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Analysis of Large Thermal Energy Storage for Solar District Heating

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1. Abstract

The final energy consumption in Spain for the production of Domestic Hot Water (DHW) and Space Heating (SH) in the residential sector is 9700 ktoe [1]. This low temperature (< 100 ºC) thermal energy demand is mainly produced with non-renewable energy sources; only 18% is covered with renewable energies. So, there is a large potential in Spain for the application of renewable energies to the production of low temperature thermal energy. The utilization of Central Solar Heating Plants with Seasonal Storage (CSHPSS) integrated with District Heating networks in Central and Northern Europe is a growing feasible solution. This technology could be interesting in different areas of Spain with abundant solar radiation and important DHW and SH thermal energy demand.

The design of CSHPSS systems is complex, requiring dynamic simulation tools for the calculation of their behavior, which is dependent on the variable radiation and demand. The main design parameters for these installations are: surface area of the solar field and volume of the Seasonal Thermal Energy Storage (STES). A simplified model proposed by the authors [2-4] has been applied to study the variation of these parameters with different design criteria and in this paper a specific analysis related to the STES technologies (*Water tank, Borehole*, *Pit* and *Aquifer)* is presented.

The behavior of the CSHPSS system and the solar heat cost depend on the technical features and investment cost of STES technologies. The obtained results show that investment costs of the seasonal energy storage highly depend on the storage technology used.

Keywords: solar thermal energy; district heating; seasonal storage; renewable energy.

2. Introduction

The final energy consumption in Spain for the production of Domestic Hot Water (DHW) and Space Heating (SH) in the residential sector is 9700 ktoe [1]. This low temperature (< 100 ºC) thermal energy demand is mainly produced with non-renewable energy sources; only 18% is covered with renewable energies. So, there is a large potential in Spain for the application of renewable energies to the production of low temperature thermal energy. District Heating and Cooling (DHC) is an energy service based on moving thermal energy from available heat sources to customers.

The fundamental idea of district heating to be economic and environmentally friendly is to use solar, local fuel, or heat sources, that would be otherwise wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place [5,6]. To become a competitive district heating system it is required: 1) a suitable and cheap heat source, 2) demands from the heat market and 3) pipes that connect production and demand with low heat losses and cost.

The production of thermal energy in a DHC system is usually coordinated obtaining the following advantages: 1) it allows using multiple energy sources providing flexibility in operation reducing the cost; 2) process integration and polygeneration in the production of heating and cooling for the DHC and production of electricity for the grid increases the efficiency of natural resources and minimize the environmental impact [7, 8]; 3) use of thermal energy storage covering a variable thermal demand while the production system operates continuously at nominal conditions; 4) fuel can be purchased at a lower price than individual users and even can be accumulated from low price periods; 5) the centralized plant can use energy efficient strategies, such as energy recovery, becoming a more cost effective system[9]; 6) use of a large and centralized plant requires less pieces of equipment reducing the facility´s overall operation and maintenance cost; 7) load diversity in the demand can substantially reduce the total equipment capacity requirement; 8) major vibration and noise produced by the equipment can be grouped away from occupied spaces; 9) plant emissions are centralized allowing a more economic and lower emission release solution; 10) alternative energy sources more environmentally friendly, as biomass or solar energy, can be used to produce thermal energy [10,11]; 11) long term thermal energy storage as seasonal storage can be used to accumulate the summer overproduction of solar systems.

Thermal energy storage and seasonal storage has a proved economic interest in solar systems and polygeneration systems for DHC in the residential & commercial sector. Sizing the thermal energy storage for a centralized district heating system with solar energy is a complex process in which it is required to know both the annual distribution of the demand and the solar radiation.

