Task 45 Large Systems

Evaluation tool for CSHPSS - Methodology

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Introduction, evaluation tools for CSHPSS

The development of solar systems covering part of the residential thermal energy is an economically viable option that reduces the consumption of fossil fuels [1]. The World energy demand in the residential sector (2035 Mtoe) represents roughly 27% of the final energy consumption [2]. Hence, the production of a significant part of this demand with solar energy might solve an important part of the energy problems: shortage, dependency, high prices fluctuation, pollution, climate change, among others [1].

Solar systems that produce domestic hot water (DHW) is a wide spread solution to cover part of the thermal energy demands for the residential sector. This production represents a small solar fraction of the total thermal energy demand of DHW and space heating of buildings for temperate or cold climates. Therefore, considering also the coverage of other heating demands in buildings as space heating or even cooling with absorption machines, the real potential of the solar thermal energy source is very high.

Central solar heating plants with seasonal storage (CSHPSS) can cover with a high solar fraction the space heating and domestic hot water demands of big communities at an affordable price. These systems already supply heat to big communities through district heating systems in the north and center of Europe. The evaluation of the performance and the design of these centralized solar systems is a complex process, due to their dynamic behavior both during the day and along the year. The production of the solar collector field depends on the solar radiation and the ambient temperature changing along the day, as well as on the operation temperature of the seasonal storage. Further, the location and the size of the demand affect to the performance of the system in such way that the sizing between the north and south of Europe is very different. As a result, the process of pre-design and study in initial stages of the project becomes a real challenge.

Dynamic simulations with TRNSYS [3] of CSHPSS provide an evaluation of the performance of its behaviour with a high accuracy [4-6] but it requires exhaustive and detailed information and a high computational effort. Simple calculation methods requiring less detailed data and a lower computational effort can complement TRNSYS for a preliminary quick evaluation of the size of the main components of an installation facilitating the design task and providing an estimate of its annual performance.

An original simple method developed by the Task participants (Guadalfajara M, Lozano MA & Serra LM) [7-9] that calculates the physical behaviour of the main equipment of CSHPSS using simple and public climatic and demand data specific for each location is presented. The proposed method calculates the behaviour of the system hourly on a typical day each month, providing the monthly and annual performance of a CSHPSS as well as information to pre-design the size of the solar field and the volume of the seasonal thermal energy storage of a CSHPSS.

The *Simple Method* has been built on the Engineering Equation Solver [10] and a distributable application of the program developed is available.

Simple Method

The *Simple Method* is based on the possibility of performing an approximate calculation, on a monthly basis, of the solar collector field production and the capacity of the seasonal thermal energy storage to match production and demand along one month.

Figure 1 shows the system scheme and identifies the main energy flows considered in the model. The radiation received, Q_r, over the solar collector is harvested and the production of the solar field, Q_c, is calculated simulating its hourly operation during a representative day of the month. It is considered a complete mixture in the thermal energy storage, i.e. without stratification; so it keeps uniform the accumulator temperature, T_{acu}, along the calculation period, which is a month in the proposed model. Thus, the solar collector performance and the heat losses, Q_l, of the seasonal storage are calculated considering the tank temperature. In a seasonal storage tank, the premise of considering constant the water tank temperature along the month is reasonable due to its high thermal inertia (high volume). A monthly energy balance is used to calculate the temperature in the thermal energy storage at the end of the month. This temperature of the water tank at the end of the month is used to calculate the solar collector performance at the next month.

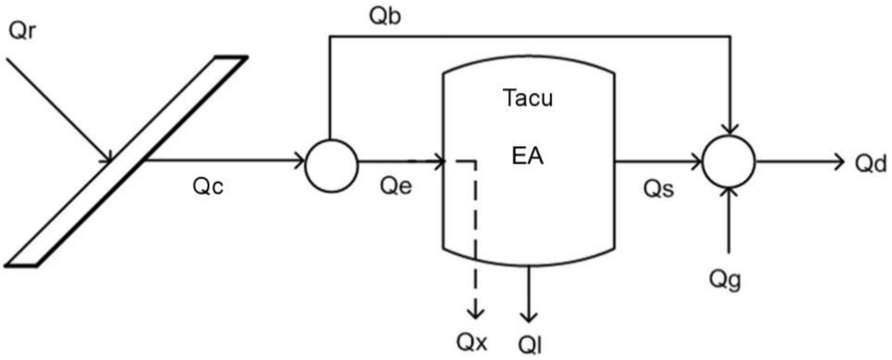

Figure 1. Energy flow chart of the simple model of central solar heating plant with seasonal storage. (Source: Authors)

