EINSTEIN

D5.5: DESIGN GUIDELINES FOR STES SYSTEM FOR ALL EUROPE

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SUMMARY

The aim of this report is to provide useful information and general guidelines that may be useful for a preliminary assessment of a new STES system. When planning a STES system, a diversity of influencing boundary conditions should be properly considered, which should be assessed in a holistic approach. The report focuses on STES systems with solar thermal energy and heat pump. When talking about seasonal storage, three different types have been considered: TTES, PTES and BTES.

In chapter 1, the main influencing boundary conditions when planning the integration of a STES system have been explained. The key issues related to the building stock characteristics and the district in which the STES will be integrated are listed and described, together with the assessment of climatic boundary conditions that highly influence the design of a STES system. More specifically, the key issues related to the integration of main subsystems of a STES system (solar collectors, storage, heat pump and other auxiliary equipment) are as well described.

In chapter 2 recommendations for subsystems integration have been summarized. A large amount of variables and of high diversity are involved when planning a STES system, which make difficult to report all the issues in detail. The objective of this chapter has been to give an overview of the most important ones and to give recommendations and indicative values for an appropriate subsystems integration than can be useful for a preliminary system completion. The key issues have been therefore listed and explained, providing recommended values when possible.

Chapter 3 provides information to help designers or any interested body that is not expert on STES systems in the sizing process of a STES system. The key issues on STES systems sizing have been identified and explained, and they have been complemented with guidelines and indicative values that can help making an idea on the expected size of the STES system.

LIST OF ABBREVIATIONS

ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
COP	Coefficient of Performance
DH	District Heating
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
FPC	Flat plate collector
GWTES	Gravel-water Thermal Energy Storage
HDD	Heating Degree Days
HP	Heat pump
HTES	Hot water Thermal Energy Storage
HX	Heat exchanger
IEA	International Energy Agency
PTES	Pit Thermal Energy Storage
SC	Solar Collector
SF	Solar Fraction
STES	Seasonal Thermal Energy Storage
TTES	Tank Thermal Energy Storage
VTC	Vacuum tube collector

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1. PRELIMINARY ASSESSMENT FOR SOLAR THERMAL SYSTEMS WITH SEASONAL THERMAL ENERGY STORAGE

Planning the integration of a solar thermal system with seasonal thermal energy storage (STES) requires a sophisticated knowledge of the location in which it will be integrated. Therefore a diversity of influencing boundary conditions needs to be determined and be assessed in a holistic approach. In this chapter all relevant technical issues will be highlighted that need to be considered for a STES system integration.

1.1. SCOPE OF ASSESSMENT

Planning the integration and construction of a STES system is a process consisting of numerous steps until the system is in operation and optimised. The scope of this assessment is for the first predesign of the concept. It will guide possible planners to make a decision if the integration of a STES system is possible at a certain location and what kind of technical challenges have to be solved. Together with the data based on comprehensive system simulations presented in this report it is possible to make a first rough dimensioning of the STES system.

1.2. BUILDING STOCK

Within the EINSTEIN project the integration of STES systems are meant for space heating and domestic hot water (DHW) preparation of buildings. Consequently, the buildings and their technical properties are some of the most important factors that affect the design of a STES system. The building stock has thus a major influence on the design and dimension of the STES system. The size and type of buildings – existing buildings or new buildings – has to be assessed as well as their location, building density and purpose of use (residential or non-residential). All this among others factors influence the total heating demand, the load profile, the operating temperature levels, the possibility of integrating the STES system components and the connection to the (district) heating net. In the following subsections the different issues will be discussed.

1.2.1. Size of potential district heating network

Within the term "size of the potential district heating network" mainly two different single aspects are combined. In this case it is the actual piping length of the district heating network as well as the heating demand of the buildings that needs to be covered by the STES system. Both together define the total heating demand consisting of the heating demand for the buildings and the heat losses by the district heating network. In general the heating demand of the buildings and the heat losses of the district heating network should be as low as possible. Consequently a higher amount of dwellings can be connected by same system size respectively the STES system can be dimensioned smaller and thus more cost-effective.

Hahne [1] describes that STES systems should cover a district heating network with a minimum heating demand of 1500 MWh/a. This equals to about 100 to 150 dwellings. Beginning from this size a STES system will start to operate energy efficient. If the heating demand is lower than 1500 MWh/a the system components especially the STES is smaller in volume. Thus the surface-to-volume ratio increases and hence the heat exchanging surface compared to the storage capacity. As a consequence the STES cools out faster by heat losses and less solar thermal energy can be used in periods of times with high heating demand. Nevertheless, smaller systems can be designed which will also operate efficient in an energetic perspective. In this case a highly sophisticated thermal insulation of the STES needs to be selected and installed such as vacuum insulation and additionally heat pumps need to be integrated into the system in order to make more thermal energy usable stored in the STES and thus increasing the usable storage capacity of the STES. It must be kept in mind that the higher technical requirements for smaller scale systems might lead to higher specific investment cost than for larger systems (Figure 31). This can increase the heating costs.

The heat losses of the district heating network depend on several factors. Those are the length of the district heating network, operating temperatures and thermal insulation of the piping. The shorter the piping of the district heating network is the lower are the heat losses compared to a longer piping network with same operational and technical properties. Consequently, the supply temperature can be decreased, which is energetically in favour for the entire system. Thus, a highly dense building environment with high connecting capacities is in favour for district heating networks. This is the case in urban areas consisting of apartment houses. The operating temperatures of the district heating network with regard to the ambience temperature are further factors that influence the heat losses. The lower the temperature difference to the ambience is the lower are the heat losses. This is usually the case if low supply and return temperatures can be realized. This requires exclusively consumers which have a low temperature distribution system such as under floor heating and accurate hydraulic balancing of their heat transferring substations. Low district heating network temperatures are of high importance as they limit the direct use of thermal energy from the STES. Last factor is the thermal insulation of the district piping. The more efficient the thermal insulation is the lower are the heat losses. Here the cost and benefits need to be analysed.

1.2.2. **Heating demand**

As indicated above determining the total heating demand is of major importance to design the STES system. Main factor is the total heating demand but also the operating temperatures of the district heating network need to be considered as well as the share of heating demand for space heating and DHW preparation. By determining the total heating demand already the capacity of the solar thermal collectors and of the STES can roughly be estimated. Depending on the share of both heating demands and their operational temperature it can be assessed if a 2 or 4-pipe district heating system is in favour for an energetic optimized system. The difference between a 2 and 4-pipe district heating system is that in a 4 pipe system the supply for DHW is separated from the heating supply whereas in a 2-pipe system both are combined.

1.2.3. **Load profile**

Beside the total heating demand the load profile of the heating demand is of high importance. The heating demand needs to be determined in as fine as possible time steps, e. g. hourly or less, for at least one year of operation in order to get a fine time-discrete load profile. If the STES system is intended to be implemented into existing buildings gathering concrete monitoring data of the heating demand is highly recommended. The actual heating demand and load profile can significantly differ from standard calculations e. g. on basis of DIN EN 12831 [2] because the individual consumer behaviour varies often and the building and integrated systems might differ from planning stages from a technical perspective. Again a separate load profile for space heating and DHW preparation enables the chance to design the STES system more efficient.

The load profile has a large influence on design and dimension of the solar thermal related components depending on its annual characteristics. If there is a more uniform heating demand during the entire year in summertime more solar thermal energy can be used directly in this time and less thermal energy needs to be stored for a long period of time. Consequently the solar thermal collector and storage capacity can be dimensioned smaller than having a load profile with a high heating demand isolated only in wintertime when the solar thermal energy needs to be stored from summer to winter for a long term of time. That means that even though the same annual heating demand exists for both systems, the dimension and design of the systems can vary significantly.

1.2.4. **Heat distribution system and operational temperatures**

The heat distribution system and operation temperatures can be distinguished on building level and district heating level. The heating system within the buildings influences the required temperatures in the district heating network. The heating systems inside the buildings e. g. radiators, under floor heating or air heating need to be determined as well as their operational temperatures. The operational temperatures of the heating systems as well as the efficiency of the heat transferring substations between district heating network and heat distribution system in the buildings are affecting the efficiency of the solar thermal applications and the district heating system. The lower the supply and return temperatures of the district heating network can be designed the lower are the heat losses of the district heating network. Moreover the solar thermal components – the solar thermal collectors and the STES – will operate more energy efficient. Lower operating temperatures of the solar collectors increase the efficiency of the collectors and higher solar yields can be achieved. Lower district heating network temperatures have several positive effects on the STES. The STES can be directly discharged to lower temperature levels. Thus the usable heat capacity will be increased by same volume of the store. Furthermore the mean temperature of the store is decreased and thus the thermal losses of the store will also be decreased. If a heat pump is attended to be integrated into the system the lower heat source (STES) and heat sink (district heating network) temperatures offer the chance to use standard heat pumps for heating purposes. These heat pumps are less costly than special high temperature application heat pumps that often have to be custom made.

In [1] the influence of district heating temperatures has been analysed. Simulations with the same systems but varying the supply and return temperature have been undertaken. Three configurations 60/30° C, 70/40° C and 90/50° C have been investigated without the use of a heat pump. The solar fraction (share of solar heat at the total heating demand) has decreased from 39 % for a return temperature of 30° C to 35.6 % for a return temperature of 50 C. More investigations on the heating temperatures have been carried out in the EINSTEIN project in work package 5.4 "New Working Temperatures in Existing Distribution Systems". Here the main outcome is that decreasing the supply temperatures without retrofitting the buildings by increasing their thermal insulation can lead to an insufficient security of supply. The implementation of passive retrofitting measures, however, allows reducing the supply temperature, maintaining the existing radiators. Another conclusion has been that retrofitting the heating system from radiators, which are often used in older existing buildings to panel heating systems such as under floor heating, is highly recommendable out of an energetic perspective. Nevertheless, this induces additional costs, which need to be considered for an overall point of view.

To operate the system at as low as possible temperatures and thus as efficient as possible the owner and operator of the system can include requirements for the connection of the consumers. The requirements could be the limitation of the supply temperature and an obligatory hydraulic balancing of their heat transfer substations.

1.2.5. Possibility of influencing development areas and retrofitting existing parts

It is important to adapt the STES system integration as effective as possible to the building stock. But this is only one part of an efficient integration if there is no possibility to change anything on building level regarding a more efficient integration of solar thermal applications e. g. thermal insulation of the buildings. Here the number of degrees of freedom is significantly higher for new development areas but there are also measures for existing building stock. Assessments for the most cost-effective energy interventions for retrofitting have been carried out in work package 2 of the EINSTEIN project in order to take energy saving measures for existing buildings into account. These measures are not subject of this report in detail but in general the most suitable measures will be highlighted in this chapter.

Development areas with new buildings are not in focus of the EINSTEIN project. Nevertheless, also in areas of existing buildings new buildings can be included either to substitute old ones or to enlarge the building density. If those buildings are intended to be connected to the STES system some factors can be considered to improve their efficient integration.

New buildings shall already be designed to fit well into STES systems. This can already be taken into account in the plat by the owner which is often the city or municipality. Within the plat the building orientation as well as roof slope angel etc. can be defined. Hence, passive and active solar uses can be optimised. Also the building alignment can be determined to achieve short distances of the district heating network. Furthermore, an obligation of getting connected to the district heating network can be defined together with requirements of limiting the heating distribution temperatures. In the plat space for the STES and solar thermal collectors can be reserved.

For an energy efficient integration of existing buildings several aspects need to be considered. Some of them are already mentioned in previous subsections above. The main two factors that improve the efficiency of STES system integration are decreasing the total heating demand of the building and adjusting the required distribution temperatures for the heating system to as low as possible temperatures. Decreasing the total heating demand has an energetic positive effect because the primary energy consumption will be reduced no matter which heating technology is used but additionally it is then easier to cover larger shares of the heating demand by solar thermal applications with reasonable system sizes. The benefits of lower distribution temperatures of the heating system have been already explained above. It makes the operation of the solar thermal applications more efficient. Additionally, further changes on the building structure can be undertaken. For instance the roofs of the buildings can be adjusted to improve the installation of solar thermal collectors (see section 1.5.2).

All changes at the building structure should be under consideration of European regulations such as the Energy Performance of Buildings Directive (EPBD) [3]. With regard to the EPBD it is worth to evaluate the lifetime impact of the measures. The energy savings by passive measures such as insulation and active measures such as integration of solar thermal applications must be considered for their entire lifetime also taking changes in the global energy supply into account e. g. the development of renewable energies within the grids.

1.3. CLIMATIC BOUNDARY CONDITIONS

Beside the building stock the climatic boundary conditions have a strong impact on the heating demand of the buildings and the design and dimension of STES systems. Europe has got a north-south extend of about 3,800 km and east-west extend of about 6,000 km. It reaches from the 35th to 70th latitude north.

Thus significant different climates can occur between the European countries. According to Köppen-Geiger climate classification [4] the European climate has a range from arid to polar with a large share of cold climate. Main factors for the classification are the ambient air temperatures in summer and winter as well as precipitation during those periods. Especially the ambient air temperature is influencing the heating demand. In Europe the annual mean ambient air temperature varies between -2 °C and +19 °C.

A further factor related to climate and latitude is the solar irradiation. It does not only determine the potential solar yield by solar thermal collectors but also influences significantly the ambient air temperature and thus the heating demand. Hence the solar thermal collector capacity needs to be dimensioned according to solar irradiation. As the STES levels out the fluctuations between solar yield and heating demand also the storage capacity needs to be dimensioned accordingly. Figure 1 illustrates the distribution of the solar irradiation in Europe. The annual sum of solar irradiation is shown on an optimally incident surface and azimuth directed to south. The range of potential solar irradiation differs between 800 and 2,200 kWh/(m² a). A north-south gradient can clearly be identified but also a west-east gradient. Especially at the coastal regions in central and northern Europe the solar irradiation is lower than in more continental regions at same latitude.

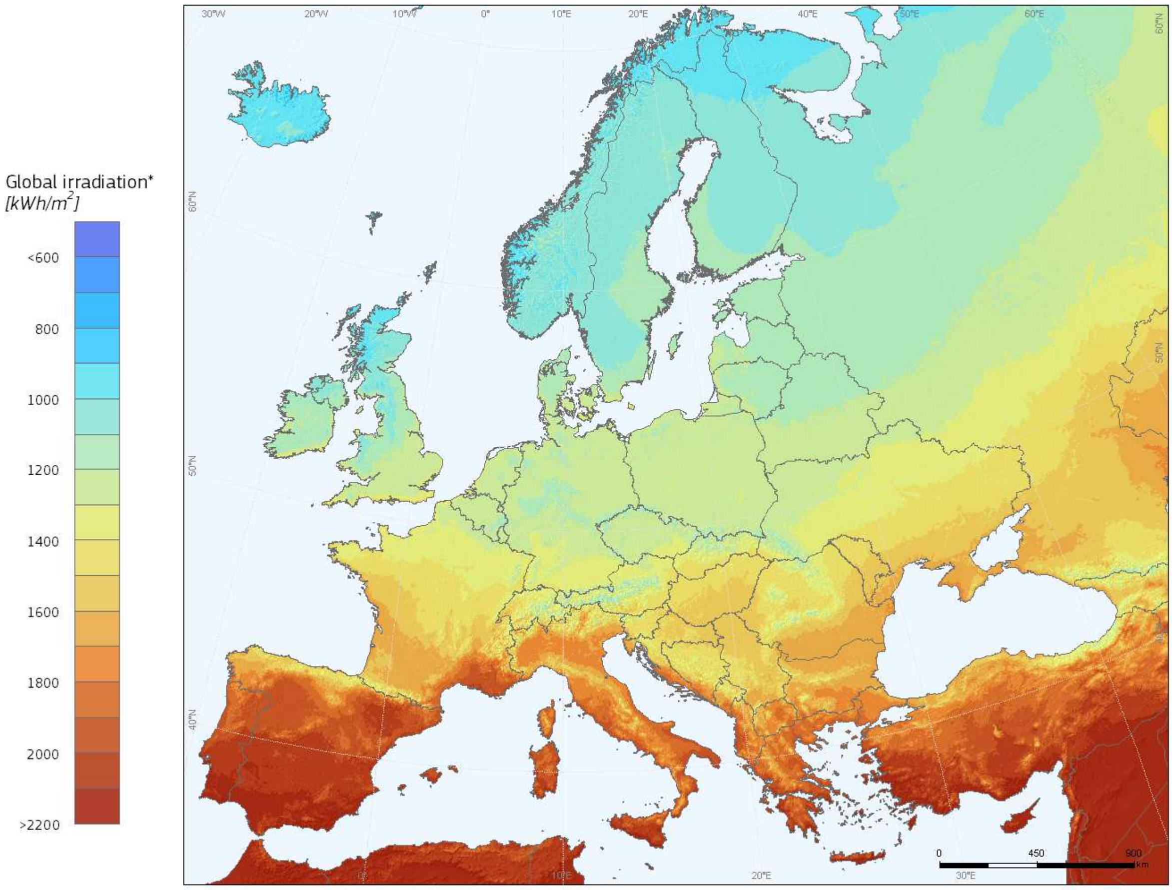

Figure 1: Solar irradiation in Europe as annual sum (*on optimally incident surface and azimuth directed to south) [5]

A method to correlate the ambient air temperature with the heating demand can be done by the Heating Degree Days (HDD). HDD is defined as the sum of daily temperature differences between an effective room temperature and the mean ambient air temperature, when it is lower than a defined limiting temperature. Within the work of Ecoheatcool and Euroheat & Power [6] a map of Europe has been developed in which HDD isolines have been implemented interpolated by 80 measurement stations (see

Figure 2). Internationally there is no harmonized definition for the limiting temperatures of HDD. In the case of Ecoheatcool and Euroheat & Power an effective room temperature of 17 °C has been defined. It is selected relatively low to consider additional internal heat gains e. g. by persons, electric energy consumption etc. The limiting ambient air temperature, when heating starts, is set to 13 °C taking passive solar gains of the building into account. It can be seen in Figure 2 that the HDD differ significantly within Europe. In south Italy the HDD is with about 500 Kd eleven times smaller than in the north of Scandinavia. Hence, it could be assumed that the heating demand is also much higher in Scandinavia than in the Mediterranean Region. This would be the case if the identical buildings were constructed all over Europe with identical internal and external heat gains. That is not the case because there are large differences in the building construction design between those regions. Thus, the HDD must always be considered together with the actual building design in order to determine the corresponding heating demand. In [6] an approach in this way has been developed introducing a European Heating Index EHI. And in fact the maximum difference between in the heating demand in Europe between Kiruna (north of Sweden) and Palermo (south of Italy) is by the factor 2.8.

