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# THERMOECONOMIC COST ANALYSIS OF CENTRAL SOLAR HEATING PLANTS COMBINED WITH SEASONAL STORAGE

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## ABSTRACT

The European Union and its Member States have committed themselves to achieving a 20% share of renewable energy by 2020. If the focus remains solely on solar thermal systems for domestic hot water (DHW) preparation, as in Spain, then the solar contribution will be very limited. Central Solar Heating Plants combined with Seasonal Storage (CSHPSS) systems enable high solar fractions of 50% and more. Most CSHPSS demonstration plants in Europe have been built in Central and North Europe, mainly in Denmark, Germany and Sweden. South Europe has little experience.

This article presents a thermoeconomic cost analysis of CSHPSS systems. The objective of thermoeconomics is to explain the cost formation process of internal flows and products of energy systems. The costs obtained with thermoeconomics can be used to optimize the design of new plants and to control the production of existing plants. A simulation study on solar assisted district heating systems with high solar fractions and seasonal thermal energy storage was carried out with TRNSYS taking into consideration the meteorological conditions in Zaragoza (Spain). A CSHPSS plant was designed for a district of 500 dwellings with an annual thermal energy demand of 2,905 MWh/year. The process of cost formation has been analyzed considering the very specific features of the CSHPSS designed system: free solar energy, seasonal and DHW thermal energy storage, continuous variation of the operation due to highly variations of solar radiation and energy demands (hourly and seasonal). These features impose important difficulties in the calculation of the costs of internal flows and products in this type of systems.

## INTRODUCTION

With the new legislation on buildings construction [1], the Spanish Government has started a lukewarm promotion of the installation of thermal solar systems in buildings. Specifically, the new Spanish legislation on buildings construction imposes the coverage with thermal solar energy of the 30% - 70% (depending on the climatic area in Spain) of energy demand corresponding to the domestic hot water. In other countries of Central and North Europe an important experience on thermal solar energy has already been gained and several high scale Central Solar Heating Plants (CSHP) have been designed to cover the thermal energy demand of urban districts and even small cities [2-4]. Some of these plants have proven the appropriate operation of seasonal thermal energy storage [5-7]. The experience gained in Central and North Europe and the better conditions of solar radiation in Spain suggest the feasibility of installing Central Solar Heating Plants combined with Seasonal Storage in those Spanish areas in which there is a significant demand of thermal energy for heating in winter.

In this work, is presented a technical and economic evaluation of a CSHPSS plant that could be able of covering close of 70% of the thermal energy demand for DHW and heating of a residential area with 500 dwellings in Zaragoza, a city located in the north of Spain. In this way it is coupled the offer of thermal energy in periods of high solar radiation (summer) with high thermal energy demand for heating (winter), obtaining energy independence, energy saving and reduction of pollutant emissions. After the analysis of preliminary studies [8-9] it is proposed a system that will be used as a reference case for the selection and sizing of the required pieces of equipment as well as for the evaluation of its economic feasibility. The dynamic behavior of the system has been analyzed using the TRNSYS software [10]

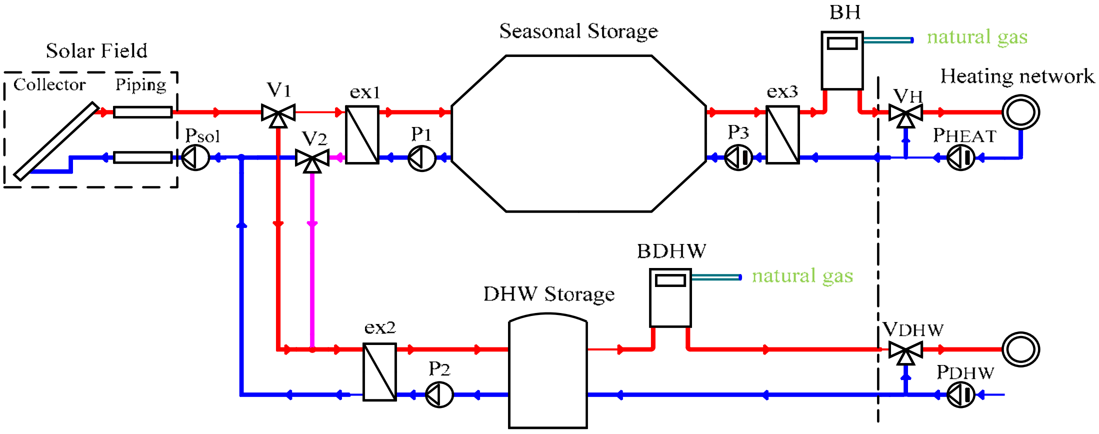

**Figure 1. Diagram of the base case of the analyzed Central Solar Heating Plant combined with Seasonal Storage**

## SYSTEM DESCRIPTION

The proposed system is depicted in Figure 1.

The energy harnessed by the solar collectors is transferred either to the seasonal thermal energy storage or to the DHW storage (preferably to this one). An independent DHW storage, which is smaller than the seasonal thermal energy storage, provides the required temperature of the water in a few hours and allows, as it is explained below, to cover a high fraction of the DHW demand with solar energy. The dynamics of loading and unloading of the seasonal thermal energy storage is significantly slower, because it is oriented to cover partially the heating demand in winter using the thermal energy stored during the summer period. The auxiliary boilers (BH and BDHW) will support and guarantee the coverage of the thermal demands when the temperature of the water in thermal energy storages is insufficient.

The CSHPSS plant is designed to serve 500 dwellings in the residential area called Parque Goya, located in Zaragoza. The thermal energy demand for DHW and heating is expressed considering 12 representative days (one for each month of the year) divided each in 24 periods of 1 hour [11]. The annual thermal energy demand is 2,905 MWh/year, being 507.5 MWh/year for the domestic hot water and 2,397.5 MWh/year for the heating.

DHW is produced at 60ºC. The proposed CSHPSS plant produces water at 50ºC for a heating network of low temperature, which is favorable for maximizing the efficiency in thermal solar plants. A typical low temperature heating system is for instance the radiant floor heating system.

The selection of pieces of equipment has been made for solar collectors, thermal energy storages, auxiliary boilers, heat exchangers and pumps, based either on the information appearing in catalogs (boilers, heat exchangers and pumps) or on the information published in the scientific literature (collector field and seasonal thermal energy storage).

Flat plate collectors are used to collect solar radiation. These collectors have surfaces higher than 10 m$^2$ and they can be installed either on the roof of a building and/or on the ground. The proposed surface to be installed, in the analyzed case, is 2,760 m$^2$ on the ground, corresponding to a ratio of 0.95 m$^2$/(MWh/year).