The monthly operation of the seasonal storage tank has two different operation modes during the year: i) charge and ii) discharge. The charge operation mode occurs when the production of the solar field, Q_c, is higher than the heat demand, Q_d. Then part of the collected heat will be used to attend the immediate demand, Q_b, and the surplus of the collected heat will be sent to the seasonal storage for its later consumption, Q_e. In the discharge operation mode, the heat demand, Q_d, is higher than the production of the solar collectors, Q_c, and the seasonal storage tank is first discharged, Q_s, and if it is still not enough, then the auxiliary system, Q_g, provides the required heat to cover the demand.

The operation of the thermal energy storage is constrained by two temperature limits, maximum and minimum. When the limit of the minimum temperature is reached, the thermal energy storage cannot be discharged anymore and the auxiliary system provides the required heat, Q_g, to fulfil the demand. The thermal energy storage can not be charged either over the maximum temperature. When it reaches this maximum temperature limit, part of the heat production is rejected, Q_x, to avoid overheating and equipment damage. The thermal energy accumulated in the storage tank is denoted by the variable EA (Figure 1).

The calculation of the Simple Method is performed in four sequential modules (Figure 2). Module one elaborates the input data, module two estimates the performance of the solar field, module three calculates the physical performance of the seasonal thermal energy storage and module four calculates the annual results and performs an economic evaluation.

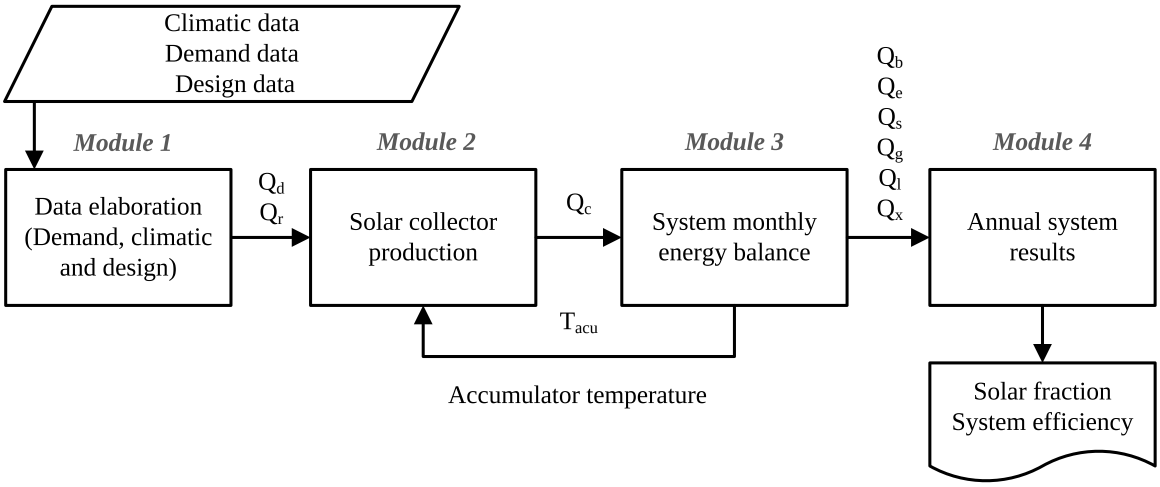

Figure 2. Information flow chart and scheme of the Simple Method calculation modules. (Source: Authors)

<u>Module 1</u>: In base of public data that can be easily obtained (daily horizontal radiation, average ambient temperature, annual space heating demand, etc), hourly and monthly climatic and demand data are elaborated. These data are required to calculate the system performance in the following modules (hourly solar radiation over tilted surface, hourly ambient temperature, monthly demand…).

<u>Module 2</u>: The monthly production of the solar field is calculated based on the hourly radiation and hourly ambient temperature of a typical day, and on the tank temperature at the beginning of the considered month. The calculation of the solar field is based on the performance equation of the solar collector. The performance of the heat exchanger between the primary and the secondary circuits (between the solar field and the seasonal storage tank) is also considered and the inlet and outlet temperatures of the solar collector are calculated.

