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REVIEW OF SEASONAL HEAT STORAGE IN LARGE BASINS: WATER TANKS AND GRAVEL-WATER PITS

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Abstract

In order to respond to climatic change, many efforts have been made to reduce harmful gas emissions. According to energy policies, an important goal is the implementation of renewable energy sources, as well as electrical and oil combustion savings through energy conservation. This paper focuses on an extensive review of the technologies developed, so far, for central solar heating systems employing seasonal sensible water storage in artificial large scale basins. Among technologies developed since the late 70s, the use of underground spaces as an energy storage medium - Underground Thermal Energy Storage (UTES) - has been investigated and closely observed in experimental plants in many countries, most of them, as part of government programmes. These projects attempt to optimise technical and economic aspects within an international knowledge exchange; as a result, UTES is becoming a reliable option to save energy through energy conservation. Other alternatives to UTES include large water tanks and gravel-water pits, also called man-made or artificial aquifers. This implies developing this technology by construction and leaving natural aquifers

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untouched. The present article reviews most studies and results obtained in this particular area to show the technical and economical feasibility for each system and specifics problems occurred during construction and operation. Advantages and disadvantages are pointed out to compare both alternatives. The projects discussed have been carried out mainly in European states with some references to other countries.

Keywords: thermal energy storage, energy conservation, artificial aquifers, CSHPSS.

1. Introduction

Large-scale consumption of fossils fuels must diminish in order to reduce CO_2, SO_x and NO_x emissions to the atmosphere; moreover, this energy source is being limited by factors such as natural source depletion, environmental damage and economics. For these reasons, many governments have decided to strengthen their national efforts to increase the deployment of energy conservation technologies and increase utilization of renewable energy sources. However, renewable energy sources are only a small contribution to the total energy demand, for several reasons varying from cost effectiveness to long-term technological reliability. Therefore, further attempts are being made to resolve these issues, especially for many new energy storage technologies and concepts that have not yet been implemented on a large scale in the market.

Heat storage for solar thermal applications is a way to compensate the mismatch between heat production and energy needs. Since fluctuating energy sources generate energy supply at different times from the demand, the temporary excess will be wasted. In this way, heat storage improves the efficient utilization of renewable energy sources and energy conservation [1]. Heat storage can also be used for cooling to reduce or eliminate the demand for electricity, including the most expensive electrical energy that is generated during periods of peak power demand [2].

Seasonal storage of solar thermal energy for space heating purposes has been the subject of many previous investigations and has also found practical applications in the past. Seasonal storage of thermal energy was proposed in the USA during the 1960s and research projects were carried out in the 1970s. The technology of seasonal heat storage has been under investigation in Europe since the mid 70s within large-scale solar heating projects. The first demonstration plants were developed in Sweden in 1978/79 [3] based on results from a national research programme. The seasonal storage concept research work continued within the IEA (International Energy Agency) “Solar Heating and Cooling” programme and experiences have been worked out and exchanged in Task VII “Central Solar Heating Plants with Seasonal Storage (CSHPSS)” since 1979 in many countries; most of them were interested in long-term thermal energy storage mainly to distribute heat from renewable energy sources when in need. In the past decade, the aim was to carry on the work initiated in the CSHPSS Working Group, IEA Solar, Heating & Cooling Programme as well as the work carried out in Europe within the EU/APAS-project RENA CT94-0057 "Large-Scale Solar Heating Systems" [4].

The Energy Conservation through Energy Storage (ECES) programme started in 1978 through an Implementing Agreement of the International Energy Agency (IEA), providing funds for research, demonstration and development of new energy storage technologies by means of international cooperation. Initially, the objectives were mainly focused on energy storage technologies to improve energy efficiency of energy supply, which implies energy conservation for longer periods of time. Technologies able to satisfy this condition are underground thermal energy storage and technologies which use phase change materials or chemical reactions [5]. Ongoing activities try to develop alternatives for cooling systems with thermal energy storage, evaluating the sustainability (energy saving and CO_2 emission reduction), due in part to the rapid growth of energy consumption expected, especially in Asian countries. Future work is related to material development for improving thermal energy storage systems.

This paper attempts to summarize developments during the last three decades in seasonal thermal energy stores in the ground using large artificial basins instead of using natural sources for heat storage underground. Sensible heat is stored in water for a long time, saving energy through energy conservation.

2. Description of technologies

Thermal energy storage (TES) systems provide energy savings and contribute to reduce environmental pollutants. The one to be selected strongly depends on the storage period required, economic viability, operating conditions and environmental issues [6]. The high heat capacity and low cost of water often makes tanks of water an appropriate choice for TES systems that operate in the temperature range needed for heating or cooling, but being a liquid, special considerations about water quality and the container must be taken into account.