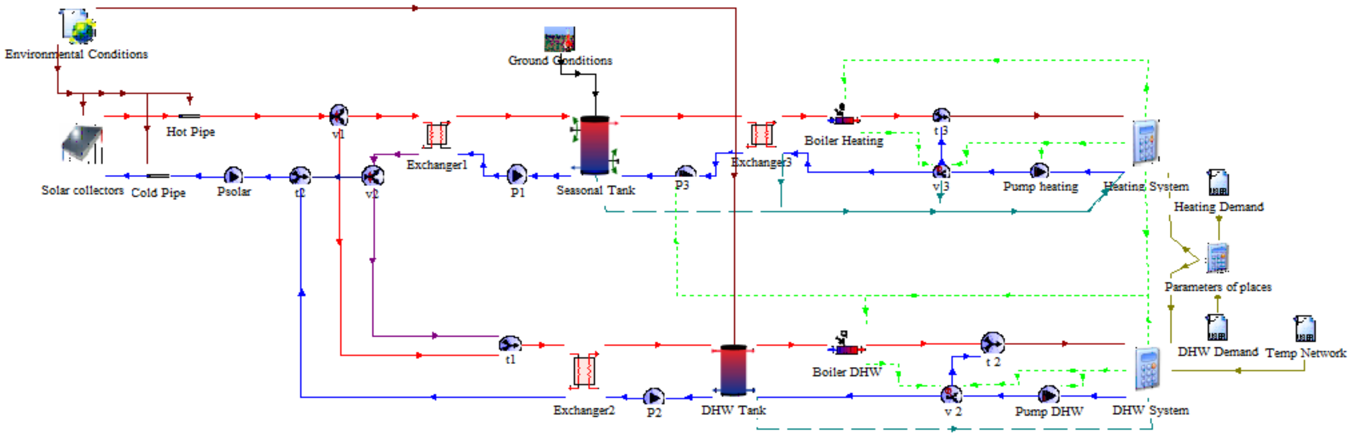

**Figure 2. TRANSYS model of the Central Solar Heating Plant**

The sizing of the DHW storage was based on the medium demand corresponding to a daily coverage of 23 $m^3$. The volume of the selected DHW was 47 $m^3$, sufficient for two days.

The volume of the seasonal thermal energy storage required for reaching a solar fraction close to 2/3 of the annual heating demand was estimated about 15,810 $m^3$. Due to the big size, this thermal energy storage should be built in the place where it will be located.

Auxiliary boilers with a thermal power of 208 kW for the production of sanitary hot water and 1,800 kW for heating are able of covering all the thermal demand (100%) without usage of the solar thermal system.

The heat exchangers were designed establishing a overall UA coefficient that could guarantee a heat exchanger effectiveness of 0.95, even in the worst operation conditions.

The sizing of the feed pumps was established considering the maximum volume of flow and the pressure loss in the ducts. This pressure loss is the addition of the pressure loss in the different pieces of equipment connected in series to the pump and the pressure loss corresponding to the length of the ducts and auxiliary components.

## TRNSYS MODEL

TRNSYS is a software tool providing a complete environment for the dynamic simulation of energy systems, including buildings. Figure 2 and Table 1 shows the TRNSYS model of the analyzed CSHPSS plant depicted in Figure 1.

Climatic data (solar radiation and ambient temperature) for the city of Zaragoza (Height: 247 m; Latitude: 41.39º N; Longitude: 1.00º W) were obtained from EnergyPlus [12]. Cold temperature from the domestic water supply network is taken from Standard UNE 94002 [13].

Hourly thermal demands, both for domestic hot water and for heating, are registered in a text file and are provided to the model. All the demand values were obtained from direct measurements taken in several dwellings located in the residential area or Parque Goya, located in the city of Zaragoza.

In Table 1 are shown the different TRNSYS types that have been used for the simulation of the components, as well as the most relevant technical parameters of the designed system.

### Annual energy balance

The energy balance of the whole system for a year of operation is shown in Figure 3. The annual energy efficiency of the solar field is 46%. The DHW storage has higher efficiency (98%) than the seasonal thermal energy storage (90%), which is reasonable. One of the most important conclusions obtained from the analysis of the results of existing CSHPSS demonstration plants in Europe is the appropriate thermal insulation of the seasonal energy storage. In real plants in operation it has been detected higher thermal losses (30% - 300%) than evaluated in the design. This fact provokes a significant reduction of the real solar fraction with respect to that one evaluated in the design of the system [14].

**Table 1. TRNSYS model of the different plant components**

| Component | | Type | Parameter | Value |
|---|---|---|---|---|
| Solar field (sf) | Collectors | 1a | Collector area | 13.575 $m^2$ |
| | | | Collector number | 204 |
| | | | Slope | 50º |
| | | | Azimuth | 0º |
| | | | a0 | 0.738 |
| | | | a1 | 1.63 $W/(m^2K)$ |
| | | | a2 | 0.0299 $W/(m^2K^2)$ |
| | | | Specifc flow | 20 $kg/(h\cdot m^2)$ |
| | Pipes | 709 | Total length | 1000 m |
| | | | Diameter | 0.1 m |
| | | | Ins. thickness | 0.06 m |
| | | | Ins. conductivity | 0.144 kJ/(h·m·K) |
| Seasonal storage (a1) | | 4c | Volume | 15810 $m^3$ |
| | | | Thermal loss | 0.45 $kJ/(h\cdot m^2\cdot K)$ |
| | | | Height/Diameter | 0.6 |
| | | | Number of nodes | 12 |
| DHW storage (a2) | | 4a | Volume | 47 $m^3$ |
| | | | Thermal loss | 1.6 $kJ/(h\cdot m^2\cdot K)$ |
| | | | Height/Diameter | 1.5 |
| | | | Number of nodes | 6 |
| Heating Boiler (BH) | | 6 | Nominal power | 1800 kW |
| | | | Efficiency | 0.93 |
| | | | Service Temp | 50ºC |
| DHW Boiler (BD) | | 6 | Nominal power | 208 kW |
| | | | Efficiency | 0.96 |
| | | | Service Temp | 60ºC |
| Heat exchanger 1 (ex1) | | 5b | Area | 282 $m^2$ |
| | | | Overall U | 3942 $W/m^2\cdot K$ |
| Heat exchanger 2 (ex2) | | 5b | Area | 282 $m^2$ |
| | | | Overall U | 3942 $W/m^2\cdot K$ |
| Heat exchanger 3 (ex3) | | 5b | Area | 580 $m^2$ |
| | | | Overall U | 3931 $W/m^2\cdot K$ |
| Pump - primary (PS) | | 3b | Nominal flow | 54 $m^3/h$ |
| | | | Nominal power | 15 kW |
| Pump 1 (P1) | | 3b | Nominal flow | 51 $m^3/h$ |
| | | | Nominal power | 1.4 kW |
| Pump 2 (P2) | | 3b | Nominal flow | 51 $m^3/h$ |
| | | | Nominal power | 1.4 kW |
| Pump 3 (P3) | | 110 | Nominal flow | 104 $m^3/h$ |
| | | | Nominal power | 3.7 kW |