<u>Module 3</u>: Each month an energy balance, considering production, demand and losses, calculates the energy charged, discharged and accumulated in the seasonal storage and if required the auxiliary energy required. It is also calculated the temperature of the water tank at the end of the calculation period and the heat rejected, in case the storage tank would be fully charged (Module 3).

<u>Module 4</u>: The technical results are calculated and presented: annual energy balance, solar fraction, global efficiency of the system and of the considered components. It is also estimated the investment, operation and maintenance costs of the system and the solar heat cost.

Calculation process

To make easier the evaluation of CSHPSS systems with the simple method a few public and available data are used. The minimum input climatic and demand data required are the next:

- Annual demand of DHW and annual demand of space heating.
- Latitude of the location and ground reflectance, ρ_g.
- Monthly average of the daily global radiation over horizontal surface, H (monthly data).
- Average, minimum and maximum ambient temperature, T_a (monthly data).

As an illustrative example of the calculation process is presented the calculation of a system called ”Base Case”. The considered base case is located in Zaragoza, Spain and it will supply heat for space heating and domestic hot water for a community of 1000 dwellings in multifamily buildings, with an average size of the dwellings of 100 m^2. The annual demand of space heating and DHW can be estimated from reference values for a specific location according to the surface of the dwellings. The demand considered has been taken from the reference values in Spain for new multifamily buildings [11]. In the case of Zaragoza the annual demand for space heating in multifamily buildings is 40.6 kWh/m^2 and the domestic hot water demand is 12.9 kWh/m^2. Therefore for a community of 1000 dwellings of 100 m^2 each, the annual space heating demand is Q_{SH} = 4060 MWh/year, the annual DHW demand is Q_{DHW} = 1290 MWh/year and the total annual demand results Q_d = 5350 MWh/year.

The latitude in Zaragoza is 41.6º and the considered ground reflectance is $\rho_g = 0.2$. Daily average horizontal radiation can be obtained from multiple sources (Meteonorm, Energyplus, …), as well as the data shown in Table 1: radiation [12], degree-days[13], average minimum, average medium and average maximum ambient temperatures [14] and cold water temperature of the supply network [15].

Table 1. Monthly input climatic data to the simple method for Zaragoza.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (MJ/(m^2·day)) [12]	6.4	9.8	13.8	17.4	21.5	23.8	25.3	22.5	16.5	11.6	7.5	5.7
DD_{15} (K·day) [13]	285	222	187	99	26	1	0	0	3	52	176	286
Ta_{min} (ºC) [14]	2.4	3.5	5.2	7.4	11.2	14.8	17.6	17.8	14.7	10.3	5.8	3.5
Ta_{ave} (ºC) [14]	6.4	8.4	10.9	13	17.2	21.3	24.5	24.4	20.7	15.5	10.0	7.1
Ta_{max} (ºC) [14]	10.3	13.3	16.6	18.7	23.2	27.7	31.5	31.0	26.7	20.7	14.3	10.7
T_{net} (ºC) [15]	8	9	10	12	15	17	20	19	17	14	10	8

The design variables considered in the simple model presented in this paper are the next:

1. Area of solar collector, A (or RAD, which is the ratio of the area of the solar field, m^2, divided by the annual demand in MWh/year).
2. Volume of the seasonal storage tank, V (or RVA, which is the ratio of the volume of the seasonal storage tank, m^3, divided by the area of the solar field in m^2).
3. Efficiency curve of the solar collector, η_0, k_1, k_2.

4. Tilt and orientation of the solar collectors.
5. Specific mass flow rate of working fluid circulating through the solar collectors, m_s.
6. Heat exchanger efficacy of the solar field, E_{ff}.
7. Temperature of the water supplied to the district heating network, T_{SH}.
8. Temperature of the water returning from the district heating network, T_{ret}.
9. Maximum temperature in the seasonal storage tank (accumulator), T_{max}.
10. Global heat transfer coefficient in the accumulator for the calculation of the heat losses, U_{acu}.

For the Base Case, the system will be calculated with the design ratios RAD = 0.6 and RVA = 6. Hence, for the total annual demand of 5350 MWh/year the solar collector area required is 3210 m^2 and the volume of the accumulator is 19,260 m^3.