Depending on the storage timing requirements, storage can be classified in shot-term heat storage, which has a storage capacity from a few hours to a maximum of one week, and long-term storage, with a storage requirement up to three or four months. In the first type the heat stored is kept at high temperatures (maximum 95ºC) to allow direct discharge into the heat distribution network and it rarely supplies more than 60% of the domestic heating demand; nevertheless, it is cost competitive. For seasonal or long-term storage, low temperature concepts with the use of heat pumps, to raise the temperature of the water used for space heating and tap water to a suitable level, seem to be an appropriate option [1]. This technology becomes possible in large-scale central solar heating systems and it enables to reduce the solar collector area required achieving nearly 100% of the total heating demand, the difficulty lies in making it cost effective [7].

Seasonal storage requires great volumes, involving great amounts of energy to be stored. The objective of very large scale water storage is either to store solar heat collected in summer for space heating in winter, or to provide heating and cooling by storing solar heat underground in summer and cold in winter. In winter, the heat pump extracts heat from the water and in summer it extracts the heat from the building to store it in the water. These systems contribute significantly to improving efficiency of energy use. Therefore, the use of fossil fuels and consequently CO_2, SO_x and NO_x emissions to the atmosphere can be reduced considerably, avoiding the need for primary energy supply at the current extent. Fig 1 shows a scheme of the three main components of a central solar heating plant with seasonal storage (CSHPSS), which are the collector array, the interseasonal heat storage unit and the piping network.

Due to the large volume necessary for seasonal purposes, heat stores are in most cases in the ground or placed close to the surface. Systems using natural underground sites for storing thermal energy are called Underground Thermal Energy Storage (UTES) systems; they are mostly used for seasonal heat/cold storage. Among the UTES systems developed since the 1970s there are:

- Aquifer thermal energy storage (ATES)
- Borehole thermal energy storage (BTES)
- Cavern thermal energy storage (CTES)
- Pit storage
- Water Tanks

Aquifer Thermal Energy Storage (ATES) uses natural water in a saturated and permeable underground layer as the storage medium. The transfer of thermal energy is carried out by extracting groundwater from the aquifer and by re-injecting it at a modified temperature at a separate well nearby.

Borehole Thermal Energy Storage (BTES) consists of vertical heat exchangers deeply inserted below the soil, which ensures the transfer of thermal energy towards and from the ground (clay, sand, rock, etc.). Many projects are about the storage of solar heat in summer for space heating of houses or offices. Ground heat exchangers are also frequently used in combination with heat pumps ("geothermal heat pump"), where the ground heat exchanger extracts/transfers low-temperature heat from/to the soil.

Cavern Thermal Energy Storage (CTES) uses large underground water reservoirs created in the subsoil to serve as thermal energy storage systems. These storage technologies are technically feasible, but the actual application is still limited because of the high level of investment.

Water tanks and *pit storage*, also called man-made aquifers, are artificial structures built below ground, like buried tanks, or close to the surface to avoid high excavation cost. They will then need to be insulated both on the top and along the walls, at least down to some depth. Hydro-geological conditions at the specific site are not as relevant as in the other concepts.

The construction of such large structures must consider the optimization of heat losses and economic aspects. Duffie [9] formulated that "the volume of a storage unit increases as the cube of the characteristics dimension, and its area for heat loss increases as the square, so increasing the size reduces the loss-to-capacity ratio". So far, the development of seasonal storage has been aimed at heating large district system stores instead of single house solutions, in order to fulfil technical viability and cost effectiveness by augmenting the stores' volumes.

In that way, many advances have been made in Europe since government programmes included energy storage among their objectives of sustainability. Fisch et al. [4] reviewed large scale solar plant development in Europe during more than ten years at that time. They refer to two major large-scale solar heating applications: systems with short term (diurnal) storage designed to supply 10-20 % of the annual heating demand or 50 % of the domestic hot water; and systems with long term (seasonal) storage capable of supplying 50-70 % of the annual heating demand, which is more effective in reducing fossil fuel use and complying with CO_2 emission policies. Among the main results of the evaluation of the existing projects was the need to reduce the cost-benefit ratio for CSHPSS. The experimental plants built in some European countries involve the development of new concepts of seasonal storage such as duct storage, natural aquifer, man-made aquifer and pit storage concepts using high performance concrete and new construction technologies; or an improvement of the existing ones to reduce energy costs, like improving insulation in buildings, implementation of solar heating plants and the use of gas condensation boiler instead of a conventional gas boiler. Related to this, Lottner et al. [10] reviewed long-term national monitoring programme Solarthermie2000 of large-scale solar heating plants, with and without seasonal storage, in Germany. Nowadays, the specific storage costs are still too high for many applications and many efforts must be made to achieve technical and economic feasibility.