3. Thermal Energy Storage

Three different forms of energy are used to accumulate thermal energy: sensible heat, latent heat and chemical energy. The capacity to accumulate thermal energy in a sensible heat storage depends on the temperature amplitude between the minimum and maximum temperature in the TES. It also depends on the storage volume V (m^3), and the thermal capacity $\rho \cdot c_p$ ($J/(m^3K)$) of the storage material.

$$EA_{max} = V \cdot \rho \cdot c_p \cdot (T_{max} - T_{min}) \qquad (1)$$

In Table 1 is shown the energy that can be stored per cubic meter in a thermal energy storage with an amplitude, of 30 K and 60 K.

Table 1. Thermal capacity of common materials for sensible heat storage [12]

	$MJ/(m^3 \cdot K)$	$kWh/(m^3 \cdot K)$	(kWh/m^3)	(kWh/m^3)
Temperature difference			30 K	60 K
Water	4.19	1.16	34.8	69.6
Saturated clay	3.60	1.00	30.0	60.0
Moist earth	2.50	0.69	20.7	41.4
Granite	2.30	0.64	19.2	38.4
Concrete	2.00	0.55	16.5	33.0
Bed of gravel (45% empty space)	1.20	0.33	9.9	19.8
Dry clay	0.80	0.22	6.6	13.2

Thermal energy storage has thermal losses to the environment through the storage envelope with an area A (m^2) at a heat transfer coefficient U ($W/(m^2 \cdot K)$).

$$Q_l = U \cdot A \cdot (T - T_{amb}) \qquad (2)$$

In the case of storages that are insulated on all sides, it is easy to determine the volume V, the surface area of the storage envelope A and the global surface heat transfer coefficient U, but in the case of rock caverns, aquifer storage or underground stores that are partially insulated or uninsulated (basins, boreholes, etc…) it is not always easy to determine V, A and U.

Latent heat from phase change materials has been used in thermal energy storages for many applications [13]. Different problems have been encountered in the use of latent heat storages: aggressiveness, hysteresis, slow transfer of thermal energy and high cost compared to sensible heat storages. On the other hand latent heat storage can accumulate the same amount of energy as sensible heat storage in a significant smaller volume. Thermochemical energy storage requires even less volume than latent heat energy storage but requires higher investment cost [13].

Thermal energy storage used for strategies of operation in which the thermal energy is accumulated from a couple of hours to several days is called short-term thermal energy storage. Long-term thermal energy storage or seasonal storage accumulates thermal energy lasting several weeks or months.

4. Seasonal Storage

The production of solar energy to cover thermal energy demands in the residential sector through district heating requires the storage of thermal energy during long seasonal periods. The difference between production and demand in the period of summer can be accumulated to be used in those periods of higher demand and lower production, e.g. in winter. The storage needs of a solar system rises with the solar fraction objective.

In Table 2 is shown a brief description of central solar heating plants with seasonal storage in operation.

Table 2. Description of Central Solar Heating Plants with Seasonal Storage in operation [14-22]