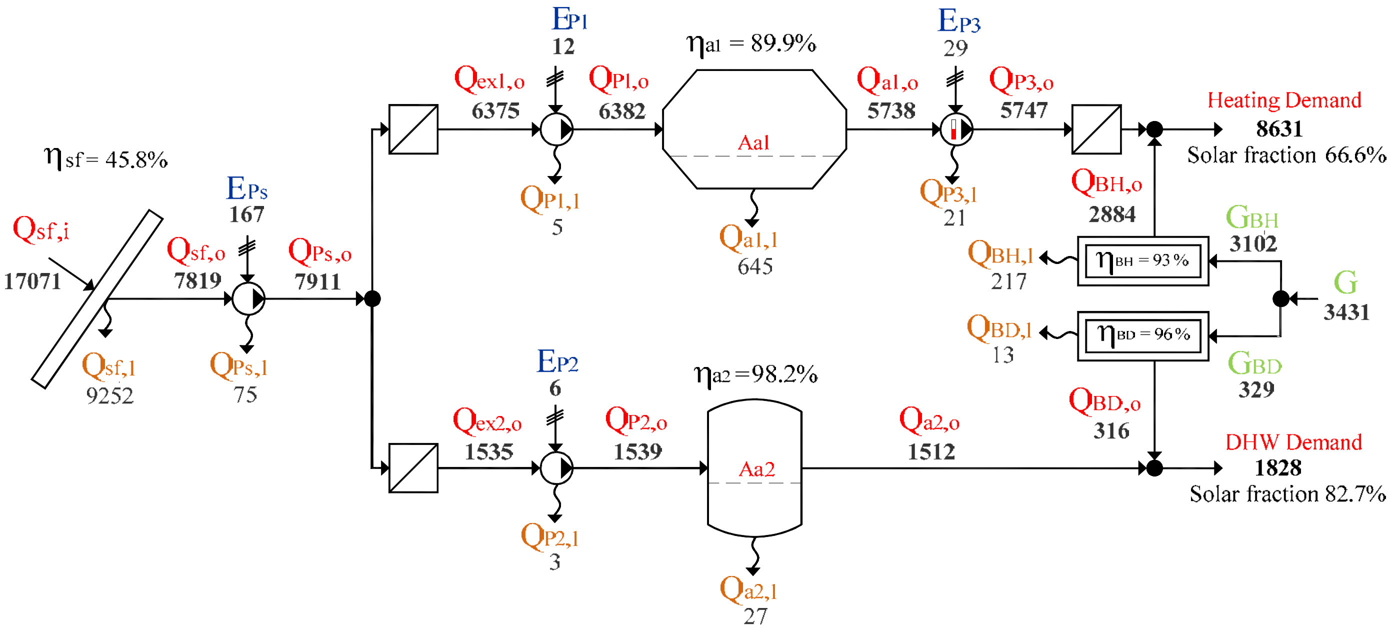

**Figure 3. Annual energy balance of the designed system (Energy flows, GJ/year)**

**Table 2. Monthly operation of the analyzed system (GJ)**

| | Qsf,i | Qsf,o | EPS | QPS,o | Qex1,o | EP1 | QP1,o | ΔAa1 | Qa1,o | EP3 | QP3,o |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Jan** | 975.6 | 506.7 | 10.96 | 512.8 | 356.7 | 0.69 | 357.2 | -278.0 | 609.1 | 5.48 | 610.7 |
| **Feb** | 1166.3 | 638.7 | 12.25 | 645.5 | 501.0 | 0.87 | 501.6 | 20.8 | 457.3 | 4.41 | 458.6 |
| **Mar** | 1528.7 | 861.0 | 15.49 | 869.5 | 704.6 | 1.13 | 705.2 | 42.8 | 634.5 | 3.99 | 635.7 |
| **Apr** | 1486.3 | 835.5 | 16.37 | 844.5 | 693.3 | 1.25 | 694.0 | 347.2 | 316.3 | 2.80 | 317.2 |
| **May** | 1612.4 | 893.3 | 18.07 | 903.2 | 769.4 | 1.39 | 770.2 | 730.1 | 0.0 | 0.00 | 0.0 |
| **Jun** | 1615.6 | 845.3 | 17.41 | 854.9 | 742.1 | 1.40 | 743.0 | 691.2 | 0.0 | 0.00 | 0.0 |
| **Jul** | 1819.2 | 865.0 | 17.53 | 874.7 | 800.5 | 1.51 | 801.4 | 734.2 | 0.0 | 0.00 | 0.0 |
| **Aug** | 1865.0 | 752.6 | 16.00 | 761.4 | 723.1 | 1.38 | 723.9 | 644.7 | 0.0 | 0.00 | 0.0 |
| **Sep** | 1597.9 | 439.8 | 11.30 | 446.0 | 349.8 | 0.77 | 350.3 | 265.0 | 0.0 | 0.00 | 0.0 |
| **Oct** | 1430.3 | 400.7 | 10.62 | 406.5 | 263.8 | 0.72 | 264.3 | -11.2 | 186.7 | 2.62 | 187.5 |
| **Nov** | 1056.9 | 377.6 | 10.92 | 383.7 | 220.0 | 0.45 | 220.3 | -1055.5 | 1199.1 | 4.22 | 1200.3 |
| **Dec** | 916.8 | 402.6 | 10.17 | 408.2 | 251.0 | 0.54 | 251.3 | -2132.7 | 2335.0 | 5.79 | 2336.7 |
| **YEAR** | 17071 | 7819 | 167.08 | 7911 | 6375 | 12.11 | 6383 | -1 | 5738 | 29.31 | 5747 |

| | GBH | QBH,o | HD | Qex2,o | EP2 | QP2,o | ΔAa2 | Qa2,o | GBD | QBD,o | DD |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Jan** | 1581.00 | 1470.3 | 2081.1 | 156.0 | 0.84 | 156.5 | -0.3 | 154.4 | 75.82 | 72.8 | 227.2 |
| **Feb** | 1067.90 | 993.1 | 1451.8 | 144.4 | 0.80 | 144.9 | 2.2 | 140.6 | 59.81 | 57.4 | 198.0 |
| **Mar** | 389.00 | 361.8 | 997.5 | 164.9 | 0.80 | 165.4 | -0.5 | 163.4 | 41.07 | 39.4 | 202.8 |
| **Apr** | 17.10 | 15.9 | 333.1 | 151.2 | 0.55 | 151.5 | 1.1 | 147.9 | 20.36 | 19.5 | 167.4 |
| **May** | 0.00 | 0.0 | 0.0 | 133.8 | 0.57 | 134.2 | -0.1 | 131.9 | 14.20 | 13.6 | 145.5 |
| **Jun** | 0.00 | 0.0 | 0.0 | 112.7 | 0.56 | 113.1 | 0.7 | 110.2 | 10.24 | 9.8 | 120.1 |
| **Jul** | 0.00 | 0.0 | 0.0 | 74.2 | 0.23 | 74.3 | 1.2 | 71.0 | 2.26 | 2.2 | 73.2 |
| **Aug** | 0.00 | 0.0 | 0.0 | 38.3 | 0.11 | 38.3 | -3.5 | 39.7 | 0.90 | 0.9 | 40.6 |
| **Sep** | 0.00 | 0.0 | 0.0 | 96.2 | 0.28 | 96.4 | -0.9 | 95.1 | 7.05 | 6.8 | 101.9 |
| **Oct** | 0.00 | 0.0 | 187.5 | 142.7 | 0.28 | 142.9 | -0.3 | 140.7 | 8.79 | 8.4 | 149.1 |
| **Nov** | 0.00 | 0.0 | 1200.3 | 163.7 | 0.57 | 164.0 | 2.1 | 159.2 | 29.27 | 28.1 | 187.3 |
| **Dec** | 46.54 | 43.3 | 2380.0 | 157.2 | 0.87 | 157.7 | -2.7 | 157.7 | 59.30 | 56.9 | 214.6 |
| **YEAR** | 3101.54 | 2884 | 8631 | 1535 | 6.46 | 1539 | -1 | 1512 | 329.07 | 316 | 1828 |