Which of the technologies described above is selected depends very much on the local hydro-geological site conditions. Natural aquifers are a costs effective seasonal storage concept but require, among other things, water-saturated sand layers with high permeability without ground water movement. Water tank and water-gravel pit storage seem to be a viable option when environmental restrictions about natural ground water are involved or unfavourable hydro-geological and geochemical conditions are available on site, which involve problems as clogging of the wells, scaling of the external heat exchangers, necessity of water treatment, high heat losses [10]. Table 1 summarises some of the characteristics of the main seasonal storage concepts.

3. Status of seasonal storage in water tank

Due to the high specific heat of water and the high capacity rates for charge and discharge, it seems to be the most favourable of the storage types from a thermodynamic point of view. Large water tanks are roofed over and energy is added or removed from the store by pumping water into or out of the storage unit. Their large capacity makes stratification more likely and heat extraction/recovery can be done through pipes or via heat exchangers.

The most common use of water tanks in Europe is in connection with solar collectors for production of warm water for space heating and/or tap water. The main application is in smaller solar plants for single-family houses but there are some examples of large water tanks being used for seasonal storage and also used as a buffer storage (intermediate tank), in connection with large-scale solar heating systems [11].

It usually consists of a reinforced concrete tank partially buried in the ground, which can be built nearly independently of geological conditions. It is thermally insulated at least in the roof area and on the vertical walls. Furthermore, steel liners are introduced in the structure to guarantee water tightness and to reduce heat losses caused by vapour transport through the walls [12].

Different heat stores integrated in CSHPSS have been developed in Germany since 1995 within the national R&D programme Solarthermie-2000, as were described by Schmidt et al. [12]. The water tank storage concept was tested in small pilot heat store of 600 m^3 in Rottweil. The shape was cylindrical; half the store was immersed in the ground, excavated soil was distributed around and on top of the store. It was built with concrete walls and roof, stainless steel liners and insulation was only applied on the top and on the side walls [13]. The 4,500 m^3 store in Hamburg and the 12,000 m^3 store in Friedricshafen were also built with an additional inner stainless-steel liner to ensure water tightness and to reduce heat losses caused by steam diffusion through the concrete wall. Outside, a polyethylene or polyvinylchloride film was applied and a drainage system was installed to prevent the insulation from getting wet. These plants operate with no major technical problems even when optimization of the design was necessary to improve the heat capacity of the tank; however, they do not satisfy the cost effectiveness goal unless construction cost is reduced.

With the development of a new high-density concrete (HDC) material with lower vapour permeability, it was possible to build the store in Hannover without an inner steel-liner [12]. Consequently the entire construction from the concrete wall to the surrounding earth had to be open for water vapour diffusion in order to avoid water condensation on the insulation. As insulation material, granulated blown-up glass packed in large textile bags was used. Another development was to add a charge and discharge device with variable height in the middle of the store improving stratification inside the tank. New demonstration plants for solar-assisted district heating with seasonal thermal energy storage were planned to be built within the R&D programme Solarthermie-2000plus [14]. Advances were made in stratification devices and heat insulation in the water tank storage projected for building in Munich during the summer

2006; and the specific storage cost is expected to be significantly lower. For designing the seasonal stores, simulations were made with the simulation programme TRNSYS.

Regarding the experiments developed in Germany, the Solar-Campus working group at the Aachen University of Applied Sciences, constructed low energy buildings on that site. A solar district heating concept, with seasonal storage is described by Melіß and Späte [15]. The store was a 2,500 m^3 reverse pyramidal tank with a steel or polypropylene liner to guarantee water tightness and covered by thermal insulation. The top cover consists of several insulated floating pontoons which were connected to each other. The solar system with seasonal storage was planned to cover 50 % of the heat demand but it turned out that the specific energy cost was relatively high compared with conventional energy price.

A number of demonstration plants for large-scale solar-heated seasonal heat storage units were constructed in Sweden during the early 1980s. In 1979, the solar heating plants connected to newly-built residential areas at Ingelstad and Lambohov became operative. In the first one, the solar heating plant was designed to cover the 50 % of the annual energy demand of 52 separated houses and the heat store was a 5,000 m^3 cylindrical free standing concrete tank constructed on the ground with thermal insulation. The results were different from those expected because of the low solar collector efficiency and great heat losses, covering 14 % of the annual energy. The heat store of the second plant was a 10,000 m^3 excavated rock pit insulated with cement-bound lightweight sintered clay granules and lightweight concrete; and water sealed with butyl rubber. The solar heating plant was designed to meet 100% of the annual energy demand for space heating and domestic hot water of 55 houses [3]. The performance revealed good agreement with the predictions except for the heat losses caused by wet thermal insulation. The experimental data were employed to validate simulations and calculate the annual thermal performance in relation to the solar collector system, heat losses through the thermal insulation and economic factors. At that time, it was necessary to bring down in the near future the cost of heat from solar systems to the same level as that of heat from oil combustion to become economically attractive for residential heating purposes. According to the solar heat cost (see Table 4), it is estimated a period of 20-30 years assuming the real annual oil prices increment in witch this technologies could be competitive reducing heat costs.