Name	Year Built	Collector Area (m^2)[*]	Seasonal Storage Volume (m^3)[†]	Solar Fraction	Investment (€)
Friedrichshafen [14,15]	1996	FPC 4050	TTES 12000	47%	3,200,000
München [14-16]	2007	FPC 2900	TTES 5700	47%	2,900,000
Mongolia [14]	2012	CPC 5000	TTES 5000		
Hamburg [14-16]	1996	CPC 3000	TTES 4500	49%	2,200,000
Rise Fjernvarme [14,15,17]	1998	FPC 3582	TTES 4000	80%	697,200
Hannover Kronsberg [14-16]	2000	FPC 1350	TTES 2750	39%	1,200,000
AEroeskoebing [17,18]	1998	FPC 4875	TTES 1400	20%	1,200,000
Neuchatel [15]	1997	UG 1120	TTES 1000		
Tubberupvaenge [14,15,17,19]	1991	FPC 1030	TTES 1000		1,270,000
Marstal Fjernvarme [14,15,18]	1996	FPC 33000	PTES 75000 PTES 10340 TTES 2000	55%	9,440,000
Ottrupgaard [14,19]	1995	FPC 565	PTES 1500		
Chemnitz [16,20]	2000	ETC 540	WGTES 8000	30%	1,400,000
Augsburg [14,19]	1998	FPC 2000	WGTES 6000		5,100,000
Eggenstein [14-16,20]	2008	FPC 1600	WGTES 4500	37%	1,100,000
Sonderborg Vollerup [14,15]	2008	FPC 7681	WGTES 4000	20%	
Steinfurt Borghorst [14,19,20]	1999	FPC 510	WGTES 1500	34%	500,000
Neckarsulm Amorbach [14-16,20]	1997	FPC 5670	BTES 63000	50%	3,500,000
Anneberg [14,15]	2002	FPC 2400	BTES 60000		
Crailsheim [14-16]	2003	FPC 7464	BTES 37500	50%	4,500,000
Drake Landing, DLSC [14,21]	2007	FPC 2164	BTES 34000	96%	2,600,000
Braedstrup [14,15,22]	2011	FPC 18600	BTES 19000 BTES 7500	30%	12,300,00
Attenkirchen [14,16,20]	2002	FPC 800	BTES 9350	55%	760,000
Rostock Brinckmanshöhe [14-16]	2000	FPC 980	ATES 20000	62%	700,000

[*] FPC: Flat Plate Solar Collector, UG: Unglazed Solar Collector, ETC: Evacuated solar collector, CPC: Compound parabolic collector.

[†] TTES: Tank Thermal Energy Storage, PTES: Pit Thermal Energy Storage, WGTES: Water Gravel Thermal Energy Storage, BTES: Borehole Thermal Energy Storage, ATES: Aquifer Thermal Energy Storage.

The number of installations with seasonal storage is still limited while the number of large solar thermal systems (> 500 m^2) is rising exponentially: 244 large solar thermal plants have been installed worldwide since 1985 till 2012; 138 have been installed in the last period since 2006 till 2012; and in the last year (2013), only in Denmark, 9 plants have been installed with a total area of 81,000 m^2 [18]. Large solar thermal systems without seasonal storage can only produce a limited solar fraction, between 10% and 25%. To increase the solar fraction in these systems, large seasonal storages will be required to accumulate thermal energy produced in summer to cover the demand in winter, otherwise the solar collectors will be underused and stagnation problems will harm the equipment.

As larger is the seasonal storage, the better is the thermal performance. A cylindrical hot water tank with height equal to its diameter that reaches a maximum average temperature of 90ºC at the end of the charging season and a minimum average temperature of 30ºC at the end of the discharging season ($T_{max} - T_{min} = 60$ K) can accumulate 69.6 kWh/m^3 (see Table 1). The tank will have thermal losses to the ambient proportional to the envelope area and the heat transfer coefficient. For a tank with 25 cm of insulation ($U = 0.12$ W/(m^2·K)) the annual thermal losses to the environment can be estimated along the 8760 h of the year at the average storage temperature (60 ºC) with the ambient at its yearly average temperature (15ºC). Storage capacity and thermal losses per cubic meter have been calculated for a wide range of volume in Table 3.

Table 3. Efficiency of a cylindrical seasonal storage with height equal to its diameter.

Volume (m^3)	0.1	1	10	100	1000	10,000	100,000
A (m^2)	1.193	5.54	25.7	119.3	553.6	2570	11927
A/V (m^2/m^3)	11.93	5.536	2.570	1.193	0.554	0.257	0.119
EA_{max} (MWh)	0.007	0.07	0.7	7	70	700	7000
Q_l (MWh)	0.056	0.26	1.2	5.6	26	121	564
EA_{max}/V (kWh/m^3)	69.6	69.6	69.6	69.6	69.6	69.6	69.6
Q_l/V (kWh/m^3)	560.0	260.0	120.0	56.0	26.0	12.0	5.6

