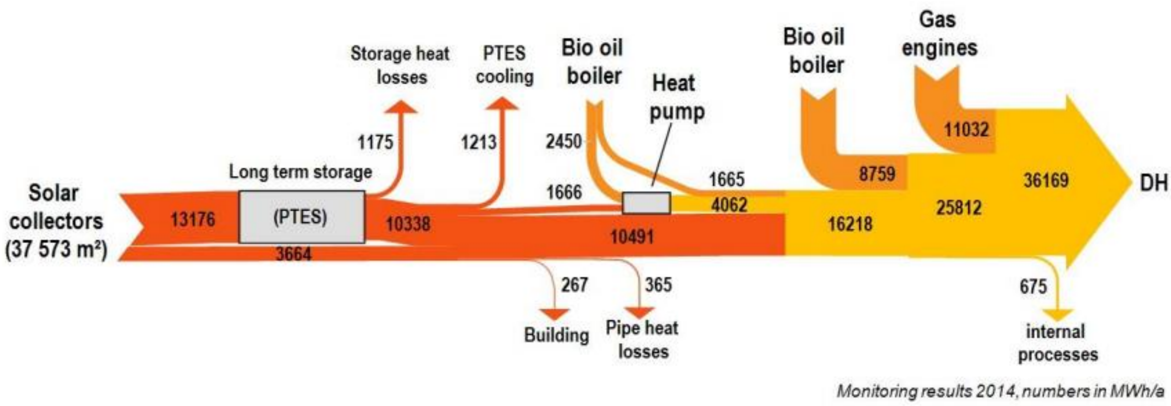


Figure 36 – Annual monitored energy flow of the SUNSTORE 3 project (PlanEnergi, 2015).

In general, there is a good agreement between the calculated and monitored figures, including the numbers for heat loss. In a report from The Danish Energy Agency, several Danish PTES storages are compared according to calculated heat loss – and some measured heat losses. The numbers are given in the following table.

Table 3 – Heat losses in Danish PTES storages collected from The Danish Enegry Agency (www.ens.dk).

PTES	Ottrup-gård	SUNS-TORE 2 Marstal	SUNSTORE 3 Dronninglund	SUN-STORE 4 Marstal	Vojens	Gram	Toftlund
Project type*	Demonstration project				Commercial project		
Calc. heat loss, total, MWh/y	85	402	1,602	2,475	5,500	4,024	1,900
Measured heat loss, MWh/y#	70		1,175	2,927			

3.8.3 Heat loss BTES

Heat losses from BTES depends on a rnge of parameters, such as soil type, temperature levels, borehole depth and the shape of the BTES. The technology is to store heat in the soil – it is therefore difficult to control how much heat and thermal loss there are transferred to the surrounding soil. Heat is also lost through the top of the storage – therefor a lid is necessary to reduce the heat loss.

For the BTES storage in Brædstrup in Denmark, it is possible to find design figures and monitoring resultsgoing back to 2013. These data can be found at www.varmelagre.dk. From this site, the energy flow diagram from 2017 from Brædstrup BTES is shown in the Sankey diagram below. Here iti is possible to see, that the measured heat loss (blue numbers) after several years is quit below the initial design figures (black numbers).

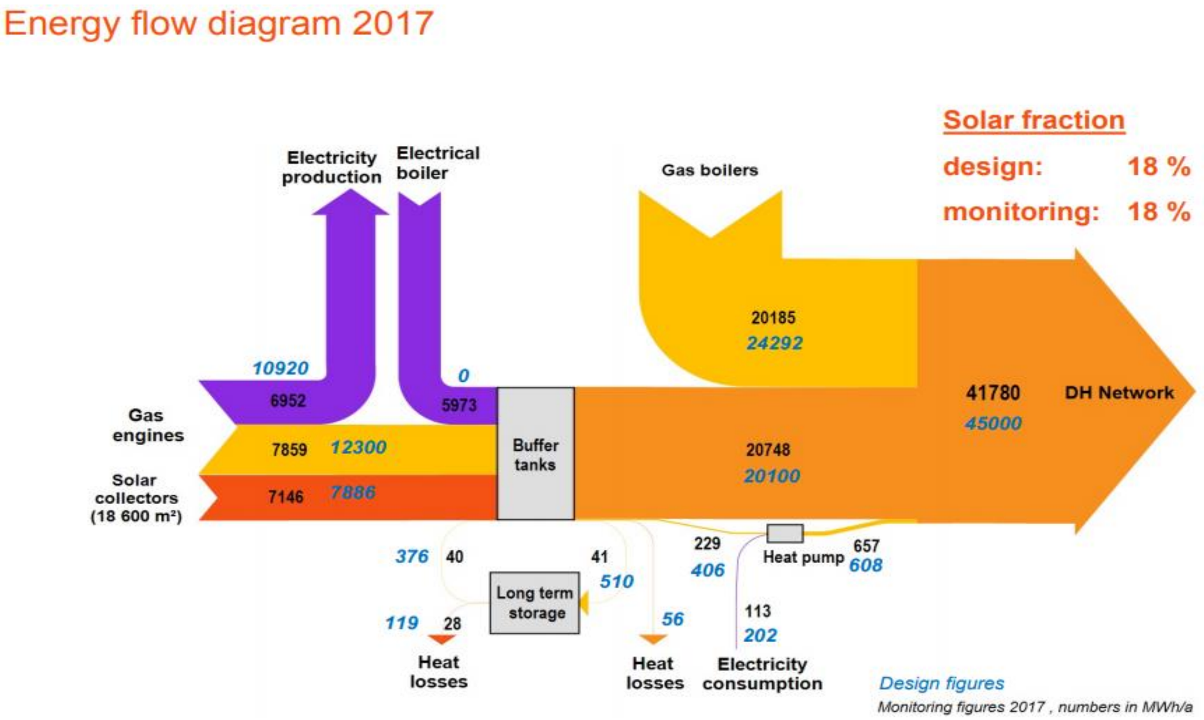


Figure 37 – Design and monitoring figures (2017) from Brædstrup BTES in Denmark (www.varmelagre.dk, Solites).

3.8.4 Heat loss ATES

The energy that can be stored in an ATES is strongly depending on the geology of a site. The ATES technology requires the presence of a suitable aquifer that is able to accept and yield water. Because of the geoogical uncertainties it is difficult to calculate the theoretical loss from ATES.

When the ATES is established, the thermal balance of the underground is important. Therefore, monitoring and maintaining the thermal balance in the underground has become the most important operational and permit condition for an ATES system. Energy balance is when the total amounts of heat and cold added to the gound is equal at a point (www.iea-dhc.org). Examples of moments of energy balances are seen in the figure below.

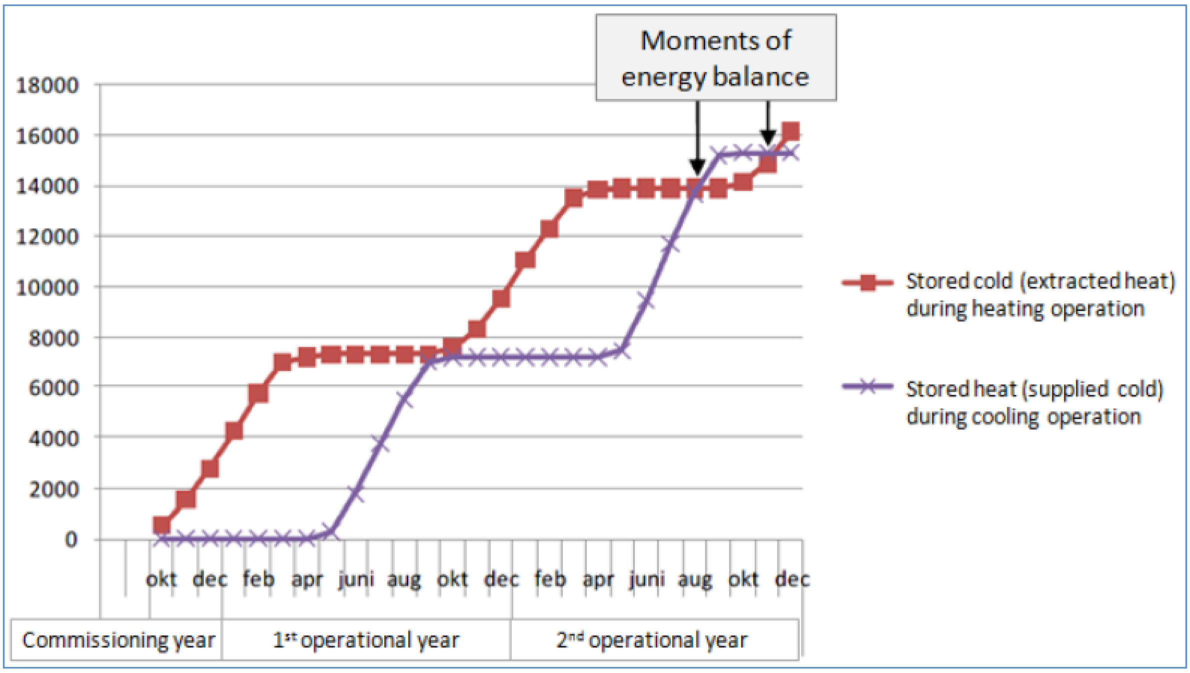


Figure 38 – Monitoring of energy balance. Figure is reproduced from (www.iea-dhc.org).

3.9 Summary and comparison of storage types

In Table 3.4, the key parameters mentioned in the sections of the investigated storage technologies are summarized to give an overview and comparison between the technologies.

For large-scale TES, PTES has the advantage of lower specific investment costs compared to TTES, though they have many similar characteristics. They both use water as storage medium, have relatively high efficiencies and high charge/discharge capacities. The area requirements are the most significant disadvantage of PTES. BTES can be implemented almost independent of the geological properties (though these will affect the cost). An issue with BTES is that it has a relatively low charge/discharge capacity, which can be a problem depending on the specific application for it to be used in. ATES has the advantage of being able to supply both heating and cooling, and has relatively low costs compared to alternative cooling options. ATES systems are, however, only able to store at low temperatures and with a low ΔT.

Table 3.4 – A summary of the key properties for TTES, PTES and BTES. Reproduced from (Solites, 2012) and from (PlanEnergi, 2013).

Type	TTES	PTES	BTES	ATES
Storage medium	Water	Water (Gravel-water[1])	Soil surrounding the boreholes	Groundwater in aquifers
Specific capacity [kWh/m^3]	60 - 80	60 - 80 30 - 50 for gravel-water	15 - 30	30 - 40
Water equivalents	1 m^3 storage volume = 1 m^3 stored water	1 m^3 storage volume = 1 m^3 stored water	3 - 5 m^3 storage volume = 1 m^3 stored water	2 - 5 m^3 storage volume = 1 m^3 stored water
Geological requirements	• stable ground conditions • preferably no groundwater • 5 - 15 m deep	• stable ground conditions • preferably no groundwater • 5 - 15 m deep	• drillable ground • groundwater favourable • high heat capacity • high thermal conductivity • low hydraulic conductivity (k_f < 10^{-10} m/s) • natural ground-water flow < 1 m/a • 30 - 100 m deep	• high yield aquifer

[1] Water is preferred thermodynamically. Gravel-water can be used, if the surface is used for other purposes such as parking.

Application	Short-time/ diurnal storage, buffer storage	• Long-time/ seasonal storage for production higher than 20,000 MWh • Short time storage for large CHP (around 30,000 m^3)	Long-time /seasonal for DH plants with production of more than 20,000 MWh/year	Long-time /seasonal heat and cold storage
Storage temperatures [°C]	5 - 95	5 - 95	5 - 90	7 - 18
Specific investment costs [EUR/m^3]	110 - 200 EUR/m^3 (for TTES above 2,000 m^3)	20 - 40 EUR/m^3 (for PTES above 50,000 m^3)	20 - 40 EUR/m^3 (for PTES above 50,000 m^3 water equivalent incl. buffer tank)	50 - 60 €/m^3 (for ATES above 10,000 m^3 water equivalent) Investment costs are highly dependent on charge/discharge power capacity
Advantages	High charge/discharge capacity	• High charge/discharge capacity • Low investment costs	Most underground properties are suitable	• Provides heat and cold storage • Many geologically suitable sites
Disadvantages	High investment costs	Large area requirements	Low charge/discharge capacity	• Low temperatures • Low ΔT

Figure 39 shows a summary of the economics of scale data for TTES, PTES and BTES from Figures 5, 14, 19 and 22 respectively. Figure 40 shows the same, but per unit of energy content instead of volume. For storing 100 MWh of heat or more, PTES is more cost effective than TTES. For storing 200-400 MWh of heat, BTES seems to be similar or slightly less expensive than PTES. The suitability of the technologies of course also depends on the time scale of the storage, i.e. if it is intended as a daily/weekly storage or a seasonal storage.

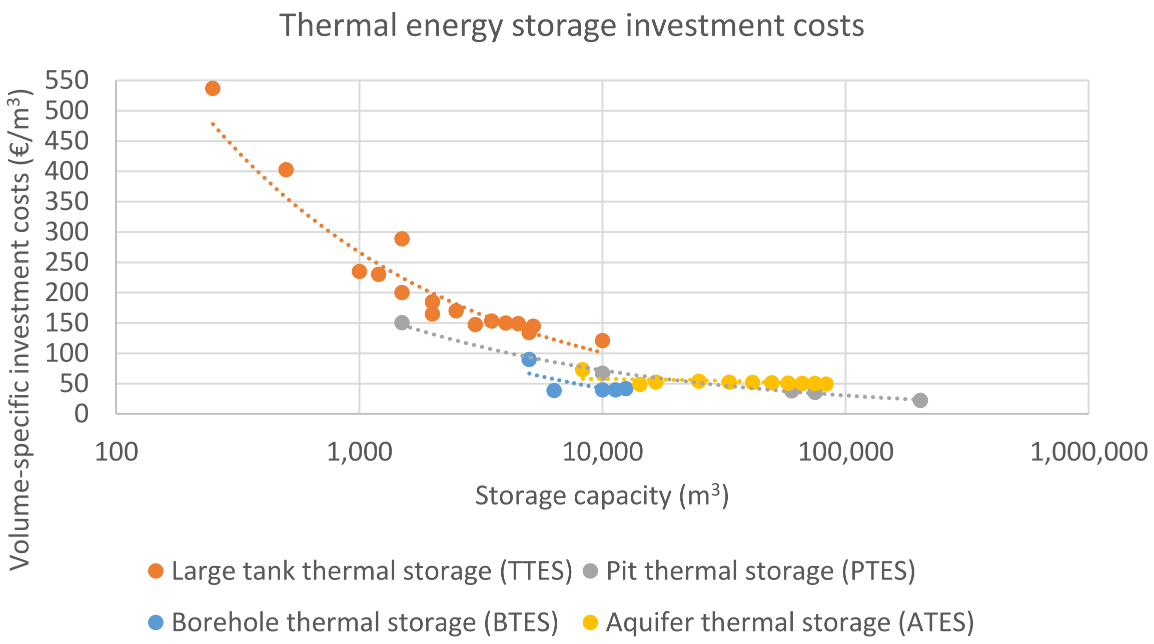


Figure 39 – A comparison of the economics of scale (on a volume basis) for TTES, BTES, PTES and ATES. Note the logarithmic scale of the primary axis.

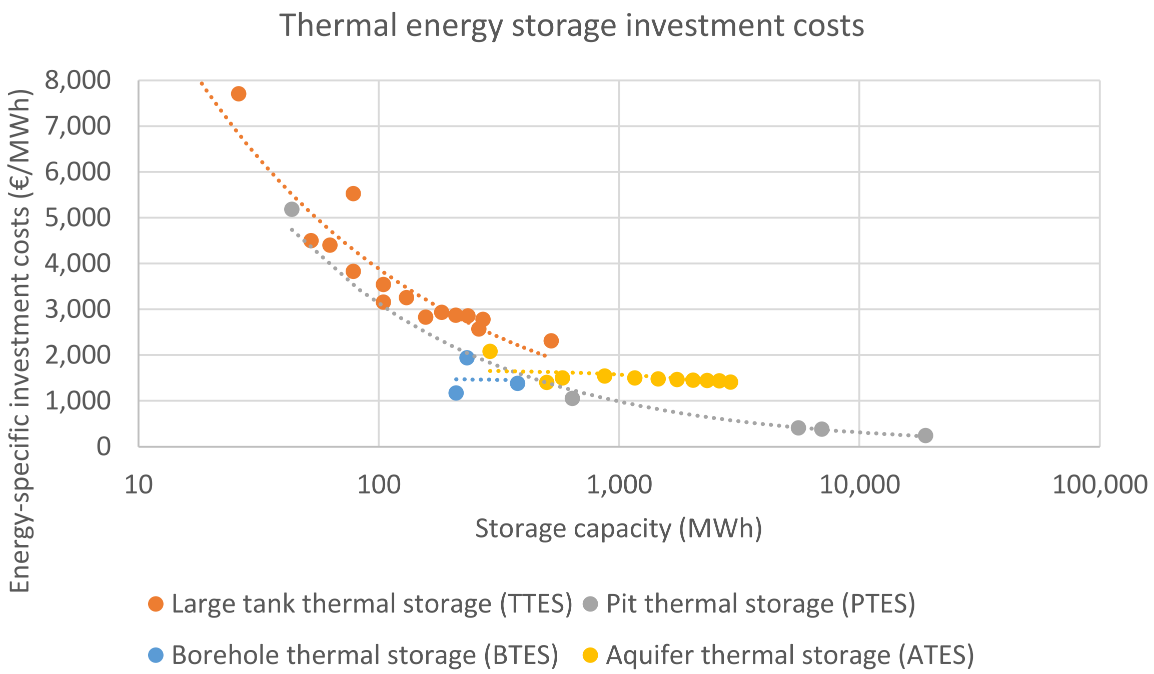


Figure 40 – A comparison of the economics of scale (on an energy basis) for TTES, BTES, PTES and ATES. Note the logarithmic scale of the primary axis.

4 Surplus heat sources and transmission pipelines to storages

One of the advantages of FLEXYNETS compared to conventional DH is that the low temperatures in the FLEXYNETS network makes it possible to utilize surplus heat from a wider variety of sources than possible in conventional DH.

In case surplus heat is available, it is unlikely that the surplus heat supply pattern matches the heat demand pattern in the FLEXYNETS network. For a flexible utilization of the surplus heat, a heat storage could be established. Due to the low value of ΔT in the FLEXYNETS network and the inverse-proportional dependence of both the storage volume and the storage investment costs on ΔT, it may not be feasible to store heat at the FLEXYNETS operating temperature. It may be more beneficial to store the heat at higher temperatures, i.e. at the surplus heat source temperature, to take advantage of the larger ΔT between the surplus heat and the FLEXYNETS return temperature. Such a heat storage may be located either close to the location of the surplus heat source or close to a FLEXYNETS heat injection point.

The feasibility of utilizing surplus heat (in case it is available) depends highly on the distance between the surplus heat source and the FLEXYNETS network. If the surplus heat is not available within the area of the network, this requires a transmission pipeline connection between the two. However, even for a free supply of surplus heat, the value of this heat must outweigh the cost of constructing a transmission pipeline for the surplus heat in order for the utilization to be beneficial. This puts a limit on how far away from the FLEXYNETS network the surplus heat can be sourced.

4.1 Transmission pipeline cost

In Figure 41 the specific costs for DH pipelines in outer-city areas are shown as a function of the nominal diameter of the pipes. The costs are shown for the case of steel pipes for normal district heating temperatures (insulation class 3) and for steel pipes suitable for the FLEXYNETS temperature levels (insulation class 1). It should be noted that the pipeline cost calculations described here are only utilized for calculating the costs of transmission pipelines for transmitting surplus heat directly from a source to a large-scale thermal energy storage, and not for calculating the costs of distribution pipelines within the FLEXYNETS network itself. The distribution pipelines in the FLEXYNETS network itself are not included in this report.

In

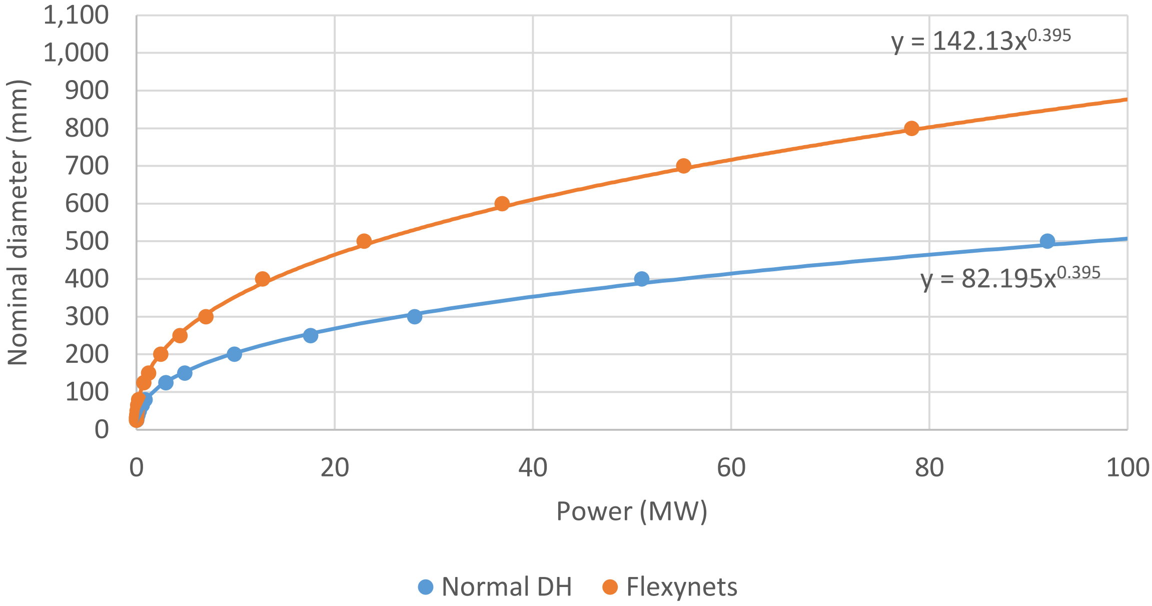


Figure 42 the required nominal diameter for the pipes is shown as function of the energy flow through the pipes, assuming conventional water pumping velocities in district heating networks. The difference between the required diameter in conventional DH systems and in the FLEXYNETS concept can be explained by the low value of ΔT in FLEXYNETS (10 - 15 K) compared to conventional DH (40 K). As ΔT decreases, the amount of water that must be transmitted to supply the same heating power increases (although this is partly compensated by the fact that a part of the thermal energy delivered by the FLEXYNETS consumers is provided in the form of electrical energy from the local heat pumps).

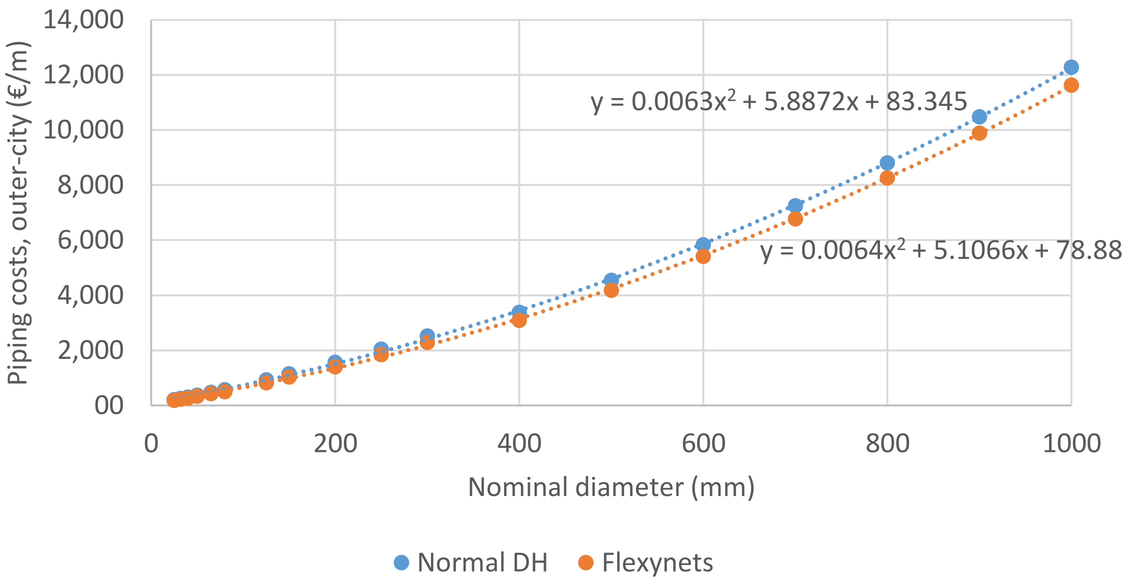


Figure 41 – The length-specific district heating piping costs, including pipe installation, shown as a function of the nominal diameter of the pipes. The values apply for outer-city areas. The data used for the figure is the same as used for the task 3.1 report in the FLEXYNETS project. The data has been fit with 2nd degree polynomials, which show a very good correlation with the data.

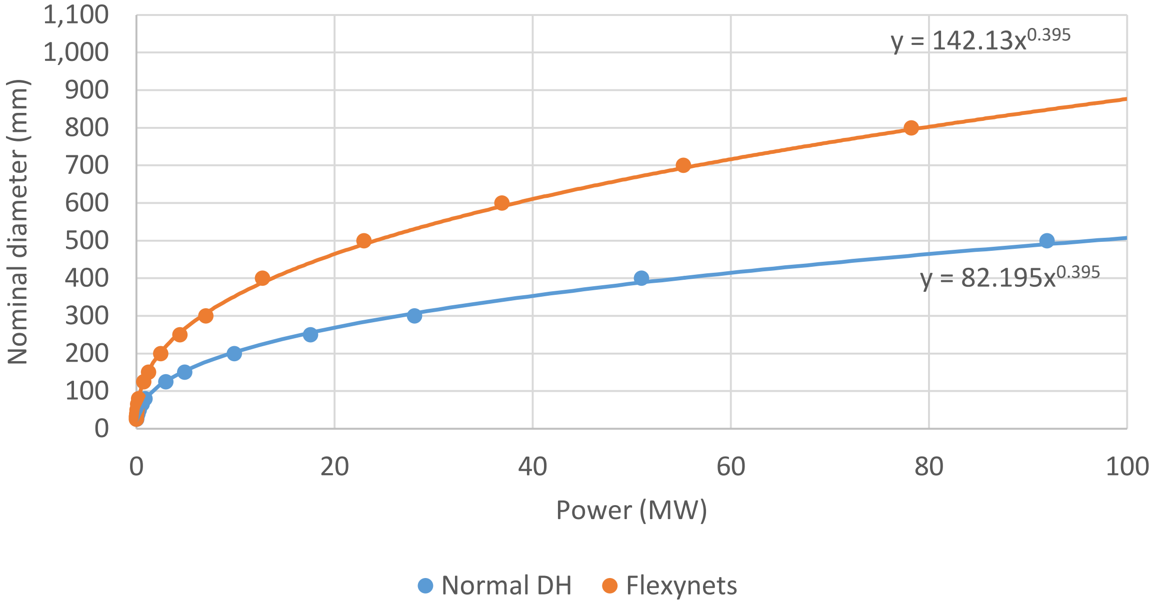


Figure 42 – The required nominal diameter for district heating transmission pipes as a function of the transmitted energy flow, for conventional pumping velocities. The data used in the figure is the same as used in the Task 3.1 report in the FLEXYNETS project. The data sets have been fitted with power curves, which show a very good correlation with the data.