The later CSHPSS in Säro was studied with several simulation tools, including TRNSYS, based on the measured data. It was designed to meet 35 % of the annual heat requirement of 48 apartments where the heat store consists of a 640 m^3 insulated steel water tank placed in a 6 m deep rock excavation [16]. The mathematical models applied combined successfully both the definition of the three subsystems: space heating and hot water subsystem, solar collector subsystem and heat storage subsystem; and the complete system. OmSim and TRNSYS simulations results are presented obtaining good agreement; it is optimized to simulate and solve large scale engineering problems.

Other attempts to validate CSHPSS technology have been made in Denmark since 1990. Experiences were realized in Hoerby by making a 500 m^3 concrete tank sealed by a dense bentonite-concrete coating inside. In 1991, a 3,000 m^3 tank store was build in Herlev with steel sheet piles and a concrete cover insulated with polyurethane plates sealed by an ethylene propylene diene monomer rubber membrane (EPDM). Both stores showed leakage problems at the beginning and were not competitive for large storage volumes. After investigations on clay layer liners for the sealing of pits, a 1,000 m^3 store pit was constructed in Ottrupgaard in 1996 with clay layer liners and a floating cover of prefabricated sandwich elements of polyurethane foam responding to economic considerations. Leakage problems were detected in the clay liners; therefore, the main goal to get technical and economical solutions was to find the optimal polymer liners and sealing materials [17]. Economical cost of the different thermal storage technologies were simulated with the Danish computer program SæSONSOL, showing the energy prices under fixed conditions; large volume pit resulted the most promising storage technology. In 2003, a 10,000 m^3 store was designed to achieve a simpler and cheaper construction. High-density polyethylene (HDPE) was used as the liner on the bottom and sides. As part of the cover solution, along with the insulation, a vapour barrier and a steel grid were installed to avoid deformation of the geomembrane shape due to thermal dilation. The monitoring results were not presented at that time [18].

CSHPSS requires simulation tools for the pre-design stage and different programmes have been applied in the performance prediction and later validated with the experimental data obtained. Argiriou [19] compares results of the performance data at Lykovrissi Solar Village, in Greece, using the software MINSUN and SOLCHIPS in order to check their results at lower latitudes. Both programmes were appropriate for the performance designs and three types of seasonal storage were simulated with SOLCHIPS: steel tank, water pit and ground storage. The results showed that ground storage and water pit systems require similar collector area whereas the steel tank system needs a higher solar collector area to achieve the same solar fraction. This behaviour is due to the fact that the steel tank has higher heat losses compared to the other two storages system, and greater solar collector area is needed to compensate for those losses. Economic results of the water pit systems are simulated in the context of conventional energy prices at that time, with solar cost ranges between 0.070 and 0.135 ECU/KWh, but the cost effectiveness of these systems should be studied case by case.

Various mathematical models were employed at the University of Calabria, Italy, to plan a prototype plant with an interseasonal storage tank for monitoring purposes [20]. Different shapes and configurations underground or externally exposed were evaluated. Finally the 500 m^3 tank was built with reinforced concrete with a flat bottom and a spherical cover made from concrete lightened by expanded clay and completely buried to avoid heat losses. It was internal heat insulated with foam glass and waterproofed by means of a geomembrane in direct contact with water. First experimental data obtained in 1996 after one year of plant operation showed good agreement with the numerical simulations, even when the solar collector efficiency and heat losses from the water tank were less than expected. The simulation overestimated a useful energy collected value 6.9 % grater than the experimental value, and the reduction of the calculated energy loss in the storage tank respect to the measured value was 10.4 %. The total energy efficiency numerically obtained was 31.3 % against an experimental value of 28.2 % [21].

Energy conservation and renewable energy sources are playing an increasingly important role in European Energy Policy as has been shown in their national programmes. However, there has been research in water tank seasonal storage in a more isolated form outside Europe. First of all, USA investigations pioneered this technology, and more recently some results have been obtained in other countries.

Different methods for determining the optimal sizes of collector area and storage volume of seasonal storage solar heating have been developed. The feasibility of these systems was studied by Besan and Byron [22] in different cities in North America with a wide range of climatic conditions and insulation of the tank. A reduction in the store volume and increase in the solar collector area was considered in order to achieve better cost effectiveness. Braun et al. [23] described a methodology for the design of these systems using the transient simulation program TRNSYS, in which significant reduction in the collector area is achieved by the use of seasonal storage.

Williams et al. [24] described a method for the determination of the optimum amount and distribution of thermal insulation on in-ground annual heat storage tanks to reduce heat losses and economic costs. The optimal insulation distribution is calculated at several storage geometries considering uniform physical, thermal and cost properties of the thermal insulation. It regards the water table distance to the tank, insulation thickness, insulation and soil resistance, and the square-cube relationship. The importance of waterproof plastic installation around the tank to avoid percolation of rain water is outlined. For the amount of insulation problem, the system is described by three variables: collector area, storage volume and thermal insulation volume; the result is a graph of costs and performances for a given specified tank temperature variations at different collector areas, storage volumes and insulation thicknesses.