The district heating network supplies heat for the buildings with water at T_{SH} = 50 ºC and the return temperature of the water from the district heating network is T_{ret} = 30 ºC. The minimum temperature of the water in the seasonal storage tank is equal to the return temperature from the district heating network, T_{min} = 30 ºC, and the maximum temperature is fixed at T_{max} = 90 ºC. The DHW is supplied at the same temperature than that of the space heating T_{DHW} = 50ºC (in the present version it is not considered that the water supply temperature for space heating could be higher than the water supply temperature for DHW).

The considered solar collectors are ARCON HT-SA 28/10 with an optical efficiency of η_0 = 0.816 and loss coefficients of k_1 = 2.235 W/(m^2·K) and k_2 = 0.0135 W/(m^2·K^2); they are oriented to the south with 45º tilt.

The considered inlet mass flow rate of the working fluid to the solar collectors is m_s = 20 (kg/h)/m^2, which is appropriate for central solar heating plants, because it facilitates stratification in the accumulator. The heat exchanger efficacy is E_{ff} = 0.9. The seasonal storage is assumed as an underground cylindrical tank with a shape ratio RHD = 0.6 (height divided by diameter). Once the volume is known the other dimensions can be calculated.

$$D = (4 \cdot V / (\pi \cdot RHD))^{1/3} \tag{1}$$

$$H = RHD \cdot D \tag{2}$$

$$A_{acu} = (RHD + 0.5) \cdot \pi \cdot D^2 \tag{3}$$

In the analyzed base case D = 34.45 m; H = 20.67 m; and A_{acu} = 4101 m^2. The global heat transfer coefficient to the ground U_{acu} = 0.12 W/(m^2K) has been obtained considering an insulation layer of 25 cm of extruded polystyrene (XPS), which conductivity is 0.03 W/(m·K). The ground temperature, T_{ter}, has been considered constant along the year and with the same value as the average ambient temperature in Zaragoza, 15.0 ºC. The maximum energy stored can be calculated with the next equation:

$$EA_{\max} = V \cdot \rho \cdot c_p (T_{\max} - T_{\min}) / (3.6 \cdot 10^9) \tag{4}$$

In the previous equation ρ = 1000 kg/m^3 is the water density and c_p = 4180 J/(kg·K) the water specific heat. For the base case the maximum amount of heat in the thermal energy storage is EA_{max} = 1342 MWh.

Module 1: Data elaboration

In Module 1 are calculated the hourly ambient temperature $T_a[m,h]$ for a representative day each month and the hourly radiation over tilted surface $q_r[m,h]$ in W/m^2. In Annex A are presented the climatic correlations used in this module.

Further, Module 1 distributes the annual space heating demand with the degree-days method. A correlation to estimate monthly degree days for a particular base temperature, knowing the monthly average ambient temperature is presented in Annex A. Centralized systems use to be unplugged in periods of low demand, then the space heating demand supplied is considered 0 in months in which the degree-days, DD_{SH}, are lower than the monthly days (N).

$$DD_{SH}[m] = if\ \ DD_{15}[m] > N[m]\ \ Then\ \ DD_{SH}[m] = DD_{15}[m]\ \ Else\ \ DD_{SH}[m] = 0 \qquad (5)$$

$$Q_{SH}[m] = Q_{SH} \cdot DD_{SH}[m] / \sum_{m=1}^{m=12} DD_{SH}[m] \qquad (6)$$

The domestic hot water demand is monthly distributed with the method proposed by the standard UNE 94002 [15], in which the DHW demand is estimated as a function of the temperature of the water supply network, T_{net}, and the number of the days of each month. Cold water temperature can be estimated from the ambient temperature using the correlation presented in Annex A.

$$DD_{DHW}[m] = N[m] \cdot (T_{DHW} - T_{net}[m]) \qquad (7)$$

$$Q_{DHW}[m] = Q_{DHW} \cdot DD_{DHW}[m] / \sum_{m=1}^{m=12} DD_{DHW}[m] \qquad (8)$$

The total monthly demand of the system is the sum of both, space heating demand and DHW demand.

$$Q_d[m] = Q_{SH}[m] + Q_{DHW}[m] \qquad (9)$$

For the base case the annual demand of space heating and domestic hot water has been monthly distributed using the climatic dada presented in Table 1, the obtained results are shown in Table 2.