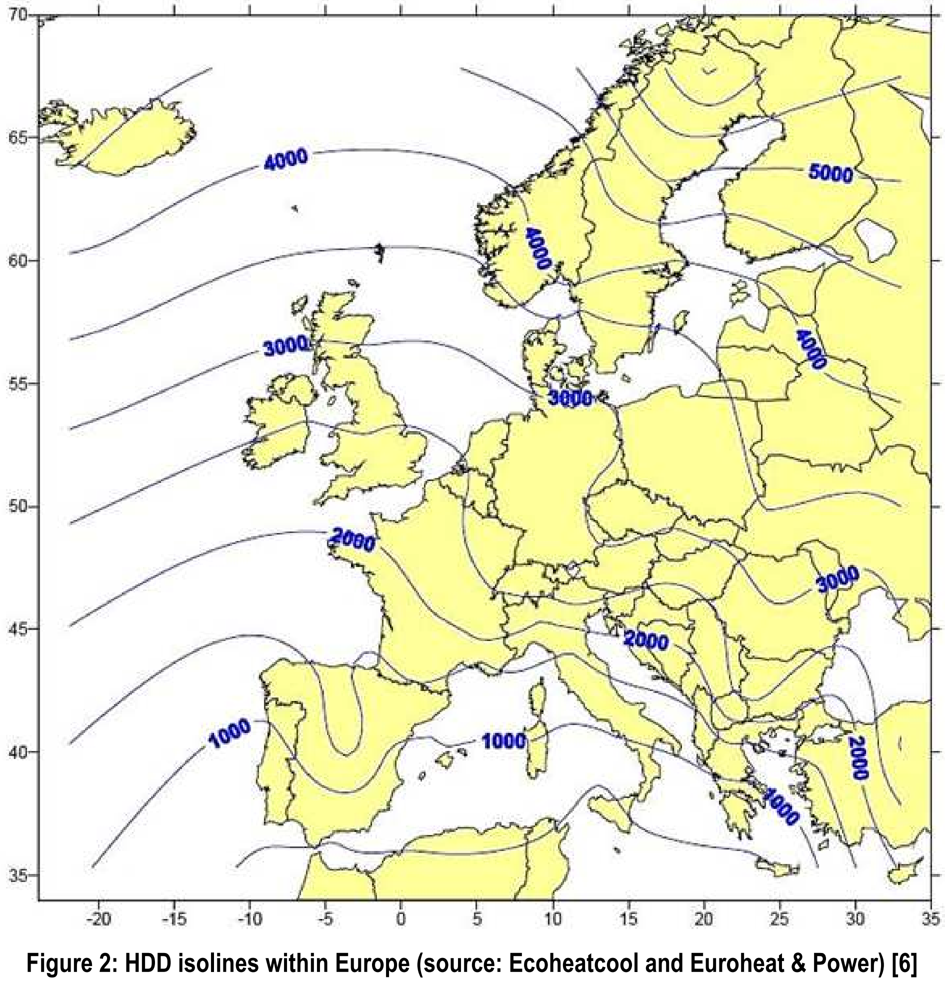

Figure 2: HDD isolines within Europe (source: Ecoheatcool and Euroheat & Power) [6]

There are some more climatic related factors that need to be considered for the integration of solar thermal collectors. Snow and wind load must be considered in order to dimension the static foundation correctly. In many regions temperature below the freezing point of water can occur. Hence, the heat transfer fluid within the collector loop must be protected from freezing by using a mixture of e. g. water and glycol or the water as heat transfer fluid needs a protective heating respectively the loop has to be emptied when danger of freezing occurs. Last two options require additional equipment that needs to be controlled. Furthermore, climates e. g. close to the sea where corrosion can occur faster must be considered in the selection of materials. Within the standard CEN/TS 12977 [7] many of those above explained factors are included and explained respectively referred to calculations how to consider their influence in the design of the installation.

1.4. SPACE REQUIREMENTS

The installation of a STES system requires space for its components. There must be enough space for the solar thermal collectors, enough space respectively volume for the STES by itself and the corresponding periphery such as heating station with backup heating and heat pump as well as the district heating network.

Each location will have its own advantages and disadvantages. Taking downtown or suburban areas as comparison it is obvious that in the downtown area the building density is higher and thus a district heating network will be shorter in length to connect as many dwellings as in suburban areas. Nevertheless, the installation might be more difficult in the downtown area as the accessibility is limited.

1.4.1. Solar thermal collectors

The space requirements for solar thermal collectors may not be underestimated. The following example will emphasise these requirements using rough values for Central Europe: assuming a solar fraction of 50 % is the design value for the installation. The average solar yield of the collector may be around 400 kWh/(m² a) for an average European heating demand of about 175 kWh/(m² a) [8]. Accordingly, it can be concluded therefore that a ratio of about 1 m² of solar thermal collector for 4.5 m² net dwelling area may be required, without considering any heat losses for storing and distribution. As already mentioned such high solar fractions will probably only be aimed for energy efficient buildings. Nevertheless, these numbers illustrate the fairly high space demand for the solar thermal collector installation. The used values are only an example.

The solar thermal collectors can be integrated in many different ways. Each suitable available space might be used. So the solar thermal collectors can be installed on the buildings' roof or façade, elevated on the flat ground or noise barriers or even on parking lots as a kind of carport. Some possible integration options for solar district heating are concluded in Figure 3.

Figure 3: a) Renovated multi-family houses with retrofitted solar thermal collectors in Crailsheim/Germany; b) Gymnasium in Eggenstein/Germany; c) Ground mounted collectors in Jægerspris/Denmark; d) Collectors on noise barrier wall in Crailsheim/Germany; e) Collectors as "carport" in Neckarsulm/Germany (source: University of Stuttgart)

Beside the availability of space some further aspects must be regarded. Important is the orientation of the available space in perspective of potential annual solar irradiation. In best case the collectors are orientated towards south with a slope angle according to the latitude. Nevertheless, deviations from this optimum may be acceptable as Figure 4 shows for the example of Germany. Even for an azimuth directly to east or west and a vertical installation the annual solar irradiation is in the range of around 65 % of the maximum.

A higher impact on the reduction of possible solar yields is caused by shading. Shading can occur from other buildings, trees etc. in a daily or seasonal fluctuating way depending on their location. The different orientations and shading must be considered for the control of the solar thermal collectors. If arrays with temporary high solar yields are connected to arrays with poor yields a mixing of the supply flows will reduce the total supply temperature and usable heat will be destroyed. Thus a supply of the district heating network or charging of the STES might not be possible although some parts would work efficient enough to do so.

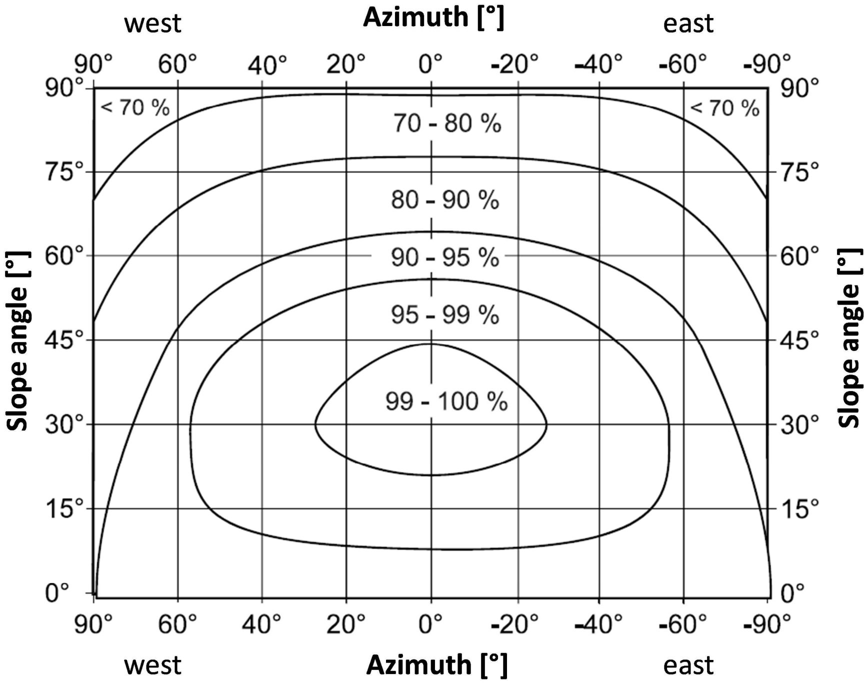

Figure 4: Potential annual solar irradiation in dependency of azimuth and slope angle as example for Germany [9]

1.4.2. STES

Same as the space requirements for the solar thermal collectors the required space for the STES may also not be underestimated. According to the example for the required space for the collectors an estimation for the required space respectively storage capacity can be made. To achieve a solar fraction of about 50 % experiences from German plants reveal that about half of the solar yield needs to be stored within the STES for long term purposes. Neglecting any heat losses to estimate a minimum capacity this is roughly 25 % of the heating demand. Taking the European average for the specific heating demand from above (175 kWh/(m² a)) [8] the required specific storage capacity is about 44 kWh/(a $m^2_{\text{net dwelling area}}$). A hot water tank as STES in combination with a heat pump can be operated between about 10 and 90° C. This equals to an usable storage capacity of about 90 kWh/m³. Accordingly, per 1 m² of net dwelling area 0.5 m³ of STES (water tank with 90 kW/m³ usable storage capacity) is required or about 2 m³ of STES per 1 m² of solar thermal collector area. Again, this is only a very rough estimation for Central Europe and depending on location and building standard the numbers may change. However, this estimation emphasises that the storage density is limited and consequently large volumes of the stores are required for seasonal thermal energy storage (more examples are as well given in chapter 4 that may help making an idea about the expected size of the system).

Additionally to the pure storage volume more space is required for the thermal insulation of the STES as long as thermal insulation is technically or economically feasible. Exceptions are ATES. But in general STES need a very good thermal insulation, in order to store the thermal energy for a long term with minimum heat losses, the thermal insulation is often relatively thick. Furthermore, cost minimization is of high importance for the construction of STES. Hence, often less expensive thermal insulation materials are used which are often less efficient. To achieve the same insulation properties as for high efficient materials larger thicknesses are required. Consequently the thickness and thus the volume for the thermal insulation of STES increase. Thicknesses of up to 100 cm are possible. To demonstrate the significance of considering both the storage volume and the volume for thermal insulation the gravel-water thermal energy store (GWTES) in Eggenstein/Germany can be taken as an example [**10**]. It is insulated around the entire surface by expended glass granules and foam glass gravel. The storage volume is 4,500 m³. The store's quite flat shape consists of a double truncated cone. The volume of the thermal insulation material is about 1,500 m³. As space is not unlimited available in urban areas for retrofitting applications and relatively expensive reducing the volume of the thermal insulation using more efficient materials might be more economic even though the costs for the STES by itself may be higher.

Depending on the type of STES many possible locations are applicable. If the system is small and space is available even indoor applications are possible. This has the advantage that the STES is usually accessible and not exposed to outdoor conditions such as weather. On the other hand space is limited and usually quite expensive.

Because of their large volume the STES are mostly integrated outdoor. Here it can be distinguished by over ground and underground installations. If STES are installed over or underground depends on the type of STES that will be integrated. Below in Figure 5 the four most common types of STES are shown. Only hot water tank thermal energy stores (TTES) as tank stores can be built over ground all others are installed in the ground and some are even using the underground as storage medium such as BTES and aquifer thermal energy store (ATES). The decision which type of STES will be chosen for an STES system depends on many different boundary conditions and requirements. The available space is only one of those boundary conditions. On basis of their construction the four different types of STES have different usable storage capacities. These capacities have a significant influence on their dimension and thus space requirement. Enlarging the usable storage capacity of STES can be utilised by integrating heat pumps that use the STES as heat source (see section 3.3.3). They can increase the maximum temperature difference between fully charged and discharged stage of the STES. Consequently, the STES can be dimensioned smaller and require less space.

The ATES has the least requirements for space. Only two dwells are needed that make an aquifer accessible. But usable aquifers are limited to only few locations. The BTES can be designed relatively thin and therefore developed larger in depth. This can reduce the required space at the surface. But it must be considered that the shape of the BTES will not be too thin as its heat transferring area to the ambient underground increases and the injected thermal energy will dissipate without being able to make it usable again. Pit stores such as the GWTES need relatively a lot of space on the surface. To build the GWTES as inexpensive as possible the natural slope angle of the underground is used when the pit is excavated. In this case no static walls or supports are necessary. In a consequence the pit stores have usually a relatively flat shape. A more compact shape and less space requirements are needed for TTES having the highest usable storage density. Nevertheless, the static requirements for their construction make them relatively expensive and the accessibility of the top of the store is limited in weight.

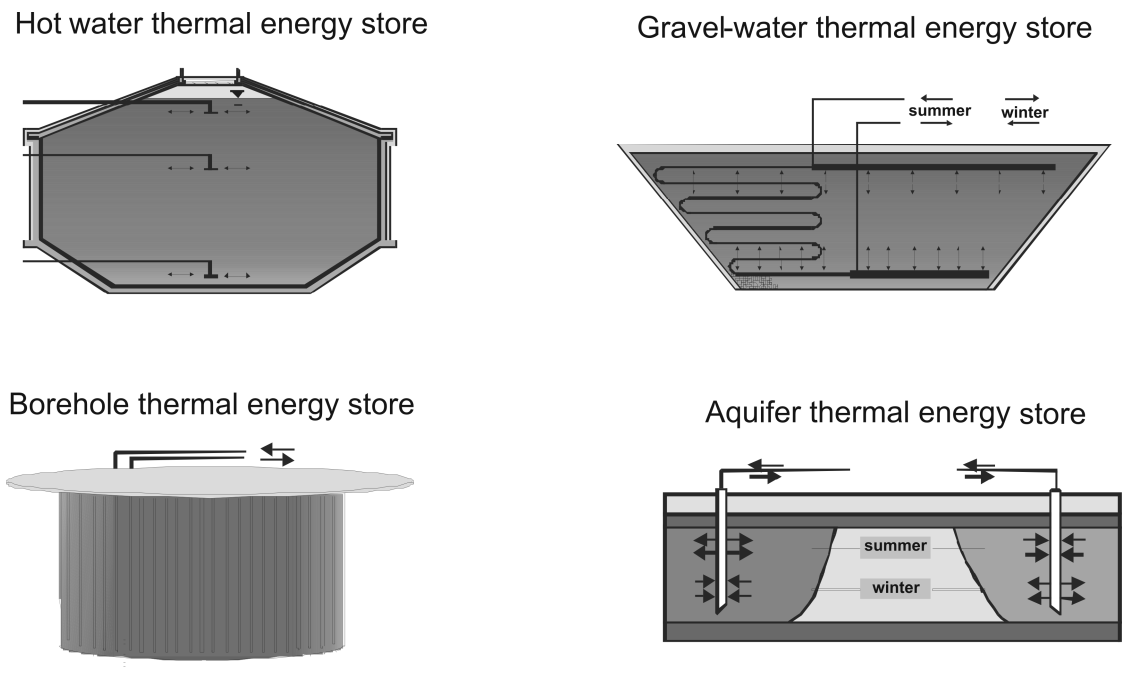

Figure 5: Different types of STES [11]

Especially for urban areas the installation of STES should be designed in such a way that the used space where STES are installed can be reused for other purposes e. g. playgrounds for children, parking lots etc. For BTES and ATES this can be done easily as they use the underground as storage medium. Also GWTES can be designed in a way that they can be used for e. g. a parking lot as it was demonstrated in Chemnitz/Germany. Even the TTES as tanks can be integrated in a way that they have an additional application although the trafficability is limited. So with an elevated shape at the top it can be used e. g. as playground.

1.4.3. **Periphery and central heating station**

In comparison to small decentralized heating systems STES systems require a heating station. In the heating station included are usually the backup heating system e. g. gas boiler as well as the heat pump. Furthermore are included the pumps for the different loops, heat exchangers, buffer tank, expansions vessels etc. as well as the control and monitoring system. Often it is useful to build an own building for the heating station. In this case the dimension can be designed according to the required space. If the heating station is integrated into existing buildings the accessibility of all components must be secured. The location of the heating station should be as close as possible to the solar thermal collectors, STES and district heating network. Hence the connection length can be minimised and thus the heat losses.

Also the solar network and the district heating network require space. As analysed within the EINSTEIN project there are different methods to install the networks. They can mainly be distinguished by trench and trenchless methods using micro-tunnelling. Both ways the piping requires space and in a highly dense building environment it can be difficult to install the piping. The required space also depends on the already installed subsurface infrastructure e. g. cable for communication, fresh water supply and sewage canals, electricity and gas supply etc.

1.5. REQUIREMENTS FOR INTEGRATION OF SOLAR THERMAL COLLECTORS

The above described space requirements are only one aspect that needs to be considered integrating large solar thermal collector fields for an STES system. Depending on the system and the integrated components the most suitable collector type needs to be selected.

1.5.1. Flat plate collectors and evacuated tube collectors

Most common solar collectors used in STES systems are either flat plate collectors (FPC) or vacuum tube collectors (VTC). Each collector has its specific efficiency curve, but it is possible to talk about general features that are common for each of the mentioned technology. Figure 9 shows typical curves of FPC and VTC.

Among FPC, large-format ones are the most usual solar collectors for large scale systems. The technology for solar capture is the same as the individual FPC, but the size of each delivered unit is higher (between 4 and 15 m2). They are based on individual FPC, but 2-6 units are mounted together forming a unique cover frame. All of the units are internally connected at the factory, providing a significant time and material savings. The internal connections are tested at the factory, avoiding many mounting errors that were given with individual FPC. They reduce the installation time and maintenance costs in large scale solar thermal plants.

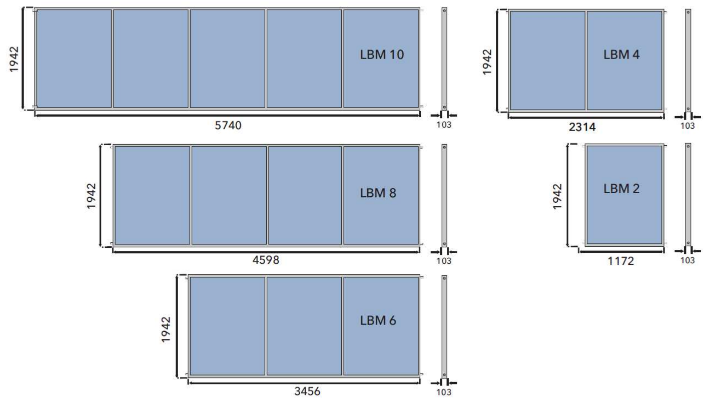

Figure 6: Large-format flat plate collectors, LBM solution from Wagner Solar. Different sizes are available to ensure a customized solution

The following figure shows a commercial large-format FPC.

Figure 7: Settings of Large-format flat plate collectors, either horizontal or vertical alignment

1.5.2. Building integrated solar collectors

Building integrated solar collectors may be an interesting option mainly in retrofitting applications, in which space availability may be limited and retrofitting of buildings may be, together with the STES system planning, part of the same energy project. Although it increases complexity from technical point of view and the efficiency may be lower than in other layouts (depending on the integration option), it is worth mentioning as an option that may be interesting for specific situations. Both FPC and VTC can be integrated in buildings if they have the required features for it.

A feasible and interesting option for retrofitting projects is the replacement of the existing roofs by new ones that have a more efficient orientation and slope angle for solar thermal collectors. Even changing flat roofs to single-pitch roofs can be interesting. The newly created space under the new roofs can be used for the hydraulics of the system. This measure is of interest for larger buildings with appropriate roof area such as apartment houses, schools, hospitals etc. Or going one step further, the replacement of the existing roofs by new roofs formed by solar collectors could be as well an interesting option. As an example of this last case, a retrofitting project implemented in Crailsheim (Germany) should be mentioned, where a new STES plant was built as part of the retrofitting project. Apartment houses were retrofitted and the existing roofs were replaced by an innovative solution in which solar collectors were part of the roof structure. Besides environmental benefits, it is an example of a successful business case. The apartments under the roof and thus close to the solar thermal collectors were sold very fast because the investors associated with those apartments a very environmentally friendly living. The development of the retrofitting is shown in Figure 8.