Envelope area and thermal losses per cubic meter are significantly reduced when the size is increased. Besides hot water tank, other construction types and materials can be used. The four main seasonal storage technologies are: (TTES) Tank Thermal Energy Storage, (PTES) Pit thermal Energy Storage, (BTES) Borehole Thermal Energy Storage and (ATES) Aquifer Thermal Energy Storage [20]. As the area of the seasonal storage is reduced with size, also does the cost of the seasonal storage. Different correlations exist to estimate the cost of the seasonal storage (type and size) [4,10,12,16,20-24]. European installations have been analyzed by Solites to evaluate the reduction of the investment cost per cubic meter for different size (see Figure 1).

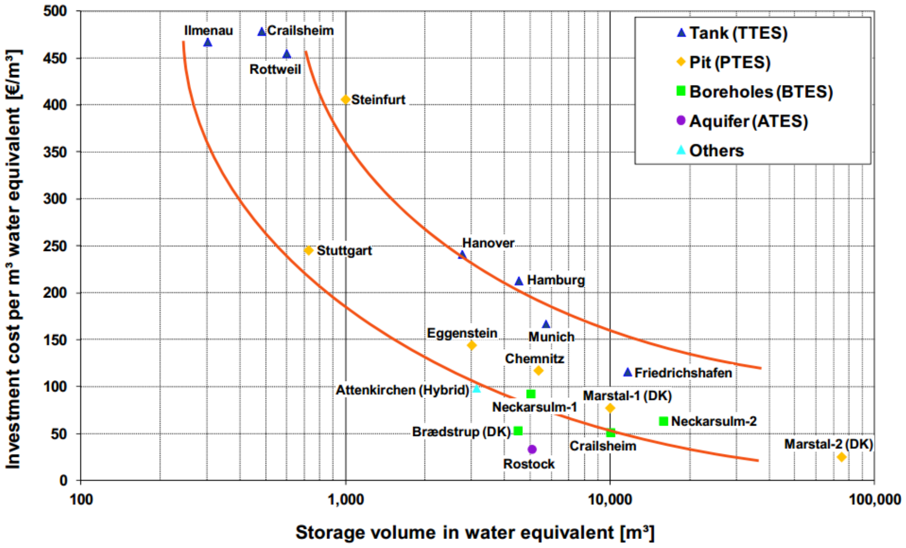

Figure 1: Specific storage costs of demonstration plants (cost figures without VAT) [20]

4.1 Water Tank Thermal Energy Storage

A water tank thermal energy storage is a tank, filled with water to store thermal energy. It can be located on ground, partially buried or underground. It is built as a reinforced concrete tank, or as a cylindrical steel tank. The tank can be insulated on the top, sides or bottom to reduce the thermal losses to the environment. Usually a vapor diffusion liner is required to avoid vapor difussion. This liner is typically built in steel, increasing the economic cost and environmental impact of the seasonal storage over the whole solar system.

4.2 Pit Thermal Energy Storage

In order to reduce the cost of the seasonal storage, for large size applications, the water tank construction is replaced by the construction of a water pit partially insulated on the sides and on the top with a watertight floating lid. This storage is filled with water or with water and gravel. The construction of the storage is cheaper than the thermal energy storage tank because less structural material is required for the construction. The sides of the pit are tilted and supported over the soil and the cover usually floats or is supported over the gravel.

Marstal seasonal storage with a total volume of 75,000 m^3 is the bigger PTES seasonal storage built and the final cost without VAT has been 41 €/m^3. Considering a short lifetime for the storage of 25 years (typically projected for 50) and an interest rate of 3% the annual amortization is 176,600 €/year. Estimating an average accumulation capacity of·60 kWh/m^3 [20] the ratio between the heat accumulated every year and the amortization cost is 39.24 €/MWh.