Table 2: Monthly demand obtained with Module 1 for the analyzed base case (1000 dwellings of 100 m^2 in Zaragoza).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Q_{SH} (MWh)	885	690	581	308	0	0	0	0	0	162	547	888
Q_{DHW} (MWh)	125	111	119	110	104	95	90	93	95	107	116	125
Q_d (MWh)	1011	800	700	417	104	95	90	93	95	269	662	1014

- Note that the simple method can be applied with very simple data using the correlations proposed in Annex A for monthly degree days, cold water temperature and horizontal radiation, but it is also possible to avoid this entire module if equivalent final data for Module 1 are provided: monthly demand, hourly radiation over tilted surface for a typical day each month, ambient temperature for a typical day each month, area of the solar collector field and characteristics of the seasonal storage.

Module 2: Solar collector field production

The production of the solar collector, $q_c[m,h]$, is calculated hourly using the efficiency curve of a solar thermal collector. The calculation requires the hourly solar radiation $q_r[m,h]$ and the temperature difference between the solar collector, T_c, and the ambient temperature, T_a. Note that only is considered heat collected when the efficiency value of the solar collector is positive (Equation 10).

$$q_c[m,h] = Max\ (\eta_0 \cdot q_r[m,h] - k_1 \cdot \Delta T[m,h] - k_2 \cdot \Delta T[m,h]^2;\ 0) \tag{10}$$

$$\Delta T[m,h] = T_c[m,h] - T_a[m,h] \tag{11}$$

The solar collector temperature is the average value between inlet and outlet temperature of the fluid in the solar collector.

$$T_c[m,h] = (T_{in}[m,h] + T_{out}[m,h])/2 \tag{12}$$

The outlet temperature of the solar collector fluid depends on its inlet temperature, a typical mass flow rate for these installations is m_s = 20 kg/(h·m^2) and its specific heat for the solar field, in this case water $c_{p,sf}$ = 4180 J/(kg·K).

$$T_{out}[m,h] = T_{in}[m,h] + q_c[m,h] \cdot 3600\ /(m_s \cdot c_{p,sf}) \tag{13}$$

Once the inlet temperature, T_{in}, is known, then the rest of variables q_c, ΔT, T_c and T_{out} can be obtained from the previous eqs. 10-13. The fluid circulating through the solar collector transfers the heat to the seasonal storage through a countercurrent plate heat exchanger. Considering that the heat capacity of the fluids circulating through the primary circuit (solar collector) and through the secondary circuit (load circuit charging the accumulator) is the same, and that the temperature of the water in the accumulator remains constant during the whole month, then the next equation is obtained:

$$T_{in}[m,h] = T_{out}[m,h] - E_{ff} \cdot (T_{out}[m,h] - T_{acu}[m-1]) \tag{14}$$

For the Base Case, a heat exchanger with an efficacy of 0.9 has been considered, the storage temperature at the beginning of January is 30 ºC. For the hourly radiation and average ambient temperature calculated in Module 1, the hourly performance of the solar collector is calculated. Climatic and performance values for the productive hours in January are presented in Table 3.

Table 3: Solar production in January, $q_c[m,h]$ in W/m^2.

Hour	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
T_{amb} (ºC)	3.6	4.7	6.1	7.5	8.6	9.5	10.1	10.5	10.5	10.2	9.8	8.4
T_{acu} (ºC)	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
T_{in} (ºC)	30.0	30.0	30.4	30.9	31.3	31.5	31.5	31.3	31.0	30.5	30.0	30.0
T_{out} (ºC)	30.0	30.0	34.2	39.1	43.1	45.4	45.5	43.4	39.6	35.0	30.4	30.0
T_c (ºC)	30.0	30.0	32.3	35.0	37.2	38.4	38.5	37.3	35.3	32.7	30.2	30.0
q_r (W/m^2)	0	71	196	325	431	490	490	431	325	196	71	0
q_c (W/m^2)	0	0	88	189	273	321	324	280	201	104	8	0

The monthly production of the solar field $Q_c[m]$ is the sum of the hourly values multiplied by the solar collector area A and the number of the days of the month (N[m]).

$$Q_c[m] = A \cdot N[m] \cdot 10^{-6} \sum_{h=1}^{24} q_c[m;h] \qquad (15)$$

The monthly radiation $Q_r[m]$ received by the solar field is calculated in a similar way, changing $q_c[m,h]$ by $q_r[m, h]$ in equation 15.