Figure 8: a) former military buildings before retrofitting; b) during retrofitting; c) completely finished (source: University of Stuttgart)

1.5.3. Key issues to be considered when selecting the most suitable solar collector type

It needs to be determined which thermal capacity at which temperatures are required. In Figure 9 typical collector efficiency curves are shown for four different kinds of collectors. In general the lower the operational coefficient[1] is, the higher is the efficiency of the collectors. It can be noticed that at different ranges of the operational coefficient and thus at different temperature levels the most efficient collector types varies. If e. g. only low temperatures (as heat source for a heat pump for instance) are required flat plate collectors or even unglazed collectors might be the favourable choice as these collector types have a high efficiency at low operating temperature differences compared to ambience. Suitable STES for such applications are BTES and ATES. Contrariwise, vacuum tube, vacuum flat plate collectors or even concentrating collectors are in favour for high temperature applications. In this case only STES with highest possible operation temperatures are suitable such as GWTES and TTES.

Table 2 summarizes the maximum temperature that can be reached for different STES types. This gives an idea on the temperature range that the solar collectors will operate, which will be a relevant issue to be considered when selecting the most suitable one as the overall efficiency will depend on it.

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[1] The operational coefficient is defined as followed:

$$\Omega = \frac{\vartheta_{fl,m} - \vartheta_{amb}}{G}$$

$\vartheta_{fl,m}$	mean fluid temperature of collector
ϑ_{amb}	ambient air temperature
G	solar irradiation on collector surface

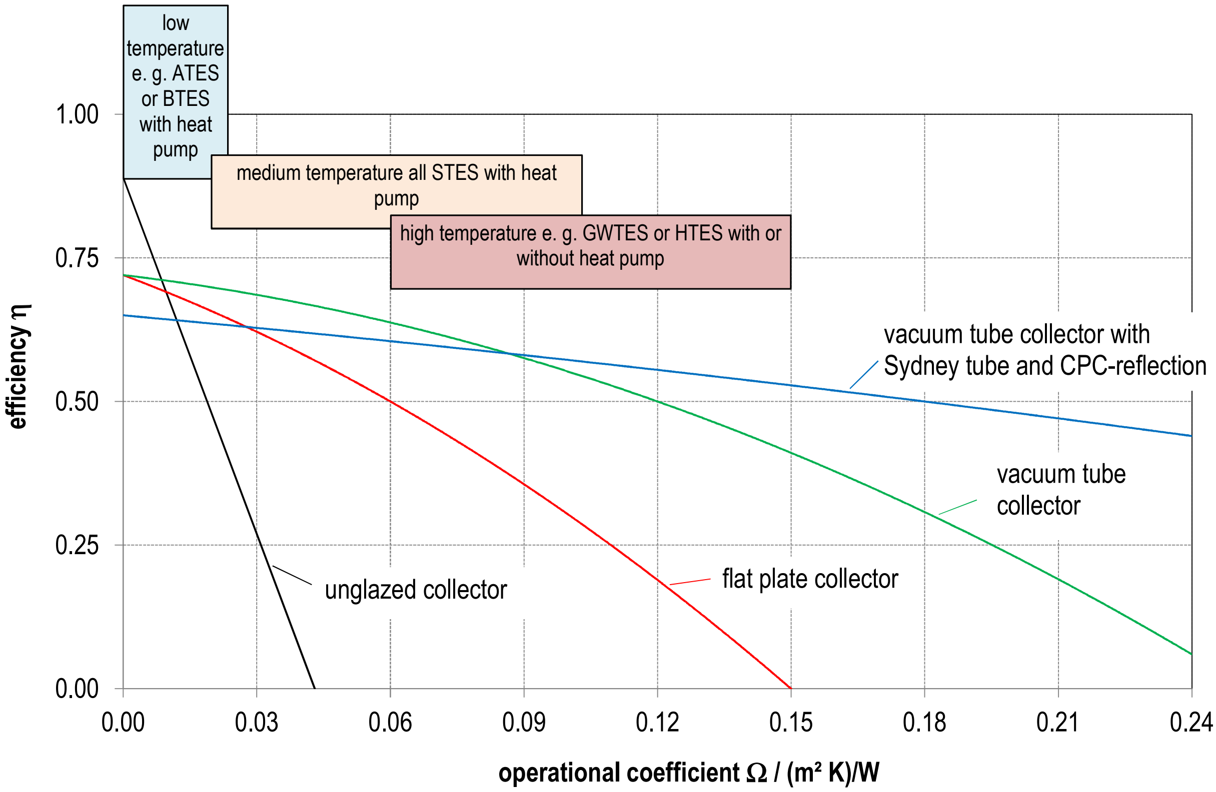

Figure 9: Classification of solar thermal collectors for different STES and system integration by use of the collector efficiency and the operational coefficient, curves are based on aperture area (source: University of Stuttgart)

The most efficient way of using solar thermal energy is to consume it at the same time that it is produced. Direct use of the solar thermal energy must be the priority as its storage implicates heat losses. In that case, the required supply and return temperature of the district heating network influences the selection of solar thermal collectors significantly. The collector output temperature, which depends on the type of collector, must be high enough to deliver heat to the network. For networks operating at high temperatures, high temperature collectors are required.

In association with the available space also the type of collector needs to be selected. If space is limited collectors with higher efficiencies must be selected in order to provide the required thermal capacity. This enables the use of limited space more efficiently. An example for this can be seen in Figure 9. Between $0.01 < \Omega < 0.09$ the flat plate collectors could be replaced by vacuum tube collectors having the highest efficiency in this section and thus having a higher solar yield at same available space as the flat plate collectors respectively the same solar yield for less required space.

In case the solar installation is a sum of several solar collectors fields with different orientation and/or slope angle, it should be carefully regarded the hydraulic integration of the different fields. If there are relevant differences mainly on orientation, the same solar irradiance may give different output temperatures, leading to significant exergy losses when mixing the different flows. An appropriate control strategy should be implemented in those cases to avoid inefficiencies.

For roof mounted collectors some aspects need to be considered. First local regulations must be clarified. If the house is under historical protection the installation of solar thermal collectors needs a special permission which might not be granted. In some rarely occasions even insurances policies must be adapted to the installation as insurance companies might see an increased risk of damages by those installations. More important is to assure that the carrying capacity of the roofs is high enough to carry the additional load by the solar thermal collectors. If the roofs will be refurbished to retrofit solar thermal collectors in a more optimised way the collectors can be roof integrated. That means the collector area is taking over the properties of the actual roof and no additional sealing, insulation etc. is needed (see Figure 8 a).

During the tendering process and at the decision which supplier respectively product should be selected the criteria should not be the specific costs per area of installed solar thermal collector. Even more important is to select the offer with the best cost to solar heat gain ratio. That means not a specific collector area by itself should be tendered but also a required solar heat gains. This will assure that collectors with the best cost-performance ratio will be selected.

1.6. REQUIREMENTS FOR STES INTEGRATION

The space requirements have been explained in the section above. Beside the space some other boundary conditions influence design, dimension and type of STES. Similar as for the selection of the solar thermal collectors the system and the integrated components as well as the system operation determine the STES. Moreover the underground properties influence the type and design of the STES. Lastly regulations and restrictions must be taken under consideration for the STES installation.

The types of STES described in section 1.4.2 are characterised by different specific usable storage capacities, temperature levels and charging and discharging capacities. These facts must be considered for the technical selection of a certain STES type. By the integration of a heat pump that is using the STES as heat source the temperature levels and thus the specific usable storage capacity can be optimized. In Figure 10 the maximum operational temperature range of the different STES technologies are shown. If no heat pump is included the lowest system temperature, which is the return flow temperature of the district heating network, is the lowest temperature to which a STES can be discharged. This temperature level depends on the system. If a heat pump is included the STES can usually be discharged to minimal temperatures of around 10 °C. The maximum operational temperatures of the STES depend on the selected type. ATES usually has the lowest maximal temperature. The underground bio-chemistry can start to change at temperatures above 50 °C (e. g. at the ATES in Rostock/Germany [**11**]). The changes at the underground bio-chemistry can harm the system operation e. g. by fouling of heat exchangers or accelerated corrosion processes. Nevertheless, the drinking water quality can be affected already at lower temperature changes. Thus the operation must be in accordance to local regulations. Thus BTES can rarely be operated above 60 °C. The charging temperatures within the boreholes might be higher but due to limited heat transferring capacity within the boreholes the underground does not reach those high temperatures. The GWTES as pit store can reach temperatures of up to 80-85 °C. This limit should not be exceeded as the commonly used plastic liners will then start to fail and leakages might occur. TTES can nearly be used up to boiling of water. So TTES have the largest usable temperature range.

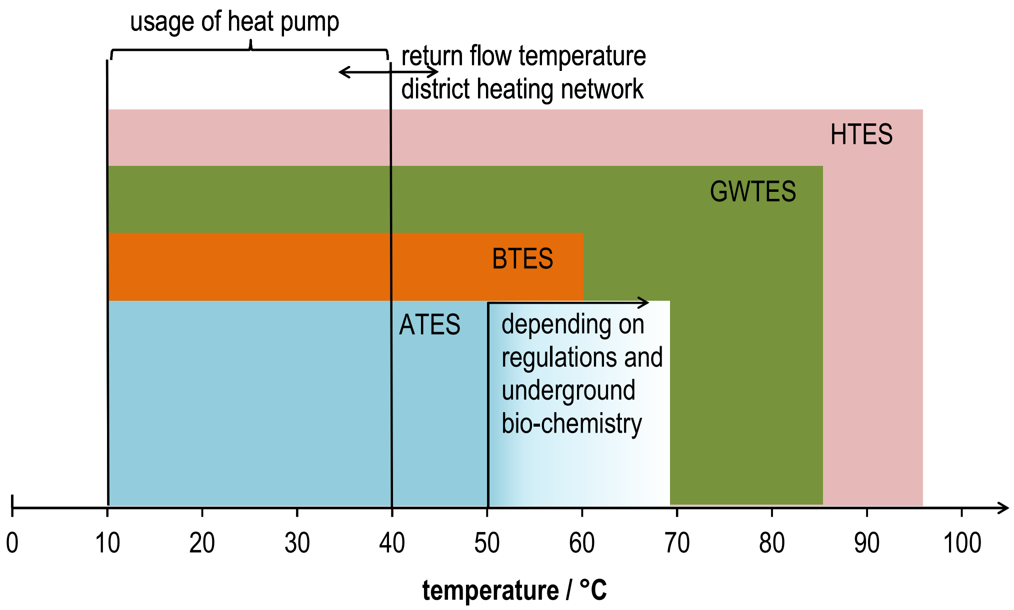

Figure 10: Maximal operational temperatures of the different STES technologies depending on the return flow temperature of the district heating network and usage of heat pumps (source: University of Stuttgart)

In Figure 11 the usable volumetric storage capacity in dependency of the minimal discharge temperature of the different STES technologies is shown. The usable volumetric storage capacity depends on the used temperature range and the specific volumetric heat capacity of the storage material. The mean volumetric specific heat capacities from Table 1 have been taken for the calculation of the storage capacity even though the values can vary in reality and this must be considered [**12**]. The highest usable volumetric storage capacity can be obtained by the TTES. It can also be seen that the lowest system temperature have a significant influence of the storage capacity as well as which STES type does actually fit into the system. For instance, ATES or BTES cannot be used for systems with high district heating networks and not including a heat pump.

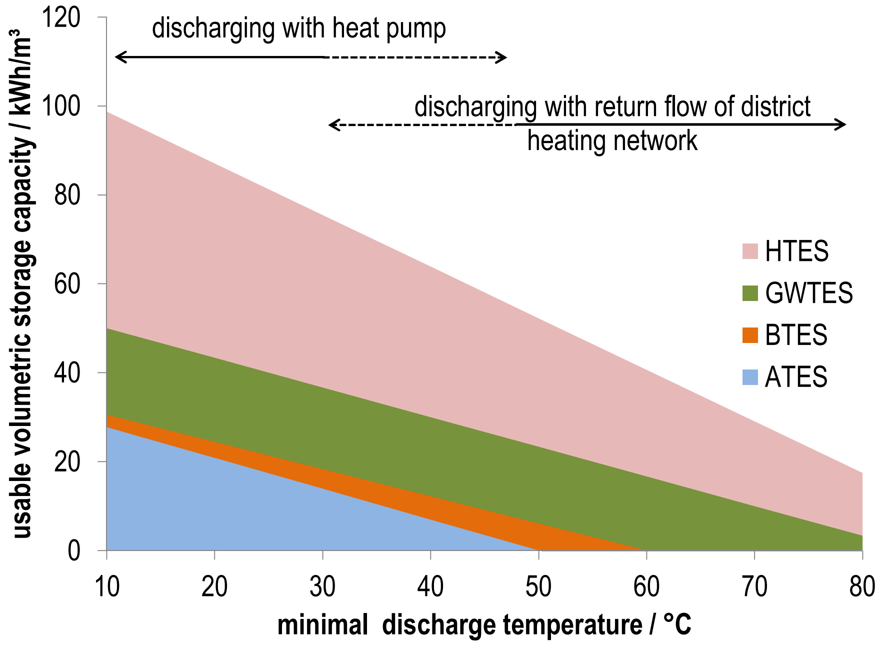

Figure 11: Usable volumetric storage capacity in dependency of the minimal discharge temperature of the different STES technologies depending on the return flow temperature of the district heating network and usage of heat pumps (source: University of Stuttgart)

Table 1: Mean volumetric specific heat capacities [13]

	mean volumetric specific heat capacities $\rho\ c_p$ [MJ/(m² K)]
Water for TTES	4.18
Gravel-water mixture for GWTES	2.4
Underground for BTES	2.2
Underground for ATES (sedimentary and unconsolidated rocks)	2.5

The charging and discharging capacities also differ within the different STES technologies. ATES, BTES and GWTES have restricted charging and discharging capacities, if an indirect charging and discharging unit is installed. Here in most cases buffer stores are required. The buffer stores can buffer the possible high solar yields from the solar thermal collectors and charge this thermal energy independent from the solar thermal collector capacity into the STES. This is also applicable for discharging purposes, if the heating demand is higher than the discharging capacity of the STES.

For STES there is often a conflict of aim between thermal efficiency and investment costs. A high share of the investment costs of a STES is caused by the thermal insulation. The better the thermal insulation is the more efficient operates a STES but also the investment costs rise. To determine an optimised STES with regard to thermal efficiency and investment costs a “standalone” calculation of the component STES is not sufficient because the thermal efficiency can hardly be estimated without the integration of the STES into the system. Thus transient system simulations are required to determine the most suitable STES for a specific system.

1.6.1. Underground properties

STES are often buried into the ground respectively use the underground as storage media. Therefore the underground properties must be analysed and determined. The hydro-thermodynamic properties as well as criteria for civil engineering are important and the analysis of the existence of groundwater and groundwater flow. If the STES is installed over ground the carrying capacity of the ground must be assured.

TTES and GWTES separate the storage medium from the underground and thus the least requirements for the underground are needed. If groundwater occurs the store should be installed above the groundwater level. This will make the construction easier and less expensive because an artificial decreasing of the groundwater level is not necessary. Furthermore, the risk that the thermal insulation of the store is penetrated by water is lower. This is a very important criterion for any STES. The thermal insulation must be installed in such a way that neither liquid nor vaporised water can penetrate it. If this happens the thermal conductivity of the insulation increases and the efficiency of the insulation decreases [**14**]. For GWTES additionally the natural slope angle of the underground material should be determined. GWTES are usually installed into excavated pits. To abstain from supports that hold the pressure of the ground it is easier and less expensive to use the natural slope angle of the ground material to shape the pit. If this slope angle is quite flat also the pit side walls will be flat. In a consequence the entire store will be relatively flat. This is an unfavourable shape for a STES because the surface to volume ratio is high and thus the heat transferring area which will cause higher heat losses than necessary. Additionally more thermal insulation material is required due to the higher surface area. Hence, a ground with steep slope angles is in favour in order to optimise the shape of the GWTES respectively pit STES.

For BTES at first the drillability of the ground must be assured. It is essential to know the heat capacity and the thermal conductivity of the ground to design the BTES, because e. g. the borehole length and pattern depends on those properties. The presents of groundwater needs to be assessed as well. Water saturated grounds are in general in favour for BTES as the heat capacity increases slightly by the water content. Significant groundwater flows must be avoided. The groundwater flow can move the stored thermal energy out of the borehole field and so it is not usable anymore.

ATES require a large aquifer that is delimited to the top and bottom. According to Fisch [**15**] at least 100,000 m³ of storage volume is required to be reasonable. The permeability should be higher than 10^{-5} m/s and only minimal groundwater flow is acceptable. The chemical and bio-chemical quality of the groundwater should be in such a range that due to the temperature changes during operation precipitation and corrosion of the wells are avoided. If this quality is not assured a plugging of the wells could be caused.

1.6.2. Regulations

As many STES are built into the ground some regulations need to be considered and permissions from local authorities must be granted. Many of those regulations apply for the security of the groundwater. Especially, if the groundwater is used as drinking water a contamination must be strictly avoided. The regulations differ regionally very significantly. Hence, if a STES system will be planned it is advisable to contact local authorities to get the information about local regulations.

1.7. REQUIREMENTS FOR PERIPHERY, HYDRAULICS AND CENTRAL HEATING STATION

Beside the main components STES and solar thermal collectors additional components such as backup heating, heat pump, district heating network etc. must be integrated. Those components do not only require space (see above) but also some technical requirements have to be fulfilled. In case of retrofitting a STES system into existing building stock the existing heating system should be assessed in order to determine a possible reuse of existing components.

1.7.1. District heating network

If there is an existing district heating network, a possible reuse can be assessed. Some requirements must be given in order to reuse the existing part. A major point is the dimension. The length and diameter determine the pressure drop of the system to which accordingly the pumps are dimensioned. If changing the use of an existing district heating network for the application for an STES system, the operating temperature levels might change. STES systems should be operated at as low as possible temperatures in order to optimise the operation of the solar thermal components. In general lower temperature levels might also lead to a lower temperature difference between supply and return flow. To transfer the same amount of heat higher flow rates are necessary. These higher flow rates will require more powerful pumps as additionally the pressure drop within the district heating network increases. So the dimensions of the district heating network need to be well known to select the proper pumps.

A further issue is the quality of the thermal insulation of the piping. If the insulation is insufficient or not in good condition anymore the thermal losses of the district heating network might be relatively high. In this case not only the extra costs for the heat losses must be taken into account but also the fact that if high heat losses occur the district heating network must be operated on higher temperatures. Consequently the solar thermal components will operate less efficient and thus additional auxiliary heating is required. On bases of this pre-assessment the decision on reuse or replacement of the existing district heating network has to be made.