If the price of the thermal energy is nearly zero, for example overproduction of thermal energy in summer from solar plants or from cogeneration plants during peak periods at high price of electricity, the final cost of the thermal energy obtained from the seasonal storage in winter can be used in a district heating system. As comparison, the cost for natural gas for consumers lower than 5000 kWh/year is 57.27 €/MWh with an extra fixed cost of 4.38 €/month [25] (amortization and operation costs are not included).

4.3 Borehole Thermal Energy Storage

Thermal energy can be stored in the ground directly, avoiding the construction of a PTES or a TTES, with a Borehole Thermal Energy Storage. A BTES is made of U pipes located in vertical boreholes to create a large heat exchanger with the soil. Hot water goes through the pipes from the inner part of the storage to the lateral sides heating the soil from the center to the sides creating a radial temperature distribution in the seasonal storage. The thermal properties of the soil, conductivity and capacity affects to the efficiency of the seasonal storage and the distance between boreholes. To build a BTES it is required to know the underground water movements and to make a geological study of the underground.

The BTES built in, Drake Landing Solar Community with a volume of 37,500 m^3 cost 620,000 CAD$ ≈ 410,000 € [26]. The annual amortization for 25 years and interest rate of 3% is 23,550 €/year. Estimating a capacity of 15 kWh/m^3 [20] the ratio between the heat accumulated every year and the amortization cost is 41.86 €/MWh which is slightly higher than the Marstal installation.

4.4 Aquifer Thermal Energy Storage

In some locations is possible to use underground caverns or aquifers to store thermal energy. In these cases the naturally underground water, is heated along the charging season and used in winter to produce thermal energy with a heat pump.

Generally this thermal energy storage performs at very low temperature and the thermal energy accumulated cannot be used directly. Besides the virtually no cost for the storage other costs, as heat pump investment and heat pump electricity consumption, have to be considered since the economic effect is significant.

5. Analysis of Seasonal Storage in Central Solar Heating Plants.

Preliminary analysis of central solar heating plants with seasonal storage can be done with the “Simple Method”, or GLS Method, presented by the authors [2-4]. This simple method only considers complete mixture water tank thermal energy storage but other kinds of seasonal storage can be implemented in the simple method and more precise correlations can be used.

5.1 Water Tank Thermal Energy Storage over the ground

A large water cylindrical tank, built over the ground and filled with water, works as a large thermal energy storage for a centralized solar system. The heat capacity of the water is known and the water tank thermal energy storage usually works between a minimum temperature that depends on the district heating return temperature, for low temperature systems 30ºC, and a maximum temperature of 90ºC or 95ºC, so EA_{max} can be calculated using Eq. 1.

Thermal losses in the tank can be calculated separating the three main surfaces, lateral, top and bottom of the tank. Thermal losses in the laterals and in the top depend on the construction but thermal losses through the bottom also depend on the ground properties. The tank is built with concrete (d_{conc}=0.5 m; λ_{conc}=1.63 W/(m·K)), a metal linner to avoid vapor diffusion and thermal insulation of extruded polystyrene ‘XPS’ (d_{xps} = variable m; λ_{xps}=0.03 W/(m·K)). The ground has a thermal conductivity of λ_{gnd}=3 W/(m·K) [12]. A convective heat transfer coefficient to the air of 10 W/(m^2·K) has been considered. Eq. 3-7 presented in “Guide to Seasonal Heat Storage” can be used to calculate the average thermal losses. The simple equations proposed by M. Chung et al. [27] or more detailed models based in a finite element model can be used.