A CSHPSS under construction in Korea was simulated using TRNSYS. The seasonal store is a 600 m^3 cylindrical steel tank with glass wool insulation made on the ground to avoid excavation cost. One of the conclusions obtained after the simulation was that the store volume of the tank in the system design turned out to be oversized [25].

Ucar and Inalli [26] evaluated the required optimum collector area and storage volume for achieving maximum savings in two types of central solar heating system in four climatically different locations of Turkey. The simulation model was calculated with the finite element software ANSYS. Two different shaped stores, trapezoidal and cylindrical, were embedded in various types of soil whose effects were negligible on long-term performance of the storage system despite their different thermal properties. When a trapezoidal tank is used a greater solar collector area is needed, which also increases with increasing storage volume. In a later author's work, a comparison between three different types of storage in central solar heating systems is made: storage tank on ground with and without insulation; and underground storage without insulation [27]. The results show smaller solar collector area for the underground storage at three loads (volume storage) due to lower heat losses than with storage on the ground.

Seasonal storage of solar energy for the city of Edirne was examined through experimental investigations [28]. The storage is a cylindrical tank made of galvanized sheets and insulated, under the ground surrounded by sand. In this study economic assessment is carried out and the optimum collector area for the heating system is determined. For the economic analysis two factors are taken into account: oil savings and cost related to initial investment, maintenance and operation. The payback period is determined by calculating the initial system investment, the benefits obtained and the numbers of years for which shall be paid; it is resulted on 19.8 years. Energy savings can be achieved when the tank is located underground and surrounded by sand.

Models of a solar-aided heat pump space heating and cooling system with seasonal energy storage have been studied under analytical and computational methods. The performance of a heating system formed of hemispherical tank buried at different depths surrounded by three different types of soil was investigated and the influence of these factors was presented in the results of the model [29]. Numerical calculations with a computer programme in Fortran 77 revealed how low thermal conductivity of the soils investigated provides better performance and, moreover, how different tank burial depths affect water temperature; it being negligible beyond one meter depth.

The model developed by Zhang et al. [30] included a surface water pond with polystyrene foam as insulating cover, which works as a heat source in winter and heat sink in summer. The heat-conducting characteristic of various soil types, volume of the store and thickness of the cover were analysed showing that the necessary thickness increases with the heat conducting characteristics of the soil, but its effect throughout one year of operation is not significant if the insulated cover is properly designed, especially for high conducting soil. Considerations about volume of the store must be made to improve the performance of the heat pump because the larger the volume, the smaller the temperatures fluctuation of the water reservoir.

4. Status of seasonal storage in water-gravel pit

Storage pits are normally filled with water, but there are examples where the pit is filled both with rock and water [12]. Pits are normally buried in the ground and need to be waterproofed and insulated at least at the side walls and on the top. The watertight plastic liner is filled with a gravel-water mixture which constitutes the storage material. Heat is charged into and discharged out of the store either by direct water exchange or by plastic piping installed in different layers inside the store. No other bearing structure is necessary apart from the cover (lid) that could be used for other purposes. The gravel-water mixture has lower specific heat capacity than water alone, for this reason, the volume of the whole basin has to be approximately 50% higher compared to hot water heat storage to obtain the same heat storage capacity (see Table 1).

The first large-scale heat storage of solar energy project was developed in the Institute for Thermodynamics and Thermal Engineering of Stuttgart University in 1984 [31]. The heat storage consisted of a truncated cone shaped pit excavated on the ground, filled with pebbles and water, lined with high density polyethylene and thermally insulated only on top with porous lava and earth layers. Related to the pilot field site, Forkel and Daniels [32] studied different storage geometries and demonstrated that the best performance of the store unit corresponds to a lower area/volume ratio since thermal losses are less and extra cost in liner and insulation materials can be avoided.

Based on the experiences in the pilot plant at the University of Stuttgart [32], the same constructive aspects were adopted in the 8,000 m^3 heat storage building in the experimental plant at Chemnitz. The liner used was high density polyethylene (HDPE) and the thermal insulation was expanded polystyrene; water was charged and discharged directly from the artificial aquifer. Another heat store of 1,500 m^3 was built in Steinfurt-Borghorst with some modifications related to the liner and thermal insulation materials corresponding to double polypropylene liner with a compound aluminium_PE foil as a barrier to steam diffusion; and insulated with granulated recycling glass. The store included an indirect heat exchanger system consisting of polyethylene (PE) tubes [33]. So far, the gravel-water store technology is presented as an alternative with great construction cost reduction. Simulations were carried out with TRNSYS and the technical data of the demonstration plant are summarized in Table 2.