1.7.2. Heat generating system

Same as for the district heating system the reuse of existing heat generating systems such as boilers should be assessed. The existing boilers etc. will face different operational conditions and it must be clarified if they can be operated within these different conditions. Beside the age of the existing system, there are two important criteria to be fulfilled. The first is if the existing heat generation system can be implemented into a new system control. Second and most important is the flexibility of the heat generation system to changing operational conditions. As the existing heat generation system will operate as auxiliary heating for the STES system a large range of requirements will be requested. In detail are those requirements a good capacity modulation and new operational temperatures. The capacity modulation is important if the solar thermal energy is not sufficient enough to cover the demand. Then the heat generation system has to start adding the missing energy beginning with fairly low capacities. Due to the change to the STES system which will operate often on lower temperature levels, the heat generation system might face lower temperatures as before. Just to name one issue among others, condensation might occur in the exhaust of combustion boilers. The condensation might lead to corrosion.

1.7.3. Heat pump integration

The integration of heat pumps into a STES system can be a meaningful measure to utilise the solar thermal energy more efficient. Only in limited occasions standard heat pumps for heating purposes can be used for STES systems. Standard heat pumps can only be used if both on heat source and sink side the temperature levels are relatively low (about 10 and 40 °C). In the case of STES systems the heat source is mostly the STES operating on higher temperature levels. The heat sink is the district heating network also operating on higher temperature levels. Additionally the temperature fluctuations are high within the annual characteristics due to the seasonal operation of the entire system. In consequence usually standard heat pumps are not applicable and custom made heat pumps are required that are often more costly.

1.7.4. Requirements for control strategy

The complex STES system needs a sophisticated control strategy. The control strategy needs to be implemented into a control system that often has to be optimised. As a STES system has a seasonal operational characteristic a monitoring of such systems by capturing all important data is advisable. On basis of this long-term data an optimisation of the system in general and the control strategy in specific can be undertaken.

For the control strategy of the system some general facts should be considered. The solar thermal energy should always have the highest priority to be used to cover heating demands. Direct use of the solar thermal energy is most important as its storage implicates heat losses. If a direct use is not possible the solar thermal energy can be used for preheating purposes of a boiler or as heat source of a heat pump. Only if no solar thermal energy is available the auxiliary heating must exclusively provide the demanded heat.

1.7.5. Miscellaneous requirements

The integration of all components of a STES system require more than space. If existing heating systems are replaced by new and different technologies the available connections must be assured. For instance, if oil boilers are replaced by gas condensing boilers a connection for natural gas is required. Heat pumps often have a high electric capacity. Also those high electricity capacities must be assured.

There will be installed several heat exchanger e. g. to separate the solar thermal collector loop from the secondary loop. Two main criteria must be considered for heat exchangers within STES systems. The heat transferring capacity must be designed according to the maximum heat capacities that will occur during operation. Additionally the logarithmic mean temperature difference [**16**] of the heat exchanger must be as low as possible in the range of about 3 K at maximum heat transferring capacity. If this low logarithmic mean temperature difference is not obtained, the solar thermal components will lose their efficiency because they will be operated at too high temperatures. Furthermore, less solar thermal energy can be utilised to cover the heating demand.

If STES systems are integrated into new development areas the building owner can be forced to be connected to the district heating network by regulations. In case of retrofitting this is not always the case. When planning to install a STES system it must be evaluated weather the consumers are willing to be connected to the district heating or not. Additionally, it might be necessary that the consumers have to adapt their heating systems (heat distribution system e. g. radiator heating to under floor heating) to the requirements of the STES system which will be a further obstacle for the acceptance of the connection because it will cause extra costs and retrofitting work. A lack of acceptance or missing will to be connected will make it difficult to operate a STES system successfully.

2. RECOMMENDATIONS FOR SUBSYSTEMS INTEGRATION

In the following table key aspects for subsystems integration and some general recommendations for an appropriate design of solar thermal systems with STES has been summarized. The information is given as guidance only. It is not possible to design a solar thermal plant with STES by easy and generic rough values of different parameters in the energy system. It is very important to consider the whole energy system as a comprehensive energy concept and assess it in a holistic approach. As it has been already stated previously in this document, the detailed dimensioning of such a plant must be realized by system simulation, in order to properly consider the dynamics of the system and all the interactions between the different subsystems. The objective of this chapter is to give indicative values for an appropriate subsystems integration that can be useful for a preliminary system completion, to establish system concepts or disregard options, etc.; in brief, to help anybody, interested in a solar thermal plant with STES that is not expert in the field, in the initial steps and understanding of STES systems.

Table 2: key parameters in subsystems integration and recommendations

Key parameter	General recommendation	Recommended value / limitations
Operation temperature in solar collectors (SCs)	The lower is the temperature in SCs, the lower are the heat losses and the higher the efficiency and the solar yield	As lowest as allowed by the application
Efficiency of solar collectors	SCs efficiency is characterized by 3 coefficients: η_o (-), a_1 (W/m^{2}K) and a_2 (W/m^{2}K). Better performance if high η_o and low a_1 and a_2 values.	Indicative values for Flat Plate Collectors (FPC) (for guidance only): Medium performing FPC: η_o=0,75; a_1=4 and a_2=0,010. High performing FPC: η_o=0,80; a_1=3 and a_2=0,008.
Design of the heat exchangers (HX)	A HX introduces a mean temperature difference between the primary and secondary circuits, which is a non-desirable effect for the thermal system. The larger the heat exchanging surface is, the lower will be the mean temperature difference.	Usual value for design temperature difference in HXs is 5K. Even they are more costly, bigger HXs that can get 3K or 2K, improving the overall performance of the thermal system, are also used and in general recommended.
Shape of STES	Heat losses from the STES may be higher or lower depending on the shape of the storage tank. It should be optimized. Spheres are the best option, but they are hard to realise as a shape for a STES. The lowest possible surface to volume ratio should be realised to minimize heat losses.	
Insulation of STES	A good thermal insulation is essential. Key properties beside a low thermal conductivity are intensitivity against water	Depending on space availability and other boundary conditions such as pressure resistance values for the

	penetration, cost-effectiveness and durability at high temperatures.	thermal conduction in the range of 0.03-0.10 W/(K m) should be selected for the applied temperature range of the storage envelop
Maximum design temperature in the STES	As higher is the maximum temperature in the STES, the higher is the heat storage density of a certain STES volume, or for a envisaged heat storage density, the smaller can be the STES volume. In general, the STES are designed for a maximum design temperature that the materials in the STES allow. However, it should be considered as well that higher temperatures in the STES mean lower efficiency of the STES due to higher heat losses.	Indicative maximum design temperatures in the STES: - TTES: 98 °C (at atmospheric pressure) - PTES: 80-85 °C (depending on plastic liner inside) - BTES: 60-75 °C (inside the borehole heat exchanger depending on material) - Aquifers: no real limitations, depending on bio-chemical conditions of the underground and depth of aquifer and must be checked at each location
Supply temperature of the heat pump (HP)	The supply temperature has to be as low as allowed by the application. As lower it is, the higher will be the COP of the HP. Technical limitations according to the specifications of the HP must be considered. The manufacturer will indicate the operational limits of the HP.	The maximum supply temperature for standard commercial HPs with conventional refrigerants is around 60ºC. There are some HPs that can reach around 70ºC but higher temperatures are not possible with conventional HPs.
Inlet temperature to the low temperature source of the HP	The higher is the inlet temperature in the low source of the HP the higher is in general the COP of the HP, but the operational limits according to the manufacturer specifications must be considered. The inlet temperature has a maximum value (that will be indicated by the manufacturer) that cannot be exceeded.	The maximum inlet temperature in the low source of the HP depends on the HP. Usual values are around 20-30ºC.
Working temperatures in the DH	As lower are the supply and return temperatures in the DH network, better will be the performance of the whole thermal system. The heat losses in the DH network will be lower and the efficiency of the equipment (especially renewable energy systems) higher.	Existing DH networks are usually operated at quite high temperatures, being around 90ºC (or even higher) the supply temperature. New DH networks are being designed for lower supply temperatures of about 70ºC, with tendency to use even lower temperatures.

Water flow in different subsystems	In general high flows mean high energy consumption in pumps and/or larger pipe diameters. SC → depending on the SC. The manufacturer specifies the design flow for each SC HX → important to have similar flow rates in both sides when using water on both sides, in more general similar heat capacity rates should be realized HP → even they have a nominal design flow, HPs can operate with variable flows. As lower is the flow, higher will be the temperature difference between the inlet and outlet of the corresponding circuit, and vice versa. It should be designed considering the whole energy system. The temperature difference should not exceed the manufacturer specifications. DH → established by the users/load	SC: Indicated by the manufacturer, but as guidance, usual values are around 15-40 l/(h·m2); large collector fields around 14-16 l/(h m²)
Buffer tanks	The integration of buffer tanks is in many cases advisable. They can decrease the cycling of the heat pump or are needed for peak shifting of high solar yields and loads	
Pipes	As lower is the fluid velocity within the pipes, lower is the energy consumption of the pumps, but bigger pipes are needed which means higher costs.	Recommended value for fluid velocity within the pipes (for heating circulation) is 1-2 m/s, for long distances higher velocities would be reasonable, around 1,5-3 m/s.
Control strategy	A sophisticated and individual control strategy is necessary. The control strategy should be kept as simple as possible to achieve a more robust operation	

3. GENERAL GUIDELINES AND RECOMMENDATIONS TO HELP DESIGNERS TO SIZE A STES SYSTEM

The scope of this chapter is to provide general guidelines and recommendations to help anybody interested in STES systems without high knowledge about the technology to make a preliminary idea on the expected size of a STES system. Key issues on STES systems sizing are identified and explained for a better understanding of the problem concerning the design and sizing of STES systems.

3.1. MAIN FEATURES OF THE DIFFERENT STES TYPES – GENERAL CONCEPTUAL SCHEMES FOR STES SYSTEMS INTEGRATION

Within the EINSTEIN project three STES types have been considered: tank thermal energy storage (TTES), pit thermal energy storage (PTES) and borehole thermal energy storage (BTES). Each of the STES type has particular features that should be known for the selection of the most suitable STES type for each case.

Figure 12 shows the differences among the different STES types regarding the expected heat storage density. TTES (called HTES in Figure 12) is the STES type with the highest heat storage density, but it is as well the most expensive system. BTES has the lowest heat storage density and lowest cost. ATES may be a very good option but it depends on the availability of an acquirer that can be used for seasonal storage.

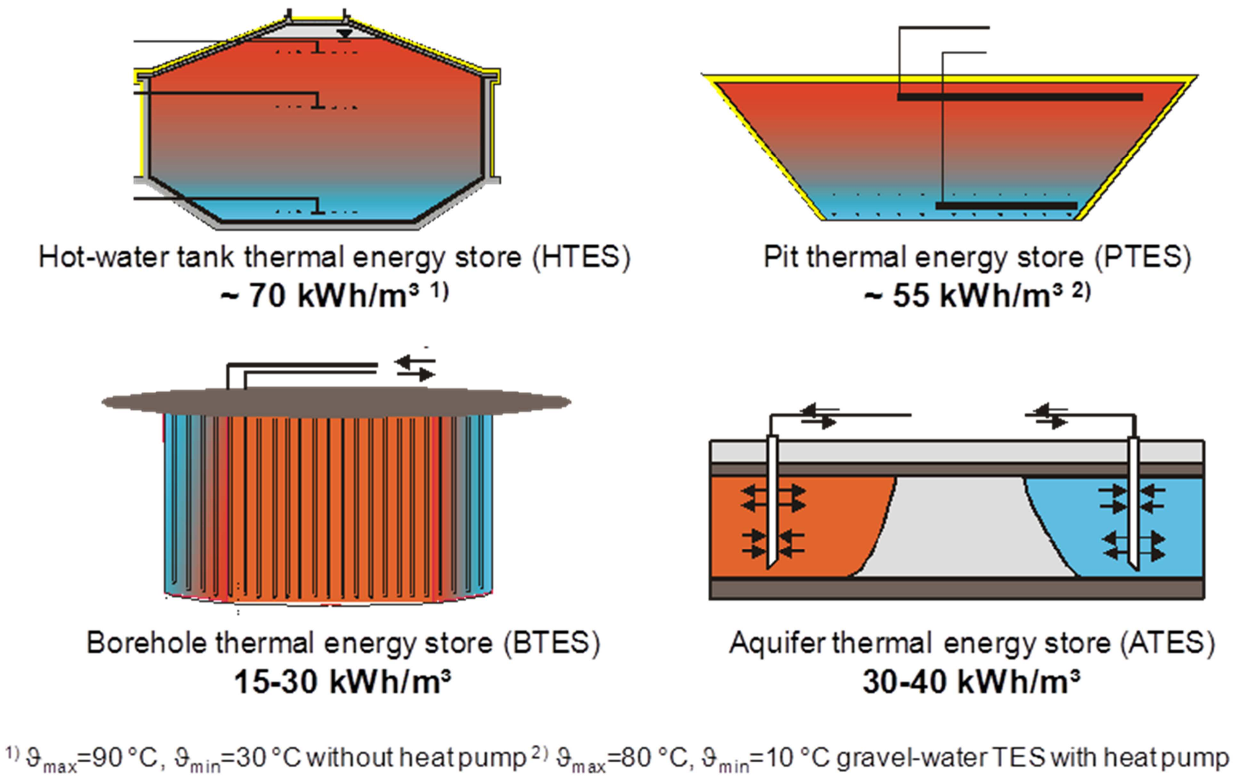

Figure 12: Different types of STES and their usable specific heat capacity (source: University of Stuttgart)

In the following chapters general conceptual schemes for STES systems considering different storage types are shown and explained (more information on different STES types is available on [17]).

3.1.1. Non-pressurized tank thermal energy storage without heat pump

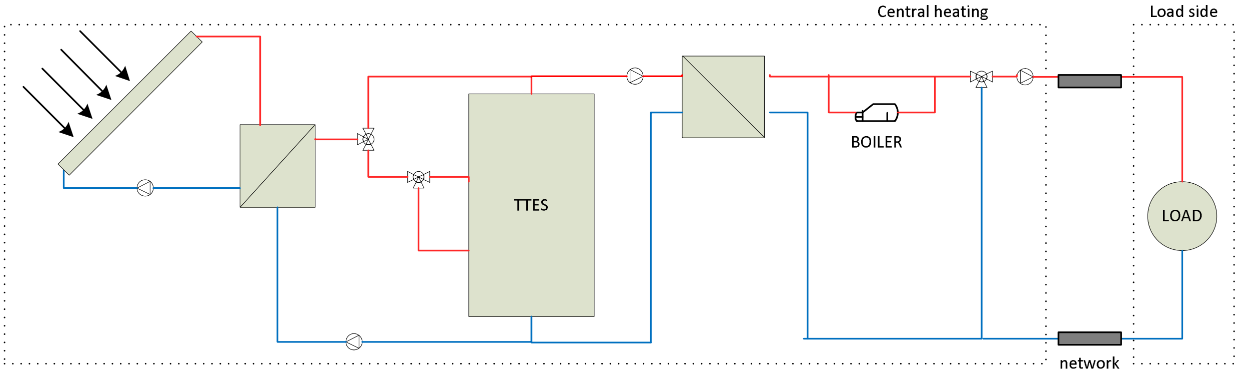

Figure 13: conceptual scheme for non-pressurized TTES without heat pump (source: Solites and Tecnalia)

Figure 13 shows a schematic for the basic system integration concept: the STES is built as a water volume in a tank, comparable with typical buffer storages in conventional heating plants. Compared to that a TTES has to be much larger due to the fact that it has to store much more heat referring to the task of storing heat seasonally.

With increasing storage size the cost for pressurized tanks is increasing more or less exponentially. Thus STES storages mainly are not pressurized due to economic reasons. This implies that the STES has to be separated from pressurized subsystems by heat exchangers like shown in the figure: on the load side the solar heat is fed from the pressurized solar circuit into the loading circuit of the TTES via an external heat exchanger. On the unload side the heat from the TTES is fed into the boiler circuit via another external heat exchanger.

In most cases external heat exchangers are most cost-effective than in TTES integrated, so called internal heat exchangers even with the additional pumps, pipes, control and installation work that is needed when using external instead of internal heat exchangers. Moreover, they are easier to maintain as internal ones.

The boiler itself is seldom connected to the TTES due to the fact that loading large water volumes like in a STES causes additional heat losses. Even more important is that heating a water storage not only by solar heat but with additional heaters comprises the risk of heating the entire storage volume by the additional heater, e.g. due to convection effects inside the storage. This might cause a severe reduction of possible solar heat gain if the storage is already heated by additional heat sources all days the solar circuit would like to heat up a cold storage.

3.1.2. Non-pressurized tank thermal energy storage with heat pump

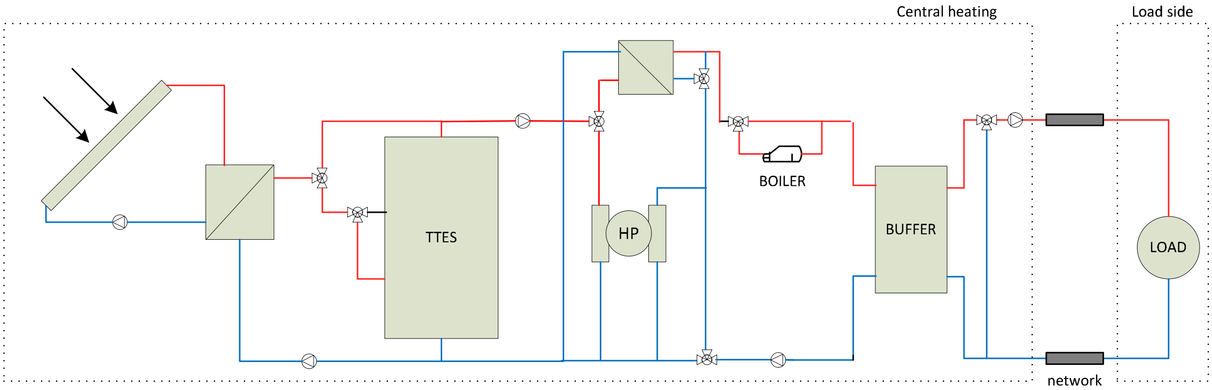

Figure 14: conceptual scheme for non-pressurized TTES with heat pump (source: Solites and Tecnalia)

When adding a HP to a STES some points have to be regarded very well: most of the standard HPs are developed for heat sources with temperatures below 30ºC. To unload a STES higher temperatures should be allowed. On the other hand typical HPs are not designed to deliver high temperatures like supply temperatures in the load side of 70 up to 90ºC. Thus also on the delivery side a HP has to be adapted to STES subsystem characteristics.

On the heat sink side the HP operates best on steady conditions regarding mass flow and temperature. If the HP is directly connected to the load side and mass flow and temperatures can vary within short time steps, like e.g. in a district heating net, the HP cannot follow this dynamic behaviour. For such cases the integration of an additional buffer storage helps a lot to enable good operation conditions for the HP, resulting in efficient COP's of the HP.