By combining the data from the figures above, an expression for the piping costs as a function of the energy flow can be obtained. The piping costs c as a function of the nominal pipe diameter can be expressed as a 2nd order polynomial:

$$c(d) = \alpha d^2 + \beta d + \gamma \qquad \text{(Equation 6)}$$

Here d is the nominal pipe diameter and α, β and γ are constants. The nominal diameter can be expressed as a function of the heating power in the form of a power law:

$$d(Q) = aQ^b \qquad \text{(Equation 7)}$$

Here Q is the power and a and b are constants. By inserting Equation 7 in Equation 6, the following expression for the piping costs as a function of the heating power can be obtained:

$$c(Q) = \alpha a^2 Q^{2b} + \beta a Q^b + \gamma \qquad \text{(Equation 8)}$$

Figure 43 shows plots of Equation 8 for the case of normal DH networks and for the FLEXYNETS concept. The assumed values for the constants α, β, γ, a and b are those from the fits in Figure 41 and Figure 42.

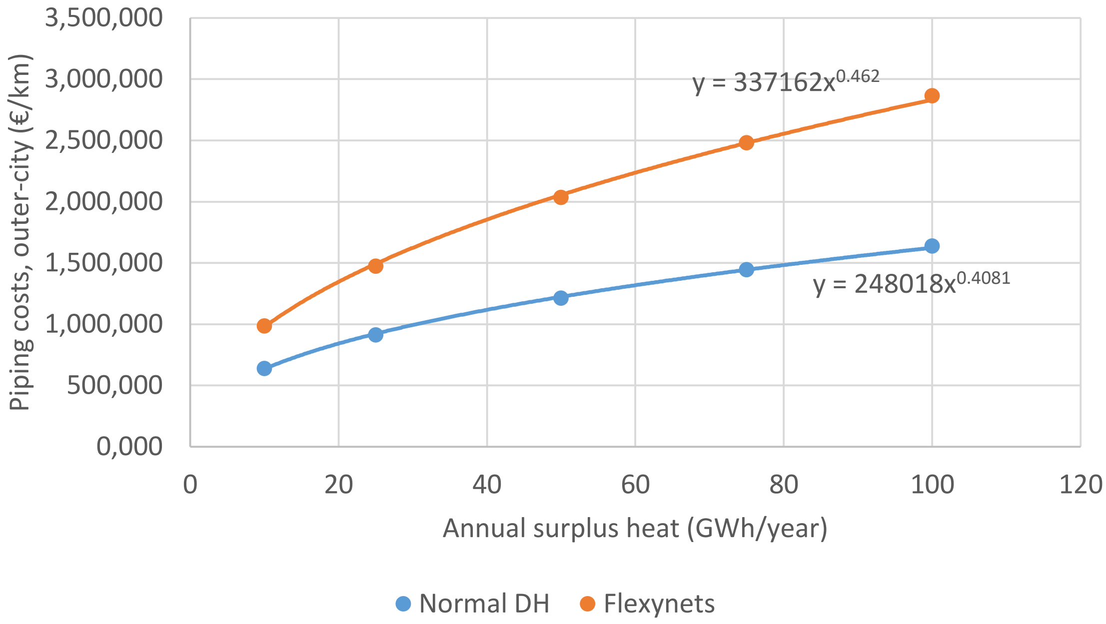


Figure 43 – The length-specific district heating piping costs for outer-city areas shown as a function of the annually transmitted surplus heat. Here it is assumed that the surplus heat is transmitted continuously with a constant power (constant temperature and flow rate) throughout the year.

Defining $E = \sum_{year}(Q)$, the length-specific, annualized investment costs for the transmission piping is:

$$c_{annual}(E) = \frac{r\, c(E)}{1-(1+r)^{-n}} \qquad \text{(Equation 9)}$$

Here r denotes the interest rate and n is the lifetime of the pipes in years (as well as the payback period).

4.2 Pipeline distance and heat price

Let us assume that the heat price is composed of three factors; the unit heat price in the existing district heating network without surplus heat utilization (p_{netw}), the unit heat price for the surplus heat (p_{exc}) and the annualized transmission pipeline investment costs for transmitting the surplus heat to the storage. The total unit heat price in the network p_{total}, including the surplus heat transmission and utilization, can then be expressed as a function of the pipeline length x:

$$p_{total}(x) = p_{netw}(1-s) + p_{exc}s + c_{annual}(sE_{tot})x \qquad \text{(Equation 10)}$$

The parameter s is defined to denote the fraction of the total network heat demand that is supplied with the surplus heat. If s = 1, all heating demand in the network (on an annual basis) is supplied by surplus heat and if s = 0, none of the heat in the network is supplied with the surplus heat. If E_{tot} is the total heat demand in the district heating network, sE_{tot} is then the annual amount of surplus heat transmitted through the pipeline. $c_{annual}(sE_{tot})$ is then the length-specific piping cost from Equation 9, with $E = sE_{tot}$.

By making some assumptions about the parameters in Equations 8 - 10, it is possible to make a numeric estimate of how the possible surplus heat utilization (including transmission) would affect the heat price in the network. It is also possible to get an indication of the maximum distance over which it could be feasible to transfer surplus heat to the network. Let us assume that the annual heat demand in the network is 100 GWh/year. For comparison, the annual heat demand in the Danish city of Sønderborg, with around 30,000 inhabitants, is approximately 370 GWh/year. It is assumed here that the average heat price in the network, without the surplus heat supply, is 50 €/MWh corresponding to an approximate cost of natural gas based boiler heat incl. taxes. The assumed price of the surplus heat, excluding transmission costs, is assumed to be 0 €/MWh here. This is intended to reflect the assumption that the surplus heat is energy that otherwise would go to waste. The lifetime of the district heating pipeline is assumed to be 25 years and the interest rate on the investment is assumed to be 3%.

The heat price in the district heating network according to Equation 10, using the assumptions from the previous paragraph, is plotted in Figure 44for five different values of s. Nothing has been assumed about the hourly or seasonal distribution of the heat demand in this simplified analysis. A constant in-flow of surplus heat to some type of a heat storage that can be utilized to fully balance the surplus heat supply and heat demand in the network has implicitly been assumed. The costs of the heat storage are not included in the analysis. The analysis also does not include any heat losses during transmission or storage. Due to these simplifications, the results in Figure 44should be interpreted as "ideal-world", upper bounds on how far it can be beneficial to source surplus heat to the DH network.

Here the values for conventional, high temperature district heating pipelines are used, as it is assumed that the surplus heat is transmitted at the source temperature, and not at the FLEXYNETS operating temperature. The black, dashed line in the figure shows the case of s = 0, i.e. when no surplus heat utilization takes place and $p_{total} = p_{netw}$. This indicates an example of the cost of alternative heat supply. The intersection of the black, dashed line and the remaining lines in the figure (for each value of s) shows for which pipeline length the total heat price (including the surplus heat utilization) equals the alternative heat price in the network (i.e. the price without the surplus heat utilization). For a given distance, if the heat price *with* the surplus heat is higher than the heat price *without* the surplus heat, it is not economically feasible to transmit and utilize the surplus heat, because it can be provided cheaper by other means. This gives an estimate of how long the heat transmission pipeline can be, before becoming too expensive.

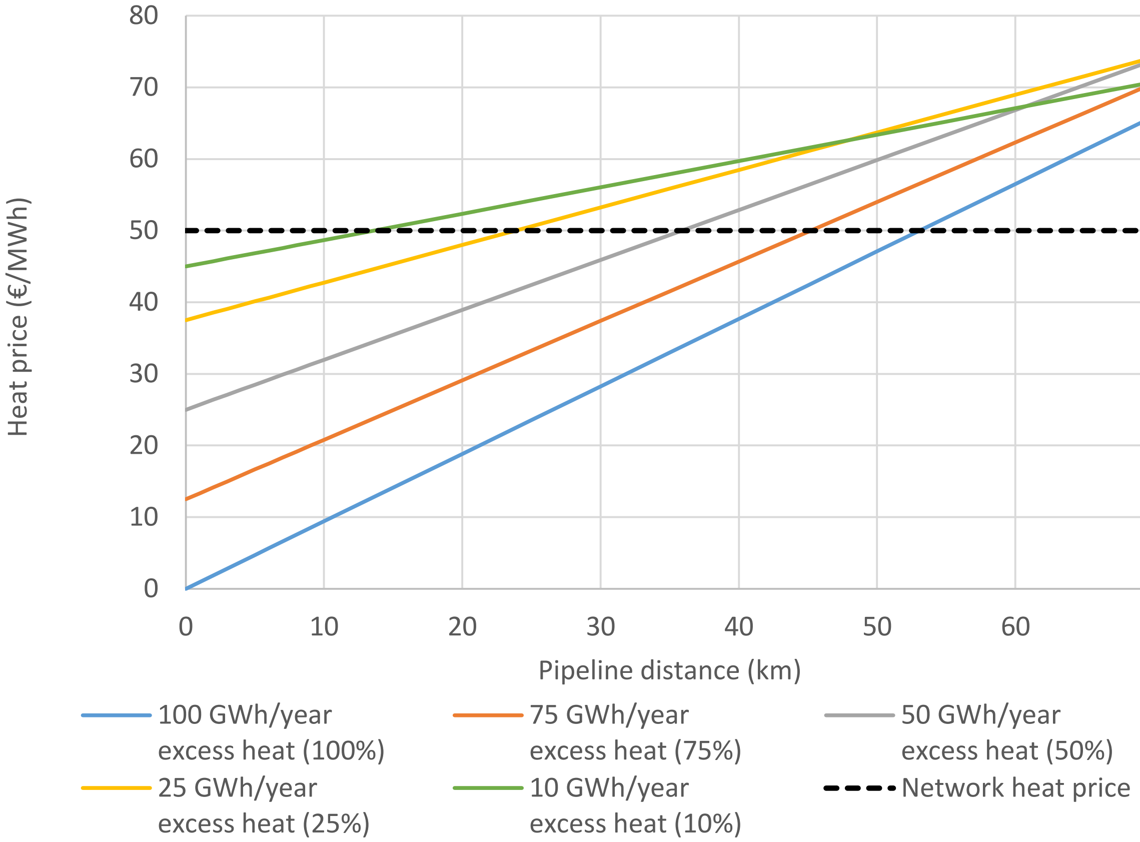


Figure 44 – The heat price in the district heating network shown as a function of the surplus heat transmission pipeline distance. This calculation is for the case of normal district heating temperatures. The price is shown for five different levels of surplus heat supply to the network. The calculation is done on an annual basis, not taking hourly and seasonal fluctuations in surplus heat supply and heat demand in the network into account, and without assuming any costs for thermal energy storage.

As can be seen in the examples of Figure 44, the limit to the feasible pipeline distance is highly dependent on the heat quantities and ranges. For the chosen parameters, the feasible distance limit ranges from approx. 12 km for the transmission of 10 GWh/year (s = 0.1) to over 50 km for the transmission of 100 GWh/year (s = 1).

These numbers should, however, only be interpreted as rough estimates, as they depend on a number of assumptions and choice of parameters. The specific construction costs of the heat transmission pipeline may also vary quite a lot depending on which type of area it is constructed through (urban, suburban, rural). The answer to the question of how far it is feasible to fetch surplus heat is therefore very dependent on the case at hand, but it is also very clear that the answer depends highly on how much surplus heat is available compared to the total heat demand in the network.

A more detailed analysis of centralized storages in the FLEXYNETS concept, including the transmission and utilization of high-temperature surplus heat, is presented in the next chapter. This analysis gives a more detailed answer to the question of how far away from the network it could be economical to source surplus heat. Here, the differences in supply and demand profiles, and transmission pipelines energy losses are taken into account.

5 TRNSYS Simulations

The aim of this report, as already mentioned, is to provide answers to the question if and in what contexts large-scale thermal storages could be beneficial for the FLEXYNETS concept. In chapters 2 and 3, the principles, technical properties and economic aspects of latent thermal energy storage have been assessed in the context of FLEXYNETS. In chapter 4 the possibilities regarding surplus heat transmission from heat sources away from the FLEXYNETS network have been addressed. In order to put these pieces together and to try to provide a more detailed answer regarding the role of large thermal storages in the FLEXYNETS concept, a model have been developed in the simulation environment *TRNSYS.* This model has been used for analysing TES (tank, pit, borehole and aquifer storages) and surplus heat utilisation in a FLEXYNETS context for various scenarios, with different geographical locations, storage types, storage sizes, operating temperatures and amounts of surplus heat availability.

A focus has been on the circumstances under which large TES is believed to have the opportunity to play the most important role and be most economical in the FLEXYNETS concept. These circumstances are when surplus heat from e.g. industry is available and is transmitted directly to a thermal storage at a temperature higher than the FLEXYNETS network temperature. Storing at a high temperature enables the storage to work with a greater ΔT than if the heat were stored at the network temperature, thus increasing the volumetric energy storage density and decreasing the energy-specific storage investment costs. The idea is then that the heating and cooling demands in the network are fulfilled to the highest possible extent by utilizing the surplus heat and the thermal contents in the storage even though the demand profiles are most likely very different from surplus heat input profile. For satisfying heating and cooling demand not provided by the surplus heat and the storages, the modelled system has centralized boiler and chiller units. The objective is, however, to operate the boiler and chiller units as little as possible. In this way, the system strives to replace as much of its fuel and/or electricity consumption for heating and cooling with surplus heat that would otherwise go to waste, and thereby also reduce the CO_2 emissions arising from the boiler and chiller operation.

For comparison, scenarios with conventional DH temperatures and scenarios where the surplus heat is transmitted and stored at the FLEXYNETS forward temperature have also been included. Calculations for various transmission pipeline distances, including scenarios where no transmission pipeline is assumed to be necessary (when the surplus heat is located within the FLEXYNETS network area) have also been carried out. To evaluate the results in each scenario, two indicators are used: The thermal energy production costs (in units of €/MWh) in the network, and the annual CO_2 emissions arising from the boiler and chiller operation (in units of ton/year).

5.1 System description and TRNSYS model layout

5.1.1 System principle diagram

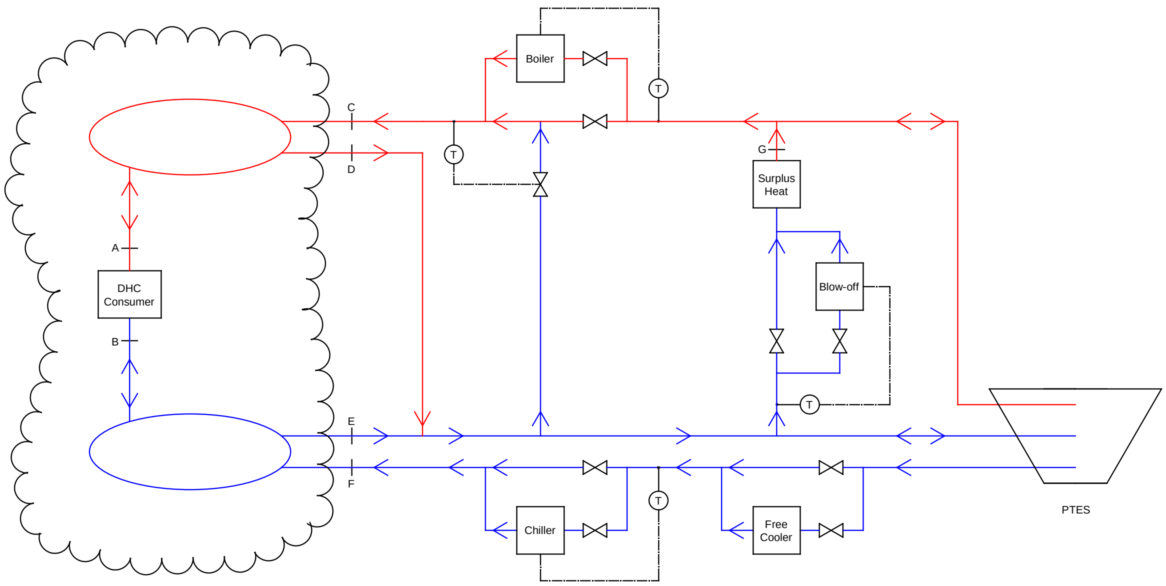
Two principle diagrams of the system outlined in the last paragraphs are shown in Figure 45. The two diagrams are identical, except for the TES on the right-hand side of the figures. The diagrams show how the system with surplus heat input, a thermal storage, a boiler and a cooler is assumed to interact with the FLEXYNETS network. The FLEXYNETS network is pictured as two rings (one warm and one cold) and a cloud of consumers on the left-hand side of the diagrams. For illustration, the connections of a single consumer are shown in the diagram (markers A and B). When the consumer demands heating, there is a flow from the warm ring to the cold ring, with the consumer extracting heat from this flow. When the consumer demands cooling, these flows switch direction. In cooling mode, the consumer thus injects heat to the network.

Surplus heat is injected into the system (at marker G), and depending on the heat demand in the given hour, the heat flows either into the storage or directly to the network (via marker C). On the way to the warm ring, a shunt mixes colder water (flowing from marker E) with the inlet heat flow for adjusting the inlet temperature to the warm ring, if needed. In times of heating demand, the return flow from the consumer is stored as cold (flowing via marker E) in the lower part of the stratified TTES or PTES, or in the cold wells of the ATES or BTES. In times of cooling demand, cold is extracted from the storage and injected to the cold ring (via marker F). The warmer return water may be returned to the TES (via marker D).

To ensure that the warm ring temperature is always sufficiently high, a boiler injects heat into the system (before marker C) in case the forward temperature to the warm ring is below the required warm ring temperature. To ensure that the cold ring temperature is always sufficiently low, a free cooler can be used to reduce the forward temperature to the cold ring down to the current ambient temperature, and a chiller (heat pump) can be used to further reduce the forward temperature (before marker F), if needed. As already mentioned, the system strives to operate the boiler and coolers as little as possible, as their operation leads to natural gas consumption and CO_2 emissions that can be avoided/reduced by fully/partly fulfilling the heating and cooling demand by using the surplus heat and the storages.

The system in Figure 45 exists in four variations; one for each type of TES. The TTES is connected directly to the system. It is assumed to be a stratified hot water storage with inlets and outlets at the top, in the middle and at the bottom (for hot, lukewarm and cold water respectively). The PTES is connected to the system via heat exchangers and is also assumed to be a stratified hot water storage with top, middle and bottom inlets and outlets. In the case of the ATES or BTES storage, a buffer tank (a relatively small TTES) is connected to the system, and the ATES or BTES connects to the buffer tank. This is because the properties of ATES and BTES do not allow for very fast heat injection or extraction. It is therefore beneficial to have relatively small TTES to handle short-term differences between thermal energy supply and demand, and to use the ATES or BTES to handle seasonal variations in the supply and demand. The ATES and BTES are not stratified, but instead have separate warm wells and cold wells for storing heat and cold. The ATES is connected via heat exchangers, but the BTES is connected directly to the buffer tank.

a)



b)

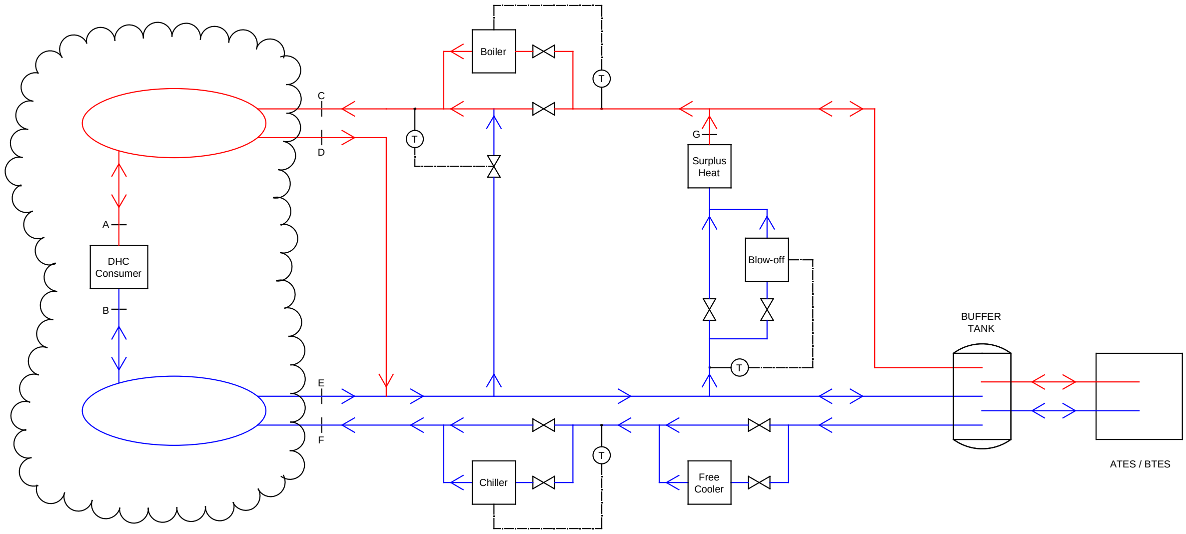


Figure 45 - Principle diagrams of the system. a) With either a tank storage or a pit storage. b) with either an aquifer storage or a borehole storage.

5.1.2 TRNSYS model layout

A screenshot of the *TRNSYS* model layout is shown in Figure 46. The layout of the model differs somewhat from the layout shown in the principle diagrams in Figure 45 due to practical modelling limitations, but the *TRNSYS* model can be considered a good approximation of the system in the principle diagrams. The red lines denote warm streams, the blue lines denote cold streams and the pink lines denote streams with lukewarm (warmer than the coldest streams but colder than the warmest streams) or highly varying temperatures. As can be seen in the model layout, all four thermal energy storage technologies have been modelled in a single *TRNSYS* model. It is, however, only possible to use one of the four TES types during each model run, and this must be done before the model run.

All storage types are connected to a surplus heat input loop, a heating demand loop and a cooling demand loop. The surplus heat loop contains a pump that uses electrical energy for pumping the surplus heat from the source to the storage. As in the principle diagram, the heating demand loop contains a peak load boiler for raising the temperature and a shunt for lowering the temperature, to ensure that the heating demand receives water at the correct temperature. Similarly, the cooling demand loop contains a free cooler and a chiller (heat pump) for lowering the temperature in order to ensure that the cooling demand receives water at the correct temperature.

In the model runs with conventional DH temperatures (i.e. 80 °C forward temperature, 40 °C return temperature and a surplus heat inflow of 80 °C), a single system for providing district heating and cooling (DHC) is no longer energy-efficient in this model setup. This is because in the model, it does not make sense to cool the 40 °C warm heating return water down to the required 15 °C inlet temperature of the cooling demand and then heat the same water up again (to 80 °C) when it exits the cooling consumers at 20 °C. The combined DHC network can make sense when the temperature of the heating and cooling supply are closer together. For these model runs, it was found more beneficial to remove the connection between the cooling loop and the rest of the model. For the scenarios with conventional DH temperatures, the model therefore functions as two separate systems for district heating (with an inflow of surplus heat) and district cooling (with a free cooler and a chiller heat pump).

The storages are connected as described above, with the PTES and ATES having heat exchangers and with ATES and BTES having small buffer TTES for balancing short term fluctuations between thermal energy supply and demand. The following *TRNSYS* types are used for modelling the heat storages: Type 4a (TTES and buffer tanks), Type 342 (PTES), Type 345 (ATES) and Type 557b + Type 3001 (BTES). These *TRNSYS* components aim to simulate the physical characteristics of each TES type and include detailed parameters for the size and shape of the storages and for the calculation of energy losses through the lid and the sides. For ATES and BTES, the components furthermore include various parameters describing the thickness, initial temperature, heat capacities, thermal conductivities etc. for the underground.

The economic part of the *TRNSYS* model, with black lines, can be seen in the lower right part of Figure 46. Here the annual investment costs, operation & maintenance costs, energy input costs for the boiler, chiller and pumps and the CO_2 amounts and costs for the model are calculated. This is used for calculating the generation price for the thermal energy (heating and cooling) and the annual CO_2 emissions arising from operating the boiler and coolers. These two parameters are used as indicators for the performance of the different model scenarios, as better described in section 5.4.