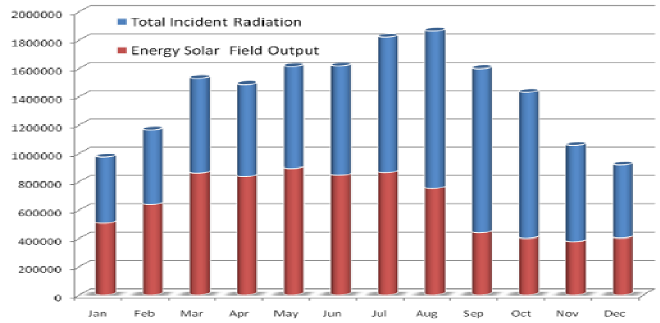

Figure 4. Incident solar energy and energy used (MJ)

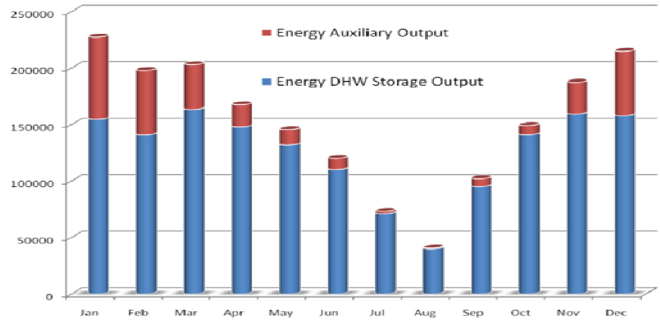

Figure 5. Monthly production of DHW (MJ)

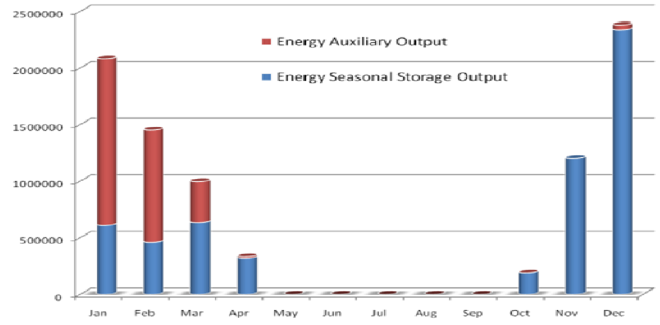

Figure 6. Monthly production of heating (MJ)

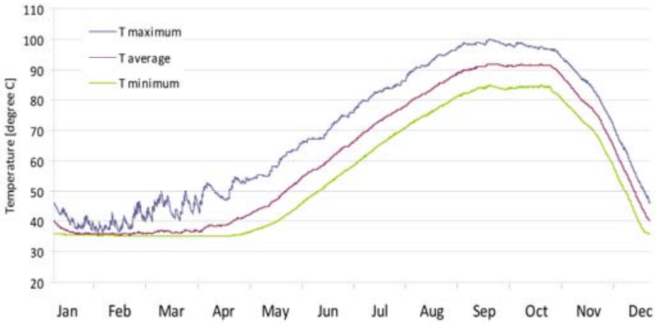

Figure 7. Temperature (ºC) on the roof (blue), medium (red) and bottom (green) of the seasonal storage

## Dynamic behavior of the installation

Figures 4 to 7 show the behavior month-to-month for a typical year of operation of the designed system. The highest solar radiation offer is in August (see Figure 4). However, since March to July is harnessed more thermal energy than in August. The reason is the reduction of the energy efficiency of the solar collectors due to the temperature raise of the working fluid when the load of the seasonal thermal energy storage increases. In Figure 5 is shown how the domestic hot water demand is covered in an important fraction with solar energy, higher than 68%, during all the year. This solar fraction is higher than 90% during the period May-October. Globally, the annual solar coverage of domestic hot water is about 83%. In the case of heating, it is shown in Figure 6 that the solar fraction is high only during the beginning of the heating season. Globally, the solar coverage of heating is about 67%. Combining both demands, domestic hot water and heating, the designed system provides an annual solar fraction of 69%.

The seasonal thermal energy storage is completely unloaded at the end of December because the heating demand between October and December has been covered with solar energy. From January to March the heating demand is still high, and all the energy received by the seasonal thermal storage is unloaded. In April the seasonal thermal storage starts to loading thermal energy, reaching the maximum temperature level in September. Temperatures of the seasonal energy storage along a typical operation year are shown in Figure 7.

## Consumption of auxiliaries

The consumption of auxiliary energy has two parts. On one hand, the natural gas consumption in the auxiliary boilers to produce the domestic hot water and heating demands not covered with solar energy (3,431 GJ/year). On the other hand, the electricity consumed by the pumps (59,710 kWh/year). In Table 2 is shown the monthly energy consumption in detail.

## ECONOMIC ANALYSIS

### Energy cost

In the case of the natural gas, the annual cost is 41,500 €, considering a natural gas price of 12.1 €/GJ. In the case of electrical energy consumed by the pumps, the annual cost is 9,200 €, considering an electricity price of 0.154 €/kWh. The total energy cost of the operation during the year is 50,700 €. Energy prices for Spain (2009) were taken from Eurostat [15].

### Amortization and maintenance costs

The total required investment, without considering any subsidy, has been estimated in about $2{,}774 \cdot 10^3$ €. This estimate considers the purchase cost of the pieces of equipment of the system, as well as the installation costs and an allowance of 15% for contingency and fees. In Table 3 are shown in detail the considered costs. Assuming the operation life-time of the system as 20 years and the annual interest rate of 6%, the corresponding annual amortization factor is 0.0872 year$^{-1}$. So the annual amortization cost is 241,840 €. The annual maintenance costs have been estimated about 1% of the investment, i.e. 27,740 €.

**Table 3. Investment [5-6, 16-20]**

| Component | Capacity | Cost | FBM* | CBM& |
|---|---|---|---|---|
| Solar Field sf | 2760 m$^2$ | 250 €/m$^2$ | - | 690.0 |
| Seasonal storage a1 | 15810 m$^3$ | 80 €/m$^3$ | - | 1214.0 |
| DHW storage a2 | 47 m$^3$ | 800 €/m$^3$ | 1.3 | 48.9 |
| Heating Boiler BH | 1800 kW | 16 €/kW | 1.7 | 49.0 |
| DHW Boiler BD | 208 kW | 24 €/kW | 1.5 | 7.5 |
| Heat Exch. ex1 | 282 m$^2$ | 220 €/m$^2$ | 1.5 | 93.1 |
| Heat Exch. ex2 | 282 m$^2$ | 220 €/m$^2$ | 1.5 | 93.1 |
| Heat Exch. ex3 | 580 m$^2$ | 205 €/m$^2$ | 1.5 | 178.3 |
| Pump Psol | 15.0 kW | 490 €/kW | 2.5 | 14.7 |
| Pump P1 | 1.4 kW | 1440 €/kW | 2.5 | 5.0 |
| Pump P2 | 1.4 kW | 1440 €/kW | 2.5 | 5.0 |
| Pump P3 | 3.7 kW | 1430 €/kW | 2.5 | 13.2 |
| Total CBM | | | | 2412.2 |
| Cont. and fees 15% | | | | 361.8 |
| Total capital | | | | 2774.0 |

*Bare module installation factor, &Bare module cost ($10^3$ €)

### Total annual cost and unit cost of heat

The sum of the previous cost is equal to 320,280 €. Being the annual heat demand equal to 2,905 MWh, the heat unit cost is 0.110 €/kWh.