Module 3: Monthly energy balance

The monthly energy balance of the system requires a control of the minimum and maximum load of the seasonal storage tank. These limits guarantee the calculation of the charge and discharge of the accumulator fulfilling the physical constraints, which affect the auxiliary energy required to cover the demand and the heat rejected in case the tank would be fully charged. All the thermal energy flows appearing in the equations of the Module 3 are expressed in MWh/month.

The system is operated in such a way that each month the heat harvested in the solar collectors, Q_c, firstly will attend the demand, Q_b, and once it has been covered, the remaining heat, Q_e, will be introduced in the thermal storage tank (see Figure 1).

$$Q_e[m] = Max(Q_c[m] - Q_d[m];0) \qquad (16)$$

$$Q_b[m] = Q_c[m] - Q_e[m] \qquad (17)$$

Heat loss of the seasonal storage tank, Q_l, is calculated multiplying the global heat transfer coefficient of the accumulator U_{acu} in W/(m²·K) by the tank area A_{acu} in m², and by the temperature difference between the tank T_{acu} and the ground T_{ter}, and by the number of hours of the month. The considered tank temperature is the temperature at the beginning of the month (temperature at the end of the previous month).

$$Q_l[m] = U_{acu} \cdot A_{acu} \cdot (T_{acu}[m-1] - T_{ter}) \cdot 24 \cdot N[m] \cdot 10^{-6} \qquad (18)$$

In order to calculate the tank discharge an auxiliary variable, Q_{sx}, which expresses the maximum amount of heat that could be discharged, is used. This maximum amount depends on the accumulated energy, EA, the heat introduced, Q_e, and thermal losses, Q_l.

$$Q_{sx}[m] = Max(EA[m-1] + Q_e[m] - Q_l[m];0) \qquad (19)$$

The monthly auxiliary energy required (Q_g) is calculated as follows:

$$Q_g[m] = Max(Q_d[m] - Q_b[m] - Q_{sx}[m];0) \qquad (20)$$

Finally the discharged heat, Q_s, is calculated as a difference of the demand minus the solar direct production and the auxiliary energy required.

$$Q_s[m] = Q_d[m] - Q_b[m] - Q_g[m] \qquad (21)$$

The monthly solar heat produced, Q_{solar}, is

$$Q_{solar}[m] = Q_b[m] + Q_s[m] \tag{22}$$

The theoretical energy accumulated, EA_x, at the end of the month is calculated without considering the temperature limit. In real installations there are security systems that stop the pumps and therefore the solar field production when the maximum temperature inside the seasonal storage tank is reached, T_{max} = 90 ºC in this case. In the *Simple Method* this effect is modeled calculating the heat rejected, Q_x. Thus, the theoretical energy accumulated, EA_x, at the end of the month is,

$$EA_x[m] = EA[m-1] + Q_e[m] - Q_l[m] - Q_s[m] \tag{23}$$

If this energy is higher than the maximum amount, part of the solar production will be rejected, Q_x. The final energy accumulated, EA, and the heat rejected, Q_x, are given by the following equations:

$$EA[m] = Min\ (EA_x[m]; EA_{max}) \tag{24}$$

$$Q_x[m] = EA_x[m] - EA[m] \tag{25}$$

The accumulator temperature at the end of the month is calculated considering the real energy stored.

$$T_{acu}[m] = T_{min} + (T_{max} - T_{min}) \cdot EA[m] / EA_{max} \tag{26}$$

All the calculations are performed for an annual cycle in which the load and the accumulator temperature at the end of the year is the same than that at the beginning.

$$EA[0] = EA[12] \tag{27}$$

$$T_{acu}[0] = T_{acu}[12] \tag{28}$$

In the calculations have not been considered: the electric consumption of pumps, the heat losses in pipes, heat exchangers and auxiliary equipment nor the district heating network. In Table 4 are shown the obtained monthly results for the analyzed case.