This type of storage can also be applied in heating and cooling systems, the heat is extracted by heat pumps whereas cold is taken, when necessary, directly from the store by coils (heat exchangers) [34].

Another option of water-gravel storage was developed at the Technical University of Denmark, Lyngby. The first construction included a floating cover on top of a 500 m^3 store. It was sealed with a HDPE liner and covered by a floating cover made of an HDPE liner, expanded polystyrene insulation and a butyl top liner. A few years later, the reservoir was reconstructed to form an artificial aquifer store by means of filling the pit with gravel and by adding direct and indirect heat exchangers; no results were obtained at that time [17].

5. Comparison

Gravel-water pit technology can reduce construction cost and the upper part of the store can be used as part of a residential area, but needs more volume to store the same thermal energy than a water tank design. Water tank technology does not need excavation operations or such a large surface but results more expensive due to the tank construction and the structure is quite visible. Table 3 and Table 4 summarise the construction materials employed and technical characteristics of some demonstration plants in central solar heating systems with tank and gravel-water pit seasonal storage described in this article. The experimental projects mentioned have been selected as they are large-scale pilot plants, so Table 4 provides an overview of the effectiveness of diverse configurations of these systems, including solar heat systems costs, and a reference for future projects.

Different contributions to the heating systems are presented and it is worth pointing out the importance of solar collector efficiency and heat losses from the storage tank and the piping network, occurring mainly due to sealing problems; which led to moistened insulation material, and high water storage temperatures. The requirement of the CHSPSS with gravel-water pit for greater storage volume is shown when compared to water tank technology. It is been showed that both technologies seem to reduce costs if large volume of storage is designed, while heating systems with water tank storage become more expensive than gravel-water pit storage. Moreover, the heat gain for the heating system is higher in the seasonal water tank systems.

6. Future prospects

The use of water as a sensible heat storage medium has been investigated deeply and it has been proven to be feasible technology. However, latent heat storage with phase change materials (PCM) in solar heat pump heating systems with seasonal storage applications is not widespread in the public-domain literature. The main advantages of using PCM are the higher energy storage density, the ability to provide thermal energy at constant temperature and the smaller volume necessary. But having larger energy storage density than sensible heat material, PCM breaks down with thermal cycling especially at high temperatures and hence it is not effective for long term applications [35]. Parameters as phase change temperature (melting point), latent heat, stability of cycling and thermal conductivity must be considered to select a PCM for a particular application [36]. The development of a mathematical model enables the simulation of the operational performance of a solar heating system employing PCM [37]. The energy extracted from the solar collectors is transferred to the PCM storage unit through the heat transfer fluid during the summer. The PCM releases this energy in the heating season to the heat transfer fluid which is conducted by the heat pump. When the operational temperature range of the PCM is lower than the water temperature range in conventional water storage tanks, such as for $CaCl_2.6H_2O$ with a melting point of 29ºC, the efficiency of the solar collector is enhanced and the energy losses from the tank to the environment decrease. However, specific store cost will be higher and a large number of PCM storage units will be installed in the storage tank, thus increasing complexity.

Experimental evaluation of seasonal latent heat storage has been carried out in the heating system of a greenhouse located in the Çukurova region of Turkey [38]. The latent heat storage unit was a cylindrical steel tank, filled with 6,000 kg of paraffin, equivalent to 33.33 kg of PCM per square metre of the greenhouse ground surface area. Perforated polyethylene pipes were installed as a heat exchanger to ensure the direct contact between the PCM and the heat transfer fluid. The results presented showed that technical and economic considerations should be considered.

7. Conclusions

Seasonal heat storage needs large volumes of water to supply the energy stored during summertime along winter. Those large stores require the development of technologies capable of guaranteeing water tightness, to minimize heat losses caused by steam diffusion through the walls and to optimise stratification within the tank; in order to preserve the thermal performance and life time of the solar heating plant. These approaches must be coupled with low investment, at least lower than conventional heating and cooling systems.

All the experience with seasonal energy storage technologies reviewed in this paper is connected to solar energy applications. Such systems are characterized by many factors such as solar collectors, annual sun exposure, heat distribution networks, heat demand, insulation of the buildings and volume of the store; all the investigations mentioned above consider the feasibility of the studies and models of related projects. Once these technologies have been well developed, the main effort consists in reducing costs in order to make them market competitive against conventional energy sources.

As some authors suggest, the specific storage costs are related to water equivalent storage volume. The water equivalent is the corresponding water volume to store the same amount of heat. Experiences carried out in demonstrations plants have achieved cost reduction by increasing the storage volume in large-scale solar applications.