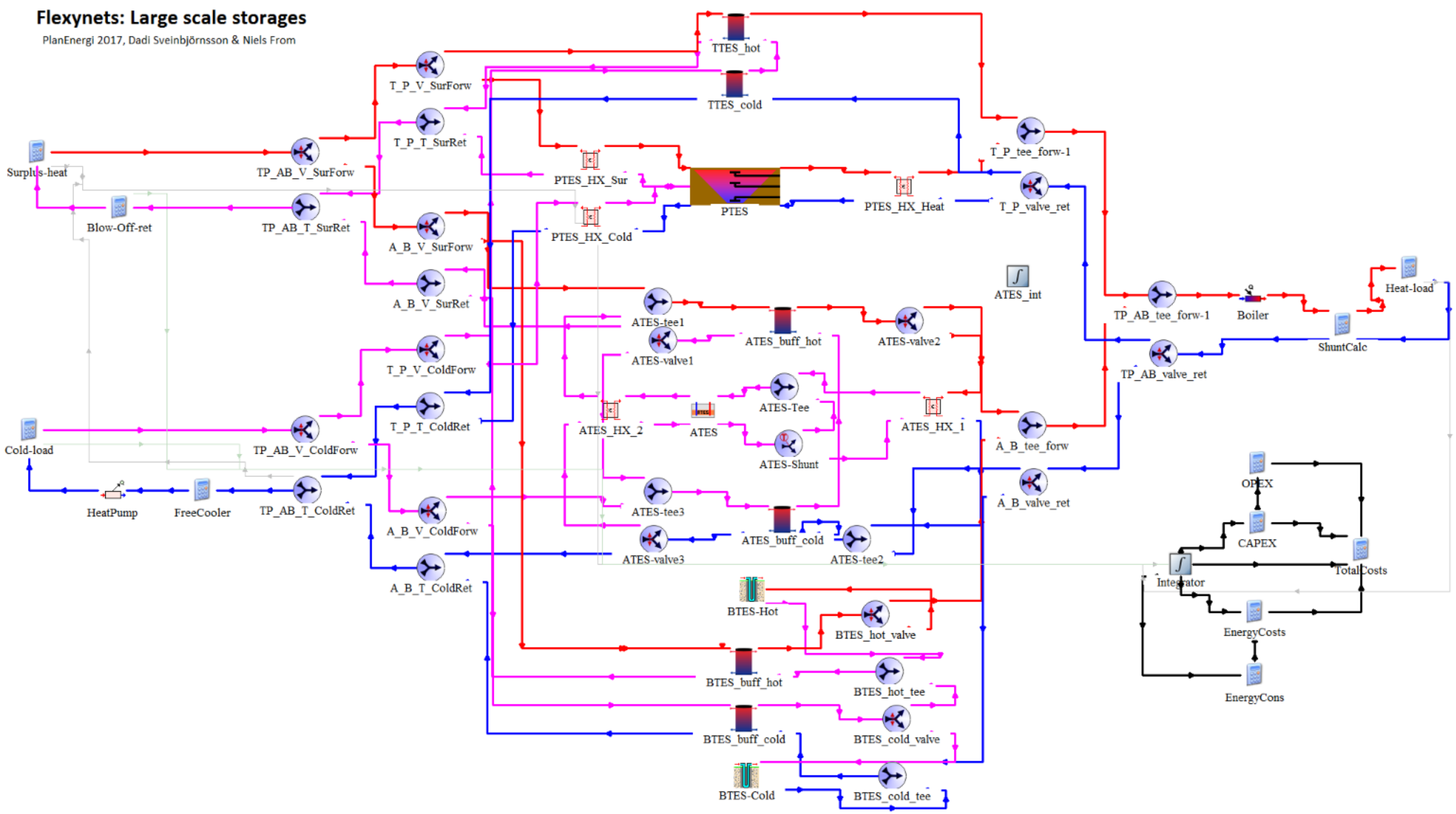


Figure 46 – The layout of the TRNSYS model. All four thermal storage technologies have been modelled in a single TRNSYS model. Prior to each model run, the modeller chooses which storage will be used, and it is only possible to use one storage type in each model run (TTES, PTES; BTES or ATES).

The FLEXYNETS network, the heat storages and the surplus heat sources have been modelled in *TRNSYS* using an aggregated, top-down approach. The model only includes a single surplus heat source, a single thermal energy storage (which has an extremely large volume compared to the demand in some scenarios), a single heat demand and a single cooling demand. In reality, there would most likely be multiple instances of most of these system components; i.e. there could be multiple surplus heat sources, multiple TES (rather than one large) and thousands of consumers with a heating and a cooling demand. However, from the storage's point of view, the connection to the network will in practice correspond to an aggregated demand profile.

The *TRNSYS* simulation software was set to calculate the mass flows and temperatures in the modelled energy system (including thermal energy storages) in 1-hour time steps. In all simulations carried out in this work, the length of the simulation period has been set to two years, or 17,520 time steps, and all results shown here are for the 2nd simulation year. This is because the initial values of some simulation parameters, such as the thermal energy storage state of charge, are not known at the beginning of a simulation. Using results from the 2nd simulation year, when the storages have already been simulated for one year, is therefore more accurate.

5.2 Model inputs and assumptions

The technical model input data is shown in Table 5.1and the economic model input data is shown in Table 5.2. Further explanation of the values in the tables is given in the notes after each table.

Table 5.1 – Model input data regarding CO_2 emissions, efficiencies and energy losses.

Technical model input data	**Value**	**Unit**	**Note**
CO_2 emissions			
CO_2 emissions pr. surplus heat energy input	0	t/MWh	A
CO_2 emissions pr. boiler energy input	0.205	t/MWh	B
CO_2 emissions pr. electrical energy input	0.202	t/MWh	C
Boiler and cooler efficiencies			
Boiler efficiency	100	%	D
Free cooler COP	50	-	E
Chiller (heat pump) COP	7.5	-	F
Other energy losses			
Heat exchanger effectiveness	90	%	G
Transmission pipeline temperature loss	0.25	K/km	H
Electricity consumption for pumping surplus heat	2	% of surplus heat in	I

Notes to Table 5.1:

A. The companies that produce the surplus heat as a part of their activities are assumed to be responsible for the associated CO_2 emissions. These emissions would take place regardless of whether the surplus heat from the process is utilized or not.
B. The peak load boiler in the model is assumed to be a gas boiler. This number is the energy-specific CO_2 emissions value for natural gas combustion, published by the Danish Energy Agency. The emissions from natural gas can be different in other areas based on the origin of the gas.
C. The free cooler, chiller (heat pump) and the pump for surplus heat supply are assumed to be electricity driven. For the energy-specific CO_2 emissions of the electricity consumption, the average CO_2 emissions value of Danish electricity consumption in 2015 is used (Energinet, 2016). The EU average for this is 0.377 t/MWh (IINAS, 2014), and this is expected to fall in the future as the share of renewables increases.
D. The gas boiler is assumed to be a modern condensing boiler with efficiency of 100%.
E. The free cooler is assumed to yield 50 units of cooling energy for each unit of electricity it consumes. This is a common COP for free coolers of the assumed type.
F. The chiller (heat pump) is assumed to yield 7.5 units of cooling energy for each unit of electricity it consumes. This is a calculated value for the average COP of a heat pump operating in the temperature range 10 - 20 °C.
G. All heat exchangers in the model are assumed to have 10% loss in temperature.
H. The temperature loss in the surplus heat transmission pipeline is assumed to be 0.25 K for each kilometre. This is realistic compared with losses of some of the longest heat transmission pipelines in the worlds located in Iceland.
I. The electrical power required to pump the surplus heat in the transmission pipeline is assumed to correspond to 2% of the thermal power provided by the surplus.

Table 5.2 – All model input data for the calculation of costs in the model.

Economic model input data	**Value**	**Unit**	**Note**
Energy price			
Surplus heat price	0	€/MWh	A
Peak load heating price (from boiler)	50	€/MWh	B
Electricity price	50	€/MWh	C
Investment costs			
TTES and buffer tanks	$5295 \cdot V^{-0.435}$	€/m³	D
PTES	$2267 \cdot V^{-0.374}$	€/m³	D
BTES	$16726 \cdot V^{-0.649}$	€/m³	D
ATES	$1467 \cdot V^{-0.098}$	€/m³	D
Transmission pipeline	$248018 \cdot Q^{0.408}$	€/km	E

Boiler	0	€/MW	F
Chiller	0	€/MW	F
Free-cooler	0	€/MW	F
Operating expenses			
TTES	2	% of inv.	G
PTES	2	% of inv.	G
BTES	2	% of inv.	G
ATES	2	% of inv.	G
Transmission pipeline	0	% of inv.	G
Economic calculation parameters			
CO_2 emission cost	28	€/ton	H
Investment lifetime	25	years	I
Interest rate	4	%	I
Price level	2017 prices		I

Notes to Table 5.2:

A. The surplus heat is assumed to be available from the source free of charge.

B. The price range for district heating from gas boilers in the analysis assumptions of the FLEXYNETS project is 40 – 55 €/MWh.

C. The assumed electricity price to the free cooler, chiller and the pump for the surplus heat. This is assumed to be the average electricity spot price, exempt from taxes and tariffs.

D. The volume-specific investment costs for the thermal storages are based on the fits for the cost curves for the storages presented in Chapter 3. *V* denotes the storage volume (water equivalent) in m^3. It is assumed that above a certain ”cut-off” volume, the economy of scale no longer apply, and the marginal investment costs continue as a constant number, rather than a volume-dependent cost curve. This ”cut-off” volume was set to 100,000 m^3 for TTES, 300,000 m^3 for PTES, 500,000 m^3 (water equivalent) for BTES and ATES.

E. The transmission pipeline costs are based on the piping costs in outer-city areas for normal district heating temperaturas (assuming a high temperature surplus heat), presented in Figure 31 in Chapter 4. *Q* denotes the annually transmitted heat (in GWh/year).

F. The investment costs and O&M (operation and maintenance) costs for the boiler are assumed to be included in the peak load heating price (see note B). The investment costs and O&M costs for the chiller and the pumps are not included in the model.

G. The O&M costs are calculated as a percentage of the total (non-annualized) investment costs. The O&M costs of the transmission pipeline are neglected.

H. The boiler and chiller are assumed to be centrally located in the network and thus be included in the ETS CO_2 quota trading system. The CO_2 cost value in the table corresponds to IEA's estimate for the price of CO_2 emission quotas in the year 2030. The 2030 price level was chosen because FLEXYNETS is still under development and is unlikely to be deployed on a large scale before 2030.

I. The investment lifetime and interest rate are used for calculating the annualized capital expenses (using the annuity loan down-payment formula). No inflation is included in the model. The model assumes a constant 2017 price level. A real interest rate of 4%, as recommended for socio-economic analysis by the Danish Energy Agency.

5.3 Scenarios description

A large number of scenarios have been modelled using the *TRNSYS* model. As already mentioned, the model has been run for four different types of storages (TTES, PTES, BTES and ATES). Each TES type has been run for seven different volumes (see Table 5.3). The model has furthermore been run with five different magnitudes of surplus heat availability (see Table 5.4). The surplus heat availability is also quantified in terms of the so called "surplus heat share", defined as the ratio between the total annual surplus heat supply and the total annual heating demand (without considering the time distributions of the supply and demand). The model has furthermore been run for different sets of temperature levels (see Table 5.5). Finally, variations have been run for three different reference cities in Europe with different weather conditions, (Rome, London and Stuttgart, see section 5.5). The different weather conditions in the three cities have resulted in three different load profiles, as shown later in section 5.5. However London and Stuttgart have similar weather patterns, and hence similar load profiles.

For investigating all these different combinations, a total of 2,100 model runs have been performed. Each model run took 30-60 seconds on a laptop computer, depending on which TES type was being simulated. After defining the scenarios and setting up the model, the model runs were automated to a large extent using the "parametrics" function in the *TRNEDIT* software that is bundled with *TRNSYS*.

Table 5.3 – The range of thermal energy storage volumes used in the model runs. These should not be interpreted as the volumes of single, extremely large storages, but rather as aggregated volumes for multiple smaller storages. The volumes of ATES and BTES are given in water equivalents.

Storage volumes (m^3)	**TTES**	**PTES**	**BTES (water eq.)**	**BTES buffer tank**	**ATES (water eq.)**	**ATES buffer tank**
Volume 1	20,000	20,000	20,000	20,000	20,000	20,000
Volume 2	100,000	100,000	100,000	20,000	100,000	20,000
Volume 3	200,000	200,000	200,000	40,000	200,000	20,000
Volume 4	550,000	550,000	550,000	110,000	550,000	55,000
Volume 5	1,000,000	1,000,000	1,000,000	200,000	1,000,000	100,000
Volume 6	1,500,000	1,500,000	1,500,000	200,000	1,500,000	200,000
Volume 7	2,000,000	2,000,000	2,000,000	200,000	2,000,000	200,000

Table 5.4 - The five different variations in the amount of annual surplus heat supply to the system (column 2) as well as the assumed annual heating and cooling demand.

Surplus heat share (%)	Surplus heat (GWh/year)	Heating demand (GWh/year)	Cooling demand Rome (GWh/year)	Cooling demand London (GWh/year)	Cooling demand Stuttgart (GWh/year)
125%	125	100	25	7.5	10
100%	100	100	25	7.5	10
75%	75	100	25	7.5	10
50%	50	100	25	7.5	10
25%	25	100	25	7.5	10

Table 5.5 – Five different variations in the operating temperatures of the system.

Variation no.	Description of variation	Surplus heat	Heating forward	Heating return	Cooling forward	Cooling return
I.	Conventional DH, separate heating and cooling systems	80	80	40	15	20
II.	HT surplus heat, FLEXYNETS ΔT = 10	80	25	15	15	20
III.	Medium surplus heat, FLEXYNETS ΔT = 10	60	25	15	15	20
IV.	Medium surplus heat, FLEXYNETS ΔT = 15	60	25	10	10	20
V.	LT surplus heat, FLEXYNETS ΔT = 10	25	25	15	15	20

Table 5.4 shows the five different variations in the amount of annual surplus heat supply to the system (column 2). The assumed values for the annual heating demand and the annual cooling demand in each case are also shown. The cooling demand is assumed to differ between the three reference cities due to differences in climate. The first column in the table shows the “surplus heat share”, which is defined as the ratio between the annual surplus heat supply and the annual heating demand. When the surplus heat share is 100%, the total annual surplus heat inflow to the system equals the total annual heating demand in the system (without any consideration of the time distribution of the supply and demand).

Table 5.5 shows the different variations in the operating temperatures of the system. Variation I corresponds to conventional district heating temperatures. Variation II assumes a FLEXYNETS system operating with forward and return temperatures of 25 °C and 15 °C and surplus heat available at 80 °C. Variation III assumes the same FLEXYNETS system, but with surplus heat available at 60 °C. Variation IV Considers a FLEXYNETS system with forward and return temperatures of 25 °C and 10 °C and surplus heat available at 60 °C. Variation V considers a FLEXYNETS with forward and return temperatures of 25 °C and 15 °C and surplus heat available at the network forward temperature, 25 °C. However the relevance of this option showed not to encourage storage option and it has therefore generally been excluded from the plots except for the large scale PTES where a stratified and centralised sensible storage could potentially incorporate it. The return temperature from the cooling demand is in all cases assumed to be 20 °C (and not 25 °C, like the heating forward temperature), due to practical temperature limitations of commercially available heat pump technology.

5.4 Indicators

Two main indicators have been used for evaluating the outcome of the model scenarios:

1) The specific thermal energy production costs (the average costs of providing one MWh of heating or cooling during the year).
2) The annual CO_2 emissions arising from the operation of the boiler and coolers.

In the following, the calculation of the two indicators is described. Note that in the terminology used here, small letters are used to denote specific values (e.g. costs per volume, emissions per MWh, etc.) while capital letters are used to denote absolute vauuiulues (e.g. total costs per year, total emissions per year).

Indicator 1: Thermal energy production costs

The energy specific thermal energy production costs (c_Q, in unit of €/MWh) are calculated as the total annual costs (C) of the system (investment costs, O&M costs, external energy input costs and CO_2 emission costs) divided by the total heating and cooling energy (Q) provided during the year:

$$c_Q = \frac{C_{Inv,annualized} + C_{O\&M} + C_Q + C_{CO2}}{Q_{Heating} + Q_{Cooling}} \qquad \text{(Equation 11) (Indicator 1)}$$

In this equation, the annualized investment costs are defined as:

$$C_{Inv,annualized} = \frac{r \cdot (C_{Inv,transmission} + C_{Inv,storage})}{1 - (1 + r)^{-n}} \qquad \text{(Equation 12)}$$

Where $C_{Inv,transmission}$ and $C_{Inv,storage}$ and denote the total investment costs of the transmission pipeline and the storage in the current scenario. Note that for ATES and BTES, the storage investment costs are the sum of the ATES or BTES investment and the investment in the associated TTES buffer respectively. The interest rate is denoted with *r* and the investment lifetime in years is denoted with *n*. The operation and maintenance costs ($C_{O\&M}$) in Equation 11 are calculated as a percentage of the total investment in transmission and storage, according to the values in Table 5.2.

The Total annual costs of external energy inputs to the system is:

$$C_Q = Q_{Boiler} \cdot c_{heating} + (E_{FreeCooler} + E_{HeatPump} + E_{Pumps}) \cdot c_{electricity} + Q_{surplus} \cdot c_{surplus} \qquad \text{(Equation 13)}$$

Here *Q* denotes thermal energy, *E* denotes electrical energy and *c* denotes the cost of energy per MWh. A shown in in Table 5.2, $c_{surplus}$ is assumed to equal zero in all cases (the surplus heat is assumed to be available free of charge).

In short this represents an average value of how much the network operator needs to pay to supply the heat to the consumer substations. However the cost on the consumer side is also evaluated in section 5.6.7.

The total annual costs of CO_2 emissions from the operation of the boiler and the coolers is:

$$C_{CO2} = M_{CO2} \cdot c_{CO2} \qquad \text{(Equation 14)}$$

Here M_{CO2} are the annual CO_2 emissions from the boiler and cooler operation (indicator 2, shown in Equation 15) and c_{CO2} denotes the costs of emitting one ton of CO_2 (shown in Table 5.2).

Indicator 2: Annual CO_2 emissions from heating and cooling

The total annual CO_2 emissions (M_{CO2}) from the boiler and cooler operation is:

$$M_{CO2} = Q_{Boiler} \cdot m_{CO2,Boiler} + (E_{FreeCooler} + E_{HeatPump}) \cdot m_{CO2,Electricity}$$ (Equation 15) (Indicator 2)

Here Q denotes the annual fuel consumption of the boiler, E denotes the annual electricity consumption of the free cooler or the heat pump and m denotes the CO_2 emissions per MWh of boiler/cooler energy consumption.

5.5 Reference cities

Three reference cities were chosen as case studies for the model; Rome (IT), London (GB) and Stuttgart (DE). These cities were chosen for consistency with other parts of the FLEXYNETS projects. The hourly time series for the heating and cooling demand were constructed using a method based on statistics on the ambient temperature and based on assumptions about the set point temperatures for the heating and cooling demand. A part of the heating and cooling demand was in each case assumed to be constant throughout the year, independent of the ambient temperature. The resulting profiles for the heating and cooling demands are shown in the following figures for the cases of Rome, London and Stuttgart respectively.

The ambient temperature profiles used in the *TRNSYS* model and for the construction of the heating and cooling demand profiles were obtained from Meteonorm TMY2 data files, which represent the temperatures in an average year at the given location. An Excel-routine was used to calculate the heating demand during each hour of the year, by counting the number of ”degree-hours” (equivalent to degree-days, but on an hourly basis). The heating degree hours are counted as the difference between the heating set point temperature and the ambient temperature in each hour of the year. Each degree hour translates to a certain heating energy demand, and consequently hours with a very low temperature (a large difference between the heating set point temperature and the ambient temperature) translate to a high heating energy demand. The heating demand profile is constructed by repeating this for every hour of the year. The cooling demand profiles were constructed in an analogous way, with cooling degree hours counted as the difference between the ambient temperature and the heating set point temperature. In reality the cooling demand in residential and commercial buildings is also determined be the incident solar irradiance, but for the purpose of this analysis, an estimate based on ambient temperatures was considered sufficiently representative.

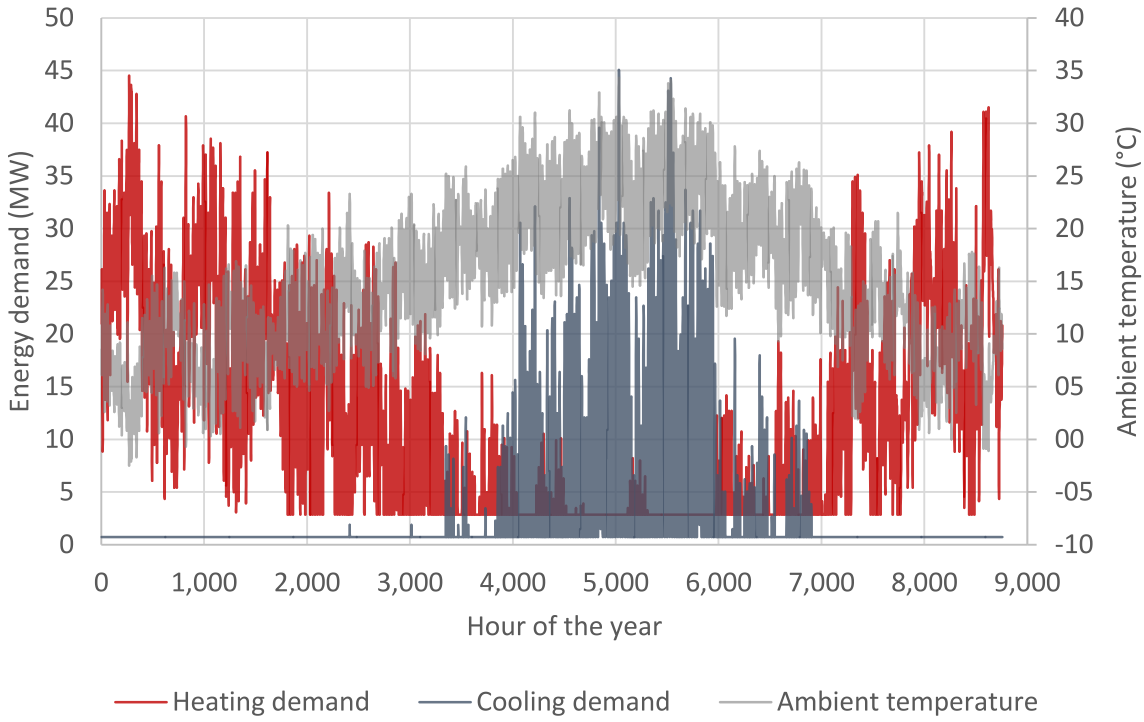


Figure 47 – The time-series for the ambient temperature, the heating demand and the cooling demand used for modelling the case of Rome.

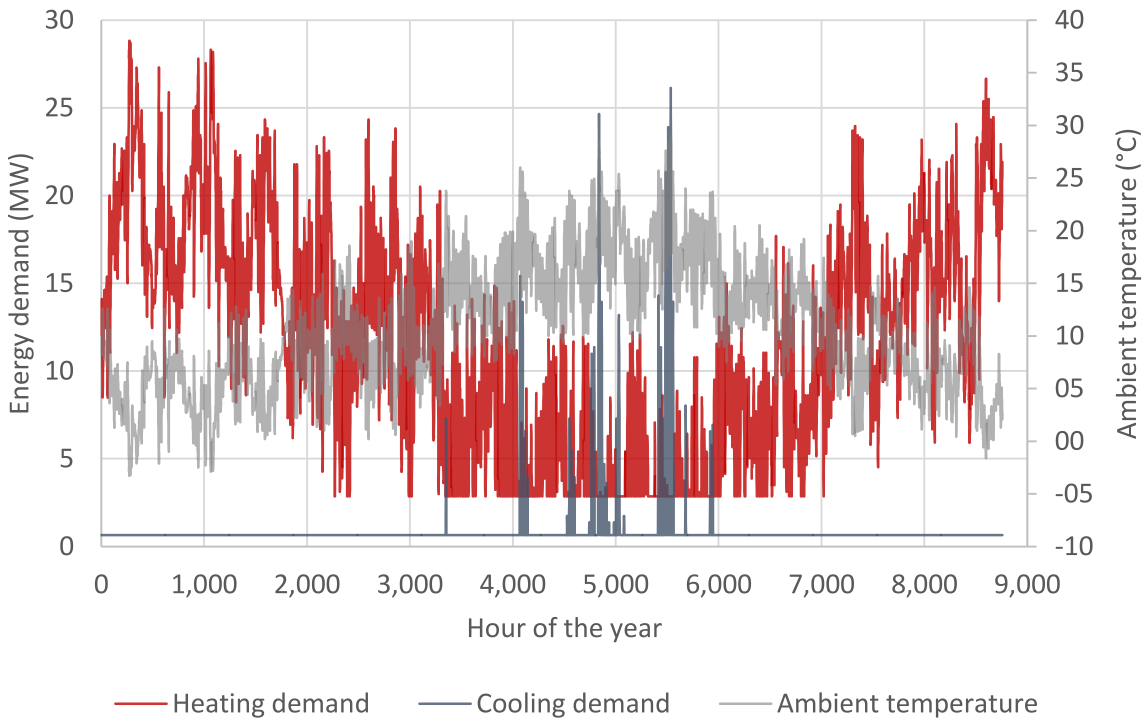


Figure 48 – The time-series for the ambient temperature, the heating demand and the cooling demand used for modelling the case of London.

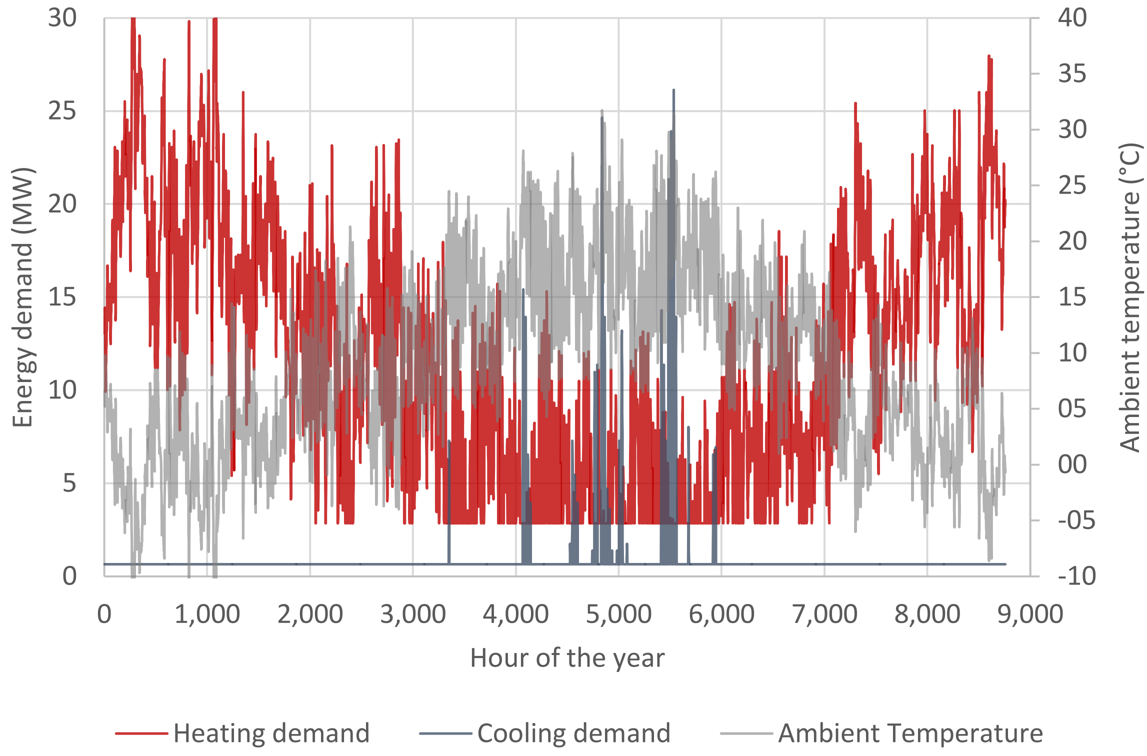


Figure 49 – The time-series for the ambient temperature, the heating demand and the cooling demand used for modelling the case of Stuttgart.