Boilers don´t produce solar heat. Therefore amortization and maintenance charges for solar heat are equal to 236,140 €/year and 27,090 €/year, respectively. All the electrical energy costs considered (9,200 €/year) are due to solar heat production. The global sum of the previous costs leads to 272,430 €. Being the annual production 2,016 MWh, then the resulting solar heat unit cost is 0.135 €/kWh.

The cost of the heat produced by the auxiliary boilers includes its amortization and maintenance charges equal to 5,700 €/year and 650 €/year, respectively, as well as the cost of the natural gas (41,500 €/year). The overall cost of the heat produced by boilers is 47,850 €/year. Being the overall production 889 MWh/year, the resulting unit cost of non solar heat is 0.054 €/kWh which is roughly half the cost of the solar heat.

### Comparison with other systems

Table 4 resumes the main characteristics of similar plants installed in Germany [6] and includes the system designed for Zaragoza. The German systems belong to the same typology as the one designed for Zaragoza and include a seasonal storage system. Furthermore, they use flat-plate solar collectors and hot water tank storage systems. However, having Spain a higher annual radiation than Germany, some deviations on the design parameters can be observed. In particular, given an energy demand and a solar fraction to cover, smaller solar collector surface and larger storage systems are required in Spain. This can be clearly observed by looking ratios A/D and V/A in Table 4. A clear tendency can be also observed when comparing the unit cost of solar heat: the larger the plant the lower the cost. This is due to two issues related to the sizing of the seasonal storage: firstly, economies of scale are significant; secondly, the heat losses are reduced for larger volumes.

In order to cover a given demand, several design options in terms of ratios A/D and V/A can be used. However, the investment cost tends to sharply rise when designing for high solar fraction. The system described in this work is able to cover a solar fraction as high as 69% with a solar heat unit cost of 135 €/MWh, significantly lower than the typical value encountered in German plants.

**Table 4. Comparison of technical and economic data from several solar thermal systems with seasonal accumulation**

| Localization | Total heat demand D MWh/y | Solar collector area A m$^2$ | Seasonal storage volume V m$^3$ | Solar fraction % | Ratio A/D m$^2$/(MWh/a) | Ratio V/A m | Solar heat cost €/kWh |
|---|---|---|---|---|---|---|---|
| Friedrichshafen | 4106 | 5600 | 12000 | 47 | 1.36 | 2.14 | 0.159 |
| Hamburg | 1610 | 3000 | 4500 | 49 | 1.86 | 1.50 | 0.257 |
| Munich | 2300 | 2900 | 5700 | 47 | 1.26 | 1.97 | 0.240 |
| Hanover | 694 | 1350 | 2750 | 39 | 1.95 | 2.04 | 0.414 |
| Zaragoza | 2905 | 2760 | 15810 | 69 | 0.95 | 5.50 | 0.135 |

## THERMOECONOMIC ANALYSIS

In energy systems, resources are used up to provide certain qualities to the internal flows until the desired final products are obtained. The cost formation process throughout the system from the energy resources to the final products is made transparent in thermoeconomic analysis, which launches an intensive analysis dose on the design and operation concepts of energy conversion systems for the purpose of revealing opportunities of energy and cost savings [21]. Thermoeconomic methods are powerful tools for the analysis [22,23], diagnosis [24,25] and optimization [26,27] of energy conversion systems.

According to Gaggioli [28] cost accounting is the process of tracking, recording and analyzing costs associated with the products or activities of a plant. The objectives of cost accounting are: 1) to determine the actual cost of products, 2) to provide a rational basis for pricing products, 3) to provide a means of controlling expenditures, and 4) to form a basis for operating decisions and the evaluation thereof. Obtaining unit costs of internal flows and products of energy systems is a cornerstone of several thermoeconomic approaches that have been presented in the literature [29,30]. In this section the thermoeconomic cost accounting of the analyzed CSHPSS system is accomplished. That is, it is evaluated the process of cost formation considering the very specific features of CSHPSS systems: free solar energy, DHW and seasonal thermal energy storage as well as continuous variation of the operation due to highly variations of solar radiation and energy demands. These features impose important difficulties in the calculation of the costs of internal flows and products, which have not been accomplished yet in actual thermoeconomic analysis methodologies.

The conservation of costs, as a first principle, is common to all thermoeconomic approaches (all costs from resources consumed in a production unit must be charged to its useful products). Applying the condition of cost conservation to each component of the CSHPSS system studied, for each considered period of time j (one year, one month, one hour, etc.) in which the internal costs are evaluated, the equations shown in Table 5 are obtained.

External resources used in the production process are valued at the prices at which they were purchased, i.e. cR (unit energy cost of solar energy, which purchase cost is zero), cE (unit energy cost of electricity) and cG (unit energy cost of natural gas).

As can be seen, the amortization and maintenance costs of the thermal energy storage devices -za1,h and za2,h- are evaluated per unit of time (hour) because they are operating continuously during the year. On the other hand, the amortization and maintenance costs of the rest of the components –*zeq*- are evaluated per unit of product. For each period of time j, hpm[j] represents number of hours of the considered period; za1,h and za2,h represent the hourly amortization and maintenance cost, which is equal to the annual cost / 8760 hours; *zeq* represent the amortization and maintenance cost per unit of product of the considered component *eq*, which is equal to the annual cost / yearly energy production of the component *eq*.

Thus, the solution of the system of equations shown in Table 5 provides the values of the unknowns represented in bold in Table 5, which are the unit energy cost of all internal flows and products of the analyzed CSHPSS system.

Figure 8 shows the unit energy costs of the analyzed CSHPSS system when considering a single time period of a year. It is shown that the solar thermal energy loading the seasonal storage has a unit energy cost of 0.0126 €/MJ, which is lower than the conventional heat obtained in the heating boiler (0.0149 €/MJ). However, the seasonal storage increases significantly the cost of the thermal energy, reaching the value of 0.0416 €/MJ at the outlet of the CSHPSS system.

A similar situation is found in the case of domestic hot water. The solar thermal energy, prior to the DHW thermal energy storage has a unit energy cost of 0.0181 €/MJ, which is close to the unit energy cost of the conventional heat obtained in the boiler (0.0153 €/MJ). In this case the increase of the unit energy cost reaching the value of 0.0221 €/MJ is lower because the storage time of the domestic hot water is significantly shorter and as a consequence the heat losses are smaller.