3.1.3. Pit thermal energy storage (PTES) with heat pump

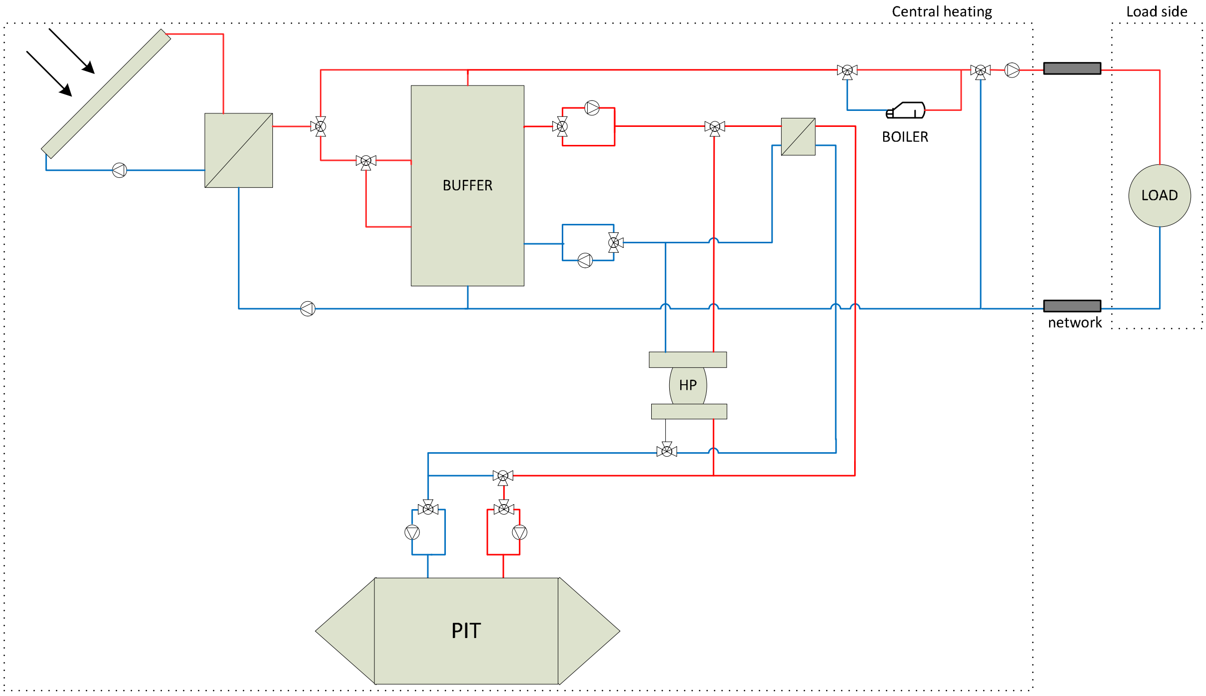

Figure 15: conceptual scheme for PIT with heat pump (source: Solites and Tecnalia)

One important difference between TTES and PTES is that PTES may need a buffer storage. The reason for this is the limited charging and discharging power of the PTES which can be lower than the thermal power of the collectors or the heat demand of the district heating network. The buffer storage should be considered therefore for peak-shifting the thermal power of the solar yield and the charging and discharging of the STES, if required.

The surface to volume ratio of PTES typically is higher and thus worse compared to TTES. In consequence, the heat losses are higher. This can lead to systems where the integration of a HP in a system with PTES is more economic than in a comparable system with TTES.

Due to lower heat storage density compared to TTES, PTES requires higher volumes than TTES. They are, however, less costly. The most suitable STES type (from technical and economical point of view) for a specific case depends on the particular boundary conditions.

3.1.4. Borehole thermal energy storage (BTES) with heat pump

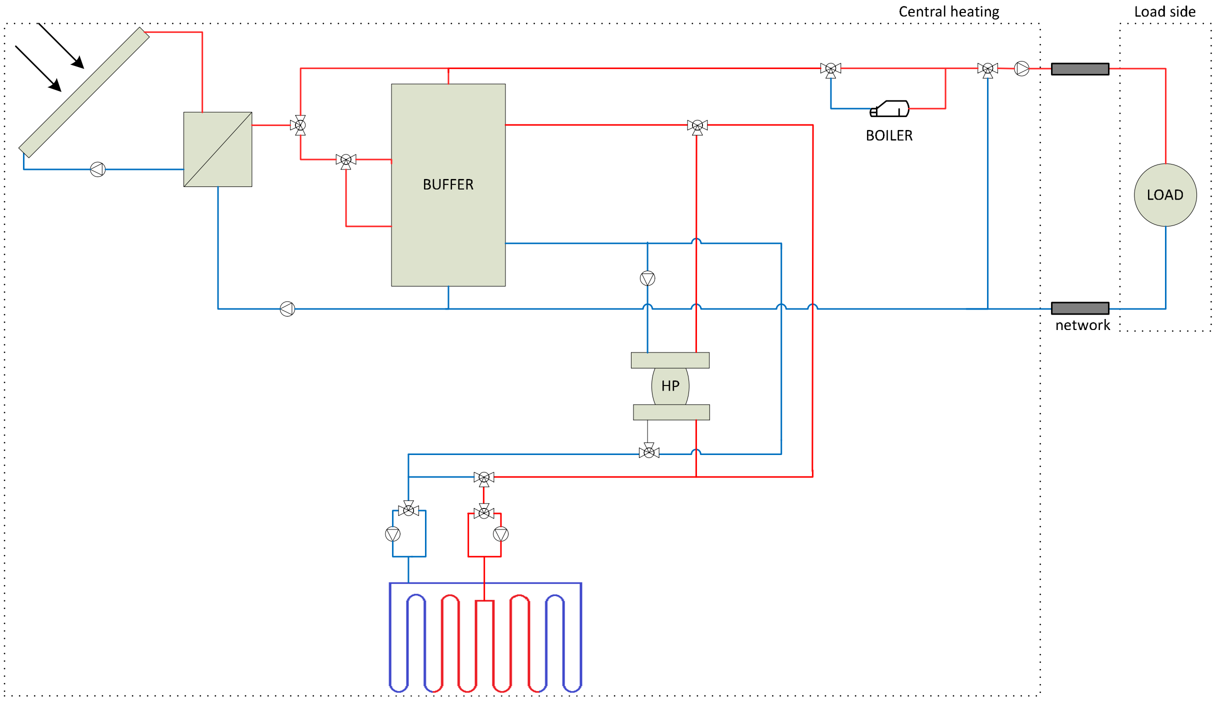

Figure 16: conceptual scheme for BTES with heat pump (source: Solites and Tecnalia)

Regarding the buffer storage, the same as said for PTES is applicable for BTES.

Compared to the schematic of a system with PTES as shown in the Figure 15, the only difference to the schematic with BTES as shown in Figure 16 is, beneath the other type of STES, the absence of the heat exchanger between STES and buffer storage. In consequence, the group of pumps between buffer storage and heat exchanger that is no longer necessary. As described above, the heat exchanger between buffer storage and pit is necessary by reason of separating the pressurized buffer storage circuit from the non-pressurized PTES and to avoid oxygen diffusion into the buffer storage water circuit. In a BTES the storage circuit consists of pressurized pipes. These pipes can withstand the pressure in a typical buffer storage circuit.

The buffer storage offers the big advantage that the BTES does not have to take all solar thermal load immediately when it occurs. The solar circuit delivers high heat power loads during the day time of high solar irradiation, only some few hours per day. If the BTES is designed to take all of this load immediately into its storage volume, the BTES needs a very long piping to the grid of the maximum load power. The buffer storage can store the peak power of solar thermal energy easily because of its water volume.

BTES are the STES type with higher volume requirements. They are as well the less costly out of the three STES types mentioned.

3.2. IMPORTANCE OF A CORRECT INTEGRATION OF SUBSYSTEMS

A Seasonal Thermal Energy Storage system with solar thermal energy and heat pump is a complex thermal system. The different subsystems cannot be sized independently but they are closely interrelated. The transient operation that characterizes STES systems makes mandatory to consider the whole system from a comprehensive point of view with a deep analysis on integration issues.

The Figure 17 clearly shows the importance of finding the best combination of solar area, STES volume and HP capacity. There are different combination options that are possible to achieve a certain solar fraction. All of them may be technically feasible, but not to optimize the system size and correctly consider integration aspects may give as a result a system that is much more costly than necessary. The problem of sizing a STES system is not to find a system that fulfils the specified energy savings, but to find the best combination of solar area, STES volume and heat pump capacity (in case there is a heat pump). According to the results that have been plotted in Figure 17, for a solar fraction of around 70% several combinations are possible with a heat cost that may vary from ~80€/MWh up to ~140€/MWh. This makes clear the need of finding the best system size, correctly considering the integration of different subsystems. Besides economic optimization, it should be mentioned that to optimize the system energetically is as well essential. In the following sections the key issues that should be taken into account for a well-balanced and energetically optimized STES system are explained.

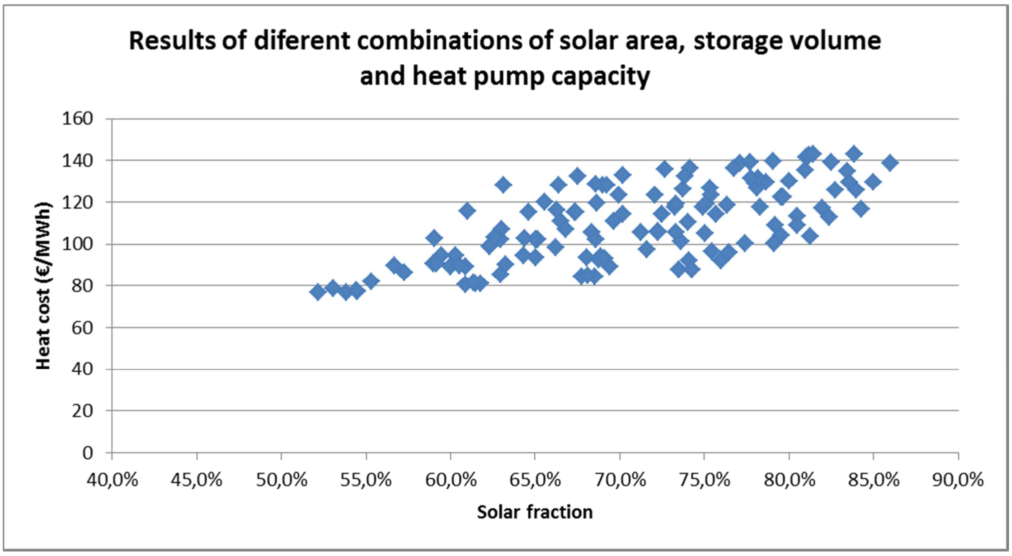

Figure 17: heat cost VS solar fraction of different combinations of solar area, STES volume and HP capacity

In the following sections some guidelines and recommendations that should be followed when sizing a STES system are given.

3.3. GENERAL GUIDELINES AND RECOMMENDATIONS FOR STES SIZING

3.3.1. Solar collector area

Solar collector area is probably the variable with the highest relevance in the final result. A small change in the solar collector area may cause significant differences in the system performance compared to other variables of the system. This does not mean that the rest of the parameters are less important, as for an optimized STES system (and therefore to optimize the energetic performance as well as economic figures) everything must be correctly sized, but it can be said that when roughly sizing a STES system the preliminary estimation of the solar collector area is the first step.

Usually the variable that is used to refer to the required solar collector field is the solar area per MWh of heat demand (m2/MWh). The required solar area will be higher as higher is the desired solar fraction.

The sizing of the solar collector area should be done according to the following statement: it should be ensured that the selected solar collector area is high enough to achieve the specified solar fraction and the lowest possible to avoid stagnation problems and over costs.

If the area of the solar field is too small it will not be possible to achieve the envisaged solar fraction; it should be increased therefore until it makes possible to bring the system up to the specified solar use. Once the solar area is roughly in the correct range, it should be ensured that there are not stagnation problems. Increasing the solar area unnecessarily means to increase the system cost (the cost related to the solar field may be as high as 40% of total costs). The lowest area possible, while fulfilling the mentioned requirements, should be therefore selected.

Problems related to stagnation are probably one of the most important issues in solar collectors. In a STES system this will happen when it is not possible to use the solar heat (because there is no heat demand at that moment and the STES is fully charged, or technical problems) but there is still solar radiation. The temperature in the solar collectors may increase so much that the fluid can evaporate and this may cause pause in the operation or even important damages in the equipment. To ensure a correct performance of the solar field the possibilities to reach stagnation conditions should be reduced correctly sizing the solar collector area.

The two important steps to ensure a correct sizing of the solar collector area can be summarized therefore in the following two points:

- Check the temperature profile in the STES; the maximum temperature and the charging profile should be reasonable
- Check the expected stagnation days with the selected solar area; the system should be sized to avoid reaching stagnation conditions.

Some preliminary studies have been performed within the Einstein project for 4 European cities (Amsterdam, Warsaw, Stockholm and Madrid). They have allowed to get preliminary information on the required solar collector area for different boundary conditions. The results shown in Figure 18 are only valid for the specific boundary conditions considered for the simulations (see Annex 1).

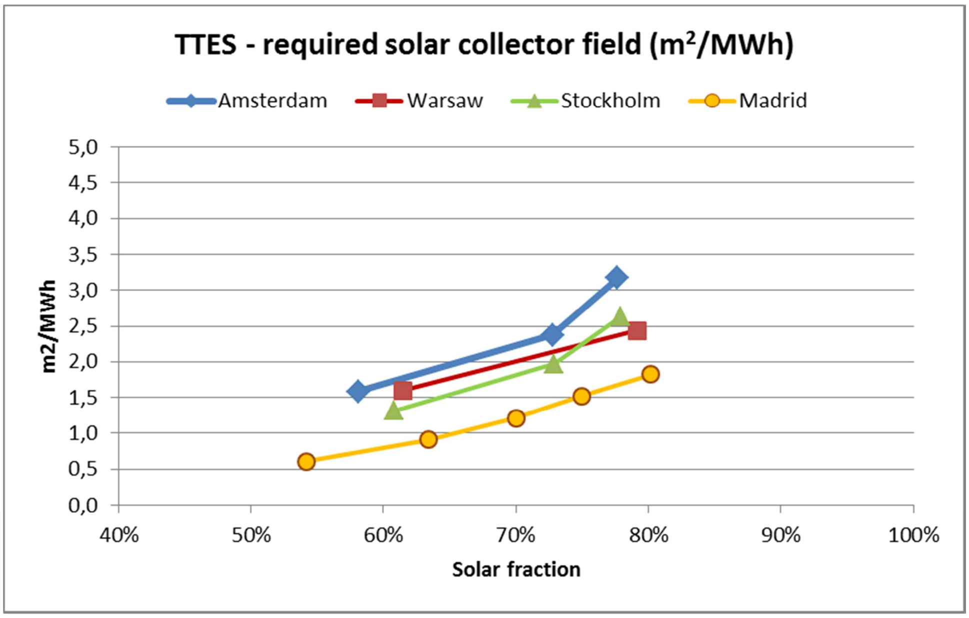

Figure 18: required solar collector area (m2/MWh) depending on the solar fraction for Amsterdam, Warsaw, Stockholm and Madrid. Considered STES type: TTES. Solar irradiance in the different locations: Amsterdam 1.129 kWh/(m2·a), Warsaw 1.106 kWh/(m2·a), Stockholm 1.204 kWh/(m2·a), Madrid 1.830 kWh/(m2·a).

The required solar collector area is in a similar range for Amsterdam, Warsaw and Stockholm, being significantly lower for Madrid. For a TTES system of around 70% of solar fraction, a solar collector field or ~1,2 m2/MWh is required in Madrid for the considered case study, while in the other considered locations higher areas are required, around 2,2 m2/MWh, 2 m2/MWh and 1,8 m2/MWh, respectively for Amsterdam, Warsaw and Stockholm. These values are useful only as guidance, as the specific required area must be calculated for each specific case. The heat profile and the incident solar radiation profile are, for instance, two variables highly affecting the requirements on the solar field.

The specific solar gain can be as well a good indicator on whether the estimated solar collector area is in the correct range. Assuming a solar fraction or around 50-60%, the specific simulation results performed within the Einstein project show the following values for the specific solar heat gain for the considered locations: Amsterdam, Warsaw and Stockholm around ~400-450kWh/m2, while in Madrid higher values around ~750-800 kWh/m2 are reasonable.

3.3.2. Seasonal thermal energy storage

The volume of the STES has to be aligned with the solar collector area. If it is too large, the maximum temperature that is achieved in the STES will be too low and it may not be possible to cover part of the heat load exclusively with the stored solar energy. If the volume is too small, the maximum temperature will be achieved very early in summer and stagnation problems may occur in the solar collectors and thus potential solar yields will be wasted.

A good indicator to check the quality of the integration between solar collectors and STES is the temperature profile within the STES. The following figures show the temperature profile in two different system sizes (the STES type is a TTES). Both of them are representative of a non-appropriate integration among subsystems. The figure on the left side shows a too short charging period. The temperature in the STES should be increasing until the end of the summer; in this figure, the maximum temperature is reached almost at the beginning of summer. During summer months stagnation conditions will be surely reached. The figure on the right side, on the other hand, represents the opposite situation: the storage volume in that case is too large. It can be easily concluded from the maximum temperature that is reached, which is not high enough for a TTES (assumed a non-pressurized tank and unless there are some particular limitations due to the materials that have been used for the construction of the tank). The maximum design temperature in non-pressurized TTES is usually around 95-98ºC (a bit lower temperature than boiling temperature of the water at atmospheric pressure). In the figure below the maximum temperature that is reached is 80ºC, meaning probably that that volume is too large for the selected solar collector field.

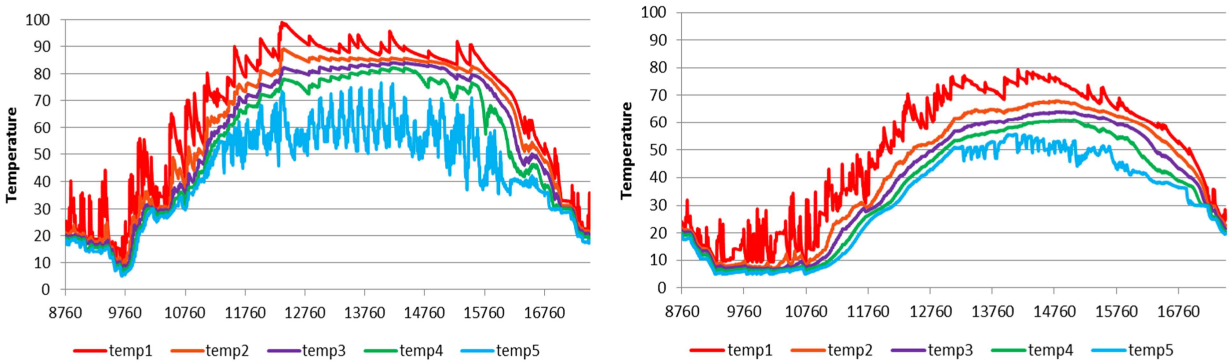

Figure 19: temperature profile inside the STES for two different system sizes, representing situations with too small (left) and too large (right) storage volumes

Regarding the required STES volume the following indications should be taken into account:

- The higher is the SF, the higher is usually the required STES volume per solar collector area
- The integration of the heat pump reduces the required STES volume compared to a STES system without a heat pump. The main influence of having a heat pump is that the temperature in the STES can further be reduced, the heat storage density is therefore increased, reducing the required STES volume for a certain solar heat to be delivered.
- PTES and BTES systems require higher volumes compared to TTES. The storage density of the different STES types (and therefore, the required volume) depends among other variables on the operation temperatures and in the thermal properties of the storage material. As guidance, in general terms, it can be said that PTES may require two times higher volume than a TTES and BTES around four times higher compared to TTES.