Generally, the specific hot-water storage costs in large tanks are rather high. To avoid an expensive water tank construction, gravel-water heat storage seems to reduce costs because no structural frame is necessary; however, due to the lower heat capacity of gravel, the storage volume of gravel-water required between 1.3 – 2 m^3 per 1 m^3 of water equivalent. This corresponds to larger construction site availability, but in addition, total occupation of the upper part of the store is possible, such as with car parks, gardens or recreational areas, which results in a lower landscape impact. Both water tanks and gravel-water pits do not require previous geological research and leave the aquifers untouched, since they are expected to be placed close to the surface at some depth, less than the depth required for the rest of UTES systems with values up to 30 meters.

For large scale projects, the concept of seasonal storage in large basins becomes a viable option; therefore, economic cost revision must be taken into account to decide the most suitable option.

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Figure

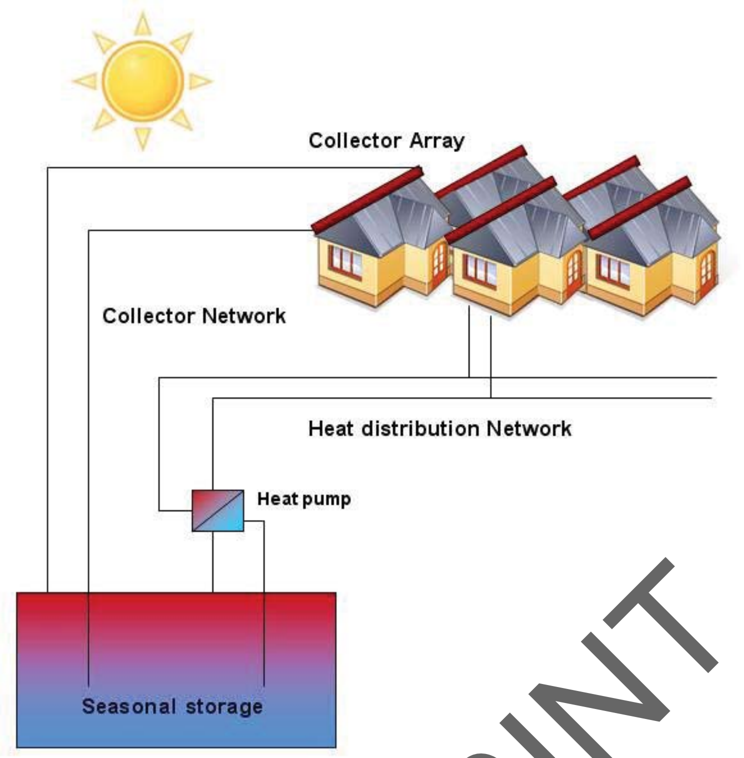

Fig. 1 Scheme of CSHPSS

** Colour figure only required on the web*

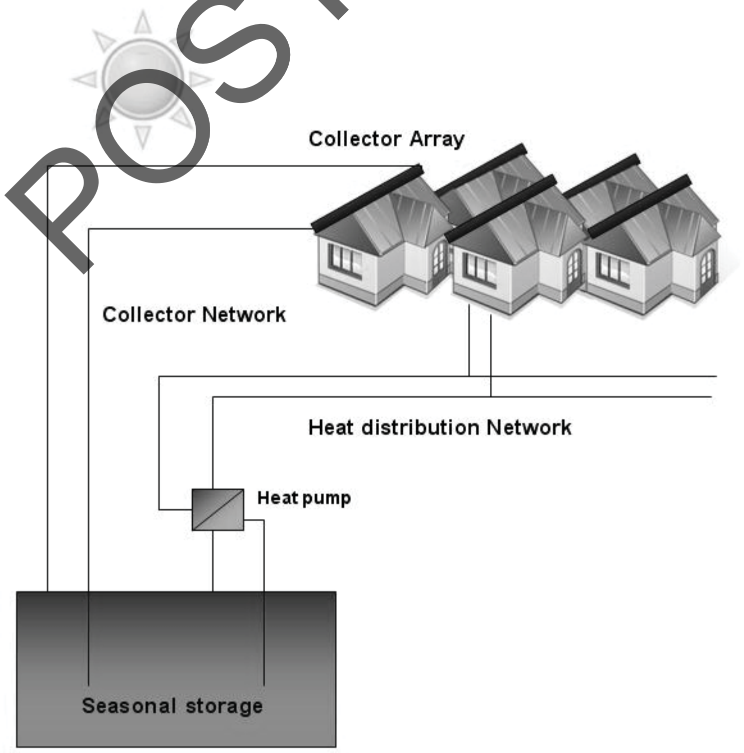

Fig. 1 Scheme of CSHPSS

Table 1

Table 1
Comparison of storage concepts [8]