The heating set point temperature was assumed to be 17 °C for all three locations. The cooling set point temperature was assumed to be 23 °C for Rome and 22 °C for London and Stuttgart, due to possible differences in comfort requirements between Southern Europe and Mid-Europe. The ambient-temperature independent share in the heating demand was assumed to be 25% in all locations. This corresponds to hot water for other purposes than space heating, such as for bathing. The ambient-temperature independent share in the cooling demand was assumed to be 25% for Rome, 75% for London and 60% for Stuttgart. This was intended to reflect the fact that the need for space cooling is highest in Rome, and that a large share of the cooling demand in London and Stuttgart is not needed for space cooling that directly relates to the ambient temperature, but rather for cooling of supermarkets and large buildings (e.g. large office complexes, airports) that have some cooling demand all year round.

In this modelling, it was not the intention to model the total heating and cooling demand in each of the reference cities. The model is rather intended to represent a district or a neighbourhood within each of the cities; this could e.g. be a new development area in the city, where the FLEXYNETS concept would be implemented. Therefore, the same heating demand, 100 GWh/year, has been assumed regardless of the size of the reference city. To give an idea of the scale of the heating demand of 100 GWh/year, this can be compared to the heating demand of the Danish municipality of Sønderborg (population 27,000), which is approx. 370 GWh/year. In Danish climate, the heating demand modelled in the *TRNSYS* model can therefore be thought of as the demand of a district of approximately 7,500 inhabitants. The annual heating demand per person in London, Stuttgart and Rome is lower than in Denmark, and 100 GWh heat per year can therefore supply a somewhat larger population in those cities than in Denmark.

5.6 TRNSYS model results

5.6.1 Model dynamics and energy balance in the storages

The *TRNSYS* model calculates, among other things, the temperatures in the thermal storages, the energy injection and extraction to and from the storages and the storage state of charge for each time step (hour) of the simulation period. The model furthermore calculates the required heating power (from the boiler) and cooling power (from the free cooler and the heat pump) for each time step, based on surplus heat supply, the heating demand, the cooling demand and the storage injection and extraction in that time step. In the following, some examples of the results of a PTES model run for Rome are shown for one simulation year, in order to illustrate the dynamics of the model system.

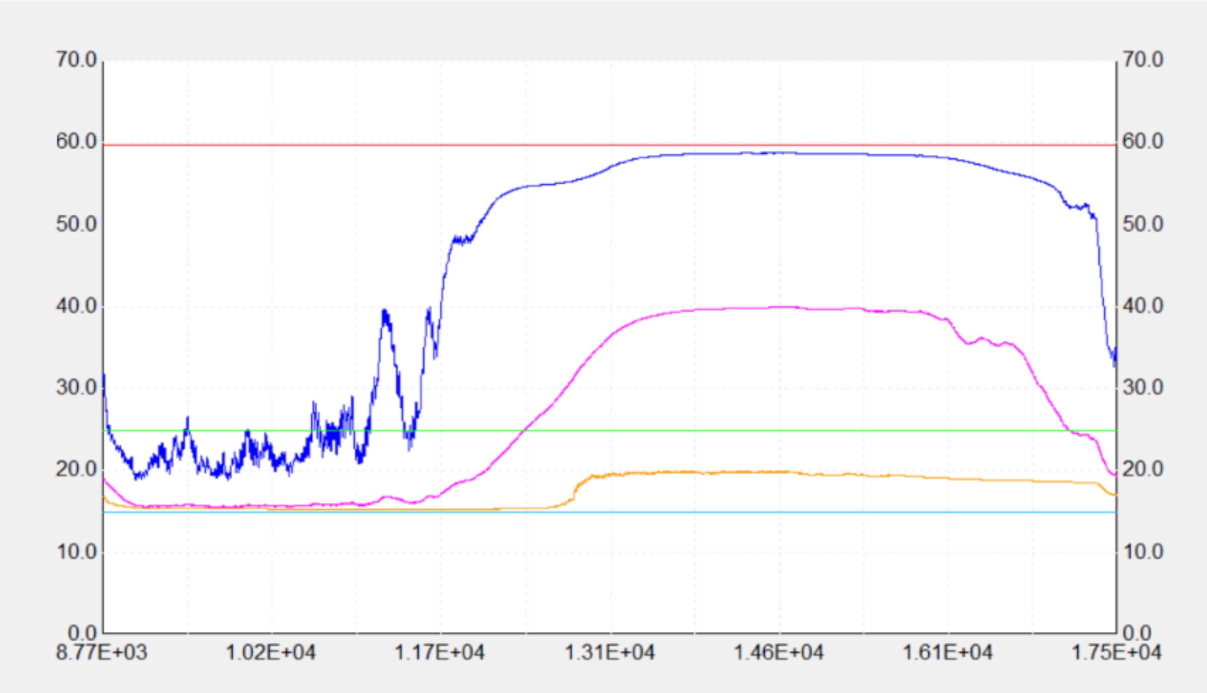


Figure 50 – An example of the development of the temperatures in the pit storage throughout the course of one simulation year in time steps of one hour. This example is for the case of Rome, a PTES storage of 500,000 m^3, a 100% surplus share, 60 °C surplus heat temperature (red line), 25 °C forward temperature (green line) and 15 °C return temperature (cyan line). The dark blue and yellow line shows the temperature at the top and bottom of the PTES respectively. The pink line shows the average PTES temperature.

Figure 50 shows an example of the temperature development in the PTES storage during a single model run. The temperature is measured in a number of different heights in the storage; the figure shows the temperature at the top and the bottom of the storage as well as the averages temperature in the PTES.

Figure 51 shows the energy injection and extraction to and from the PTES for the same model run, as well as the PTES state of charge. The state of charge is defined as the current energy contents of the storage divided by the theoretical maximal energy contents of the storage (i.e. if all water in the storage were at the maximum storage temperature). The x-axis of the graphs covers one year, starting on January 1st (simulation hours 8,761-17,520, corresponding to the 2nd year of simulation). As can be seen in the figures, the storage is empty and cold after the winter, but is charged again during spring. In the summer, the storage has been charged to its maximum temperature. The storage remains at the maximum temperature until the autumn, where it is slowly discharged and eventually emptied during the winter. This development is as expected. The same kind of analysis was also performed for the other storage types.

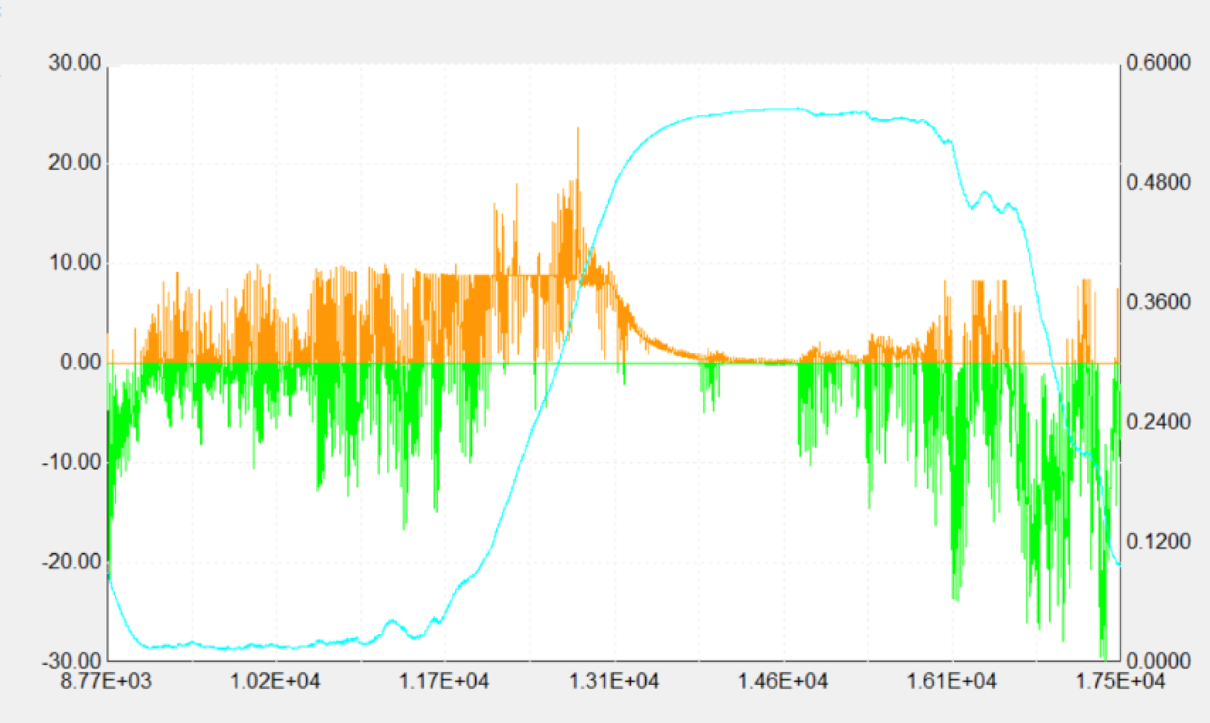


Figure 51 – An example of the PTES energy input (positive, yellow line) and output (negative, green line) as well as its state of charge (cyan line) throughout the course of one simulation year. The left secondary axis shows the energy input or output in MW and the right secondary axis shows the state of charge (as a fraction of a perfectly charged storage). This example is for the case of Rome, a PTES storage of 500,000 m³, a 100% surplus share, 60 °C surplus heat temperature, 25 °C forward temperature and 15 °C return temperature.

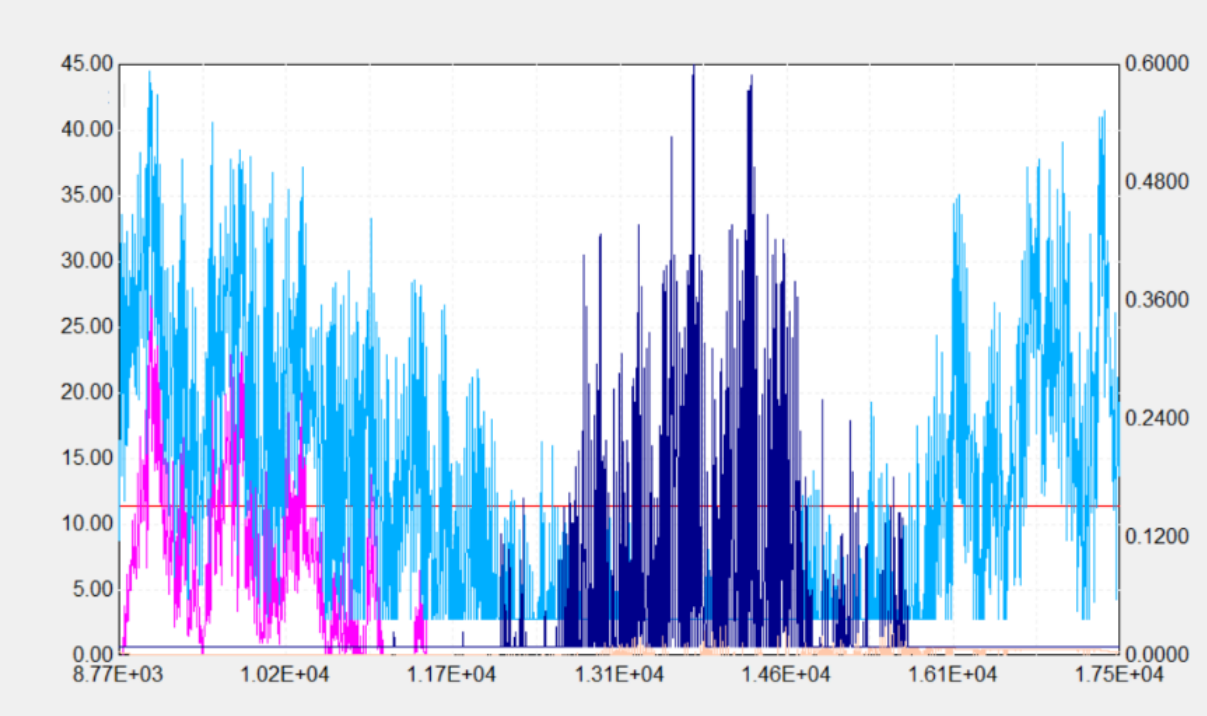


Figure 52 – The energy flows in the system during one simulation year: Surplus heat inflow (red line), heating demand (light blue line), cooling demand (dark blue line), boiler energy input (pink line) and chiller energy input (peach line). This example is for the case of Rome, a PTES storage of 500,000 m³, a 100% surplus share, 60 °C surplus heat temperature, 25 °C forward temperature and 15 °C return temperature.

Figure 52 shows the energy flows (surplus heat inflow, heating demand, cooling demand, boiler energy input and chiller energy input) in the system during one simulation year, for the same PTES model run as discussed above. As can be seen, the boiler operates quite a lot during the first quarter of the year. This is because in this part of the year, the PTES is mostly empty. The boiler does, however, not operate during the last quarter of the year, even though there is a large heating demand. This is because the storage is full at the beginning of this quarter and can be used for fulfilling the required heating demand. Similarly, the coolers operate more in the late summer, because the bottom of the PTES is cold at the beginning of the summer but becomes warmer over the summer as the cold water is extracted to fulfil the cooling demand. It can be observed that the PTES is filled up long before the end of the summer period and is emptied long before the end of the winter. The graphs shown here therefore indicate that from a technical point of view, a larger PTES could benefit the system in this particular scenario by enabling more effective storage and usage of the surplus heat that is injected to the system, and thereby reducing the CO_2 emissions from boiler and cooler operation (indicator 2). This does, however, not provide any information about if a larger PTES would be feasible from an economic point of view (indicator 1). Also, an alternative control of the surplus heat injection to the network (i.e. restrictions during some periods) might improve the system as a whole due to a lower auxiliary cooling demand.

5.6.2 Energy flows and heat losses

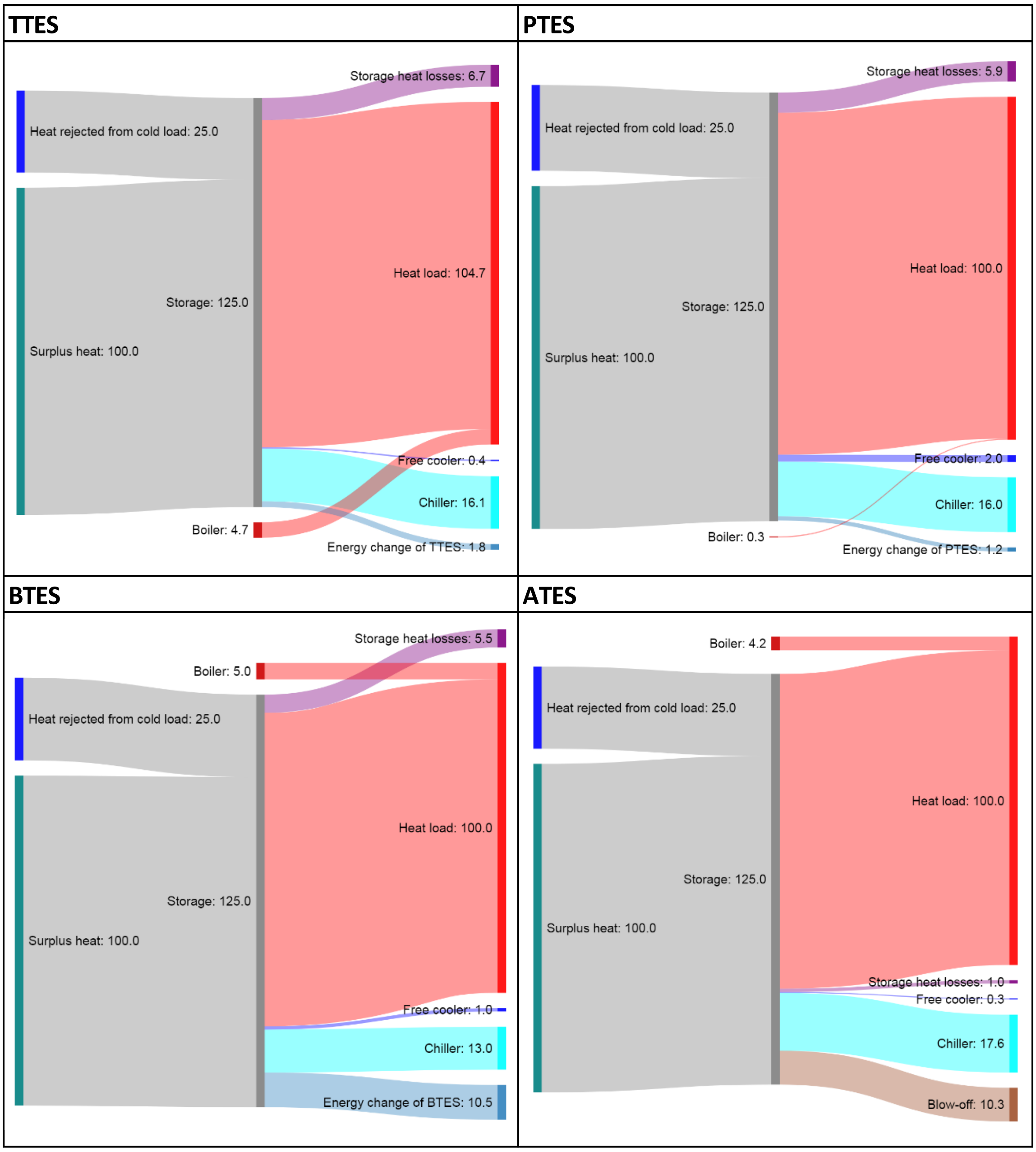
Error! Reference source not found. shows Sankey diagrams of the energy flows for the second year of operation for all four different TES technologies in the case of Rome, with surplus heat of 100 GWh at a temperature of 60 °C; forward and return temperature for the heating load of 25 °C and 15 °C, respectively; forward and return temperature for the cooling load of 15 °C and 20 °C, respectively. In the four presented scenarios, the total volume (in terms of water equivalents) was assumed to be 1,500,000 m^3. Fort he same assumptions, the Sankey diagram of Stuttgart is seen in **Error! Reference source not found.**.

Both for the case of Rome and Stuttgart, it can be seen that the high availability of surplus heat and of the heat rejected by the cooling load strongly limited the operation of the central boiler in all cases. On one side the boiler needs to operate to meet the requirements of the DH load during winter, on the other side the chiller needs to operate in summer, when the colder temperatures that can be extracted from the TES are higher than the design forward temperature for cooling (i.e. 15 °C in these examples).

It can also be observed that the system equipped with TTES has the highest thermal losses. In case of TTES, the storage volume of 1,500,000 m^3 should be seen as the cumulated volume of multiple smaller TTES, whose maximum size is usually within 10,000 m^3. Having multiple smaller TTES instead of a single and very large TTES increase the surface area of the storage and so its losses, which are therefore higher for the TTES example compared to the TES technologies, for which much larger size can be assumed.

Looking at the Sankey diagrams of the example referring to the BTES, the energy balance during the second year of operation shows that the BTES has not reached a steady state condition yet, as a non-negligible amount of injected heat (9.4 GWh) is used to increase the energy content of the BTES. Because the heat losses from the BTES represented roughly 10 % of the heat supplied to the BTES, it can be estimated in first approximation that, when the BTES reaches steady state conditions, the heat extracted from the BTES and supplied to the heat load would likely be about 8.5 GWh higher than what shown in the Sankey diagram. It is therefore likely that no (or very limited) boiler operation will be needed, as in the case of the PTES storage. The reason why the two years of operation are not sufficient for the BTES to reach steady-state condition is represented by the rather large storage volume considered in the example and the slower dynamic response of the BTES with respect to water-based TES.

The lowest heat losses are seen for the case of ATES. Due to some contraints in the ATES TRNSYS model, there is seen some blow off. This is due to the low difference temperature allowed in the ATES (in the model max inlet temperature is 30 °C, while the lowest temperature which can be reached is 15 °C because this is the return from the FLEXYNETS network (i.e. the temperature difference = 15 K). Therefor the ATES has a small capacity despite its volumetric size. So in summer time the ATES gets „filled up“, and since the heat load is low also the hot buffer tank of the ATES is warmed up. The return to the surplus heat source is therefore warmer than the max allowed temperature (in the model 40 °C). Therefore some excess heat is dissipated in the blow off component to lower the temperature to 40 °C before entering the surplus heat sources. From additional modellings, it was seen that the blow off is larger for smaller sizes of ATES.



TTES
Storage heat losses: 6.7
Heat rejected from cold load: 25.0
Heat load: 104.7
Storage: 125.0
Surplus heat: 100.0
Free cooler: 0.4
Chiller: 16.1
Boiler: 4.7
Energy change of TTES: 1.8
PTES
Storage heat losses: 5.9
Heat rejected from cold load: 25.0
Heat load: 100.0
Storage: 125.0
Surplus heat: 100.0
Free cooler: 2.0
Chiller: 16.0
Boiler: 0.3
Energy change of PTES: 1.2
BTES
Storage heat losses: 5.5
Boiler: 5.0
Heat rejected from cold load: 25.0
Heat load: 100.0
Storage: 125.0
Surplus heat: 100.0
Free cooler: 1.0
Chiller: 13.0
Energy change of BTES: 10.5
ATES
Boiler: 4.2
Heat rejected from cold load: 25.0
Heat load: 100.0
Storage: 125.0
Surplus heat: 100.0
Storage heat losses: 1.0
Free cooler: 0.3
Chiller: 17.6
Blow-off: 10.3

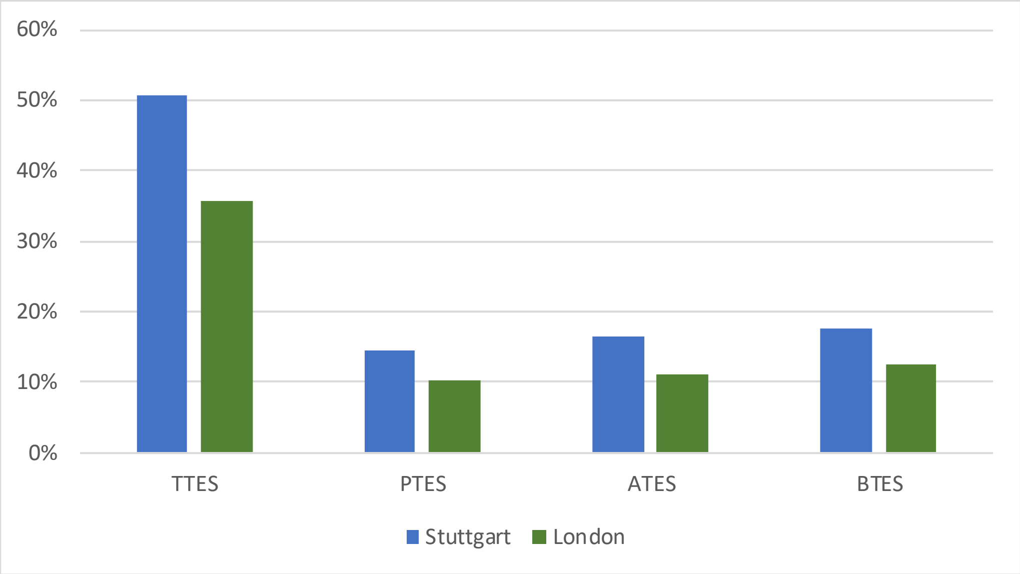


Figure 53 – Increased heat losses in the case of Stuttgart and London compared to Rome.

For the shown example, the load profile was Rome, the volume of the four TES types was 1 mio. m^3 water equivalent, the surplus heat share was 100 % at 60 °C. Further the supply temperature was 25 °C, the return temperature 15 °C abd the cooling supply temperature was 15 °C.

As seen a significant increase in the heat losses for TTES is seen. Some of the explanation for this high increase should be found in the model assumptions, as described above.

The increase in heat loss for PTES, ATES and BTES can be explained by the different weather conditions and hence also the ambient temperature as well as the temperature of the soil in the three different locations.

5.6.3 Reference case: Rome

Results for the case of TTES in the reference city Rome are shown below for the two indicators described in section 5.4 (thermal energy price and CO_2 emissions from heating and cooling).

The results for five different sets of operating temperatures, a constant "surplus share" of 100% (i.e. the annual surplus heat inflow equals 100% of the annual heating demand) and assuming no surplus heat transmission pipeline is seen. It is clear from the figure that the lowest thermal energy price and the lowest CO_2 emissions are obtained when the surplus heat temperature is high and the forward and return temperatures are as low as possible. The scenarios with the conventional district heating temperatures performs worst on both indicators, followed by the scenarios with the surplus heat temperature equalling the FLEXYNETS forward temperature.

For the case of TTES in Rome, the lowest thermal energy price is obtained when no TES is present. This may not be very surprising, since TTES are mostly not designed as seasonal storages in practice, but rather for balancing daily or perhaps weekly fluctuations in supply and demand. Investing in sufficient TTES capacity to store between summer and winter can therefore be expected to be expensive, compared to the other storage types (as seen in Figure 39). However, regarding CO_2 emissions, it is possible to obtain significant emission reductions by introducing TTES in the system (in case of FLEXYNETS operating temperatures and high surplus heat temperature). It should be noted that the heat price in the system without the surplus heat is assumed to be 50 €/MWh, and by introducing 1.5

- 2.0 million m^3 of TTES in the system, the CO_2 emissions from boiler and cooler operation can be lowered by more than 95% while still keeping the thermal energy price below 50 €/MWh.

Below the results are shown for different amounts of surplus heat inflow to the system ("surplus share") for one sets of operating temperatures. As expected, the best results on both indicators are obtained for the highest amount of surplus heat inflow, as the surplus heat is assumed to be available free of charge and is not assumed to contribute to the system's CO_2 emissions. However, electricity demand for pumping, and the associated CO_2 emissions and costs are taken into account. The thermal energy price increases when TTES is introduced, but the price level depends highly on the amount of surplus heat inflow. The CO_2 emissions from heating and cooling can in all cases be reduced by introducing TTES, but the magnitude of the CO_2 reduction is higher for large amounts of surplus heat inflow than for small amounts. This is because the storage capacity can be better utilized when there is a large inflow of heat to the storages.