A common variable that is used to refer to the required STES volume is the ratio storage volume to collector area (m3/m2). It refers to the water equivalent volume, which differs from the real volume in case of PTES and BTES. The water equivalent volume is the volume that would be required in case the STES (PTES or BTES) had the storage density of a TTES.

Figure 20 shows the results obtained within the Einstein project (based on the assumptions and boundary conditions explained in Annex 1).

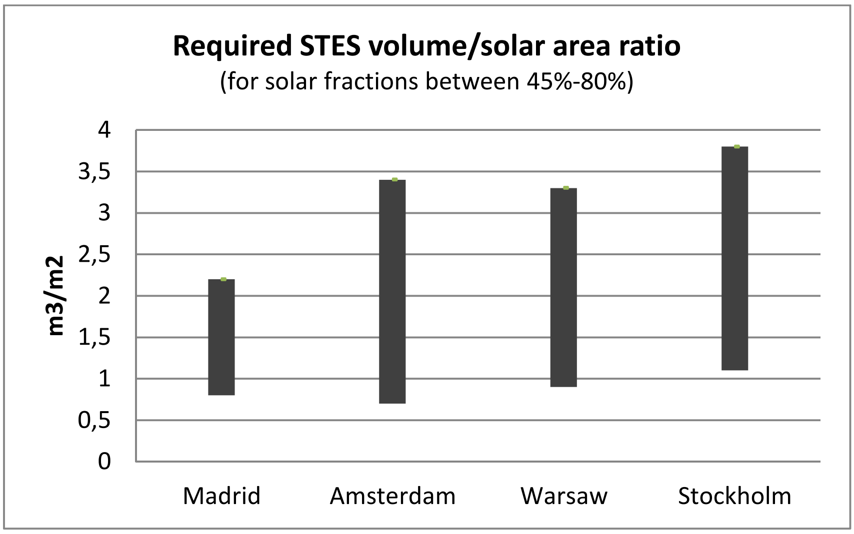

Figure 20: optimal storage volume / collector area ratio for Madrid, Amsterdam, Warsaw and Stockholm, for the boundary conditions and assumptions explained in Annex 1. The results include three STES types (TTES, GWTES and BTES); m3 refers to water equivalent volume.

Different type of STES, means different system performances. The three STES types under consideration have different storage densities. TTES is the STES type with the highest storage density and BTES with the lowest. As lower the storage density is, the higher is the required storage volume for a certain heat to be delivered from the storage. Another important difference is that the heat losses in PTES are usually higher, and even higher in BTES, compared to TTES (see section 3.4.). As higher the heat losses are, the higher will be the required solar area. These are two of the variables, among many others, influencing the design and performance of STES systems. According to them, BTES and PTES may require a larger volume compared to TTES due to lower heat storage density. They may require higher solar collector area due to higher heat losses. Regarding the optimal storage volume / solar area ratio, therefore, there may be differences depending on the storage type but a general rule cannot be stated as it depends on the specific characteristics of the design of the storage.

3.3.3. Heat pump integration into a STES system

How a heat pump may be integrated in a STES system has been explained in sections 3.1.2. (TTES), 3.1.3. (PTES) and 3.1.4. (BTES), in which conceptual schemes have been provided. The integration of the heat pump has to regard the transient operation characteristics of the heat pump itself and the subsystem the heat pump is integrated in: on the heat source side the heat pump has to be connected as direct as possible to the STES enabling direct unloading of the STES to the load side.

The heat pump causes extra cost not only for the heat pump itself but in addition for its system integration, its implementation in the control strategy and the operation cost. The hydraulics of the system are more complex as well. But on the other hand, some benefits are as well brought to the system.

An important issue when adding a heat pump to a STES is related to the operational limits of the heat pump. Most of the standard heat pumps are developed for heat sources with temperatures below 30ºC. To unload a STES higher temperatures should be allowed. On the other hand typical heat pumps are not designed to deliver high temperatures like supply temperatures in the load side of 70 up to 90ºC. Thus also on the delivery side a heat pump has to be adapted to STES subsystem characteristics. It should be considered that until this kind of systems are mature and well known in the market, non-standard heat pumps may be required, increasing their cost.

The main effect of the heat pump from technical point of view is that its operation reduces the bottom temperature of the storage. Depending on the operation conditions of the heat pump this effect may result in high benefits from the whole system point of view.

As already said, the main effect of the heat pump from technical point of view is that its operation reduces the temperature in the STES. Depending on the operation conditions of the heat pump this effect may result in high benefits from the whole system point of view.

Example: a TTES system for heat delivery to a district heating network operating at 70/30ºC of supply/return temperature. Maximum temperature in the TTES 90ºC.

The lowest temperature in the TTES in a system without heat pump is the return temperature of the load side. In the considered example: 30ºC.

The storage density of the TTES in a system without heat pump:

$$storage\ density = \rho \cdot c_p \cdot \Delta T = 1000 kg/m3 \cdot \frac{4{,}18}{3600}\ kWh/kgK \cdot (90-30)K$$

$$storage\ density = 69{,}7\ kWh/m^3$$

If a heat pump is integrated and assuming that it can work until the temperature in the TTES is 10ºC, then the storage density of the TTES would be:

$$storage\ density = 1000 kg/m3 \cdot \frac{4{,}18}{3600}\ kWh/kgK \cdot (90-10)K$$

$$storage\ density = 92{,}9\ kWh/m^3$$

The storage density is increased from ~70kWh/m3 to ~90kWh/m3 due to the integration of the heat pump. This means that for the same amount of energy to be stored, 22% smaller volume would be required.

The increase of the storage density means that with the same STES volume higher solar fractions may be achieved, or that for the same solar fraction a lower storage volume is required. The level of the mentioned benefits is strongly dependant on the particular working conditions and operational limits of the heat pump. The maximum temperature that the heat pump allows in the low temperature source should be significantly lower than the return temperature of the network so that the heat pump effect is beneficial. The maximum temperature that is allowed in the low source should be as well suitable for the characteristics of the thermal system, if it is very far from the return temperature the heat pump may not be able to operate.

Another benefit of reducing the temperature in the storage is that the efficiency of the solar collectors will increase, increasing therefore the solar heat produced with the same solar collectors field or in other words, reducing the required solar area for a certain amount of solar yield.

As said previously, the addition of a heat pump causes extra costs. Besides the higher investment cost due to the heat pump itself and other equipment required for system integration, the electricity consumption of the heat pump should be considered. However, due to the already explained issues, the solar fraction may be increased, leading to reduce the consumption of the auxiliary heating system (boiler, district heat…). The addition of a heat pump might better the total economics of a STES system despite the higher cost: the additional heat gain out of the STES via a heat pump can allow to earn more money than it has to be spent for the heat pump. The final energy and economic results will depend, however, on the energy generation framework and energy prices in each country.

It is clear therefore that it is not possible to find specific rules to define how a heat pump should be integrated into a STES system due to the plenty of very diverse issues that are present. In fact, the following figures visualize this last statement. Simulation results of STES systems with and without heat pump are shown for three different locations (Warsaw, Stockholm and Madrid). It can be clearly seen that the final effect of having a heat pump may be different depending on the particular boundary conditions. The simulations performed for Warsaw shows that the integration of a heat pump would be very beneficial in those conditions, for the case of Stockholm the benefit is not so high and in for the case study in Madrid the results show that the integration of a heat pump does not bring any reduction of the heat cost.

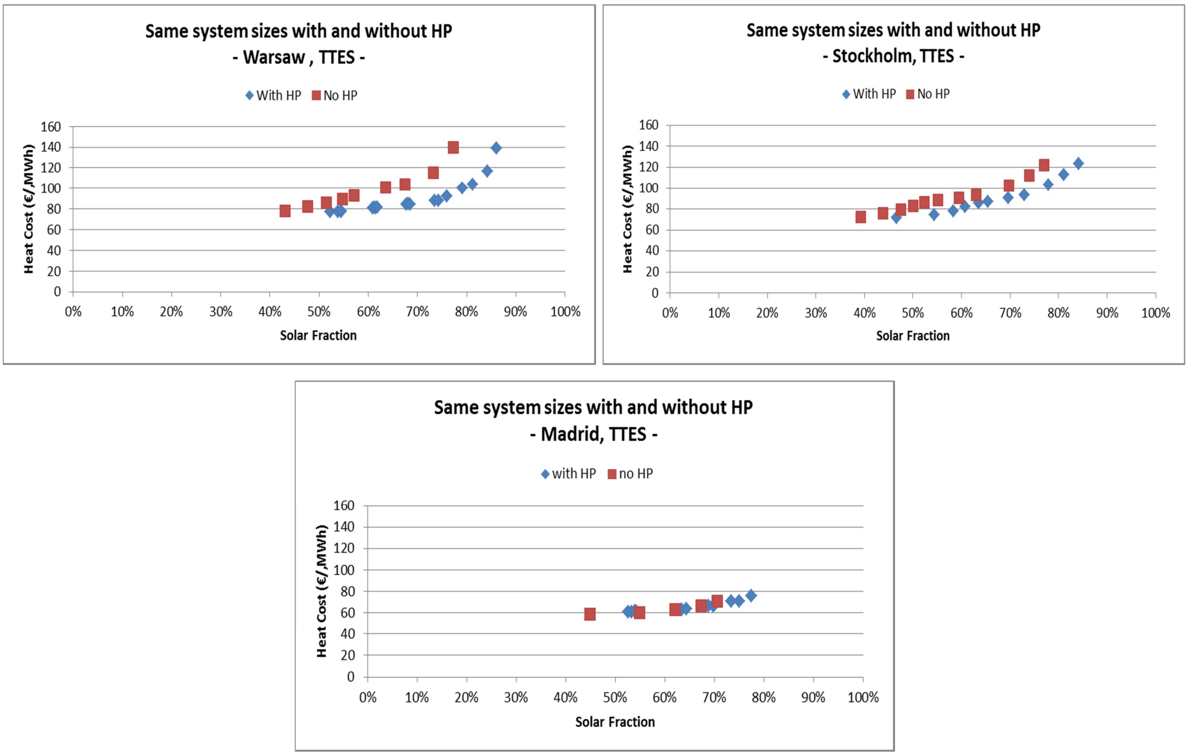

Figure 21: Influence of the heat pump: simulation results of STES systems with and without heat pump. Heat pump capacity that best suit in each case: Amsterdam 650-800kW, Warsaw 650-800kW, Stockholm 400-800kW, Madrid 350-550kW.

The heat pump should be well balanced into the thermal system: it should be aligned with the heat load and also with the STES volume. A too small heat pump for the available STES volume will mean not using all the potential of the thermal energy stored in the STES and the reduction of the temperature in the storage may be low. Too large heat pumps may reduce this temperature up to the minimum value very quickly, limiting the use of the STES and increasing the use of auxiliary equipment to deliver the required heat. A good indicator for the quality of this integration is the temperature profile inside the STES.

Figure 22 shows a possible temperature profile inside the STES in case there is not any heat pump integrated to the thermal system. The return temperature seems to be ~30ºC. The lowest temperature that the storage can be cooled down is therefore ~30ºC (the return temperature).

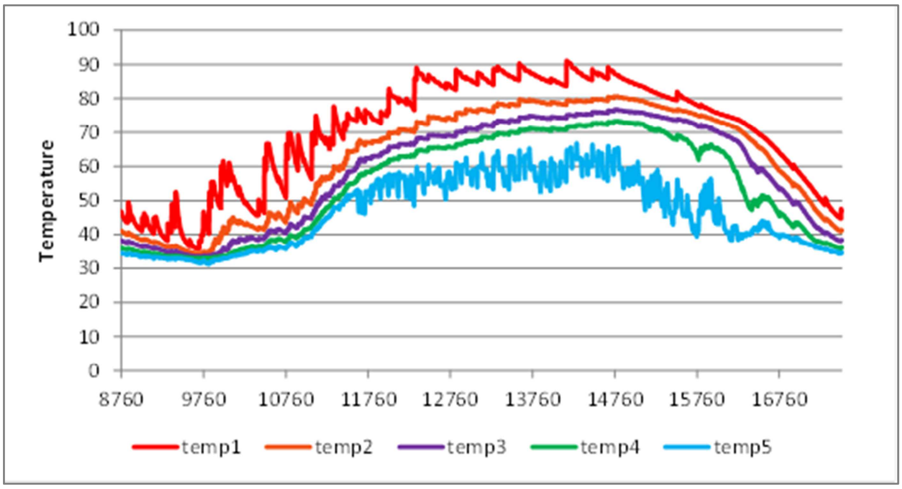

Figure 22: temperature profile inside the storage for a TTES without heat pump

Figure 23 shows a possible temperature profile inside the storage, having a heat pump integrated into the STES. The effect of the heat pump can be clearly observed: the temperature of the STES is significantly reduced. This reduction will depend on the technical specifications of the heat pump. In general terms, as lower is the minimum temperature allowed by the heat pump in the low source, the higher will be the obtained benefits, but the minimum acceptable temperature in the heat pump is linked to other technical features (as the maximum temperature that heat can be delivered, the COP, etc.), the decision on the most suitable technical features should be therefore taken based on a comprehensive assessment of the whole energy system. Independently of the characteristics of the heat pump, a minimum temperature must be fixed in order to avoid water to freeze due to the cooling effect of the heat pump into the STES.

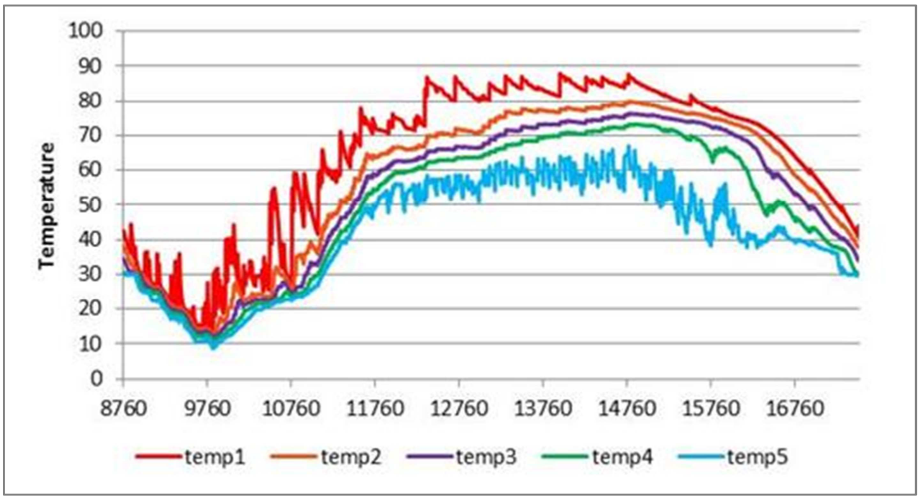

Figure 23: temperature profile inside the storage for a TTES with heat pump

Figure 24 and Figure 25 show a non-appropriate integration of the heat pump into the STES. In Figure 24, the heat pump capacity is too high for the STES volume under consideration. It is shown that the minimum temperature in the STES is reached very quickly and thus the heat pump cannot operate for a period of time, until the temperature in the storage increases again.

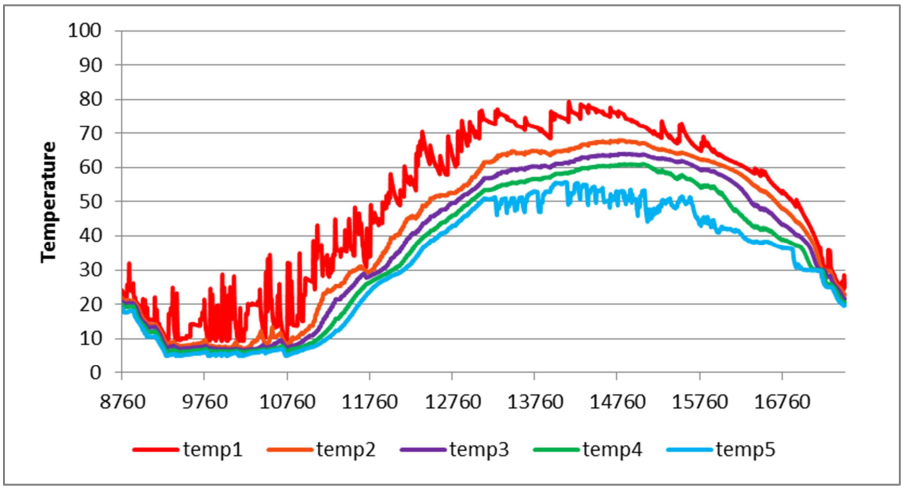

Figure 24: temperature profile inside the storage showing an inappropriate integration of the heat pump (too large)

Figure 25, on the other hand, shows a situation in which the heat pump is not well-balanced with the storage due to too low capacity. A small storage temperature reduction is shown, which is due to the heat pump operation, but it is too small to make use of all thermal energy within the STES. The insignificant benefits that are brought by the heat pump in this case will never justify the over costs and increase of complexity that its integration brings.

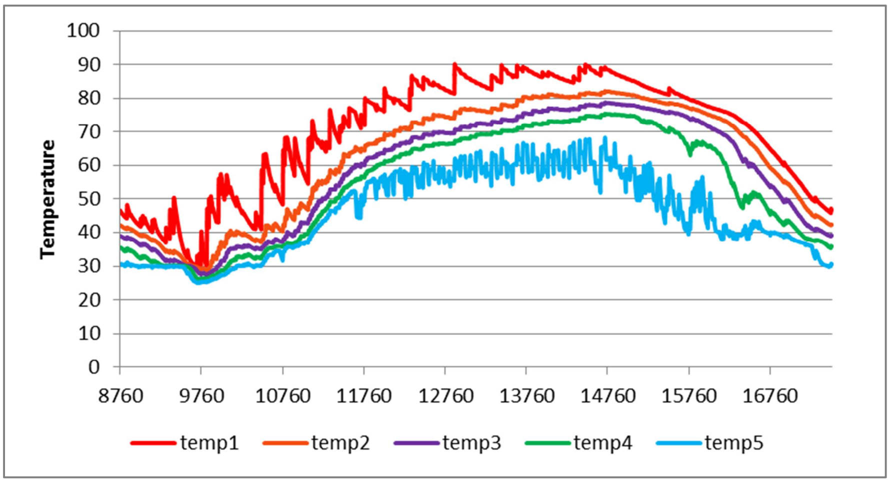

Figure 25: temperature profile inside the storage showing an inappropriate integration of a heat pump (too small)

3.4. COMPARISON OF DIFFERENT STES TYPES

Table 3 summarizes some important features related to the different STES types that should be considered when designing a STES system (more information on different STES types is available on [17]).