Storage concept	Hot-water	Gravel-water	Duct	Aquifer
Storage medium	water	gravel-water	ground material (soil/rock)	ground material (sand/water-gravel)
Heat capacity (KWh/m^3)	60 - 80	30 - 50	15 - 30	30 - 40
Storage volume for 1 m^3 water equivalent	$1m^3$	1,3 – $2m^3$	3 - $5m^3$	2 - $3m^3$
Geological requirements	- stable ground conditions - preferably no ground water - 5 – 15m deep	- stable ground conditions - preferably no ground water - 5 – 15m deep	- drillable ground - ground water favourable - high heat capacity - high thermal conductivity - low hydraulic conductivity $(k_f<1\cdot10^{-10}m/s)$ - Natural ground water flow <1m/a - 30 – 100m deep	- natural aquifer layer with high hydraulic conductivity $(k_f>1\cdot10^{-5}m/s)$ - confining layers on top and below - no or low natural ground water flow - suitable water chemistry at high temperatures - aquifer thickness 20 – 50m

Table 2

Table 2
Technical data of the experimental plant in Steinfurt [12]

	Units	Steinfurt
Housing area		42 apartments in 22 houses
Heated living area	m^2	3800
Total heat demand	MWh per annum	325
Solar collector area	m^2	510
Heat storage volume	m^3	1500 (gravel-water)
Heat delivery of the solar system [a]	MWh per annum	110
Solar fraction [a]	%	34
Cost of the solar system	Million euro	0.5
Solar heat cost [a]	Euro/MWh	424

[a] Calculated values for long-term operation

Table 3
Construction materials of the heat storage in the experimental plants

CSHPSS water tank	Tank	Liner	Thermal insulation
Hamburg, DE [12]	Concrete	1.2 mm stainless stell	0.3 m mineral wool
Friedricshafen, DE [12]	Concrete	1.2 mm stainless stell	0.3m mineral wool
Hannover, DE [12]	High density concrete		Granulated foam glass in textile bags
Hoerby, DK [17]	Concrete	Bentonite-concrete	
Herlev, DK [17]	Concrete and stell sheet piles	Ethylene propylene diene monomer rubber membrane	Polyurethane foam
Ottrupgaard, DK [17]		Clay layers	Polyurethane foam
Ingelstad, SE [3]	Concrete		
Lambohov, SE [3]		Butyl rubber	Cement-bound light weight sintered clay granules
Särö, SE [4]		Stainless stell	
Lykovrissi, GR [4]			
Calabria, IT [21]	Reinforced concrete		0.2 m foam glass
CSHPSS gravel-water pit			
Stuttgart, DE [31]		2.5 mm high density polyethylene	Pumice and polyurethane
Chemnitz, DE [12], [39]		2.5 mm high density polyethylene	Extruded polyestyrene plates
Steinfurt, DE [12]		Polypropylene	Granulated foam glass in textile bags

DE = Germany, DK = Denmark, GR = Greece, SE = Sweden, IT = Italy

Table

Table 4
Technical data of demonstration plants

CSHPSS water tank	Total heat demand (GJ/a)	Heating living space	Solar collector area (m²)	Storage volume (m³)	Contribution to total heat load (%)	Heat losses (GJ/a)	Ratio storage volume to collector area (m³/m²)	Ratio storage volume to heating living area (m³/m²)	Solar heat cost at analysis date
Hamburg, DE [12]	5796	14800 m^2	3000	4500	49		1.5	0.3	256 Eu/MWh
Friedricshafen, DE [12]	14782	39500 m^2	5600	12000	47	943	2.14	0.30	158 Eu/MWh
Hannover, DE [12]	2498	7365 m^2	1350	2750	39		2.04	0.37	414 Eu/MWh
Hoerby, DK [17]				500					
Herlev, DK [17]	4520		1025	3000	35		2.93		
Ottrupgaard, DK [17]	1630		560	1500	16		2.68		
Ingelstad, SE [3]		52 houses	1320	5000	14	432	3.78		1900 SEK/MWh
Lambohov, SE [3]		55 houses	2700	10000	37	1422	3.70		1100 SEK/MWh
Särö, SE [4]		48 houses	740	640	35		0.86		
Lykovrissi, GR [4]		1700 m^2	162	500	70	159	3.09		70-135 ECU/MWh
Calabria, IT [21]	111	1750 m^3	91.2	500	28.2	362	5.48		
CSHPSS gravel-water pit	Total heat demand (GJ/a)	Heating living space	Solar collector area (m²)	Storage volume (m³)	Contribution to total heat load (%)	Heat losses (GJ/a)	Ratio storage volume to collector area (m³/m²)	Ratio storage volume to heating living area (m³/m²)	Solar heat cost at analysis date
Stuttgart, DE [31]	360		211	1050	60		4.97		
Chemnitz, DE [12], [39]	4320	4680 m^2	2000	8000	42		4	1.71	240 Eu/MWh
Steinfurt, DE [12]	1170	3800 m^2	510	1500	34		2.94	0.39	424 Eu/MWh

DE = Germany, DK = Denmark, GR = Greece, SE = Sweden, IT = Italy

[a] Predesigned phase