Similar to the TTES case, the best performance on the two indicators is obtained for high surplus heat temperature and FLEXYNETS network temperatures for PTES. The lowest thermal energy price can be obtained by not investing in thermal storage. However, an investment in PTES capacity up to 1 million m^3 only leads to very minor increases in the thermal energy price (an increase of 2-3 €/MWh, depending on PTES capacity). By investing in 1 million m^3 of PTES capacity, the CO_2 emissions from heating and cooling can be lowered from approximately 6 kton/year to 1 kton/year (a reduction of over 80%). This strongly indicates that PTES could be a very relevant thermal energy storage technology for this system.

The effect of PTES storage on the indicators for different amounts of surplus heat inflow to the system can be seen below. The positive effects of the storage on both indicators are more pronounced for high amounts surplus heat inflow than for low amounts. It is interesting that for 1 million m^3 PTES or larger, the indicators show the same results for a surplus share of 100% and 125%. This shows how investing in sufficient storage capacity enables more efficient usage of the incoming surplus heat, i.e. that over-dimensioning the surplus heat inflow compared to the system heat demand is not beneficial in case a sufficiently large thermal storage is available.

The results for ATES for the case of Rome are shown below too. It can be seen that the introduction of ATES in the system substantially lowers both the thermal energy price and the CO_2 emissions. The best results for both indicators are obtained for the case of 60 °C surplus heat, 25 °C forward temperature and 10 °C return temperature. For this case, the thermal energy price has a slight optimum for an ATES volume of 1 million m^3 (water eq.). For an ATES of 1 million m^3 (water eq.), the CO_2 emissions in this case are lowered from around 6 kton/year to 2 kton/year (a reduction of approx. 65%). By increasing the ATES volume to 1.5 million m^3 (water eq.), the thermal energy price only increases by less than 1 €/MWh while the CO_2 emissions are lowered below 1 kton/year (a reduction of approx. 85%). These results clearly indicate that ATES can be highly suitable thermal energy storage technology for the type of system investigated here.

The good performance of the ATES technology in the modelled system can largely be explained by the fact that it has dedicated warm and cold storages (in the form of separate drillings) and operates at temperatures (approx. 8 °C - 20 °C) very close to the cooling and heating temperatures in the FLEXYNETS concept (approx. 10 °C to 25 °C). This can save the system considerable amounts of external energy consumption for heating but especially for cooling, which results in reduced CO_2 emissions.

No BTES results are shown for conventional DH temperatures, as the *TRNSYS* model developed in this work was not designed to work with these temperature levels together with a borehole storage. The introduction of relatively small BTES capacity (up to 200,000 m^3 water eq.) leads to a lowering of the thermal energy price, for all scenarios that have a high surplus heat temperature and FLEXYNETS forward and return temperatures. The introduction of 200,000 m^3 of BTES leads to a reduction in CO_2 emissions from around 6 kton/year to approx. 4.5 kton/year (a reduction of 25%). It can also be seen in the figure that the CO_2 emissions can be reduced from approx. 6 kton/year to approx. 1 kton/year (a reduction by 80%) by investing in 1 million m^3 (water eq.) BTES capacity. The thermal energy price for this size of BTES is roughly the same as with no BTES storage capacity. These results indicate that BTES could be a very relevant storage technology for this system.

It can be seen in Figure 62 that both the thermal energy price and the CO_2 emissions have an optimum for the case of high-temperature surplus heat and FLEXYNETS network temperatures. The most likely explanation for this is that the heat losses associated with BTES are rather large, and the required heating and cooling energy to make up for these losses increases as more water (with increasing storage size) is circulated in and out of the BTES (with corresponding losses in temperature). This could perhaps be improved upon by reducing the flow through the BTES, compared to the flow settings used in the calculations shown here.

Figures are grouped in one page per storage technology in the following four pages (TTES, PTES, ATES and BTES respectively). A summary of the results for all four thermal energy storage types for the case of Rome are shown below for a 100% surplus share and for the temperature levels that performed best in most of the scenarios: 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature.

The lowest thermal energy price (approx. 50% reduction compared to no storage) among these scenarios can be obtained by investing in 1 - 2 million m^3 of ATES (water equivalents), which also results in a large reduction in CO_2 emissions (approx. 60 - 85%). In case obtaining the largest possible CO_2 reductions has 1st priority, investing in 1.5 - 2 million m^3 PTES would be the best option. This would result in CO_2 emission reductions of over 90% and a thermal energy price 8 - 15 €/MWh higher than in the case of no storage (which is still more than 20 €/MWh lower than the assumed price in the network without the surplus heat availability). An investment in 1 million m^3 would reduce the CO_2 emissions by approx. 80% while increasing the thermal energy price by only 2 - 3 €/MWh.

Investing in BTES yields a slightly lower thermal energy price than PTES, but more CO_2 reductions for BTES volumes of 1 million m^3 (water eq.) or smaller. TTES performs well in reducing the CO_2 emissions, but is considerably more expensive than the other technologies for usage as a seasonal storage.

To illustrate the composition of the thermal energy price, an example for different PTES capacities for the case of Rome is shown in Figure 51. For reference, the CO_2 emissions are also shown in the graph. It can be seen that for small storage volumes (up to 200,000 m^3), the expenses for natural gas and electricity for heating and cooling are the principal component in the thermal energy price. As the storage volume increases, the expenses for gas and electricity shrink, but the system becomes heavier on capital costs and O&M costs due to the extensive investment in thermal energy storage. The CO_2 emissions decrease as the storage volume increases (for volumes above 100,000 m^3). Consequently, the expenses for CO_2 emissions, which account for approximately 10% of the thermal energy price for storage volumes of 200,000 m^3 or less, almost disappear for very large storage volumes. These general trends regarding the composition of the price also hold for other PTES scenarios and for scenarios with other storage types (TTES, ATES, BTES).

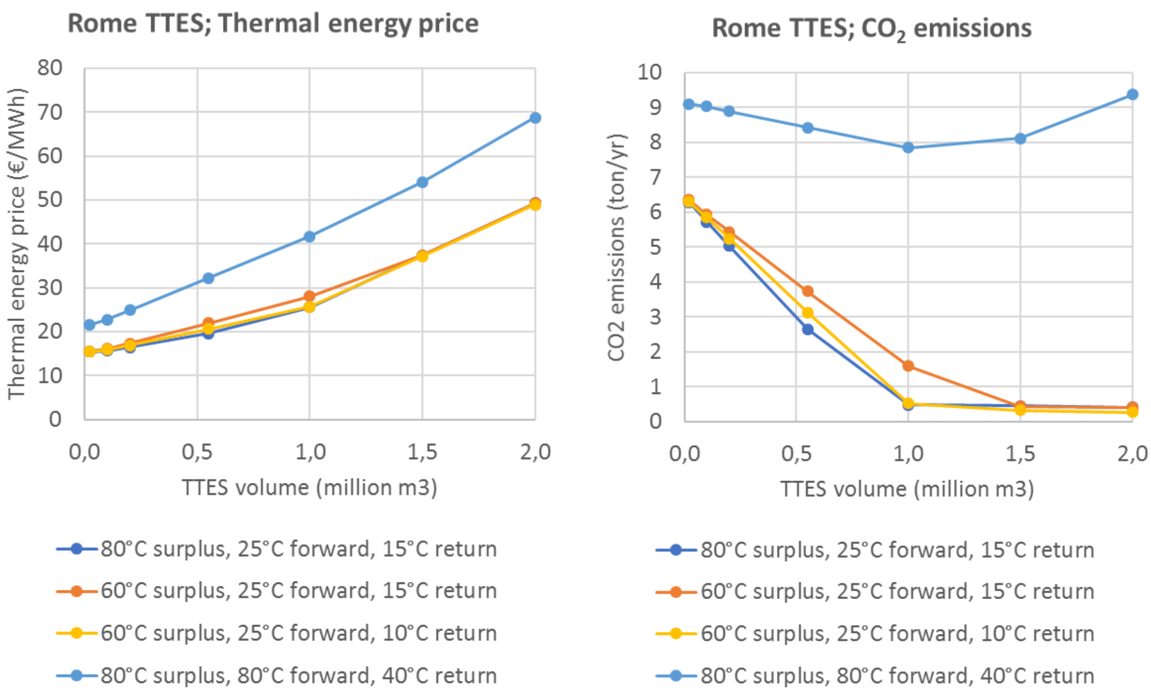


Figure 54 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%.

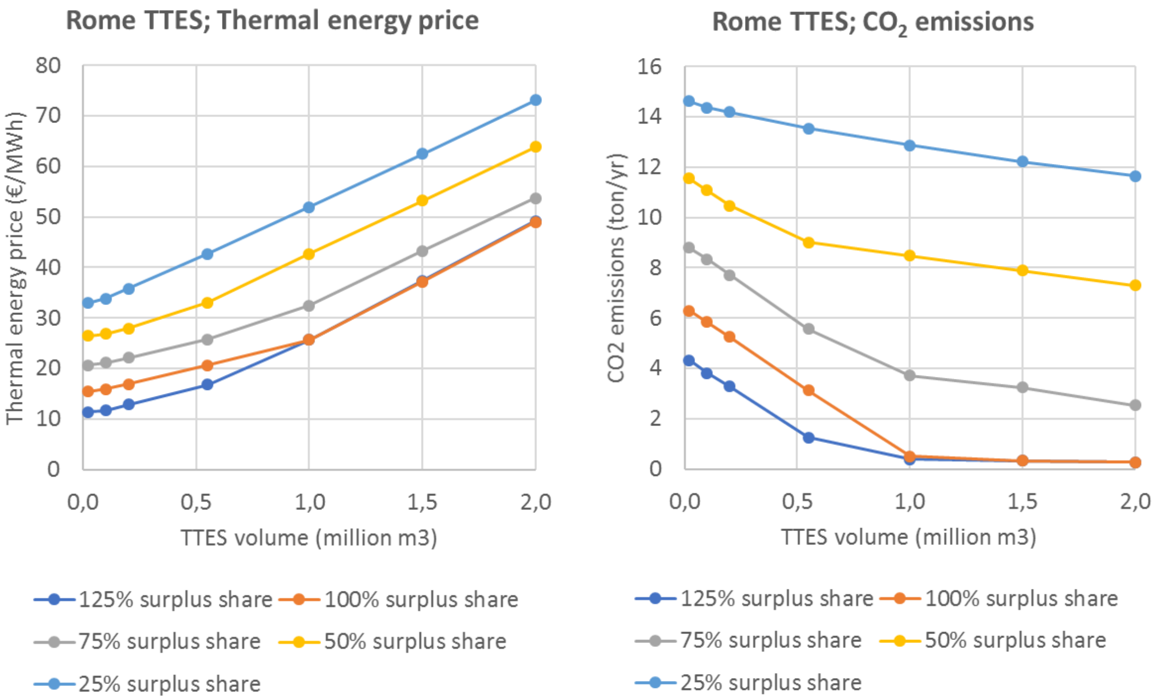


Figure 55 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

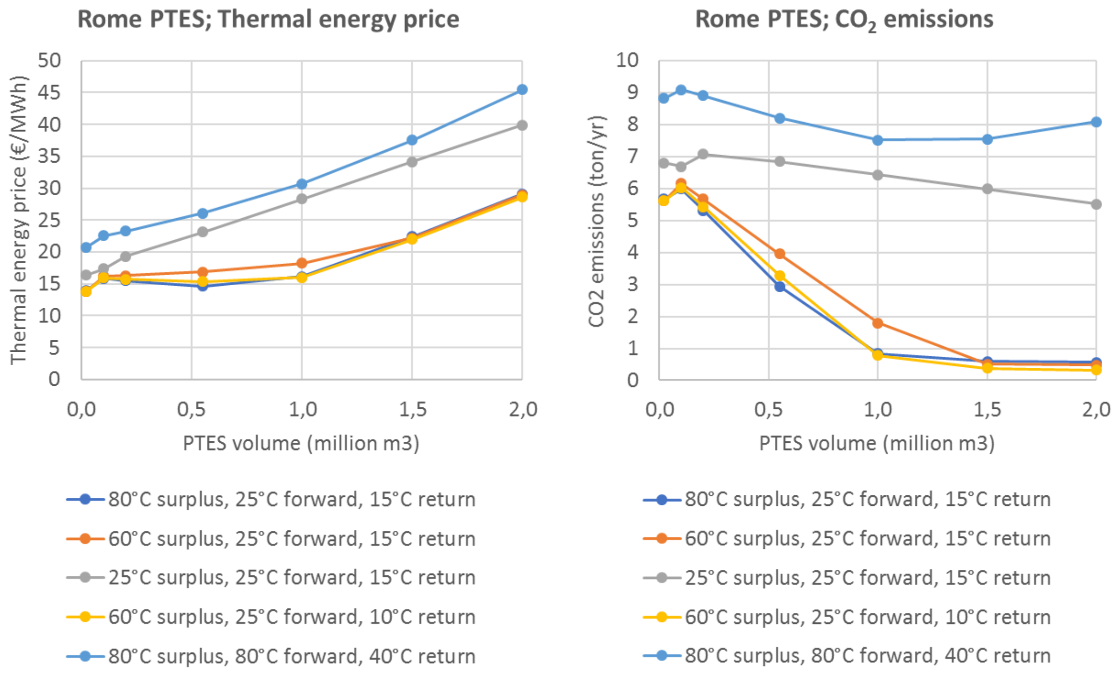


Figure 56 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%.

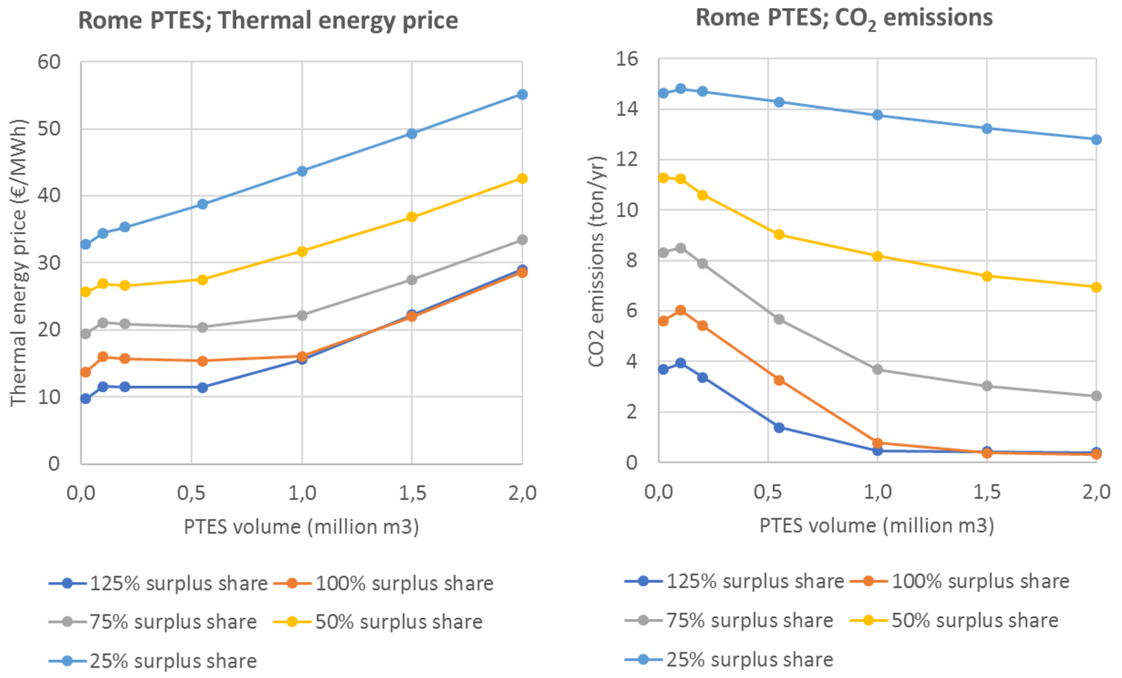


Figure 57 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

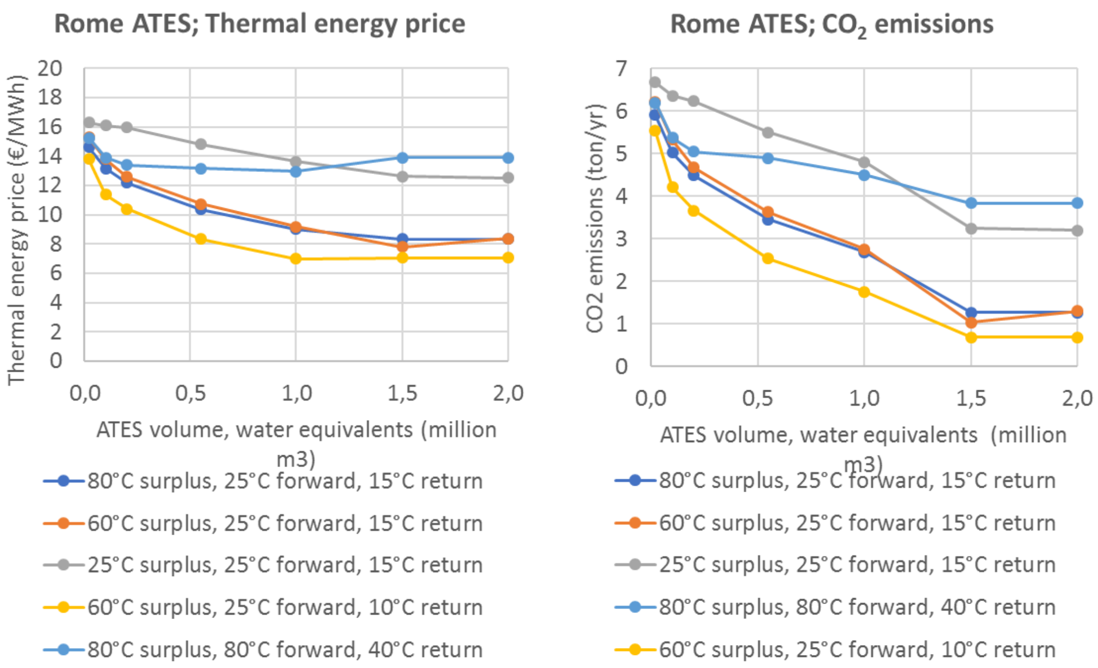


Figure 58 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%.

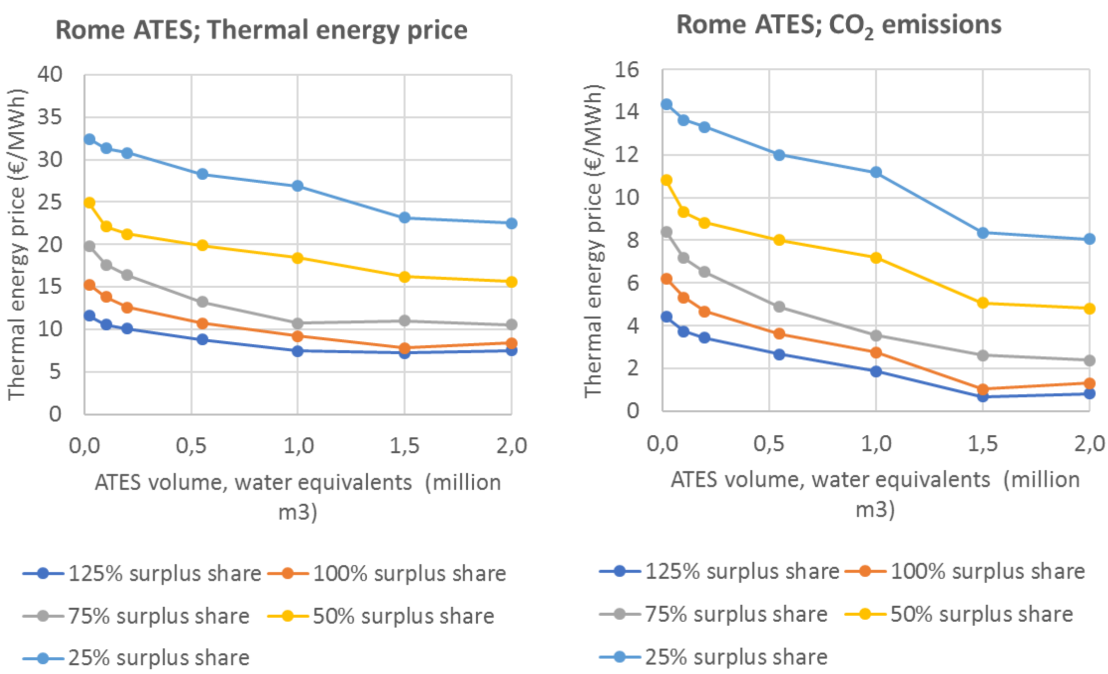


Figure 59 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

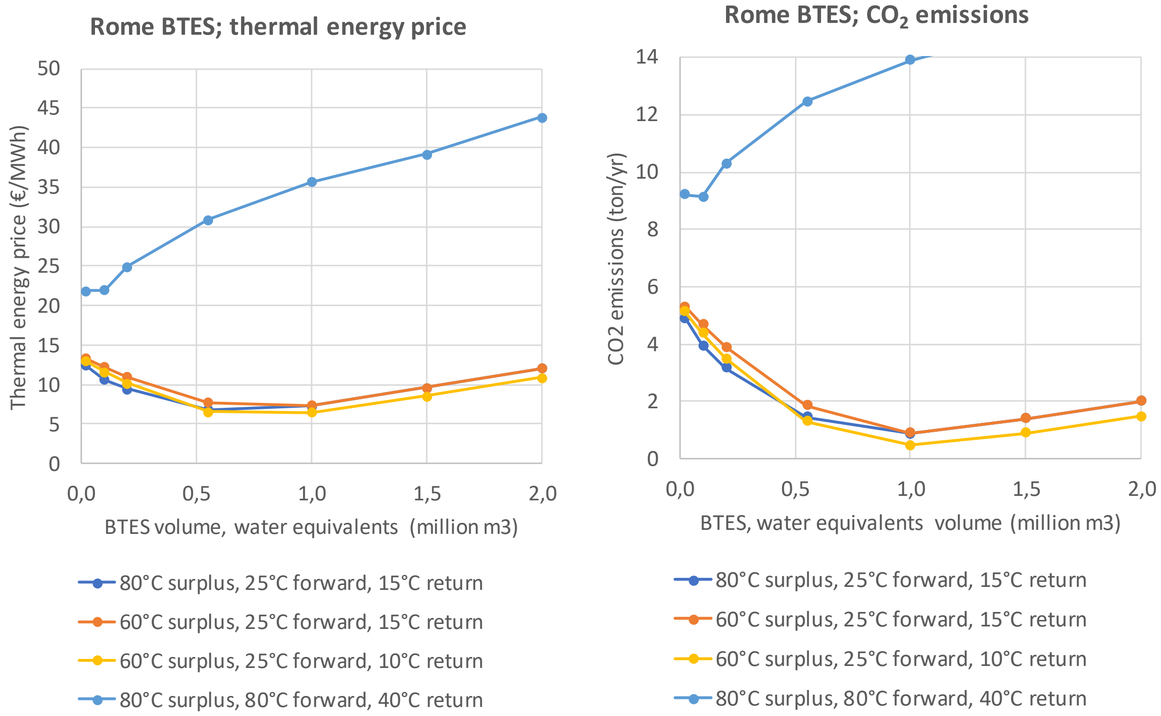


Figure 60 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%.

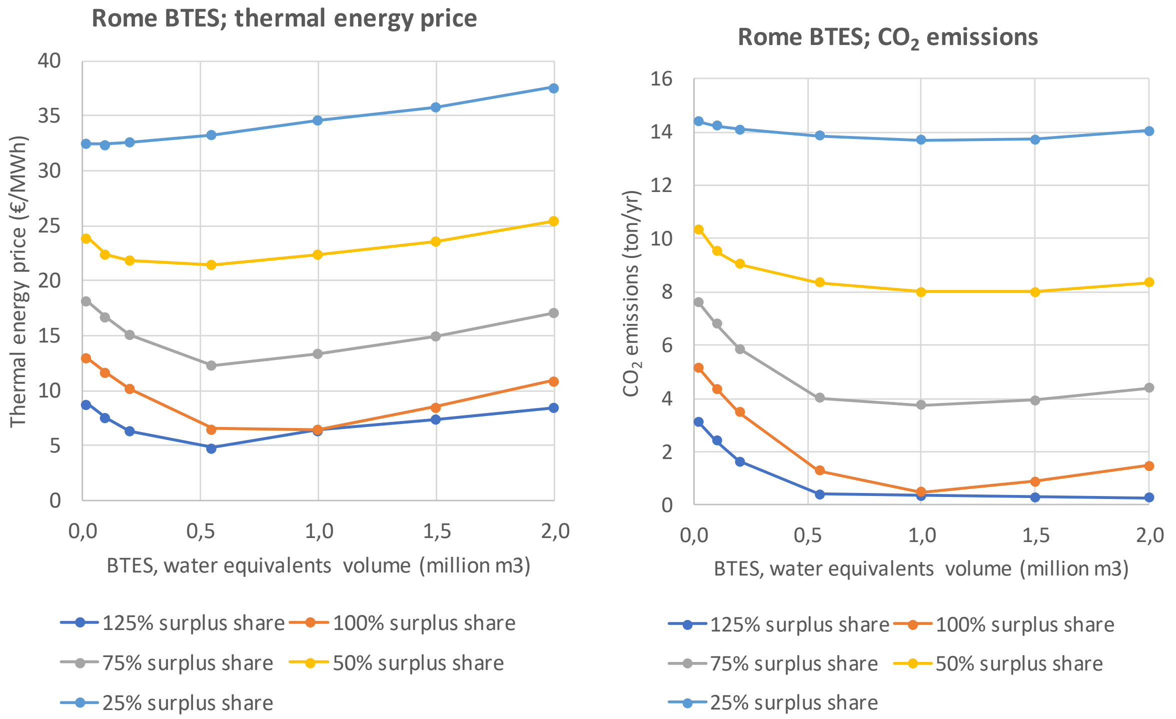


Figure 61 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

Though higher temperatures reduce the required volume to store a certain quantity of energy, there will often be a difference between the amount of available surplus heat depending on the temperature.

In Figure 65 the thermal energy price is shown for 100,000 m^3 PTES for the case of Rome as a function of the length of the surplus heat transmission pipeline (all results shown before Figure 65 have assumed no transmission pipeline costs). Assuming a network heat price of 50 €/MWh without surplus heat availability, this price can be used as an upper limit for how far it could be economically feasible to source the surplus heat. For a surplus share of 100%, the results show that the transmission pipeline length can be up to 40 km before the thermal energy price equals 50 €/MWh. This distance should be understood as an upper limit to the feasible transmission pipeline distance, obtained based on the assumptions of the model. As these assumptions may not correspond to reality in all district heating and cooling systems, the real feasible distance can be considerably lower and must be evaluated individually based on local conditions. The results also show that this distance is slightly different for different PTES sizes and for different storage types (TTES, ATES, BTES), but the general conclusion is that for large shares of surplus heat (but not fitting the demand profiles) it is reasonable to consider the opportunity of large-scale storages even several kilometres away from the network. Based on the assumptions used in the model, the surplus heat can be sourced a few tens of kilometres away from the network before the thermal energy price exceeds 50 €/MWh.