$$Q_{losses} = Q_{top} + Q_{lateral} + Q_{bottom} = (U_t \cdot A_t + U_l \cdot A_l + U_b \cdot A_b) \cdot (T_{WTES} - T_{amb}) \tag{3}$$

$$U_t = 1/(d_{conc}/\lambda_{conc} + d_{xps}/\lambda_{xps} + 1/h_{conv}) \tag{4}$$

$$U_l = 1/(d_{conc}/\lambda_{conc} + d_{xps}/\lambda_{xps} + 1/h_{conv}) \tag{5}$$

$$U_b = 2/R^2 \cdot \{a \cdot (\lambda_{gnd}/\pi)^2 \cdot \ln[a/(a-(R \cdot \pi/\lambda_{gnd}))] - R \cdot \lambda_{gnd}/\pi + 1/h_{conv}\} \tag{6}$$

$$a = R \cdot \pi/\lambda_{gnd} + (d_{conc} + d_{xps})/\lambda_{gnd} + d_{conc}/\lambda_{conc} + d_{xps}/\lambda_{xps} \tag{7}$$

Knowing the thermal capacity and the thermal losses of the thermal energy storage a CSHPSS can be calculated. An analysis of the thermal losses vs investment cost can be performed to choose the seasonal storage insulation thickness. The insulation cost can be estimated using “CYPE, Price Generator” [28]. The insulation cost is not homogeneous, it is more expensive to install it in the laterals than in the top, but average prices of 7 €/m^2, for the operations to install the insulation, and 120 €/m^3 per volume of insulation material are considered. An additional indirect cost of 5.0% has been added to the investment cost. With an average lifetime of 20 years for the insulation and with an interest rate of 3% the annual amortization can be calculated as function of the size of the storage and the thickness of the insulation.

An auxiliary boiler, fueled with natural gas complement the installation, so thermal losses in the seasonal storage will produce an extra consumption of natural gas. For large consumers >100MWh/year (Spain, January 2014), the variable cost of natural gas is 41.1 €/MWh [25].

As application example, the optimum insulation for a CSHPSS is presented next. It is considered a CSHPSS located in Zaragoza supplying thermal energy to a community of 500 dwellings in multifamily buildings of 100 m^2 in Zaragoza, with thermal needs of space heating and domestic hot water according to Spanish reference values [4]. The considered system consists of: flat plate solar collectors, model ARCON HT-SA 28/10 [22] with a solar collector aperture area of 1,600 m^2; a cylindrical TTES is used as seasonal storage with a volume of 7,000 m^3 and performing between 30ºC and 90ºC; a heat exchanger in the solar field with an efficacy of 90%. The operation of system has been calculated monthly with the simple method considering different insulation thickness in the seasonal storage. Annual results are presented in Table 4 as well as the amortization cost for the insulation and the economic savings for the reduction of required auxiliary energy.

Table 4. Annual results for different insulation thickness, calculation with the Simple Method [2-4] and eq 3-7.

d_{xps} (m)	Qc (MWh)	Ql (MWh)	η_{SS} (Qs/Qe)	Solar Fraction	Amortization (€/year)	Savings (€/year)	Balance (€/year)
0.00	1727	638	2.2 %	40.7 %	0	0	0
0.05	1508	236	57.4 %	47.6 %	1859	7760	5901
0.10	1455	149	72.0 %	48.8 %	2716	9188	6472
0.20	1425	85	83.6 %	50.1 %	4432	10617	6185
0.50	1403	37	92.7 %	51.1 %	9579	11714	2135
0.75	1400	26	94.2 %	51.2 %	13868	11885	-1983
1.00	1398	19	94.8 %	51.3 %	18157	11960	-6197

For the analyzed case, the optimum results are obtained when insulation thickness is between 0.1 and 0.2 m. An insulation level of 0.75 m or higher generates a negative result, the investment required do not have a payback for the annual savings obtained. To compare with a real case, Friedrichshafen water tank has an insulation level of mineral wool in laterals and cover of 20-30 cm.