**Table 5. Equations used for the calculation of internal costs of the analyzed CSHPSS system**

| Comp. | Equation | Nº |
|---|---|---|
| sf: | cR·Qsf,i[j] + zsf·Qsf,o[j] = **csf[j]**·Qsf,o[j] | (1) |
| Ps: | csf[j]·Qsf,o[j] + cE·EPs[j] + zPs·QPs,o[j] =<br>= **cPs[j]**·QPs,o[j] | (2) |
| ex1: | cPs[j]·Qex1,i[j] + zex1·Qex1,o[j] =<br>**cex1[j]**·Qex1,o[j] | (3) |
| P1: | cex1[j]·Qex1,o[j] + cE·EP1[j] + zP1·QP1,o[j] =<br>= **cP1[j]**·QP1,o[j] | (4) |
| P3: | ca1[j]·Qa1,o[j] + cE·EP3[j] + zP3·QP3,o[j] =<br>= **cP3[j]**·QP3,o[j] | (5) |
| ex3: | cP3[j]·QP3,o[j] + zex3·Qex3,o[j] =<br>**cex3[j]**·Qex3,o[j] | (6) |
| BH: | cG·GBH[j] + zBH·QBH,o[j] = **cBH[j]**·QBH,o[j] | (7) |
| HD: | cex3[j]·Qex3,o[j] + cBH[j]·QBH,o[j] =<br>= **cHD[j]**·QHD[j] | (8) |
| Ex2 | cPs[j]·Qex2,i[j] + zex2·Qex2,o[j] =<br>**cex2[j]**·Qex2,o[j] | (9) |
| P2: | cex2[j]·Qex2,o[j] + cE·EP2[j] + zP2·QP2,o[j] =<br>= **cP2[j]**·QP2,o[j] | (10) |
| BD: | cG·GBD[j] + zBD·QBD,o[j] = **cBD[j]**·QBD,o[j] | (11) |
| DD: | ca2[j]·Qa2,o[j] + cBD[j]·QBD,o[j] =<br>**cDD[j]**·QDD[j] | (12) |
| a1: | cP1[j]·QP1,o[j] + ca1,i[j]·Aa1,i[j] + za1,h·hpm[j] =<br>= **ca1,f[j]**·Aa1,f[j] + **ca1[j]**·Qa1,o[j] | (13) |
|  | **ca1[j]** = **ca1,f[j]** | (14) |
| a2: | cP2[j]·QP2,o[j] + ca2,i[j]·Aa2,i[j] + za2,h·hpm[j] =<br>= **ca2,f[j]**·Aa2,f[j] + **ca2[j]**·Qa2,o[j] | (15) |
|  | **ca2[j]** = **ca2,f[j]** | (16) |

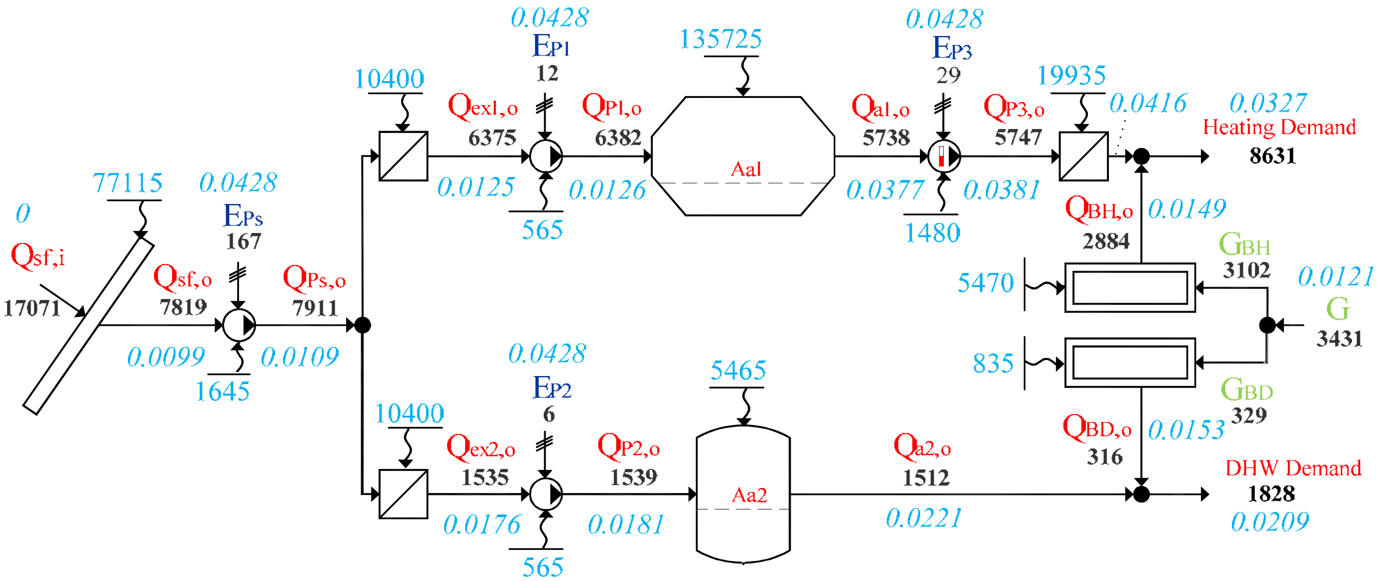

**Figure 8. Annual cost balance: energy flows (bold) in GJ/year, equipment cost (normal) in €/year, unit energy cost (italics) in €/MJ**

**Table 6. Monthly unit energy costs (€/MJ)**

| | **csf** | **cPs** | **cex1** | **cP1** | **ca1,i** | **ca1,f** | **ca1** | **cP3** | **cex3** | **cBH** | **cHD** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Jan** | 0.0099 | 0.0109 | 0.0125 | 0.0127 | 0.0400 | 0.0446 | 0.0446 | 0.0451 | 0.0486 | 0.0149 | 0.0248 |
| **Feb** | 0.0099 | 0.0108 | 0.0124 | 0.0126 | 0.0446 | 0.0350 | 0.0350 | 0.0355 | 0.0390 | 0.0149 | 0.0225 |
| **Mar** | 0.0099 | 0.0107 | 0.0124 | 0.0125 | 0.0350 | 0.0302 | 0.0302 | 0.0307 | 0.0341 | 0.0149 | 0.0272 |
| **Apr** | 0.0099 | 0.0108 | 0.0124 | 0.0126 | 0.0302 | 0.0300 | 0.0300 | 0.0305 | 0.0340 | 0.0149 | 0.0331 |
| **May** | 0.0099 | 0.0108 | 0.0124 | 0.0126 | 0.0300 | 0.0294 | - | - | - | - | - |
| **Jun** | 0.0099 | 0.0108 | 0.0125 | 0.0126 | 0.0294 | 0.0295 | - | - | - | - | - |
| **Jul** | 0.0099 | 0.0108 | 0.0125 | 0.0126 | 0.0295 | 0.0295 | - | - | - | - | - |
| **Aug** | 0.0099 | 0.0109 | 0.0125 | 0.0126 | 0.0295 | 0.0300 | - | - | - | - | - |
| **Sep** | 0.0099 | 0.0110 | 0.0126 | 0.0128 | 0.0300 | 0.0322 | - | - | - | - | - |
| **Oct** | 0.0099 | 0.0110 | 0.0127 | 0.0129 | 0.0322 | 0.0348 | 0.0348 | 0.0355 | 0.0389 | 0.0000 | 0.0389 |
| **Nov** | 0.0099 | 0.0111 | 0.0128 | 0.0129 | 0.0348 | 0.0373 | 0.0373 | 0.0376 | 0.0411 | 0.0000 | 0.0411 |
| **Dec** | 0.0099 | 0.0110 | 0.0126 | 0.0128 | 0.0373 | 0.0400 | 0.0400 | 0.0404 | 0.0438 | 0.0149 | 0.0433 |