Table 3: important features for different STES types

	TTES	PTES	BTES
Temperature in the STES *(see* Table 2 *for more*	Usually they operate at the highest temperature among the three STES	The maximum temperature is used to be slightly lower than	Among the three STES types, BTES is the ones that works with the

information)	types under consideration. Maximum temperature in non-pressurized TTES 95-98ºC	TTES (~80-85ºC)	lowest maximum temperature (~60-75ºC)
Surface / volume ratio	The best value, lower than in PTES and BTES	Relatively high ratios, significantly higher than in TTES	Usually the highest value
Insulation	Usually insulation in all the surfaces: at the bottom, top and walls.	All the surfaces can be insulated but sometimes only insulation at the top. Considering existing plants, PTES are often poorer insulated than TTES	Only insulation at the top, due to the difficulties to add insulation at the bottom and periphery.
Heat losses (mainly depending on the above variables)	Although TTES usually operates at higher temperatures, due to the most favourable surface/volume ratio and unless they are poorly insulated, the heat losses are the lowest	Usually the heat losses are higher than TTES, although the operation temperature and insulation properties can be the same (usually lower and poorer, respectively), the surface/volume ratio is less favourable than in TTES.	For the same volume, the heat losses in BTES are higher than in PTES and TTES, due to the fact mainly that they are only insulated at the top.
Required volume	Due to higher storage density than PTES and BTES, the required volume is the lowest	Depending on the specific boundary conditions (thermal properties of the storage material, operation temperatures…) but the required volume may be around two times higher than TTES	Depending on the specific boundary conditions, but the required volume may be around four times higher than TTES
Investment cost	Usually highest specific cost (€/m3)	In terms of specific cost (€/m3), usually less expensive than TTES in and more expensive than BTES	Usually lowest specific cost (€/m3)
Cost-effectiveness (the most cost-effective STES depends on the	Although having the highest specific cost, due to the fact that a	Although requiring a higher volume than TTES, due to lower	Although requiring a higher volume than TTES and PTES, due to

particular boundary conditions of each project)	lower volume is required and it may be more efficient, TTES may be the most cost-effective STES	specific cost, PTES may also be the most cost-effective STES	lower specific cost, BTES may also be the most cost-effective STES

Figure 26 shows the results for a specific case study. The required system size for different STES types has been calculated, together with the heat cost in each case. The case study represents a STES system for a solar fraction of 58% and energy savings of around 38% (compared to a heating system with individual gas boilers). In the case of TTES a storage volume of 6.000m3 is required, while higher volumes are required for PTES and BTES, 12.200m3 and 30.400m3, respectively. PTES is the one that offers the lowest heat cost, ~75,5€/MWh, while the heat cost for TTES and BTES is 81,1€/MWh and 81,7 €/MWh, respectively. As explained in the above table, although requiring a higher volume, PTES may be more cost-effective than TTES (and/or BTES) depending on the specific boundary conditions. It should be highlighted, therefore, the importance of assessing all the STES types that are possible with the local boundary conditions. For the final decision on the best STES type, the heat cost may be one criterion, but not the only one. The space availability may be as well a key issue (see chapter 1).

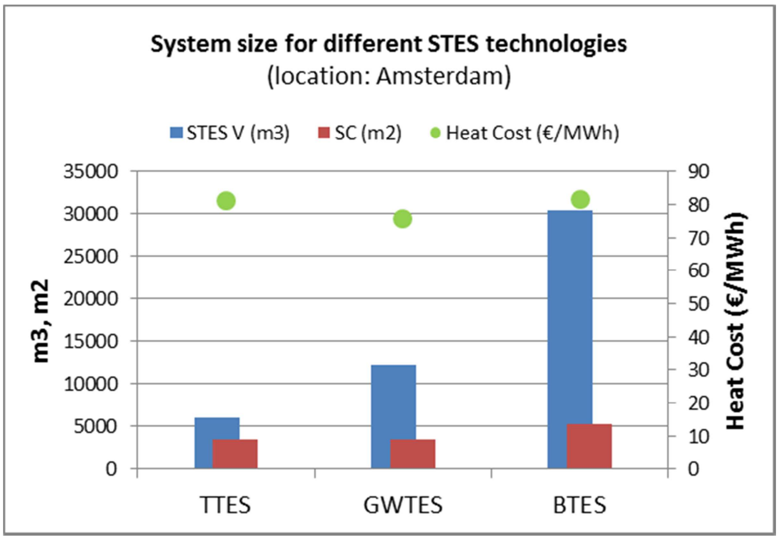

Figure 26: comparison of different STES types for a case study in Amsterdam, to achieve a solar fraction of 58% and primary energy savings of 38%.

3.5. GUIDELINES FOR ECONOMIC CALCULATIONS

Although there may be different criteria in the design of a STES system, economic criteria are usually the ones used to take the final decision. The information that is given here is not useful to calculate the investment cost of a new STES plant that is planned; they are given only as guidance. Technical performance may vary significantly depending on the boundary conditions, but economic figures are even more strongly linked to the specific boundary conditions. The cost of a new STES plant may be significantly far from the figures given here; there may be specific issues such as geological conditions, regulation, experience of the involved people, etc. that may be very favorable or unfavorable, increasing or decreasing the average values that are given. Nevertheless, due to the fact that STES is not a mature technology yet, to give some guidelines to roughly estimate the cost of such plants based on existing pilot plants and installations may be helpful.

3.5.1. Estimation of the cost of solar collectors

The cost of solar collectors depends on several factors. Depending on the manufacturer, technical specifications, place in which they will be installed (ground mounted or in the roof, characteristics of the roof in which they will be placed…), etc. different costs are expected. Figure 27 can be used for preliminary cost estimations.

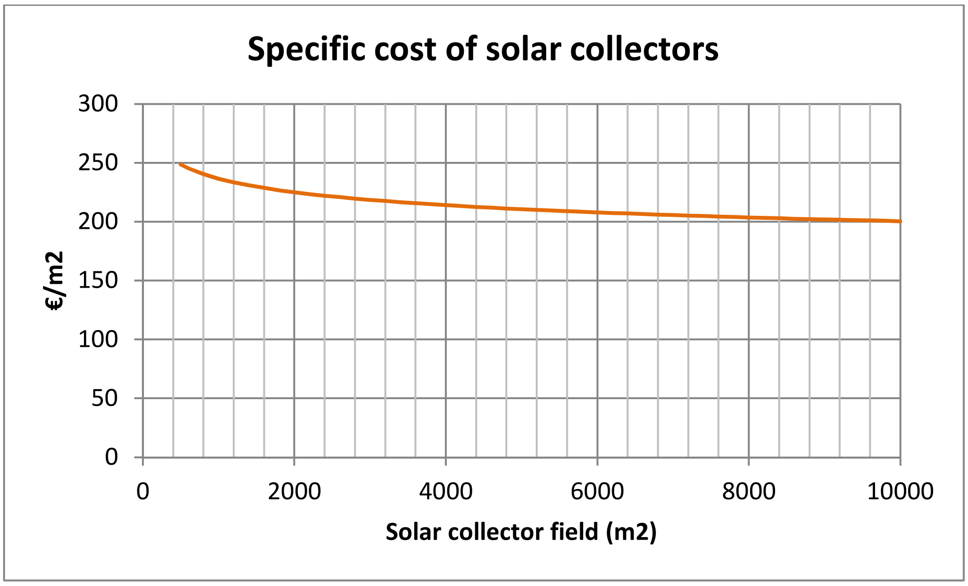

Figure 27: Specific cost of solar collectors. Source: Einstein project

3.5.2. Estimation of the cost of STES

It is not easy to estimate the cost of a STES as there are some real plants in operation in Denmark, several pilot plants in Germany, but in general terms they are not a mature technology yet and only limited number of installations have been built so far. Figure 28 shows the specific investment cost of seasonal thermal storages that have been built (and studied) in the last years. Based on this information, cost curves that are shown in Figure 29 have been developed. They can be used for preliminary cost estimation of different STES types (they refer only to the storage itself, not to the whole STES system).

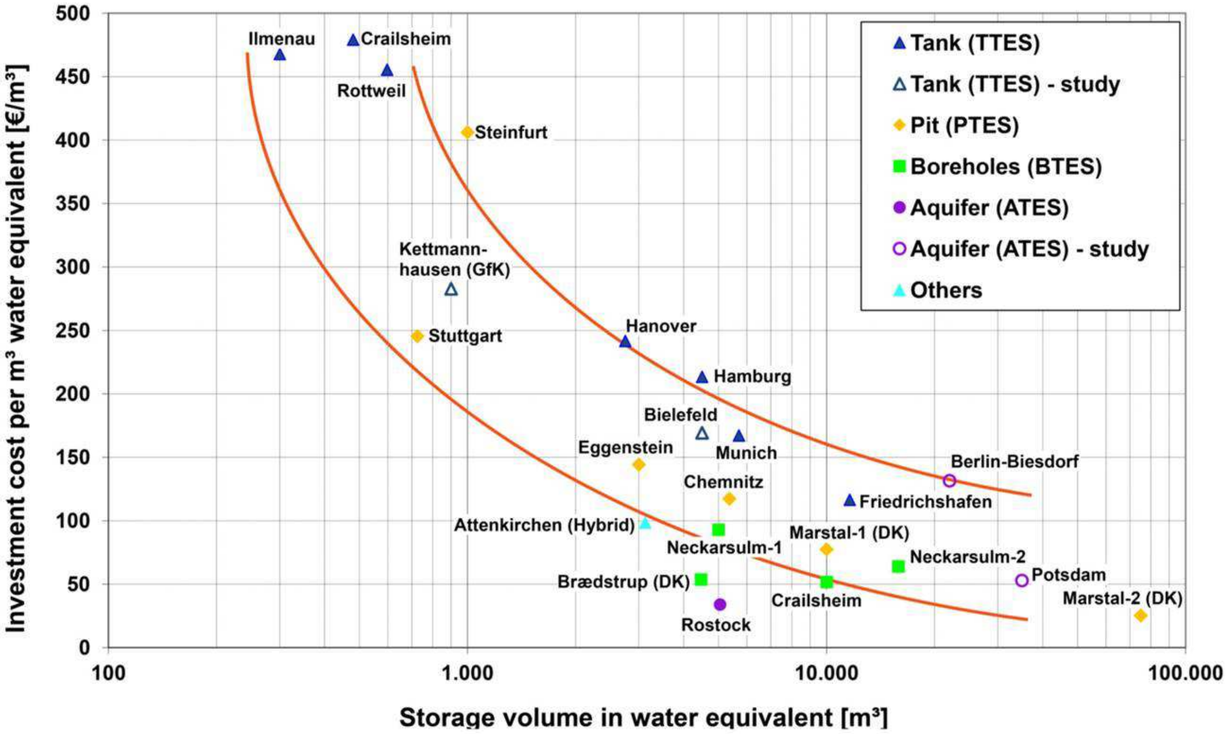

Figure 28: Investment cost per m3 water equivalent of seasonal thermal storages that have been built (and studied) in the last years (Source: Solites)

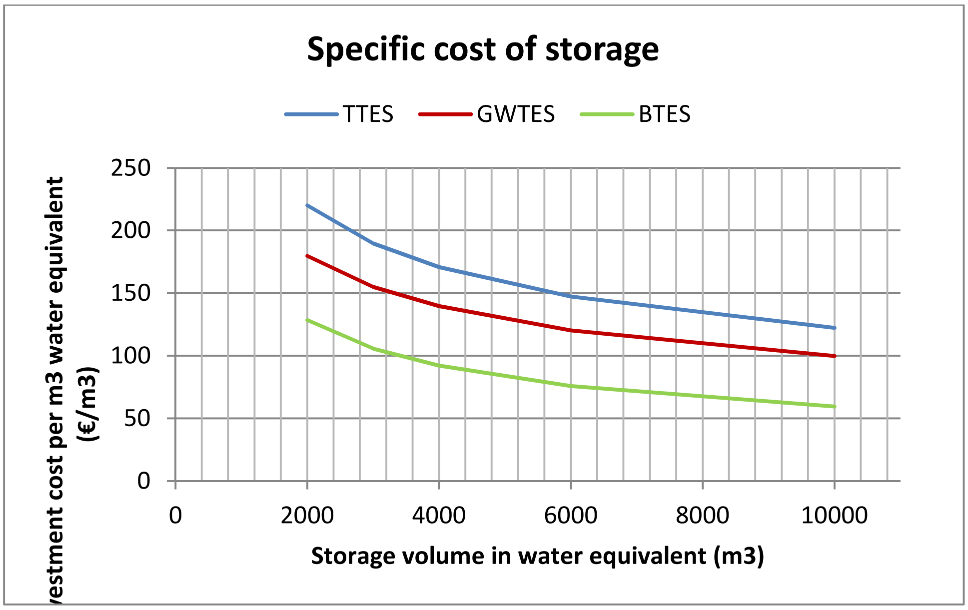

Figure 29: Investment cost per m3 water equivalent of seasonal thermal storages (Source: Einstein project, Tecnalia)

3.5.3. Estimation of the cost of the heat pump

As explained in section 3.3.3. the selected heat pump should have suitable technical specifications to be integrated into a STES and bring quantifiable benefits that justify the over costs and the increase of complexity due to its integration. The required specifications depend on the boundary conditions of the thermal system, the cost may significantly vary as well depending on these requirements. Figure 30 may be used for preliminary cost estimation of the heat pump to be integrated within a STES system.

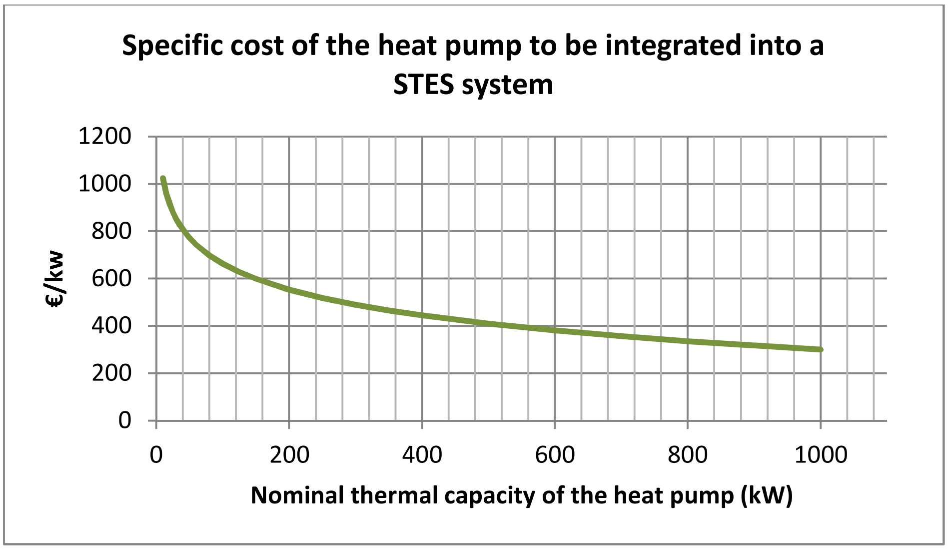

Figure 30: specific cost of the heat pump (source: Einstein project)

3.5.4. Operational and maintenance costs

The electricity consumption of STES systems without heat pump was analysed by [**18**] based on the performance of realized STES systems. According to this study, the electric consumption accounts for 1-2% of the total heat delivered to the district heating, including the energy consumptions of pumps and also the control system.

With a heat pump the total electricity consumption will be obviously higher, but it is not possible to give specific numbers about the expected electricity consumption as it may highly vary. Depending on the boundary conditions of the STES system and district heating network, energy prices, performance map of the heat pump, etc. very diverse options are feasible for the heat pump integration. The simulations that have been performed within the Einstein project, for instance, show that the total electricity consumption in a STES with heat pump may vary from 6% up to 10% of total heat delivered to the district heating network. It may be lower as well as higher, however, depending on the several and so diverse technical and non-technical boundary conditions.

STES systems give higher solar fractions than conventional large solar thermal plants. But unless they are designed for a 100% of solar fraction they require an auxiliary heating system to cover the part of the heat load that is not covered by solar energy. This is usually covered with a centralized gas boiler in case of small and medium scale plants, in these cases there is usually a district heating network for the STES plant itself. A STES plant can be integrated as well into a large district heating network that is fed with different heat sources. In that case, the load that is not covered by solar energy will be covered by the district heat. The cost of the auxiliary heating (understanding auxiliary heating as the part of the heat load that is not covered with the heat coming from the STES system) will depend, therefore, on the system complexion. For small-medium scale STES plants that operate with gas boilers, the operational costs will depend on the gas cost for the owner of the plant. As it is obvious, the operational costs will be lower as higher is the solar fraction.

As well as other costs, maintenance costs may as well vary significantly from one site to another. The system size, labour costs, experience of the company, etc. are some of the factors affecting the specific cost related to maintenance work. According to the report “Renewables for Heating and Cooling – Untapped Potential” by International Energy Agency [19] the maintenance costs of solar thermal plants are around 1-3% of the total investment.

3.5.5. **Influence of the size**

STES systems require a minimum storage size so that they can be technically feasible (see section 1.2.1.). The surface to volume ratio of the storage is too high for small storages to ensure a seasonal performance of the stored heat (with common insulation materials). As explained in Table 3, the heat loss rate of the storage is closely related to the storage surface to volume ratio, as higher is this parameter, the higher are the heat losses. For very small volumes, the heat losses are so high that is not technically feasible to store heat for a long period of time. The only solution from technical point of view for small storages for seasonal use is to use insulation with much better properties, such as vacuum insulated hot water tanks. It should be noted, however, that although they are commercially available up to about 100 m3, the cost is relatively high.

When talking about STES systems that are implemented at district level as a centralized heating plant, the minimum system size that is required so that STES system can be technically feasible is around 100-150 dwellings ([1], [20]). Besides technical feasibility, to ensure economic feasibility very large STES systems are required within current energy and market conditions.

The following figure shows how the heat cost of a STES system decreases as higher is the heat load to be provided. It refers to a specific case study but in general terms similar tendency is expected for other situations.

The heat cost in Figure 31 refers to the heat cost of the entire thermal system which is formed by solar collectors, STES, heat pump and gas boiler and it delivers all the heat that the connected buildings require. The calculated heat cost refers to the cost of all the heat that is delivered to the buildings, in concrete in this case, ~60% comes from solar energy, ~34% of the heat load is delivered by the boiler and the rest ~6% is related to the electricity consumption of the heat pump. It can be seen that for very large districts (around 10.000MWh/a of heat load) the heat cost in the assumed conditions is ~60€/MWh. According to Eurostat [21] the gas price for domestic use in Stockholm is 63,9 €/MWh (2014), concluding that STES systems may be competitive depending on the boundary conditions. This is confirmed as well with the Danish STES systems: the very large scale STES systems that are built in Denmark and thanks to the current energy framework that is favourable for renewable energy systems, STES plants are competitive without the need of subsidies.

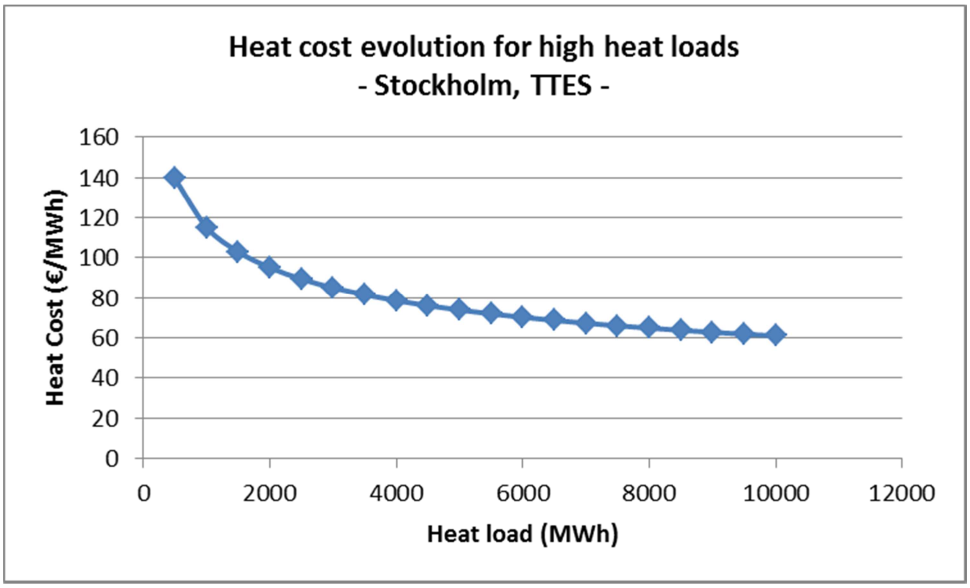

Figure 31: heat cost evolution against heat load for a STES system with hot water tank and a solar fraction around 60% for Stockholm

3.5.6. **Heat cost of STES systems**

In this chapter some specific results that have been obtained within the Einstein project are collected. The following figures show the heat cost of the STES system versus the solar fraction for different STES types (TTES, GWTES and BTES) for four European cities: Amsterdam, Warsaw, Stockholm and Madrid, representing different heat loads and weather conditions. The calculated heat cost is the cost of all the heat that has been provided to the buildings by the entire thermal system, including the part of the heat load that is not covered by solar energy.