5.2 *Pit thermal Energy Storage*

With the aim of reducing the cost of the seasonal storage for large size applications (more than 50,000 m^3) pit thermal energy storage dug in the ground has been developed with a construction cost lower than 35 €/m^3 [23]. In 1996 in Ottrupgaard a PTES was built with bottom and sideliner of 85 cm of clay, placing on the outside an EPDM-rubber, and with a floating cover made of cold store wall elements. The design was expensive to construct and difficult to tight and localize and repair leakages or to prevent the seeping of moisture.

Therefore a new design was tested in Marstal in 2003 for a 10,000 m^3 PTES. This PTES has a single welded liner on bottom and sides, and has a simple floating cover using a plastic liner for the underneath. To reduce the construction cost, height and level of storage is chosen to obtain "earth balance" so the PTES is surrounded by a soil bank from the hole dug. The bank is insulated on the top with EPS but the U-value is higher in this place compared with the cover construction that has 125-335 mm of insulation (EPS) and 75 mm of mineral wool. To solve vapor diffusion problems, the liner has a 2.5 mm of HDPE and an aluminum foil.

PTES can be built as a truncated cone or as a truncated pyramid and the thermal losses can be calculated with simple equations or with finite elements models such as large tanks buried underground. Eq. 8-11 [12] calculate the heat transfer coefficient for a truncated cone on the top U_t, laterals U_l and bottom U_b.

$$U_t = 1/(R_{tank} + d_{gnd}/\lambda_{gnd} + 1/h_{conv}) \tag{8}$$

$$U_l = 1/(H\cdot\pi/\lambda_{gnd} \cdot ln(1 + (H\cdot\pi/\lambda_{gnd}) / (R_{tank} + H\cdot\pi/(2\cdot\lambda_{gnd})))) \tag{9}$$

$$U_b = ln(1+(B\cdot\pi/\lambda_{gnd}) / (R_{tank} + H\cdot\pi/(2\cdot\lambda_{gnd}))) / (2\cdot B\cdot\pi/\lambda_{gnd}) \tag{10}$$

$$R_{tank} = d_{conc}/\lambda_{conc} + d_{xps}/\lambda_{xps} \tag{11}$$

5.3 *Borehole Thermal Energy Storage*

With the climatic and operational data of a real installation the empirical performance coefficients of the seasonal storage can be obtained. The system presented in Figure 2 represents the installation of Drake Landing Solar Community and the main energy flows of the system that has been used to determine the empirical performance coefficients of the system and the performance.

The system has two thermal energy storages, the BTES stores the thermal energy from summer to winter and the short term thermal storage (STTS) stores the thermal energy as hot water to cover the variable demand of the community. Both thermal storages have thermal losses to the environment.

The STTS is built as two hot water tanks with a volume of 240 m^3. The envelope area of both tanks is A = 339.4 m^2 and its average temperature is 50 ºC. The annual average ambient temperature in Drake Landing Solar Community is 7.7 ºC. Annual thermal losses have been calculated from an energy balance in the STTS as Ql_{STTS} = 159.2 MWh. Using Eq. 2 along the 8760 hours of the year the global heat transfer coefficient of the STTS has been calculated as U_{STTS} = 1.27 W/(m^2·K). For the seasonal storage, a large borehole thermal energy storage was built in Drake Landing. The total volume of the seasonal storage is 37,500 m^3 and it has a diameter of 35 m and the boreholes reach 35 m. The envelope area of the BTES is 4841 m^2 and the annual average temperature is 50 ºC. Annual thermal losses have been calculated from an energy balance along the year $Ql_{,BTES}$ = 448.5 MWh. The average global heat transfer coefficient along the year has been calculated U_{BTES} = 0.25 W/(m^2·K) and it is much lower than the obtained for the STTS.