| | **cex2** | **cP2** | **ca2,i** | **ca2,f** | **ca2** | **cBD** | **cDD** |
|---|---|---|---|---|---|---|---|
| **Jan** | 0.0176 | 0.0182 | 0.0216 | 0.0215 | 0.0215 | 0.0153 | 0.0195 |
| **Feb** | 0.0176 | 0.0181 | 0.0215 | 0.0213 | 0.0213 | 0.0153 | 0.0195 |
| **Mar** | 0.0175 | 0.0180 | 0.0213 | 0.0212 | 0.0212 | 0.0153 | 0.0200 |
| **Apr** | 0.0176 | 0.0181 | 0.0212 | 0.0214 | 0.0214 | 0.0153 | 0.0207 |
| **May** | 0.0176 | 0.0181 | 0.0214 | 0.0219 | 0.0219 | 0.0153 | 0.0213 |
| **Jun** | 0.0176 | 0.0181 | 0.0219 | 0.0225 | 0.0225 | 0.0153 | 0.0219 |
| **Jul** | 0.0176 | 0.0181 | 0.0225 | 0.0249 | 0.0249 | 0.0153 | 0.0246 |
| **Aug** | 0.0176 | 0.0181 | 0.0249 | 0.0311 | 0.0311 | 0.0153 | 0.0307 |
| **Sep** | 0.0178 | 0.0183 | 0.0311 | 0.0236 | 0.0236 | 0.0153 | 0.0230 |
| **Oct** | 0.0178 | 0.0182 | 0.0236 | 0.0219 | 0.0219 | 0.0153 | 0.0215 |
| **Nov** | 0.0179 | 0.0184 | 0.0219 | 0.0215 | 0.0215 | 0.0153 | 0.0205 |
| **Dec** | 0.0178 | 0.0183 | 0.0215 | 0.0216 | 0.0216 | 0.0153 | 0.0199 |

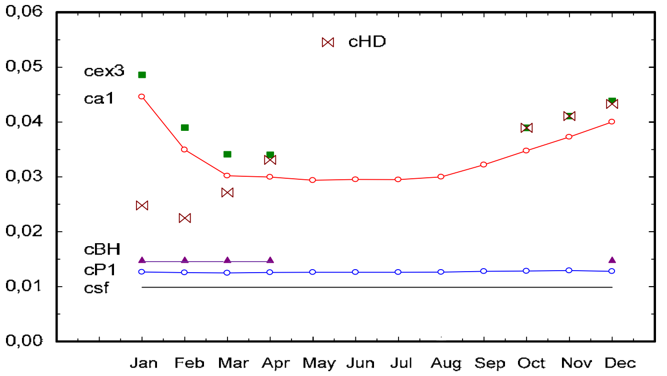

**Figure 9. Monthly unit energy cost (€/MJ) of heating cHD**

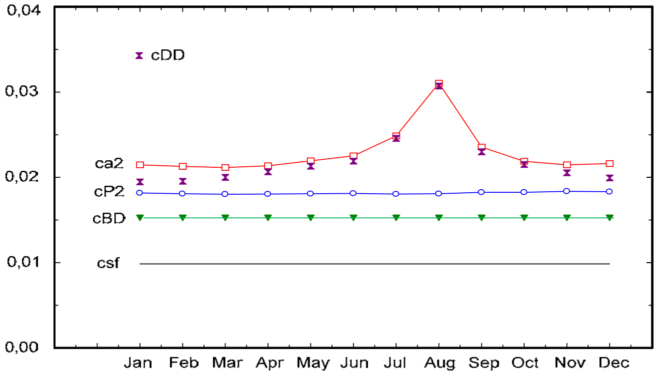

**Figure 10. Monthly unit energy cost (€/MJ) of domestic hot water cDD**

A relevant problem in the evaluation of the internal costs of the CSHPSS system is the cost apportioning of the thermal energy storage system, particularly in the case of the seasonal thermal energy storage, in which the thermal energy is stored for a long period of time and the heat losses are greater than in the case of the DHW storage. In a thermal energy storage system it is necessary to evaluate properly the cost of the thermal energy stored, in particular when there is thermal energy flowing out of the storage. In this case it is necessary to assess unit costs to two different energy products, a) thermal energy stored at the end of the period, and b) thermal energy flowing out the storage tank during the period (see equations 13 and 15 corresponding to a1 and a2 in Table 5). As the working fluid, transporting the thermal energy, going into the thermal energy storage is mixed with the working fluid already stored, is complex to determine physically which part of the thermal energy going out proceeds from the already thermal energy stored and which part has just flown through the storage tank.

As a first approach to solve this problem it is proposed to assess the same unit energy cost to both products of the thermal energy storage (see equations 14 and 16 in Table 5). Applying the same system of equations (Table 5) for each of the 12 months of the year the results shown in Table 6 are obtained, in which are shown the internal unit energy costs of the analyzed CSHPSS system separately for each month.

The monthly evolution of the unit heating cost CBH produced with the heating boiler versus the unit solar heating cost cex3 is shown in Figure 9. In this Figure 9 it is also shown the unit energy cost of: heating demanded cHD, thermal energy stored ca1, thermal energy from solar field csf, and thermal energy after pump cp1. Between October to December when the heating demand is covered with stored solar energy, the unit heating cost is closer to the unit solar heating cost cex3. During the months (January – March) in which the seasonal energy storage is unloaded, the cost of heating is a mix of cex3 and cBH, in proportion to the solar and boiler contribution, respectively. Note that the solar heating cost increases when the load of the seasonal thermal energy storage is decreasing as well as when increasing the storage time of thermal energy stored. Also note that the highest cost of the thermal energy stored is three times higher than the thermal energy produced in the conventional heating system.

In Figure 10 are shown the monthly unit energy cost of: DHW demanded cDD, thermal energy stored ca2, thermal energy from solar field csf, thermal energy after pump cp2, and thermal energy from DHW boiler cBD. The cost of supplied domestic hot water is very close to the cost obtained from the solar system ca2, because a big fraction of the DHW demand is covered with the solar system. The cost of the domestic hot water is highest in August due to the low demand. This maximum cost is about two times higher than the cost of the DHW produced in the boiler. The rest of the year the difference between both costs is less than 50%.

## CONCLUSIONS

This work is intended to be a design guide to promote the installation of solar systems with seasonal storage in Spain. These systems are able of covering heating and DHW demands with high solar fractions and they represent an innovation opportunity in the domestic market due to the unused solar potential and the needs for policies aiming at reducing the energy dependency from other countries.