As described in section 5.2, it is assumed that the heating demand that cannot be fulfilled using the surplus heat and the storage is fulfilled by operating a gas boiler with a generation price of 50 €/MWh.

It should be noted here that in case the alternative to the surplus heat and storage is not a gas boiler, but another form of heat generation with different costs and CO_2 emissions (e.g. geothermal heat, oil boilers, electrical boilers, heat pumps etc.), the curves in all result figures will be shifted, based on the generation price and the CO_2 emissions associated with the given heat generation unit. In comparison, if the alternative to using surplus heat and storage is a heat source with lower marginal operation costs and lower CO_2 emissions per energy unit than the gas boiler (e.g. geothermal heat), the economic and environmental benefits of implementing surplus heat utilization will be smaller. Although the numerical values of the results will shift based on the alternative heat generation type in the system, it is nonetheless expected that the major trends and conclusions of the results shown here will remain the same.

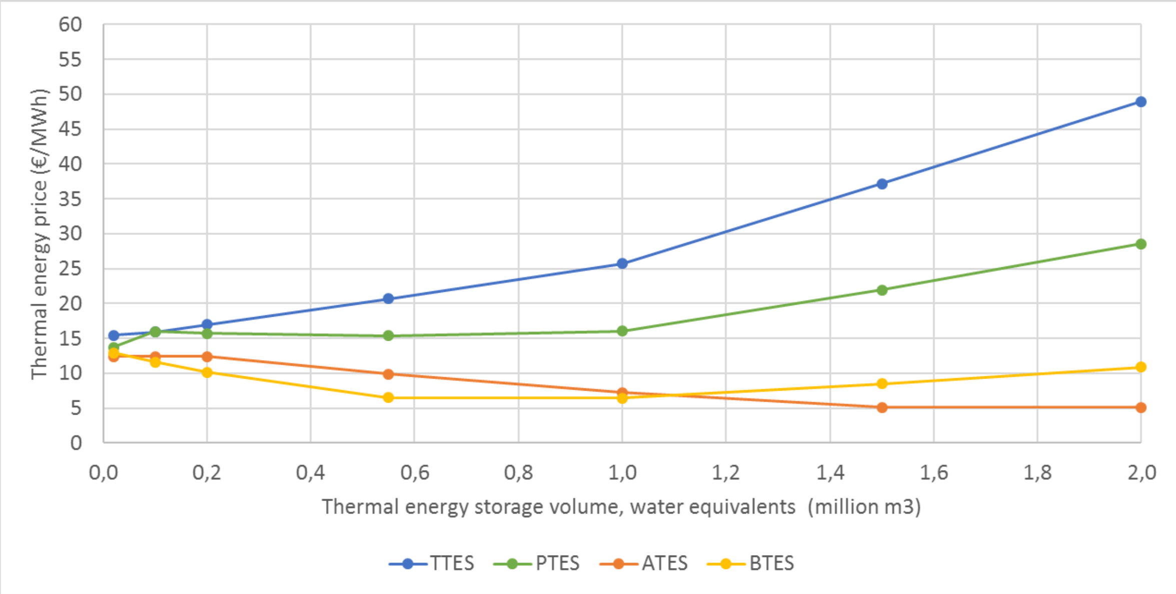


Figure 62 – The thermal energy price for all four thermal energy storage technologies, shown as a function of the storage volume. This is for the case of Rome, assuming no surplus heat transmission pipeline, a 100% surplus share and 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature.

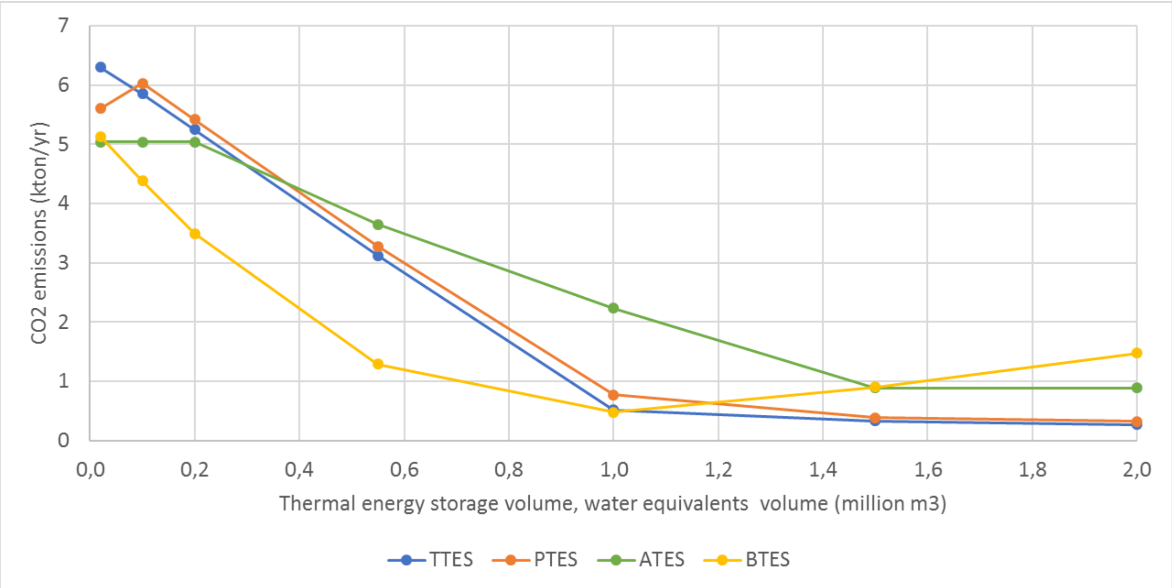


Figure 63 – The CO_2 emissions from external heating and cooling, for all four thermal energy storage technologies, shown as a function of the storage volume. This is for the case of Rome, assuming no surplus heat transmission pipeline, a 100% surplus share and 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature.

For BTES the CO_2 emission minimum indicates that at some point (volume) there is no need for further m^3 of storage. Increasing the storage volume beyond this point will only increase the modelled heat losses as the available heat is spread over a larger volume thus increasing the losses.

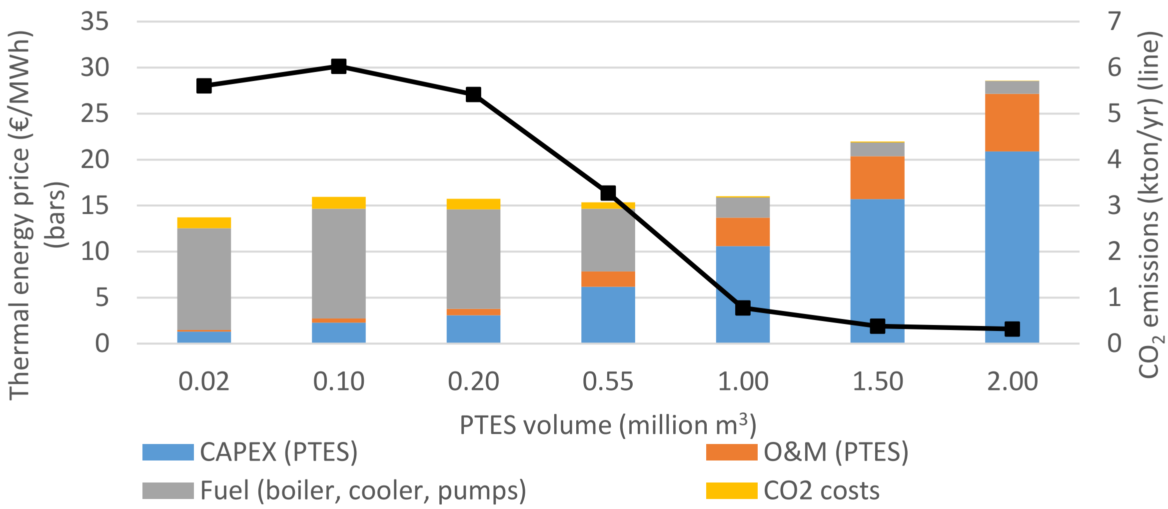


Figure 64 – The calculated thermal energy price composition (bars) and CO_2 emissions (line) for different PTES volumes. This is for the case of Rome, assuming no surplus heat transmission pipeline, a 100% surplus share and 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature.

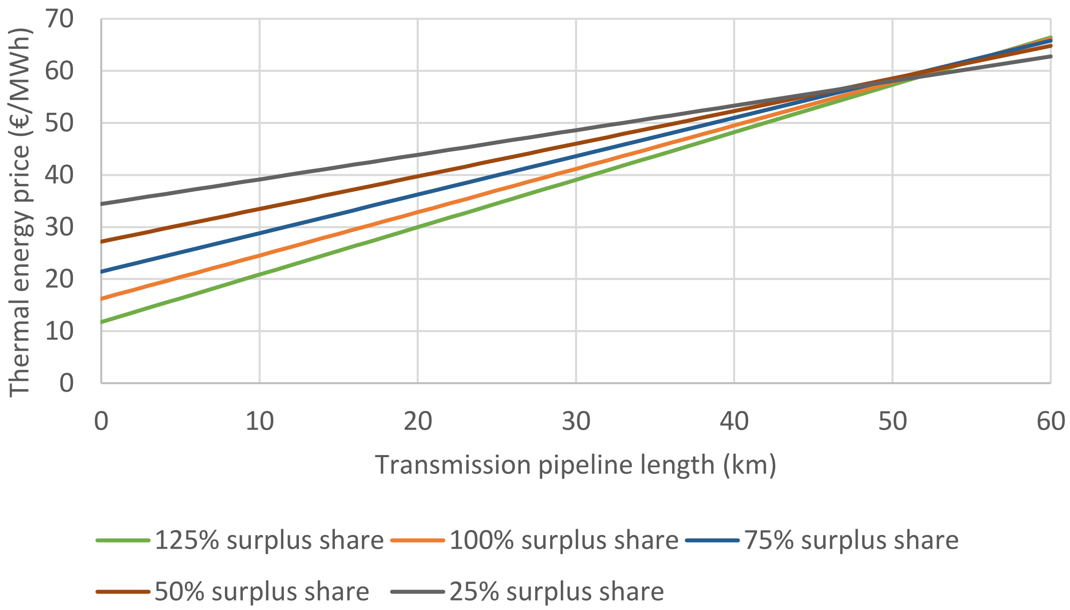
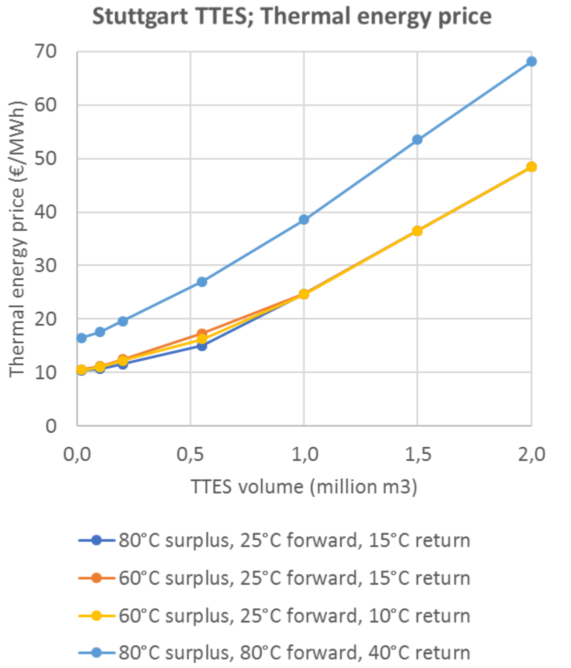


Figure 65 - Rome: Thermal energy price and transmission pipeline length. 100,000 m³ PTES volume, 60 °C surplus, 25 °C forward, 15 °C return. If the network heat price is 50 €/MWh, a transmission pipeline of up to around 40 km could be economically feasible in case of 100% or higher surplus heat share.

5.6.4 Reference case: Stuttgart

*The results for all four thermal energy storage types for the case of Stuttgart are shown in **Error! Reference source not found.**and **Error! Reference source not found.**, for a 100% surplus share and for the temperature levels that performed best* *in most of the scenarios: 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature. The full results for the case of Stuttgart can be seen in*



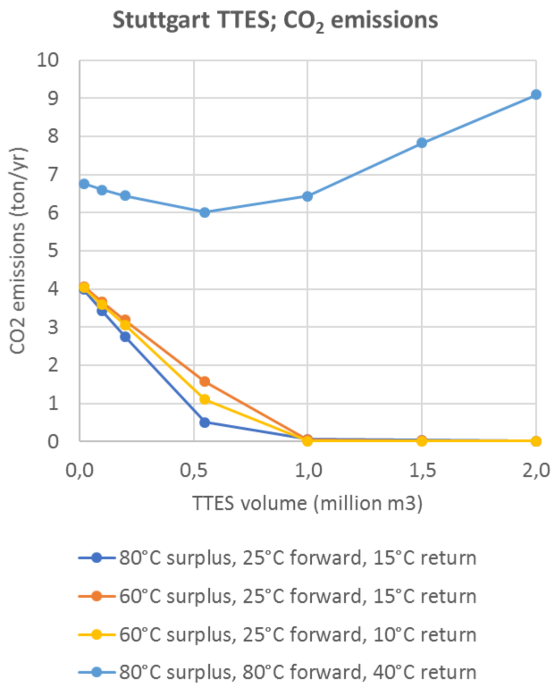


Figure 70to

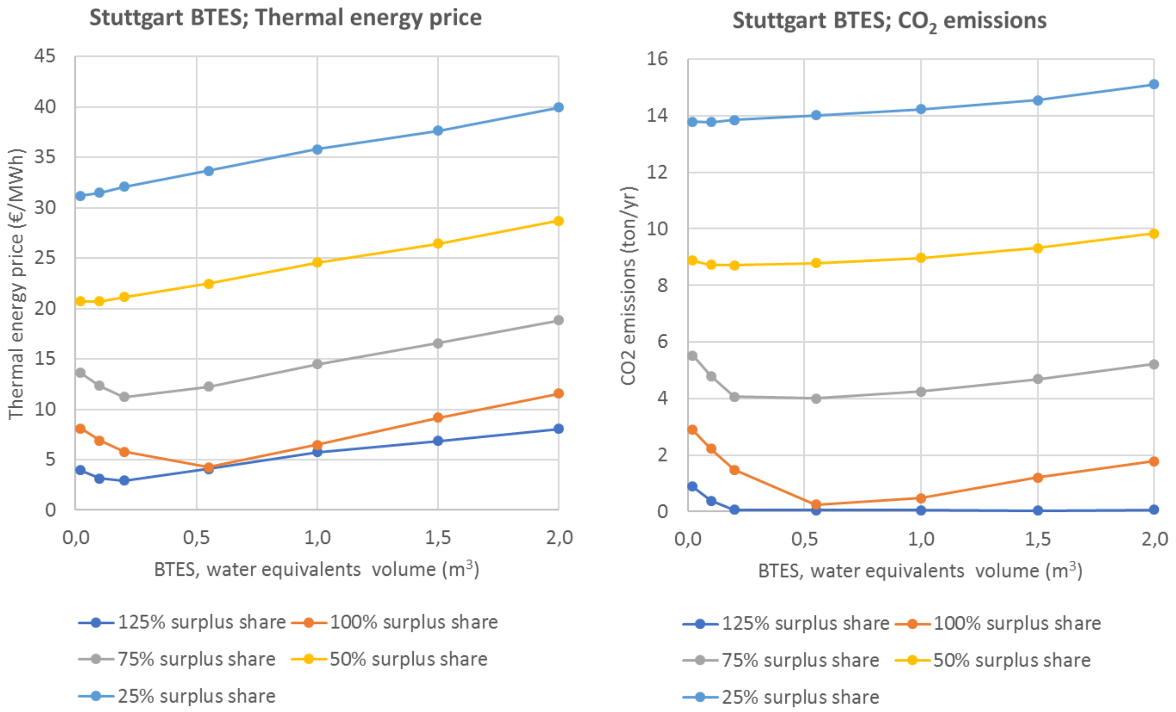


Figure 77in Appendix A.

The general trends and overall conclusions remain the same for the Stuttgart case as for the case of Rome and London. The numerical values in the Stuttgart case are generally in between the values in the case of Rome and in the case of London, and generally extremely close to those for the case of London. The lowest thermal energy price in the Stuttgart scenarios can be obtained for the scenario with 1 million m^3 (water eq.) ATES capacity, which gives a 50% reduction in the price compared to no storage. This leads to a CO_2 emissions reduction of approx. 90%. Even more CO_2 reductions can be obtained by investing in 1 million m^3 of PTES, or more than 95% lower CO_2 emission compared to a situation with no thermal energy storages. PTES is, however, more expensive than ATES and investing in 1 million m^3 PTES capacity leads to an increase in the thermal energy price by 5 €/MWh. The performance of BTES lies in between that of the ATES and PTES technologies, for BTES volumes up to 200,000 m^3 (water eq.).

The assumed annual cooling demand in the case of Stuttgart is 10 GWh/year, compared to 7.5 GWh/year for London and 25 GWh/year in the case of Rome. The annual heating demand is assumed to be 100 GWh/year in all cases. Similar to the case of London, the difference in cooling demand largely explains why the thermal energy price and the CO_2 emissions are generally lower for Stuttgart than for Rome and marginally higher for Stuttgart than for London. The reasoning behind this for the Stuttgart case is the same as explained for the case of London.

The only differences between model input values for the case of London and the case of Rome are in the time series for the ambient temperature, the heating demand and the cooling demand (described in Section 5.5) and in the size of the cooling demand (see Table 5.4). The assumed annual cooling demand in the case of London is 7.5 GWh/year, compared to 25 GWh/year in the case of Rome. The annual heating demand is assumed to be 100 GWh/year in both cases. The difference in the annual cooling demand largely explains why the thermal energy price and the CO_2 emissions are generally lower for the London case than for Rome. Providing cooling using the chiller (heat pump) is more expensive for the system than heating, because a large fraction of the heat can be obtained free of charge as surplus heat. A lower cooling demand therefore directly lowers the thermal energy price. The same is true for the CO_2 emissions. More CO_2 is emitted when providing cooling than heating, because the surplus heat utilization is not assumed to lead to increased CO_2 emissions in the system. A lower cooling demand therefore directly lowers the annual CO_2 emissions. In the case of London, most of the cooling demand can be supplied by the cold contents of thermal energy storages, if a 1 million m^3 or more ATES or PTES storage capacity is present. Therefore, the CO_2 emissions in these scenarios come very close to being eliminated in this case.

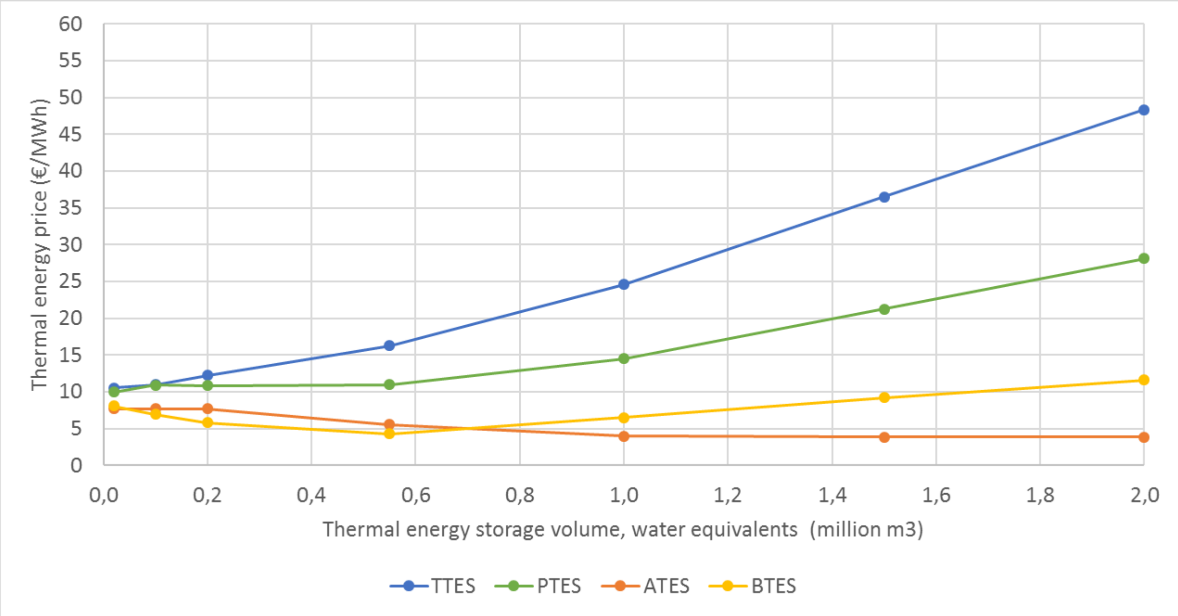


Figure 66 – The thermal energy price for all four thermal energy storage technologies, shown as a function of the storage volume. This is for the case of Stuttgart, assuming no surplus heat transmission pipeline, a 100% surplus share and 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature.

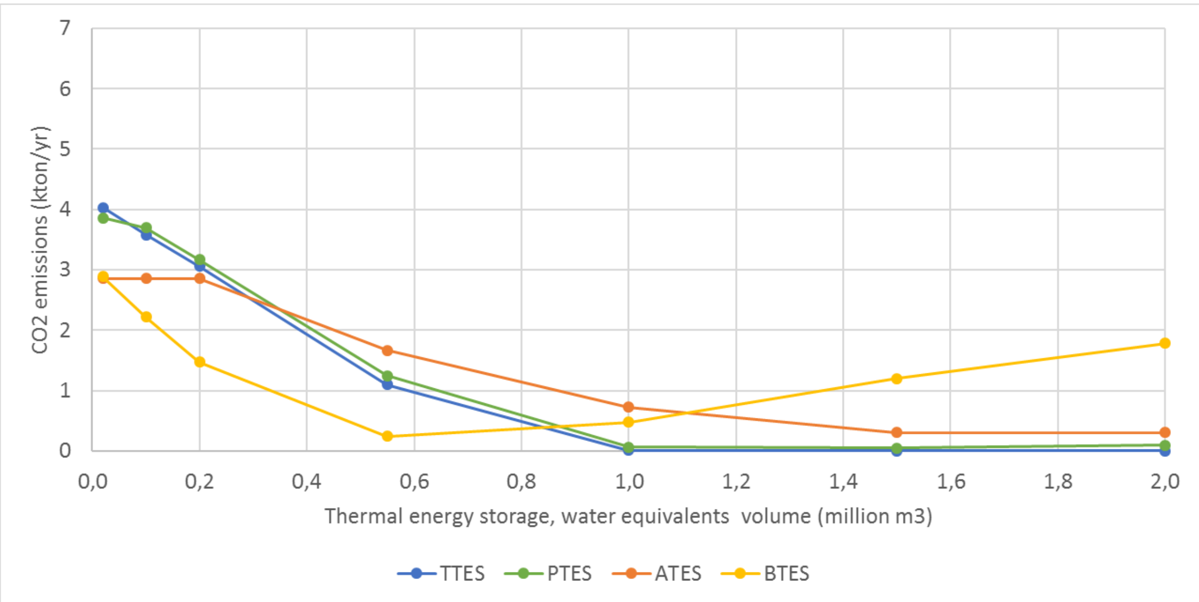


Figure 67 – The CO_2 emissions from external heating and cooling, for all four thermal energy storage technologies, shown as a function of the storage volume. This is for the case of Stuttgart, assuming no surplus heat transmission pipeline, a 100% surplus share and 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature.

5.6.5 Reference case: London

The results for all four TES types for the case of London are shown in **Error! Reference source not found.**and **Error! Reference source not found.**, for a 100% surplus share and for the temperature levels that performed best in most of the scenarios: 60 °C surplus heat temperature, 25 °C forward temperature and 10 °C return temperature. Due to the close similarities in load profiles and weather conditions between the case of London and Stuttgart, the results for the case of London are very similar to those of the case of Stuttgart. For this reason and for sake of conciseness, the results for London are not graphically reported in this deliverable, but we limit to comment and discuss them.

5.6.6 Costs and emissions related to substation operation

The thermal energy price and the CO_2 emissions shown in the diagrams in the previous sections referred only to the operation of the components which are part of the network, i.e. upstream the consumers' substations. Because the costs and emissions related to operation of the substations (heat exchangers for conventional DH and decentralized heat pumps for FLEXYNETS) were not included, the reader should look at each curve by itself to identify the effect that progressively larger storage size have on the cost and emissions of the system. In order for the curves to be fairly compared between one other, the cost and CO_2 emissions related to the consumers' substations should be added too. The additional costs and CO_2 emissions related to the operation of the consumers' substations depends on the yearly cooling load (as it depends on the geographic location), and on the network supply temperature of heating and cooling. These additional costs and CO_2 emissions are listed in the following table.

Table 6 - Additional cost and CO_2 emissions related electricity consumption of the substations in the different network configurations and locations.

Location	Heating load (on network side) [GWh]	Temp. heating forward [°C]	Cooling load (on network side) [GWh]	Temp. cooling forward [°C]	Cost for substation operation [€/MWh]	CO_2 emissions related to substations [kton/year]
Rome	100	25	25	15	14.2	6.5
Stuttgart	100	25	10	15	15.1	6.1
London	100	25	7.5	15	15.3	6.1
Rome	100	25	25	10	12.7	5.9
Stuttgart	100	25	10	10	14.5	5.9
London	100	25	7.5	10	14.8	5.9
Rome	100	80	25	15	1.4	0.6
Stuttgart	100	80	10	15	0.6	0.3
London	100	80	7.5	15	0.5	0.2

The following assumptions were used to obtain the values listed in the table above:

- In case of FLEXYNETS systems, the COP of the heat pump in heating mode was 4.5, which corresponds to the COP of a HP having a Carnot efficiency of 50%, when it operated between the network supply temperature of 25 °C and consumer's demand temperature of 45 °C.