Module 4: Annual results and economic evaluation

The annual energy flows of the system (Q_d, Q_r, Q_c, Q_b, Q_e, Q_x, Q_l, Q_s, Q_g and Q_{solar}) are calculated in the Module 4. The annual net energy balance of the system should be equal to cero.

$$Balance_{annual} = Q_c + Q_g - Q_d - Q_l - Q_x \tag{29}$$

The solar fraction, SF, and the solar collector efficiency, η_{coll}, can be calculated in monthly and annual basis.

$$SF = Q_{solar} / Q_d \tag{30}$$

$$\eta_{coll} = Q_c / Q_r \tag{31}$$

The thermal energy storage efficiency, η_{acu}, and the annual system efficiency, η_{sys}, can be calculated only in annual basis.

$$\eta_{acu} = Q_s / Q_e \tag{32}$$

$$\eta_{sys} = Q_{solar} / Q_r \tag{33}$$

Table 4 and Figure 3 present the obtained monthly and annual results for the analyzed case.

Table 4: Monthly and annual results of the system for the analyzed base case (Zaragoza, 1000 dwellings, RAD = 0.6, RVA = 6).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_d (MWh)	1011	800	700	417	104	95	90	92	95	269	662	1014	*5350*
Q_r (MWh)	305	359	458	470	536	543	610	605	501	446	338	288	*5458*
Q_c (MWh)	181	232	305	320	379	359	382	341	229	168	103	126	*3124*
Q_b (MWh)	181	232	305	320	104	95	90	93	95	168	103	126	*1911*
Q_e (MWh)	0	0	0	0	275	264	293	248	134	0	0	0	*1213*
Q_s (MWh)	0	0	0	0	0	0	0	0	0	101	559	407	*1067*
Q_l (MWh)	5.5	4.9	5.3	5.1	5.2	9.3	13.7	18.3	21.3	23.9	21.2	12.4	*146*
Q_x (MWh)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*0.0*
Q_{solar} (MWh)	181	232	305	320	104	95	90	93	95	269	662	533	*2979*
Q_g (MWh)	830	568	396	98	0	0	0	0	0	0	0	480	*2372*
EA (MWh)	-6	-10	-16	-21	249	503	782	1012	1125	1000	419	0	---
T_{acu} (ºC)	29.8	29.5	29.3	29.1	41.1	52.5	65.0	75.3	80.3	74.7	48.8	30.0	---
SF (%)	18	29	44	77	100	100	100	100	100	100	100	53	*56*
η_{coll} (%)	59	65	67	68	71	66	63	56	46	38	30	44	*57*
η_{acu} (%)	---	---	---	---	---	---	---	---	---	---	---	---	*88*
η_{sys} (%)	---	---	---	---	---	---	---	---	---	---	---	---	*54*

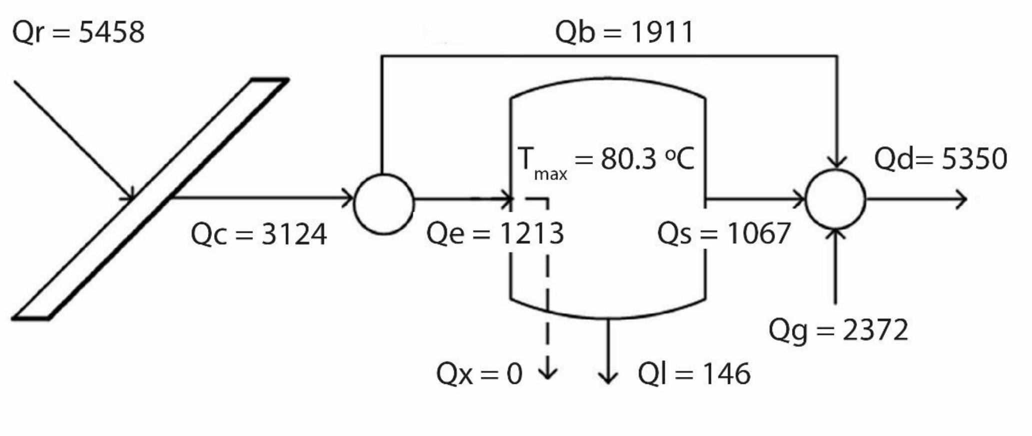

Figure 3. Annual results for the base case.