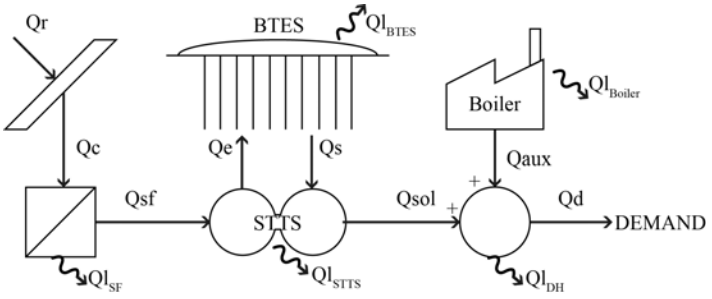

Figure 2: Drake Landing Solar Community, System scheme of the CSHPSS.

The soil properties and the temperature fluctuation in the BTES are not homogenous but the average soil properties can be estimated from the thermal performance. Using Eq. 1 the soil average heat capacity can be estimated if EA_{max}, and temperature amplitude is known. It has been estimated that the average BTES temperature changes between 40ºC and 60ºC along the year so the temperature amplitude is 20 K. Energy accumulated can be estimated from an energy balance along the charging period $EA_{max} = Qe - Qs - Ql_{BTES}$ or from an energy balance along the discharging period or as $EA_{max} = Qs - Qe + Ql_{BTES}$ along the discharging period. From monthly measured data from April to October, charging season, a maximum energy accumulated EA_{max}=389.5 MWh has been obtained. The average heat capacity of the BTES obtained with this method is 2062 kJ/(m^3·K) which is between the thermal properties of dry and wet soil. Considering the previous values of average soil heat capacity, temperature range for the seasonal storage, and the thermal losses for both storages, the system has been calculated with the simple method using the following data obtained from Drake Landing Solar Community:

1) Latitude (Lat = 50.7º)
2) Heating demand (monthly values)
3) Daily average ambient temperature and daily average horizontal radiation (monthly values)
4) Solar collector coefficients η_0 = 0.7586; k_1 = 4,5124 W/(m·K); k_2 = 0.0009 W/(m^2·K), efficacy of the heat exchanger in the solar field Eff = 80% between the primary and the secondary and solar field flow m_s = 15 l/s and heat capacity of the solar field flow capacity c_p = 3.84 kJ/(kg·K)

The system has been calculated with the Simple Method [2-4] from July of 2011 to June of 2012 using the climatic measured data for the period. Annual calculated results and measured results extracted from the annual report of DLSC [21] are presented in Table 5.

Table 5. Measured and calculated results of Drake Landing for the period July 2011 June 2012.

MWh	Qr	Qsf	Ql_{STTS}	Ql_{BTES}	Qsol	Qg	Qd
Measured [21]	3635	1275	159.2	448.5	667.5	22.4	690
Simple Method	3577	1211	153	429.3	628.7	61.2	690

6. Conclusions

Large thermal energy storage can be used in centralized solar systems to store the summer overproduction of thermal energy to supply the high thermal demand in the residential sector for the winter period. For seasonal storage applications in solar systems at least a ratio volume of seasonal storage per area of solar collector of 1 m^3/m^2 is required and it rises with the solar fraction objective of the system.

The maximum amount of thermal energy that can be accumulated in the seasonal storage depends on the temperature amplitude along the year and the heat capacity of the material, water or soil. TTES has higher investment cost than other storages but for small systems it can be built with quite high efficiency. Pit thermal energy storage has been designed for larger applications >50,000 m^3 becoming into a very cost competitive solution with high efficiency. BTES accumulates thermal energy in the soil and requires a larger volume to accumulate the same amount of energy than in water but it does not require walls, remove large amounts of soil, or bottom and/or laterals insulation to avoid water leakages.

Central solar heating plants with seasonal storage can be calculated using simple calculation methods such us the Simple Method [2-4] for different storage technologies calculating the heat transfer coefficient to the ambient and the heat capacity. Average parameters of heat transfer can be obtained from real operating plants as well as average heat capacity of the soil. The use of simple methods to calculate CSHPSS enable preliminary analysis in early stages of a project and can support de development of this kind of systems for new energy efficient communities.

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