- In case of FLEXYNETS systems, the EER of the heat pump in cooling mode was 6.9, which corresponds to the COP of a HP having a Carnot efficiency of 50%, when it operated between the network supply temperature of 15 °C and consumer's demand temperature of 10 °C.
- In case of a network cooling supply temperature of 10 °C, direct cooling is assumed, and neither cost nor emissions are associated to it.
- In case of conventional DH, the substations for heating purposes consist of a heat exchanger, so neither cost nor emissions are associated to it.
- For the electricity consumption, the same cost and CO_2 emissions factor was assumed as in the rest of the analysis (i.e. 50 €/MWh, 0.205 ton_{CO2}/MWh and 28 €/ton_{CO2}).

The cost for substation operation is obtained dividing the overall cost connected to the operation of the substations and the sum of the cooling and heating load on the network side. This definition resembles that of the thermal energy price which is shown in the diagrams in the previous sections. Therefore, the cost for substation operation can be directly added to the thermal energy price (in the same system configuration) to obtain the overall cost of the system per unit of energy (heating+cooling) exchanged by the network at the substations.

Similarly, the additional CO_2 emissions related to the substation operation can be directly added to the CO_2 emissions of the system upstream the substations, shown in the diagrams in the previous sections.

5.6.7 End user energy costs

If the thermal energy price of different systems configuration (FLEXYNETS and Conventional DH) is to be compared, the difference in definition of heating and cooling load should be considered.

In case of conventional DH, the heat load of 100 GWh corresponds to both the heat load on the network and the end-consumers' heat load.

In case of FLEXYNETS, the heat load of 100 GWh corresponds to the heat load on the network, i.e. on the evaporator side of the consumers' heat pumps. So, the end-user demand that the FLEXYNETS system covers is higher, because given by the sum of the 100 GWh load on the network side and the electricity input to the consumers' heat pumps. Assuming a COP of 4.5 (see above), the resulting end-user heat demand is 129 GWh.

In the systems having 15 °C as cooling supply temperature, a cooling demand of 25 GWh in Rome (10 GWh in Stuttgart and 7.5 GWh in London) corresponds to cooling demand seen from the network perspective, i.e. at the condenser of the consumers' heat pumps in cooling mode. The end-user cooling demand is actually lower, because given by the difference between the network cooling load and the electricity consumed by the consumers' heat pumps. Assuming an EER of 6.9 (see above), the end-user cooling demand was 21.8 GWh, 8.7 GWh and 6.6 GWh in Rome, Stuttgart and London, respectively.

In case of the FLEXYNETS system with a cooling supply temperature of 10 °C, direct cooling is assumed and therefore the stated cooling demands corresponds to both the cooling demand of the network and the end-user cooling demand.

Based on what described above, the price for unit of end-user energy was calculated as the ratio between the total cost of the system (network costs + substation costs) and the sum of the heating and cooling end-user demand.

Figure 68 shows the comparison in the resulting price for the end-user demand in the case of Rome between conventional DH and FLEXYNETS (surplus heat temperature of 60 °C, heating supply temperature of 25 °C and a cooling supply temperature of 10 °C) for the BTES volumes of 20,000 and 550,000 m³ (water equivalents). Figure 69 shows the same type of data but for the city of Stuttgart.

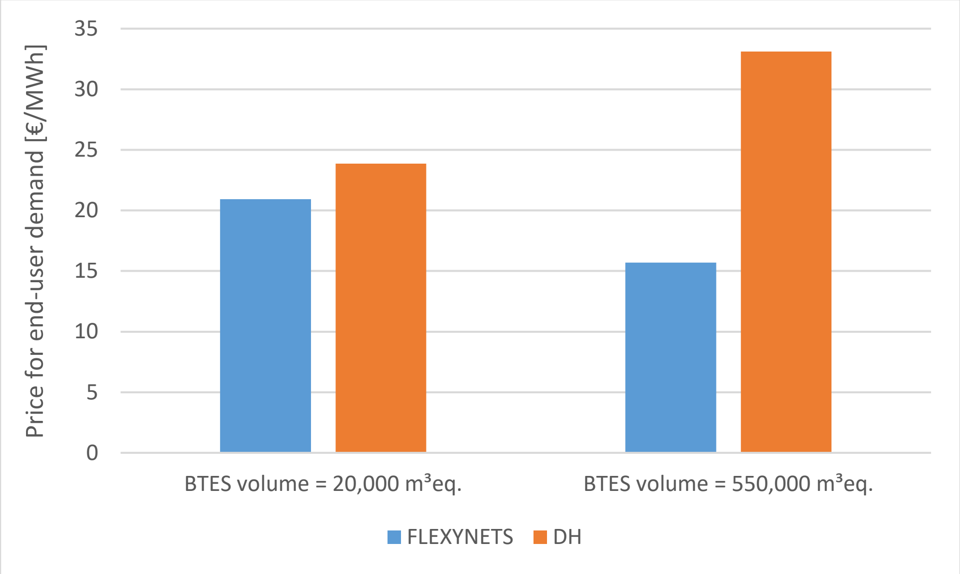


Figure 68: Comparison in thermal energy price for the end-user energy demand between a FLEXYNETS system and conventional DH in Rome, in case of a 100% surplus share, and a BTES with volume of 20,000 and 550,000 m³ of water equivalents, respectively. The FLEXYNETS case refers to a surplus heat temperature of 60 °C and a cooling supply temperature of 10 °C. No transmission pipeline is assumed.

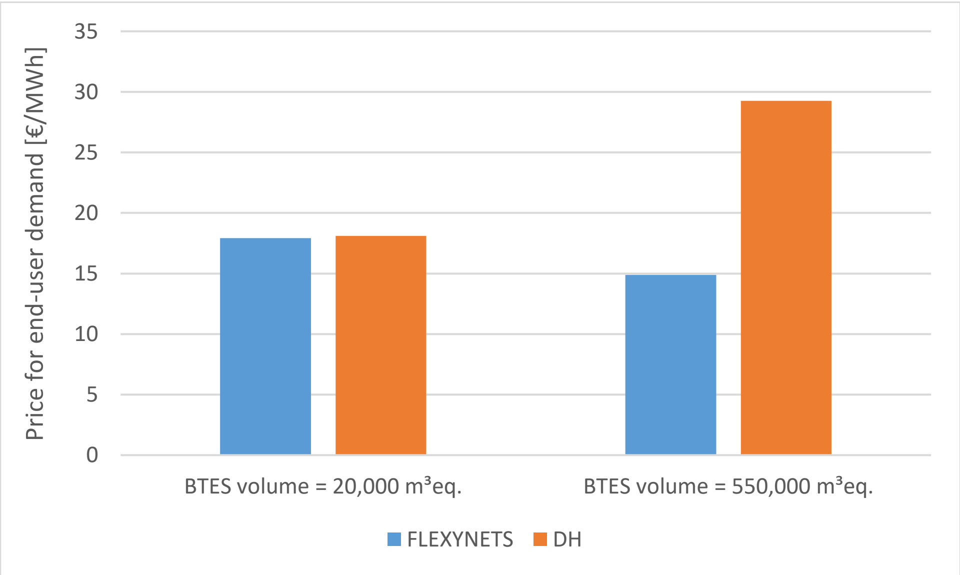


Figure 69: Comparison in thermal energy price for the end-user energy demand between a FLEXYNETS system and conventional DH in Stuttgart, in case of a 100% surplus share, and a BTES with volume of 20,000 and 550,000 m³ of water equivalents, respectively. The FLEXYNETS case refers to a surplus heat temperature of 60 °C and a cooling supply temperature of 10 °C. No transmission pipeline is assumed.

When the operation costs of the substations are considered, the difference in energy price between conventional DH and FLEXYNETS is reduced considerably, although in general FLEXYNETS remains competitive with respect to conventional DH. This is particularly true in the case of Rome. In this case the higher cooling demand and the lower temperature difference between heating and cooling pipes allow to recover more of the heat rejected by the cooling users and use it as a heat source for the heating consumers. The same synergy between cooling and heating demands is not achievable in case of conventional DH.

It can also be observed that a larger BTES decreases the energy price in case of FLEXYNETS, but it increases in case of conventional DH. A possible reason for this is that in the FLEXYNETS system there is no strong separation between hot and cold BTES, so that the cold BTES can contribute to store the large share of surplus heat. This is however not possible in case of conventional DH, due to high temperature difference between heating and cooling demands. Therefore, the cold BTES is used only to a minor extent, but its investment cost still weights on the overall economy of the system.

It should be however noted that the investment cost for the consumers' heat pumps was not considered into the calculations.

5.7 TRNSYS model discussion

The results indicate that PTES, ATES and BTES can all be suitable solutions for balancing thermal energy supply and demand on a seasonal basis in the system investigated here. The results for all three technologies show that investing in such thermal energy storage capacity can significantly lower the system's annual CO_2 emissions associated with heating and cooling (by up to around 95%). This shows that the utilization of large-scale thermal energy storages can be very relevant in the FLEXYNETS concept, in case a source of "high-temperature" surplus heat is available (i.e. higher than the network forward temperature, but similar to conventional DH temperatures).

The promising results obtained for the usage of ATES are backed up by the fact that there are already more than 1000 ATES in operation in systems where there is both a heating and a cooling demand. The principle of the ATES technology, which has separate heat and cold storages in the form of warm and cold wells with operating temperatures between approx. 8 °C and 20 °C, makes it very well suitable for integration with the FLEXYNETS concept due to the similar temperature levels. It should of course be mentioned that the actual suitability of ATES can be very case-specific, in that it relies on suitable geological conditions at the site in question.

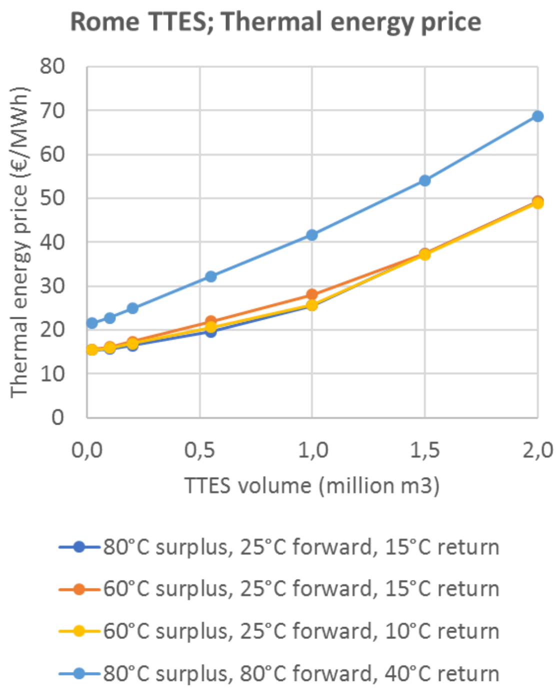
The PTES technology is already used at conventional DH temperatures in Denmark, with further PTES projects being planned in other countries. The results indicate PTES facilities with good stratification can be used for both heat (at the top) and cold storage (at the bottom) and that they can effectively reduce CO_2 emissions associated with both heating and cooling. The PTES cost is somewhat higher than the cost of ATES, based on the price assumptions used in this report. PTES could be a very relevant option in case ATES is not suitable, e.g. due to geology or the desired storage scale (as each ATES system is typically smaller than each PTES).

The BTES technology is also used already, mainly for heat storage. BTES is e.g. used in connection with a low-temperature district heating network in Drake Landing, Canada. The results indicate that it could be a relevant technology for heat and cold storage by operating separate warm and cold wells, similar to the ATES operating strategy. BTES could be relevant in areas where ATES is not suitable due to geological conditions.

The TTES technology was modelled as a seasonal storage for comparison with the other technologies. TTES is a mature and widely used technology, but is usually only considered viable for shorter term storage (daily to weekly storage). The results indicate the same, that TTES is too expensive to become relevant as a seasonal storage in the FLEXYNETS concept. TTES does, however, serve an important role as buffer storages in the case of ATES and BTES, absorbing daily to weekly fluctuations in thermal energy supply and demand that may be too fast for the relatively slowly responding underground storage technologies.

In the cases where both the key indicators (cost and CO_2 emissions) are lowered by introducing thermal storages, it is clear that the implementation of storages could help both in reaching the goal of the cheapest energy for the consumers and/or any targets regarding the reduction of CO_2 emissions. In case the two indicators show different trends (increased cost but reduced CO_2), the choice of whether or not to implement TES in the system (and to how large an extent) depends on which of the two indicators is more important to the policy makers; if lowering the thermal energy price has first priority or if reducing the CO_2 emissions is considered most important. Supplying energy at the lowest possible price may not be the foremost goal e.g. if national and international goals and treaties on CO_2 emissions reduction cannot be fulfilled at the same time. The right balance between the two indicators is therefore a question of policy, and for this reason the two indicators have not been weighted here and combined into a single scenario performance number.

The results show that the transmission and storage of surplus heat at higher temperatures (60-80 °C) generally leads to generally leads to lower thermal energy prices than the transmission and storage of surplus heat at the assumed forward the assumed forward temperature of FLEXYNETS (25 °C), when comparing identical quantities of thermal energy supply. It thermal energy supply. It should, however, be noted that in case very large amounts of surplus heat are available at low are available at low temperature (25 °C) but only smaller amounts are available at higher temperatures (60-80 °C), it can be (60-80 °C), it can be more beneficial to choose the low temperature surplus heat rather than the high temperature surplus



heat. This can be seen in the result graphs (e.g.

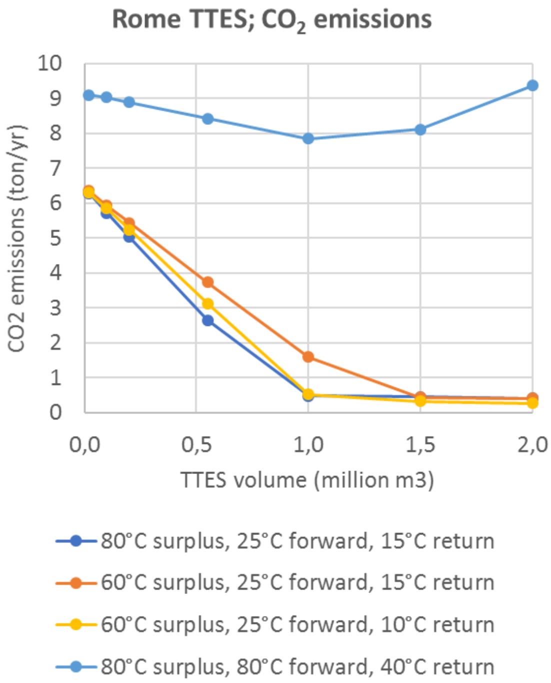


Figure 54 to

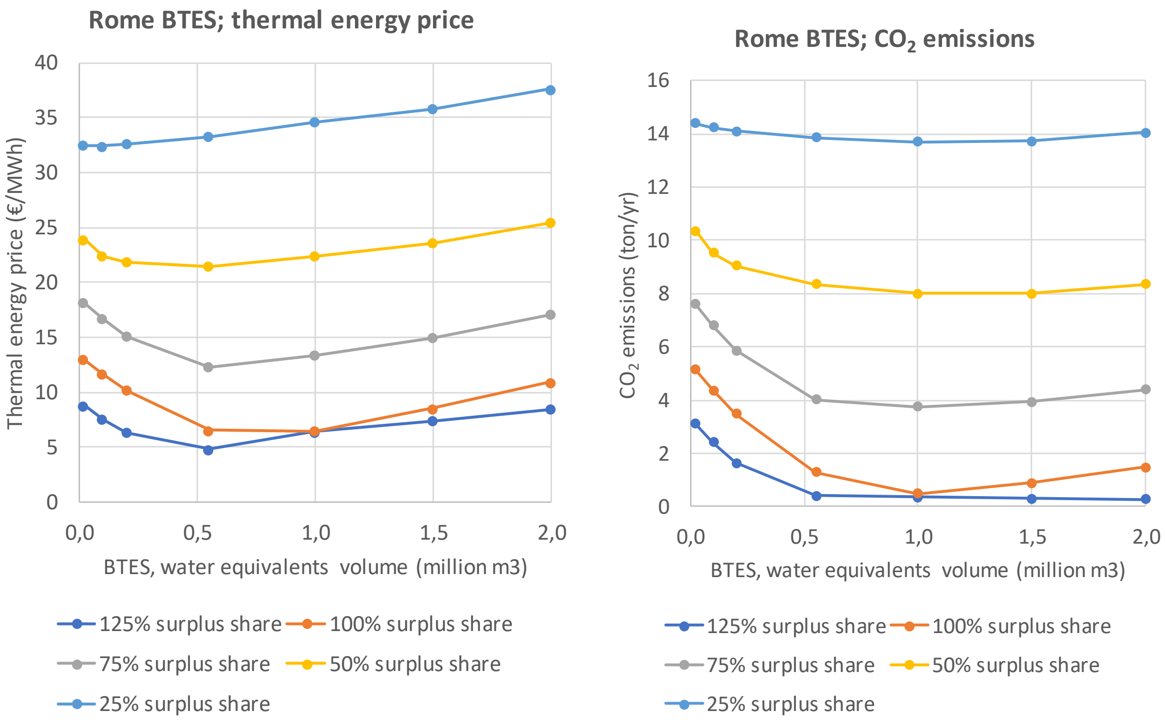


Figure 61) by noting that the transmission and storage of surplus heat at 25 °C and 100% surplus share generally leads to a lower thermal energy price and lower CO_2 emissions than the transmission and storage of surplus heat at 60 °C and 25% surplus heat. It is therefore very important to take both the temperature levels as well as the available quantities of surplus heat into account when considering which option of surplus heat utilization is most beneficial.

As already mentioned, the exact choice of TES technology is very case- and location-specific, as it depends on site-specific factors such as the geological suitability for ATES or BTES and the availability of land area for PTES. The results presented here are, furthermore, associated with considerable uncertainty. The investment costs for ATES and BTES are based on fits to data sets with only few points, due to lack of more data. The heating and cooling demand profiles for the three reference cities are based on calculated profiles, rather than statistics (due to lack of available statistics). The *TRNSYS* components used for modelling the thermal energy storages cannot model all physical aspects of the storages accurately for all cases, especially regarding the underground properties of ATES and BTES, since these are always site-specific. As mentioned in Section 5.1.2, the *TRNSYS* model layout is merely an approximation of the envisioned system, which is described in Section 5.1.1. Using *TRNSYS* and its specialized thermal energy storage components to simulate various scenarios is however expected to provide a reliable picture of the general trends and effects in the modelled system when the different thermal energy storage technologies are introduced.

The results indicate that a surplus heat transmission pipeline distance up to approx. 40 km (see Figure 65) can be viable in case the assumptions used in this model are valid, in case surplus heat can be obtained free of charge from the source and in case the thermal energy price without the surplus heat is 50 €/MWh. To compare this result with existing pipelines, it can be mentioned that a few insulated, high-temperature DH pipelines on this length scale already exist between geothermal heat sources and district heating networks in Iceland. In the context of the topic of this chapter, the geothermal sources may be thought of as cheap surplus heat sources. A 27 km long pipeline with a nominal diameter of 800 mm transmits up to 300 MW of heat to the Reykjavík city area (population approx. 200,000). The temperature drop in this highly-insulated pipeline is 0.4 – 2 K, depending on the load. A much narrower 34 km pipeline supplies DH to the town of Borgarnes (population approx. 2,000), with the temperature dropping by around 9 K on the way. A 64 km pipeline (possibly the longest district heating transmission pipeline in the world) supplies the town of Akranes (population approx. 7,000), with the temperature dropping by around 18 K on the way. Long DH transmission pipelines also exist in Sweden, where a 29 km long pipeline connects the DH networks of the cities of Helsingborg (population approx. 140,000) and Lund (population approx. 89,000).

6 Conclusions and guidelines

This conclusionary section is divided in two; first a more general summary and conclusion of the report and analysis and second, a section with more specific guidelines on chosen parameters such as temeparture ranges, economic parameters and spatial requirements.

6.1 Summary and conclusions

In this report, the potential role of large-scale thermal energy storages in the FLEXYNETS concept has been analyzed. The report focuses on four storage types; tank, pit, aquifer and borehole storage. Some general principles of thermal energy storages, such as time scales, temperatures, volume, storage medium and investment costs have been described and quantified in the context of FLEXYNETS. The physical and economic properties of the four storage types have been analyzed and presented. The analysis shows that regardless of the storage technology, the required storage volume and investment costs are highly dependent on the temperature difference in the storage though the economy of scale in general is favourable for these large-scale storages. As the FLEXYNETS concept works with very low temperature differences between forward and return temperatures (approx. 5-15 K difference), this would require any thermal energy storages that work at the FLEXYNETS network temperature to be large and expensive, compared to storages working at conventional DH temperatures. However, some storage types (e.g. ATES) cannot store heat at the temperature level of conventional DH, and the drawback of having somewhat lower supply temperature to the storage is therefore minimised.

Furthermore, transmission pipeline costs for the utilization of surplus heat, which is an important aspect of the FLEXYNETS concept, have been analyzed. The results suggest that sourcing surplus heat at even several kilometres away from the FLEXYNETS network may be economically feasible, as long as the surplus heat source is sufficiently large compared to the network heat demand. However, this highly depends on the actual cost of both the transmission line, the utilisation of the surplus heat and the alternative heat supply. In conclusion it is worth remembering that in some cases it may be worthwhile to investigate surplus heat options even “far away” from the actual network area.

Based on this, situations have been identified in which large-scale TES could be most relevant in the FLEXYNETS concept. In general, the most favourable solutions involve surplus heat available at temperatures higher than the FLEXYNETS network temperature. In that case this heat is directly transferred, via a transmission pipeline, to a thermal energy storage. The storage can then take advantage of the larger temperature difference between the surplus heat temperature and the FLEXYNETS cold pipe temperature, which lowers the required storage volume and investment compared to operating only at FLEXYNETS temperatures. However, if the amount of surplus heat is significantly higher at approx. the FLEXYNETS temperature level, it may be more beneficial to choose a connection to this low temperature heat source. Also in this case it may be feasible to include a storage even though the required volume will be significantly higher to store a certain quantity of energy. This point is especially relevant for ATES which cannot in any case store heat at high temperature and has a low marginal specific investment cost. In that case the savings in the alternative heat supply may outweigh the added cost of an increased storage volume requirement.

The storages can balance fluctuations in surplus heat supply and network heating and cooling demands, thereby facilitating more efficient usage of the incoming surplus heat and reducing the auxiliary energy supply (and any associated CO_2 emissions) needed for satisfying the heating and cooling demand in the network.

This system has been modelled in the simulation software *TRNSYS*. The simulations have been carried out for all four TES types and for different reference cities; Rome, London and Stuttgart. The simulations have furthermore been performed for different operating temperatures and for different amounts of surplus heat availability. The results of the simulations have been evaluated based on two indicators; the average thermal energy generation cost in the system (in €/MWh) and the annual CO_2 emissions arising from satisfying the heating and cooling demand in the system (in kton/year).

The results of the simulations show that especially ATES but also PTES and BTES can be very relevant as seasonal storage in the FLEXYNETS concept, in case surplus heat is available to the system. Investing in such thermal energy storages can significantly lower the system's annual CO_2 emissions associated with heating and cooling (by up to around 95% in investigated scenarios), and either lower the thermal energy price (in investigated scenarios up to 50%) in the system or at least keeping it at a similar level compared to a system without the storage. These storages' properties will be an important part of the decision process for any given case. As described in this report, they all have different benefits and drawbacks depending on the system they are a part of. The conclusion is therefore that although large-scale TES are not always relevant for the FLEXYNETS concept, they can be very beneficial to the system in certain cases, in particular if the network in question has a certain size and if surplus heat is available in large quantities. Centralized storage options are therefore worth to be considered when evaluating specific cases in more detail.

6.2 Guidelines

As concluded, large scale TES can be relevant to consider in low-temperature network design, such as the FLEXYNETS concept. This section serves to provide focus on some parameters to consider and guidelines for these, depending on the specific project type. The FLEXYNETS Guide Book contains more detailed guidelines on the entire concept of FLEXYNETS.

6.2.1 Temparature ranges

In general, the volume required for storing an energy content is depending on the temperature temperature difference, see Equation 1 to 3. In short terms – the higher the temperature difference, the smaller volume is required to store the same amount of energy.

Calculations showed that, very large volumes are required to store large amounts of heat with a small difference between the maximum and minimum storage temperature and that, the difference in the required absolute volume can be very large when storing large amounts of heat different ΔT values.

The benefit of an increased ΔT becomes less pronounced at higher values (e.g. changing from 40 K to 50 K) compared to the lower examples (e.g. changing from 10 K to 20 K). In other words, at the low operating temperatures of FLEXYNETS, a slight increase in ΔT can have a big impact when it comes to storages.

Another point in regards to temperature ranges is that smaller storage volumes (at higher ΔT) impacts the required volume and hence the required spatial requirements. But also the temperature loss can be reducered at higher ΔT; this is for instance seen in the case of PTES, where the lid area can be limited at higher ΔT and thus limiting the heat loss through the lid.

Reducing the volume also directly influences the economic costs of the storage. More about economic parameters are summed in the following section.

6.2.2 Economic parameters

As shown in Equation 4 and 5, the economic parametersof a storage depends on the energy capacity and the ΔT. But also other parameters such as density and specific heat capacity of the storage medium, and type of storage.

An analyses of economic of scale of each type of TES was performed. The results for TTES and PTES showed that there was a clear tendency between investment costs and volume; the specific costs per unit volume was significantly lower at larger storages than for smaller storages – infact the curves can be said to be inversely proportional. It can therefore be concluded that there is a clear economic benefit of scale, when it comes to TTES and PTES.

The economic parameters for BTES is not as well defined as for TTES and PTES. This can partly be explained by the fact that it is often assumed that 3 m^3 of soil volume BTES are equivalent to 1 m^3 of water storage volume because the soil has a lower specific heat capacity than water, but in practice the conversion will depend on the local conditions. The investments costs are also very depended on the depth of the boreholes. In four shown examples, the investment costs was approximately 40 €/m^3 water equivalent. More examples are necessary to provide a more detailed picture. A study of the Ministry of the Environment, Climate Protection and the Energy Sector BadenWürttemberg from 2011 showed a linear correlation between investments and ground heat exchanger length with a slope of 58 Euros per m. Another study on specific cost, reported for Austria in (Biermayr, 2013), for boreholes under 150 m deep showed numbers around 40 to 50 €/m by using hydraulics drilling technic. This price does not include taxes nor equipment such as pipes.

For ATES, the trend diviates from the three other TES types. For ATES it was found that the investments costs almost remains constant for different storage capacities. Although, there is seen a dependency on the geological conditions at each specific site, in particular depending on the water yield from each well and the ΔT. It was therefore concluded that, the economics of scale for ATES systems are not particularly attractive, because ATES systems are modular in nature, with each borehole pair yielding similar power and storage capacity. A doubling of power therefore requires a doubling of the number of wells.