The obtained heat costs cannot be generalized. They are linked to the specific boundary conditions in which the simulations have been carried out.

Concerning the obtained results for different locations, while the heat costs for the case studies in Amsterdam, Warsaw and Stockholm are in a similar range (around 70-90€/MWh), the heat cost in the case study considered for Madrid is lower (around 60-70€/MWh). The main reason is the higher solar radiation available in Madrid (~1800kWh/(m2·a)) compared to the rest of the cities (~1.100-1.200 kWh/(m2·a)). This fact reduces the required solar collector area, reducing consequently the total investment cost.

In general terms, it can be seen that there are not huge differences between different STES types considered, meaning that any of the storage types should be disregarded without a deeper analysis. As expected, higher solar fractions mean higher heat costs. It is worth to be mentioned, however, that STES systems are one of the few technologies that allow covering the 100% of the heat load by renewable energy. Although the performed simulations do not cover all the solar fraction range, suitable sizes can be found for solar fractions around 100%, although the heat cost may not be economically competitive within current energy prices. It is not easy, however, to cover high fractions with renewable energy being cost competitive. The key question is, therefore, whether the STES systems can be more competitive than other alternatives for high renewable energy fractions. Nevertheless, it should not be forgotten that this may significantly change in the future with the increase of fossil fuel prices.

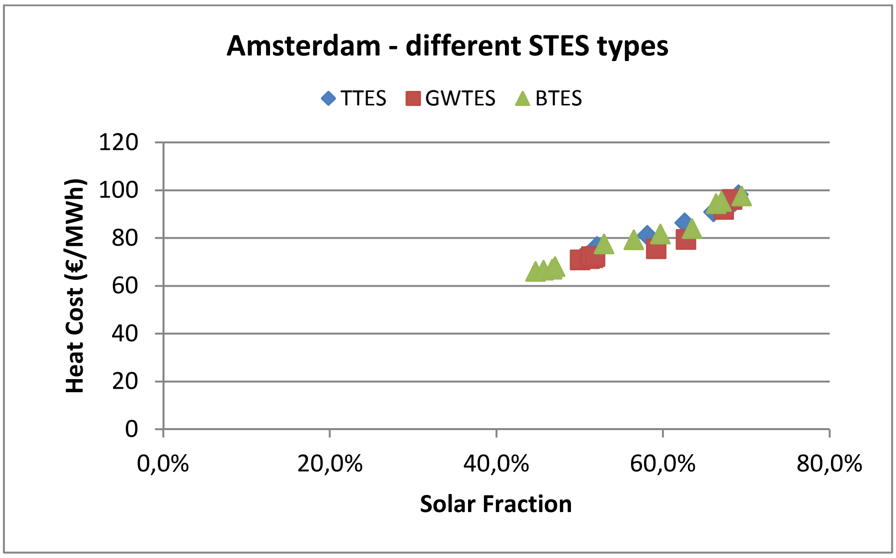

Figure 32: heat cost depending on the solar fraction for the considered case study in Amsterdam. Boundary conditions of the simulations according to Annex 1.

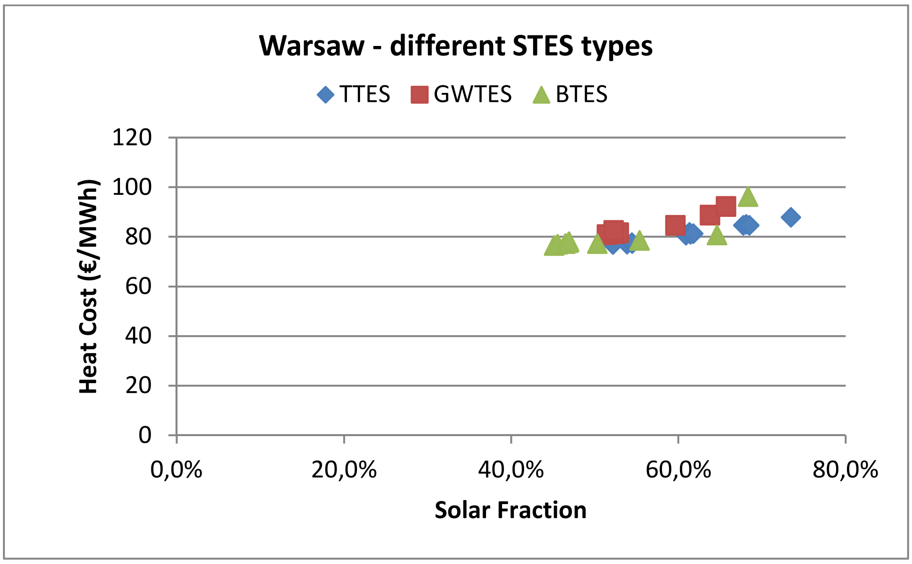

Figure 33: heat cost depending on the solar fraction for the considered case study in Warsaw. Boundary conditions of the simulations according to Annex 1.

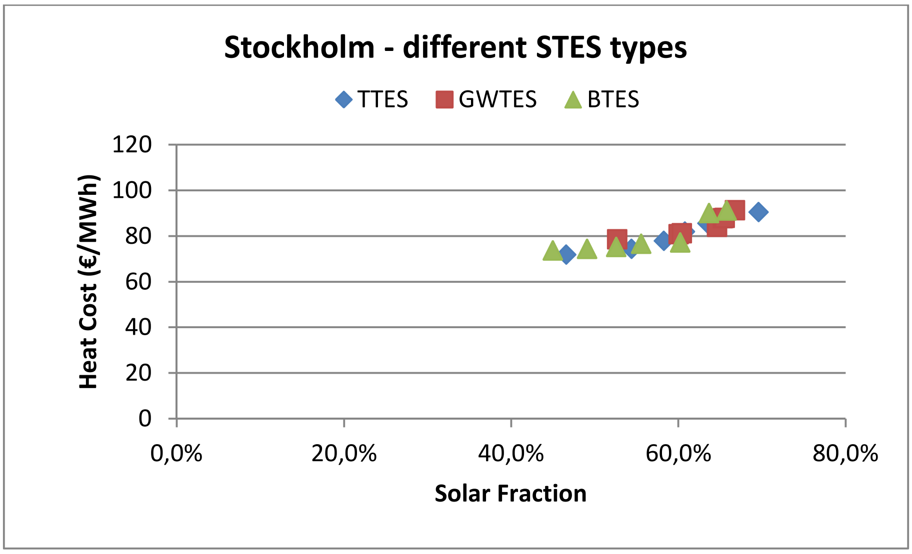

Figure 34: heat cost depending on the solar fraction for the considered case study in Stockholm. Boundary conditions of the simulations according to Annex 1.

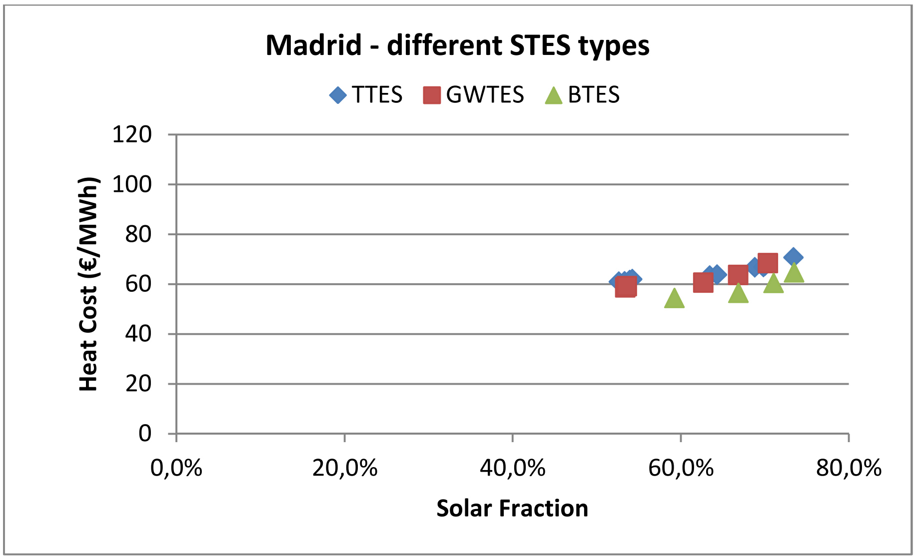

Figure 35: heat cost depending on the solar fraction for the considered case study in Madrid. Boundary conditions of the simulations according to Annex 1.

4. CONCLUSIONS

The aim of this report has been to provide useful information and general guidelines that may be useful for a preliminary assessment of a new STES system. When planning a STES system, a diversity of influencing boundary conditions should be properly considered, which should be assessed in a holistic approach. The report focuses on STES systems with solar thermal energy and heat pump. When talking about seasonal storage, three different types have been considered: TTES, PTES and BTES.

Planning the integration and construction of a STES system is a process consisting of numerous steps until the system is in operation and optimised. The scope of this assessment is for the first predesign of the concept. For a concrete planning of a STES system a more detailed design of the system needs to be developed. As said during the report, a detailed design of a STES system requires the realization of specific calculations, so that particular boundary conditions are considered in enough detail and the optimized STES system for the specific case study can be concluded.

Especial mention must be made of the fact that the report focuses on STES systems with heat pump. The integration of the heat pump gives one dimension more to the problem of the STES systems design, which makes even more difficult the sizing of such systems. The heat pump has to be well-balanced with both STES system and the load, as it is directly or indirectly connected to both elements. The many variables that are involved when integrating a heat pump within a STES system makes difficult to get concrete design values that are useful for a large range of boundary conditions. The heat pump has a strong impact on the commonly used ratios, such as the required solar collector area per heat demand (m2/MWh) and the required storage volume per solar area (m3/m2). But it is not possible to indicate the best values that are useful for a large range of situations, as besides technical boundary conditions, non-technical factors such as energy prices and primary energy factors that are specific for each country, plays an important role when defining the most suitable concept for the integration of the heat pump.

As it is reflected in the report, a lot of factors and boundary conditions must be well regarded when designing a STES system. Enough attention should be paid to all of them. Small variations on variables when designing the system may have a relevant impact on the feasibility of the STES plant. The same can be stated about the many of the boundary conditions that are present; there may be unfavourable boundary conditions that are an important barrier for the success of a STES system. It is important therefore to identify them as soon as possible, to act on them if possible. The report has provided an overview of the most important issues to be considered in initial steps.

In line with the above statement, it should not be forgotten that the unique way of designing correctly a STES system is the comprehensive approach, paying enough attention to the integration issues of different subsystems. The thermal system should be considered as a whole; it is not possible to independently size the different subsystems.

STES systems are not a mature technology yet. There are several pilot plants in Germany, several large plants in operation in Denmark and a few installations more all over the world, but in general the number of plants in operation is low and STES systems are not a known technology yet. The information that is available in the literature is as well very scarce. This report aims to contribute to this situation with providing guidelines and recommendations regarding the planning and preliminary design of STES systems.

ANNEX I

Simulations for chapter 3 have been carried out according to the following boundary conditions:

- Simulations have been performed with Transient System Simulation (TRNSYS) program [22]
- Hydraulic schemes for TTES, PTES and BTES shown in Figure 14, Figure 15 and Figure 16, respectively. A STES system with solar thermal energy and heat pump has been simulated. The heat produced by the STES plant is delivered to the customers through a district heating network, being the supply/return temperatures of 75/35ºC.
- As PTES a gravel-water thermal energy storage (GWTES) has been considered, with a mean volumetric specific heat capacity of 2,4 MJ/m^{3}K. Regarding BTES, a mean volumetric specific heat capacity of 2,2, MJ/m3K has been considered and each borehole is 50m deep, has a radius of 0,1m and the spacing is 2,5m.
- Heat delivery to residential buildings; district size: 200 dwellings.
- Heat loads: In [23] different load profiles for district heating networks have been developed. The base for the profile is the profile of the IEA Task 26 building [24]. The load for space heating and hot water preparation is temporarily distributed by standardized normal distribution taking the simultaneity factor for district heating networks [25] into account. Total heat loads for the four locations used for simulations in table A1.
- Weather data based on Meteonorm database (see table A1)
- Features of the considered heat pump: the evaporator inlet temperature is limited to 35ºC. Slightly higher temperatures are possible thanks to a return flow mixing strategy. The heat pump can produce heat up to 70ºC.
- For the comparison of the efficiency of different system concepts mainly the following two parameters have been used:

Solar Fraction, calculated according to the following expression:

$$SF = \frac{Q_{load} - Q_{aux}}{Q_{load}} = \left(1 - \frac{Q_{aux}}{Q_{load}}\right)$$

Fractional primary energy savings (compared to a system that covers the heat demand by individual natural gas boilers):

$$F_{save,PE} = 1 - \frac{\sum_i \frac{Q_{aux,i}}{\eta_{aux,i}} \cdot f_{PE,aux,i} + \sum_i E_{elec,i} \cdot f_{PE,aux,i}}{\sum_i \frac{Q_{aux,ref,i}}{\eta_{aux,ref,i}} \cdot f_{PE,aux,ref,i} + \sum_i E_{elec,ref,i} \cdot f_{PE,aux,i}}$$

Where:

Q_{load}: heat load delivered by the system, including distribution heat losses

Q_{aux}: auxiliary heat delivered to the system (by boilers, electric demand of heat pump…)

η: efficiency of heat production from fuel, natural gas boiler: 0,9

f_{PE}: primary energy factor of fuels:

- Natural gas: 1,3
- Electricity: 2,3

Economic calculations are based on the following assumptions:

- Gas and electricity prices for different locations according to Eurostat [21] (see table A1)
- Cost of solar collectors, STES and heat pump according to the curves in Figure 36. Other costs (auxiliary equipment) have been estimated in 25% of the total investment cost of solar collectors, STES and heat pump. Maintenance costs have been estimated in 1,5% of total investment cost, according to the criteria proposed by IEA [19]

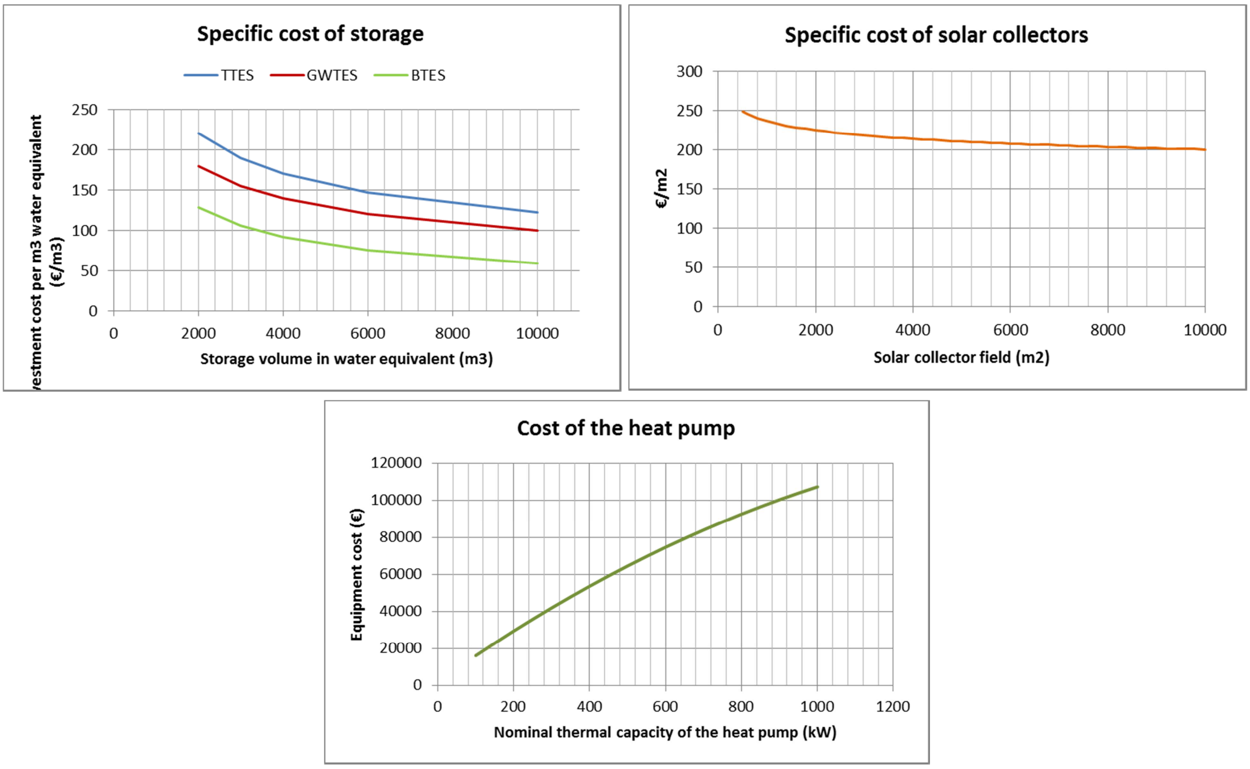

Figure 36: Specific cost of storage, specific cost of solar collectors and cost of the heat pump used for the simulations

- "Heat cost" refers to the cost of producing all the heat delivered to the buildings, including therefore solar heat as well as the heat produced by the boiler. It has been calculated according to the following formulas:

$$Heat\ cost = \frac{I_a + O\&M}{Q_{load}}$$

$$I_a = z_{coll} + z_{STES} + z_{HP} + z_{aux}$$

Where:

Ia: annual investment cost

O&M: operational and maintenance costs

z_i: for each element (solar collectors, STES, heat pump and auxiliary equipment):

$$Z_i = Inv_i \cdot \frac{i \cdot (1+i)^{ni}}{(1+i)^{ni} - 1}$$

Where:

Inv_i: investment cost of component i (collectors, STES, heat pump and auxiliary equipment)

i: annual interest rate (3%)

ni: equipment lifetime (25, 50, 20 and 15 years for solar collectors, STES, heat pump and auxiliary equipment, respectively

Table A1: heat load and solar irradiation of the four locations used for simulations

	Heat load (MWh/a)	Solar irradiation (kWh/m2·a)	Energy price (gas/electricity) (€/MWh)
Amsterdam	2210	1.129	29 / 77
Warsaw	2768	1.106	37 / 78
Stockholm	3424	1.204	38 / 68
Madrid	1481	1.830	37 / 115

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