Technical design parameters and economical data are provided for a solar system with seasonal storage coping with the heat demand from a district of 500 dwellings located in Zaragoza, Spain. Once designed, the system is able to supply DHW and heating with a unit cost of 110 €/MWh and with a solar fraction as high as 69%. Nevertheless, the unit cost of solar heat (135 €/MWh) is still 2.5 times the cost of the boiler heat (54 €/MWh). It is foreseeable that such a difference will decrease in the future due to decreasing initial investment (especially regarding the storage) and increasing fuel costs. The obtained results are compared with similar experiences available in Europe.

A thermoeconomic study of the process of cost formation through the different components of the designed CSHPSS system has been performed, considering its very specific features: free solar energy, seasonal and DHW thermal energy storage and continuous variation of the operation due to highly variations of solar radiation and energy demands (hourly and seasonal). These features impose difficulties in the calculation of the costs of internal flows and products, which are still open problems in actual thermoeconomic analysis methodologies. A key conceptual aspect of this problem is the appropriate evaluation of the cost of the thermal energy stored, in particular when there is thermal energy flowing out of the storage. In this respect, as a first approach, a cost assessment proposition has been presented. The annual and monthly analyses of the internal costs of the designed CSHPS system have been accomplished. Further cost assessment refinements are being investigated by the authors in order to provide more accurate internal cost values.

From the results obtained in this work it can be concluded that the contribution of solar energy to global energy demand can be increased by designing systems able of covering almost the whole DHW demand and a large fraction of heating needs. This approach could be significantly enhanced by the favorable climatic conditions encountered in Spain and other South European countries. Energy policy should incorporate the development of these systems in the medium and long term strategies. The high initial investment cost can be reduced with an advanced planning which would allow for the plant facilities to be built together with the buildings they will serve.

## NOMENCLATURE

| | | |
|---|---|---|
| DD | DHW demand | [GJ/year] |
| EP1 | Electricity input to pump 1 | [GJ/year] |
| EP2 | Electricity input to pump 2 | [GJ/year] |
| EP3 | Electricity input to pump 3 | [GJ/year] |
| EPS | Electricity input to solar pump | [GJ/year] |
| G | Total natural gas supplied to the system | [GJ/year] |
| GBD | Natural gas input to DHW boiler | [GJ/year] |
| GBH | Natural gas input to heating boiler | [GJ/year] |
| HD | Heating demand | [GJ/year] |
| Qa1,l | Heat loss from seasonal storage | [GJ/year] |
| Qa1,o | Heat from seasonal storage | [GJ/year] |
| Qa2,l | Heat loss from DHW storage | [GJ/year] |
| Qa2,o | Heat from DHW storage | [GJ/year] |
| QBD,l | Heat loss from DHW boiler | [GJ/year] |
| QBD,o | Heat output from DHW boiler | [GJ/year] |
| QBH,l | Heat loss from heating boiler | [GJ/year] |
| QBH,o | Heat output from heating boiler | [GJ/year] |
| Qex1,o | Heat output from exchanger 1 | [GJ/year] |
| Qex2,o | Heat output from exchanger 2 | [GJ/year] |
| Qex3,o | Heat output from exchanger 3 | [GJ/year] |
| Qp1,l | Heat loss from pump 1 | [GJ/year] |
| Qp1,o | Heat output from pump 1 | [GJ/year] |
| Qp2,l | Heat loss from pump 2 | [GJ/year] |
| Qp2,o | Heat output from pump 2 | [GJ/year] |
| Qp3,l | Heat loss from pump 3 | [GJ/year] |
| Qp3,o | Heat output from pump 3 | [GJ/year] |
| Qps,l | Heat loss from solar pump | [GJ/year] |
| Qps,o | Heat output from solar pump | [GJ/year] |
| Qsf,i | Energy input to solar field | [GJ/year] |
| Qsf,l | Heat loss from solar field | [GJ/year] |
| Qsf,o | Heat output from solar field | [GJ/year] |
| ΔAa1 | Energy variation in seasonal storage | [GJ/year] |
| ΔAa2 | Energy variation in DHW storage | [GJ/year] |
| | | |
| ηa1 | Efficiency of seasonal storage | [ - ] |
| ηa2 | Efficiency of DHW storage | [ - ] |
| ηBH | Efficiency of heating boiler | [ - ] |
| ηBD | Efficiency of DHW boiler | [ - ] |
| ηsf | Efficiency of solar field | [ - ] |
| | | |
| za1,h | Amortization and maintenance cost of seasonal storage | [ €/hour ] |
| za2,h | Amortization and maintenance cost of DHW storage | [ €/hour ] |
| zBD | Amortization and maintenance cost of DHW boiler | [ €/MJ ] |
| zBH | Amortization and maintenance cost of heating boiler | [ €/MJ ] |
| zex1 | Amortization and maintenance cost of exchanger1 | [ €/MJ ] |
| zex2 | Amortization and maintenance cost of exchanger2 | [ €/MJ ] |
| zex3 | Amortization and maintenance cost of exchanger3 | [ €/MJ ] |
| zP1 | Amortization and maintenance cost of pump1 | [ €/MJ ] |
| zP2 | Amortization and maintenance cost of pump2 | [ €/MJ ] |
| zP3 | Amortization and maintenance cost of pump3 | [ €/MJ ] |
| zPs | Amortization and maintenance cost of solar pump | [ €/MJ ] |
| zsf | Amortization and maintenance cost of solar field | [ €/MJ ] |
| | | |
| ca1 | Unit energy cost from seasonal storage | [ €/MJ ] |
| ca1,i | Initial unit energy cost in seasonal storage | [ €/MJ ] |
| ca1,f | Final unit energy cost in seasonal storage | [ €/MJ ] |
| ca2 | Unit energy cost from DHW storage | [ €/MJ ] |
| ca2,i | Initial unit energy cost in DHW storage | [ €/MJ ] |
| ca2,f | Final unit energy cost in DHW storage | [ €/MJ ] |
| cBD | Unit energy cost from DHW boiler | [ €/MJ ] |
| cBH | Unit energy cost from heating boiler | [ €/MJ ] |
| cDD | Unit energy cost of DHW demand | [ €/MJ ] |
| cE | Unit energy cost of electricity | [ €/MJ ] |
| cex1 | Unit energy cost from exchanger1 | [ €/MJ ] |
| cex2 | Unit energy cost from exchanger2 | [ €/MJ ] |
| cex3 | Unit energy cost from exchanger3 | [ €/MJ ] |
| cG | Unit energy cost of natural gas | [ €/MJ ] |
| cHD | Unit energy cost of heating demand | [ €/MJ ] |
| cP1 | Unit energy cost from pump1 | [ €/MJ ] |
| cP2 | Unit energy cost from pump2 | [ €/MJ ] |
| cP3 | Unit energy cost from pump3 | [ €/MJ ] |
| cPs | Unit energy cost from solar pump | [ €/MJ ] |
| cR | Unit energy cost of solar energy | [ €/MJ ] |
| csf | Unit energy cost from solar field | [ €/MJ ] |

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