In a project the economics of scale of the TES should be considered, but the type of TES should also be considered and chosen to fit the circumstances – for instance – it will be much more expensive to ude a very large TTES as seasonal storage, compared to use a PTES. Also spatial requirements and soil conditions should of curse be considered.

6.2.3 Balancing sources and demands

The TRNSYS model was used to investigate wether a large scale TES could be beneficial in a concept such as FLEXYNETS and under which conditions. Three different locations were investigated with all four types of TES; London, Stuttgart and Rome.

It was specifically analysed how the TES could help balance the presence of excess heat to the demand. In general it should be remembered, that the exact choice of TES technology is very case- and location-specific, as it depends on site-specific factors such as the geological suitability for ATES or BTES and the availability of land area for PTES. The results indicate that PTES, ATES and BTES can all be suitable solutions for balancing thermal energy supply and demand on a seasonal basis in the analysed systems. The results for these three technologies show that investing in such TES capacity can significantly lower the system's annual CO_2 emissions associated with heating and cooling (by up to 95 %). The use of TTES in the system showed a significantly increase in investments costs – hence TTES should mainly be used to balance shorter or smaller fluctuations – and not seasonal balance in a large system as analysed in these cases.

More specifically, promising results were obtained for ATES. This is due to the principle of the ATES technology, which has separate heat and cold storages in the form of warm and cold wells with operating temperatures between approx. 8 °C and 20 °C. The FLEXYNETS concept has similar temperature levels, which makes the ATES well suitable for integration in the FLEXYNETS concept. It should of course be mentioned that the actual suitability of ATES can be very case-specific, since the technology relies on suitable geological conditions at the site in question.

The results further indicate PTES facilities with good stratification can be used for both heat (at the top) and cold storage (at the bottom). Based on the price assumptions in this analysis, the PTES cost is somewhat higher than the cost of ATES. PTES could be a relevant option in case ATES is not suitable, e.g. due to geology or the desired storage scale (as each ATES system is typically smaller than each PTES).

BTES is typically used for heat storing purposes and are seen used in connection with a low-temperature DH. The results indicate that it could be a relevant technology for heat and cold storage by operating separate warm and cold wells, similar to the ATES operating strategy. BTES could be very relevant in areas where ATES is not suitable due to geological conditions.

6.2.4 Spatial requirements

As describes several times in this report, the choice of TES technology depends on the application and the conditions of which a DHC system is designed. A short overview of the spatial requirement in m^2 per MWh storage capacity is shown in Figure 28 in section 3.7.

The absolute lowest spatial requirements above ground level is the ATES technology, where the main volume requirement is below ground level and only the area for the wells is above ground.

Small TTES takes up the most area per MWh, but does not in itselv take up much area, since the TES technology is limited to a large cylinder tank, often placed next to other DHC facilities. However, large TTES (>20,000 m^3) does not take up more area per MWh than BTES if you include the area needed for the boreholes.

PTES takes up most area, when comparing what is considered as seasonal TES technologies (PTES, BTES and ATES). The technology may have high spatial requirements, but have other benefits, such as a large charge and discharge capacity.

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8 Appendix A: TRNSYS results for Stuttgart

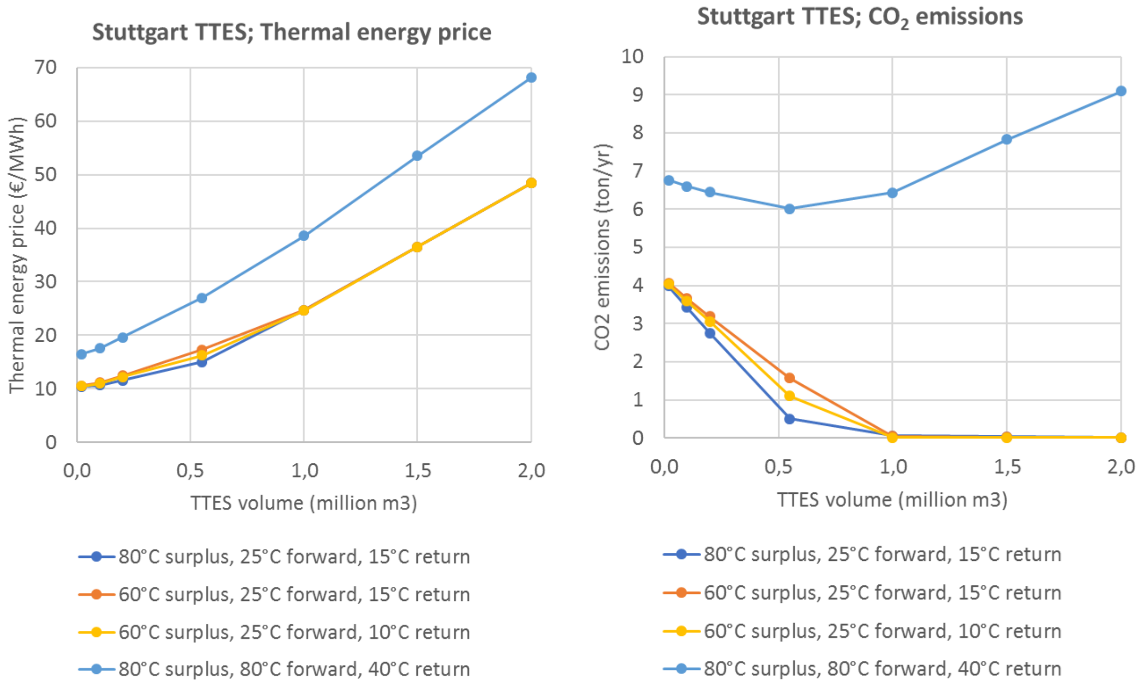

Figure 70 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%.

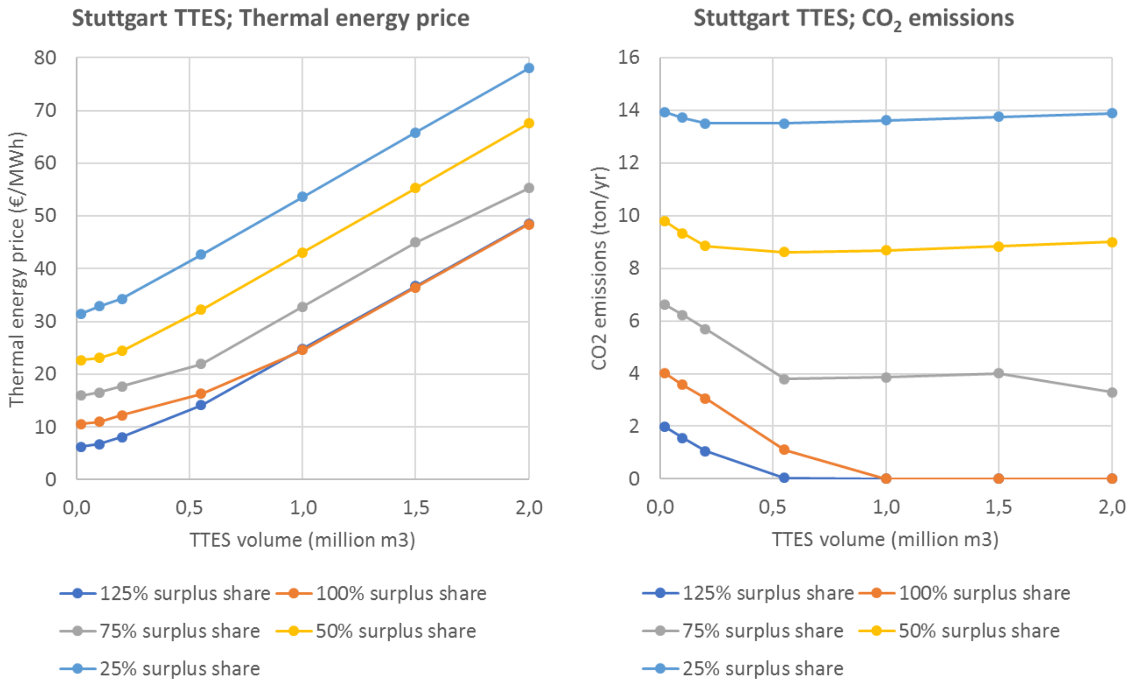

Figure 71 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

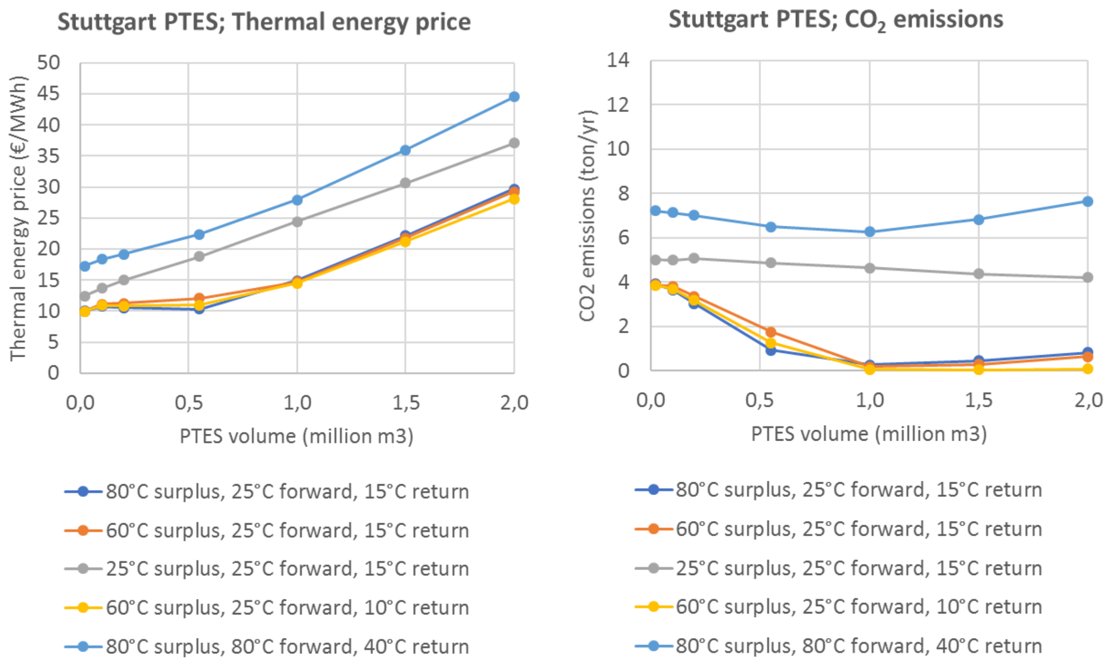

Figure 72 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%. For the largest storage volumes, the blue, orange and yellow curves are almost identical.

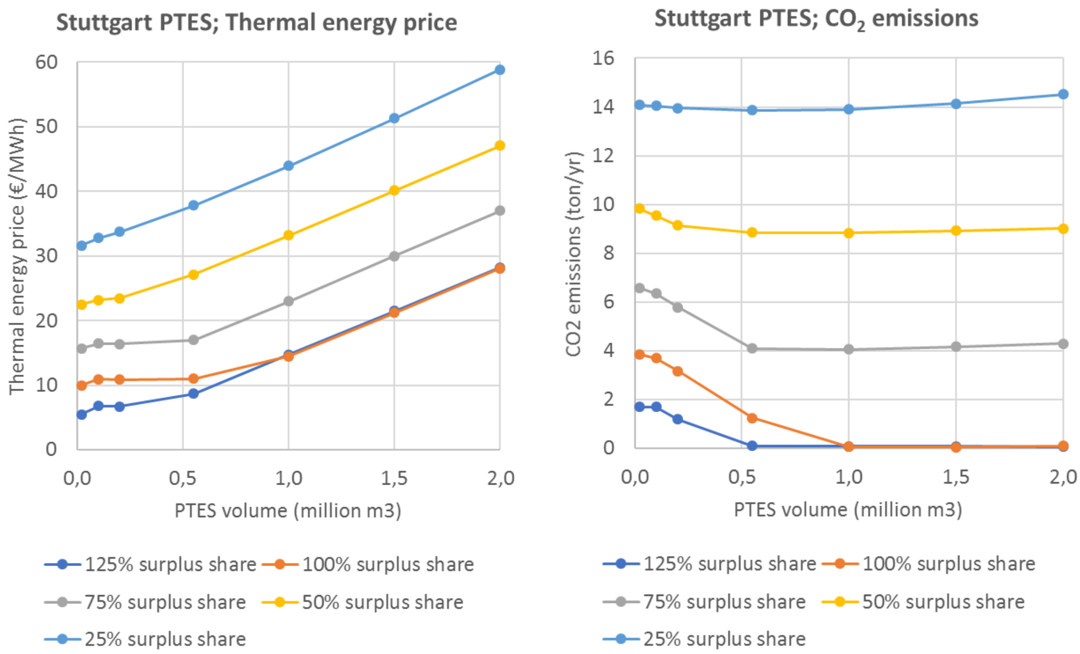

Figure 73 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

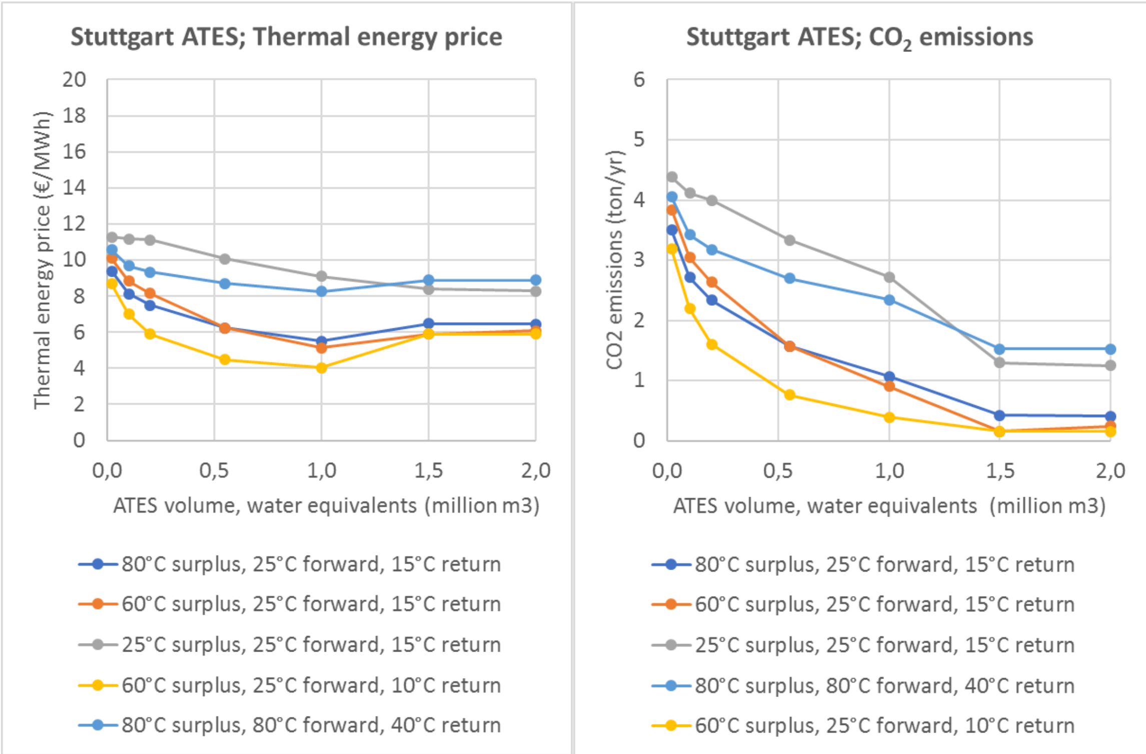

Figure 74 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%.

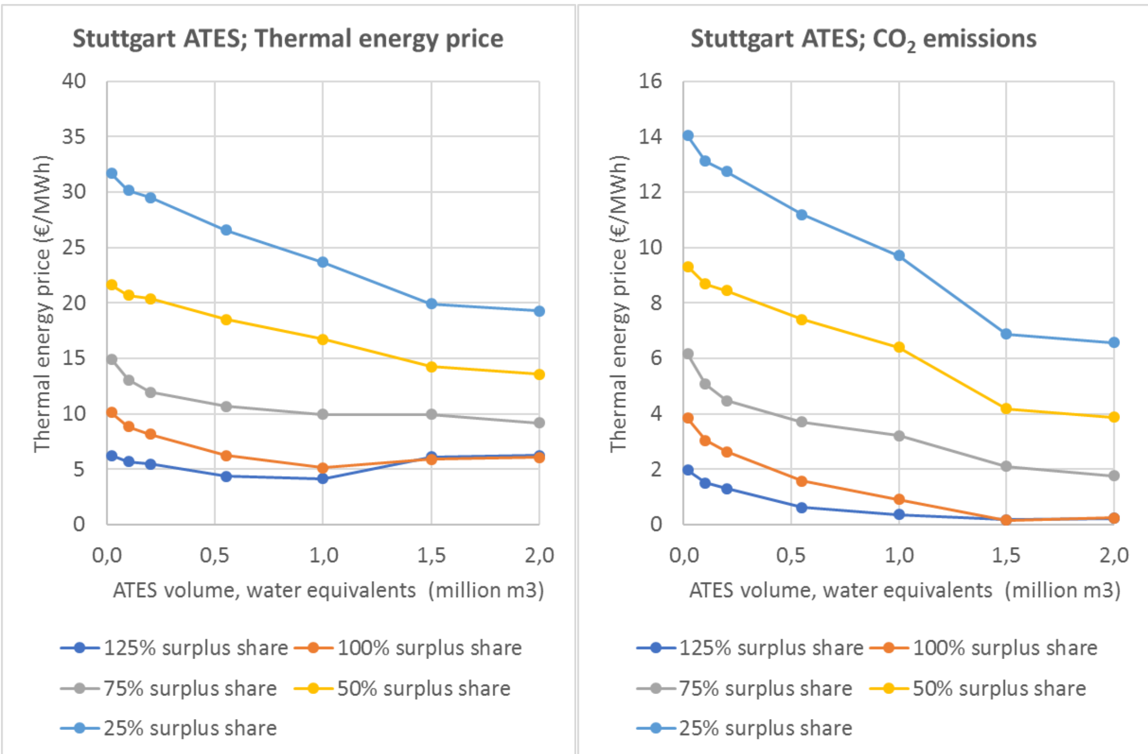

Figure 75 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

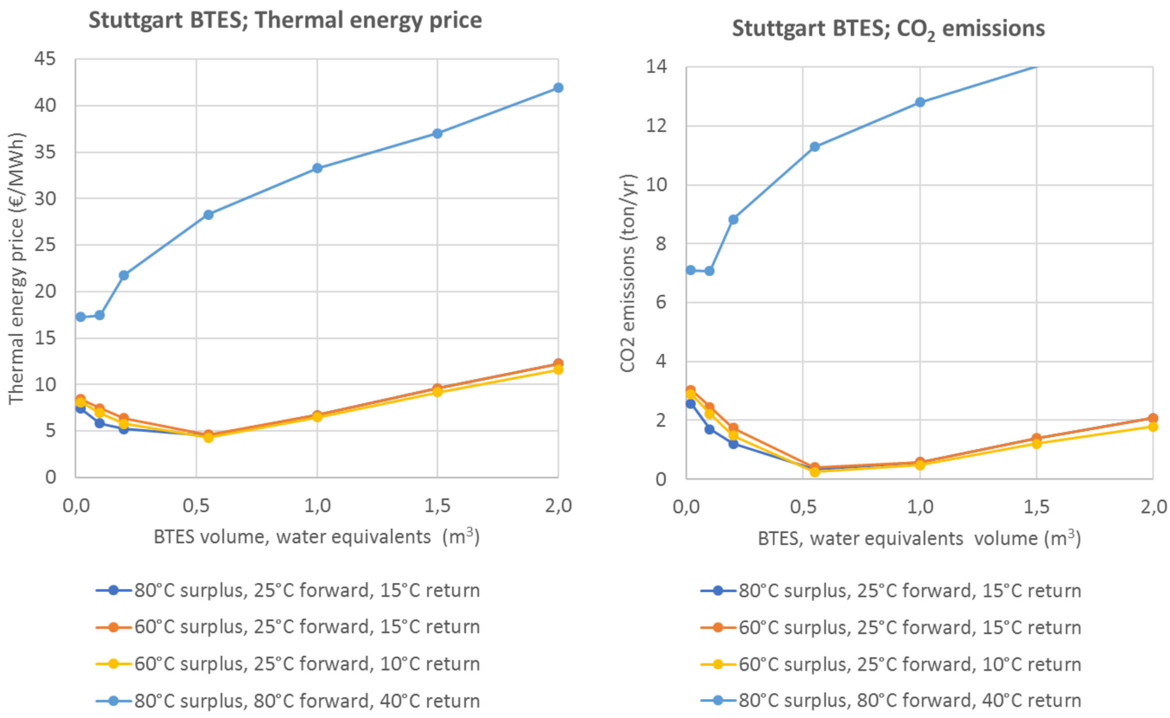

Figure 76 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no surplus heat transmission pipeline is assumed, and the surplus share is assumed to be 100%. For the largest storage volumes, the blue, orange and yellow curves are almost identical.

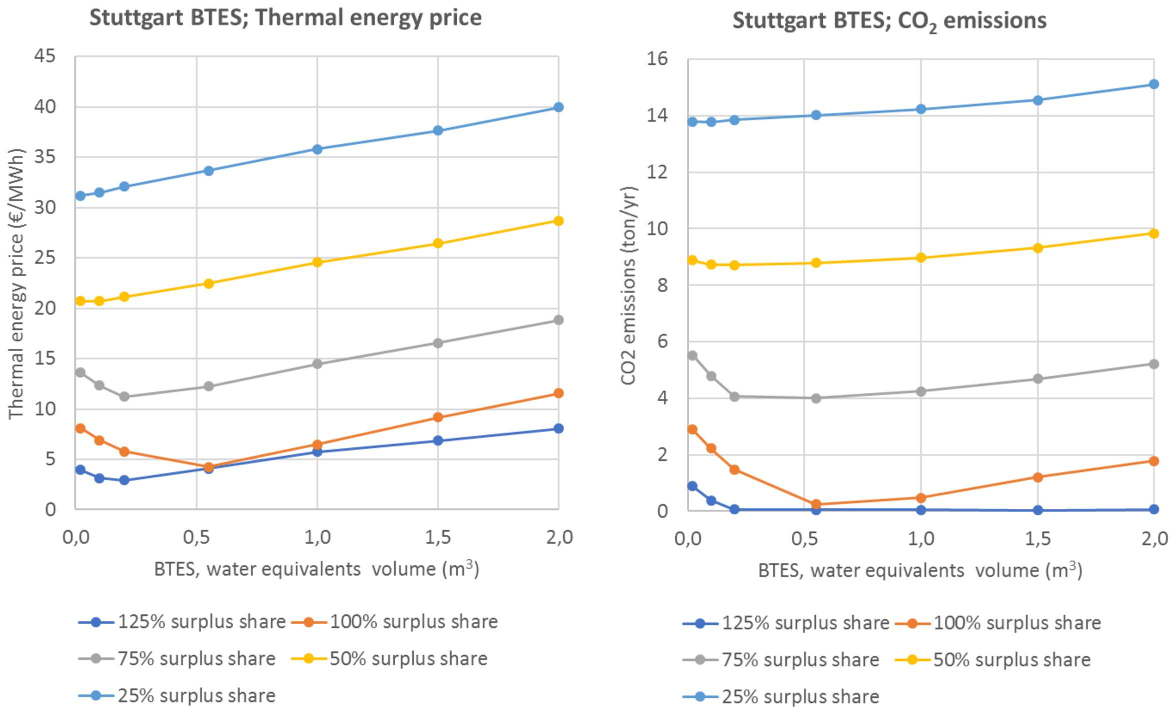

Figure 77 – Left: Thermal energy price. Right: CO_2 emissions. In these calculations, no heat transmission pipeline is assumed. The system is assumed to have a surplus heat temperature of 60 °C, a forward temperature of 25 °C and return temperature of 10 °C.

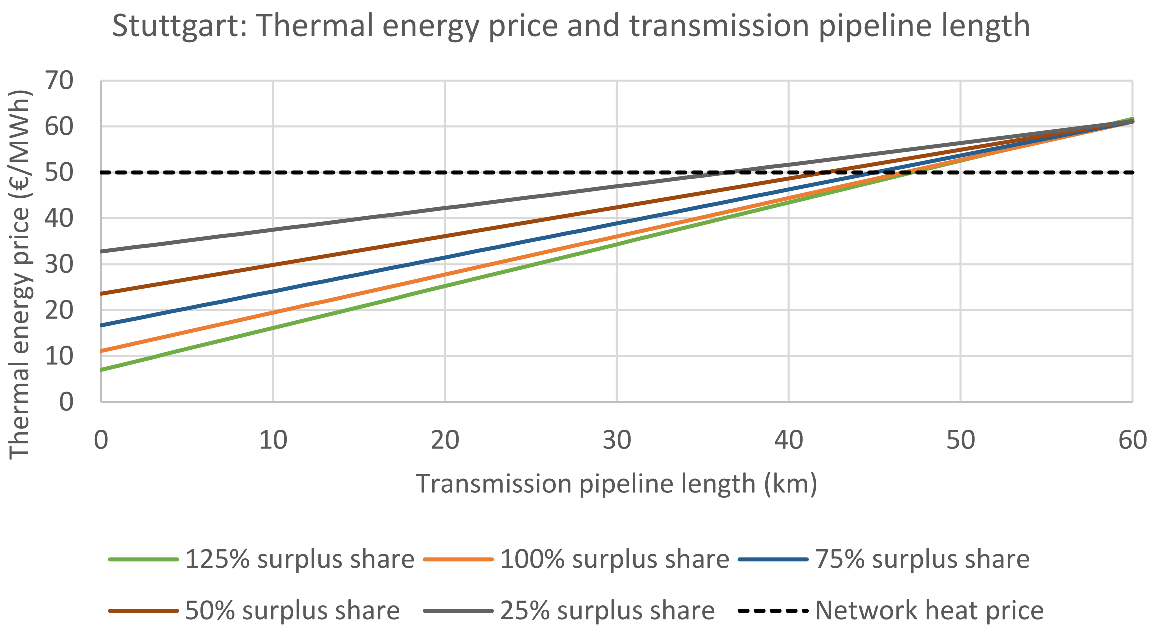

Figure 78 - 100,000 m³ PTES volume, 60 °C surplus, 25 °C forward, 15 °C return. If the network heat price is 50 €/MWh, a transmission pipeline of up to 40 km could be economical in case of 100% or higher surplus heat share.