Furthermore, Module 4 provides an economic evaluation of the proposed installation. With data from previous works [6, 7] the cost of the main equipment can be estimated: solar collector field (Inv_{col}) and seasonal storage (Inv_{acu}) expressed in Euro (€).

$$Inv_{coll} = 740 \cdot A^{0.860} \tag{34}$$

$$Inv_{acu} = \alpha \cdot 4660 \cdot V^{0.615} \tag{35}$$

The exponents in previous equations explain the scale economies of the solar collector field and the seasonal storage tank. Note that the accumulator cost per unit of volume decreases significantly with the size. The economic behavior of different technologies of thermal energy storage (e.g. water tank, pit or borehole) is considered in Equation 35 with the implementation of a parameter α. A cost reduction of 50% or even lower can be obtained with low cost technologies as Pit Thermal Energy Storage or Borehole Thermal Energy Storage. The value α = 1 proposed corresponds with the experience gained in the demonstration projects of the last two decades using a hot water tank for thermal energy storage.

The investment cost of the rest of the equipment existing in a CSHPSS (pumps, heat exchangers, pipes, valves, etc.) has been included with an increasing factor of 25% (f_{aux} = 25%). The indirect costs (engineering project, project management, assurances, etc.) are considered with an increasing factor of 12% (f_{ind} = 12%). Therefore, the total investment is.

$$Inv = (1+f_{ind}) \cdot (1+f_{aux}) \cdot (Inv_{coll}+Inv_{acu}) = 1036 \cdot A^{0.860} + \alpha \cdot 6524 \cdot V^{0.615} \tag{36}$$

The annual cost of the equipment, Z in €/year, is calculated applying the annual amortization factor and the operation and maintenance costs. The amortization factor is calculated considering an annual interest rate, i in year^{-1}, of 3.0%, which is at present a common interest rate in countries in which CSHPSS are being installed, e.g. Denmark. The amortization costs are distributed along the equipment lifetime. The estimated lifetime is 25 years (na = 25 years) for the solar collector and 50 years for the seasonal storage (nv = 50 years). The annual operation and maintenance costs are estimated in 1.5% (f_{ope} = 0.015 year^{-1}) of the investment cost according to the criteria proposed by the IEA [1]. Therefore, the annual costs are calculated with the next equations:

$$Z_{coll} = Inv_{coll} \cdot (f_{ope}+i \cdot (1+i)^{na}/((1+i)^{na} - 1)) = 54 \cdot A^{0.860} \tag{37}$$

$$Z_{acu} = Inv_{acu} \cdot (f_{ope}+i \cdot (1+i)^{nv}/((1+i)^{nv} - 1)) = \alpha \cdot 251 \cdot V^{0.615} \tag{38}$$

$$Z = (1+f_{ind}) \cdot (1+f_{aux}) \cdot (Z_{coll}+Z_{acu}) = 75 \cdot A^{0.860} + \alpha \cdot 352 \cdot V^{0.615} \tag{39}$$

For the analyzed base case (1000 dwellings located in Zaragoza) the initial investment required is Inv = $3890 \cdot 10^3$ €. The annual cost is Z = 229,445 €/year. The unit cost of the solar heat, c_{solar}, is calculated as the quotient between the annual cost and the solar heat produced. As the solar production is Q_{solar} = 2979 MWh/year, then the unit cost of the solar heat is c_{solar} = 77.0 €/MWh.

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ANNEX A: Climatic correlations

The calculation of the performance of Central Solar Heating Plants with Seasonal Storage requires climatic and demand parameters. To calculate the performance of solar collector, it is required the knowledge of the ambient temperature, and the solar radiation over a tilted surface and its distribution along the day. The calculation of the thermal losses in the seasonal storage requires the knowledge of the average underground temperature. The demand of space heating and domestic hot water can be estimated from climatic data. In this Annex, are presented the correlations proposed by different authors and used in the Simple Method to calculate CSHPSS.

In the Module 1 are calculated the hourly environmental temperature $T_a[m,h]$ for a representative day of each month and the hourly radiation over tilted surface $q_r[m,h]$ in W/m^2.

Ambient temperature

The Erbs´ correlation for the ambient temperature is used to estimate the hourly ambient temperature along the day (T); it uses the minimum (T_{min}), the maximum (T_{max}) and the monthly average daily temperature (T_m) [A1, A2],

$$\frac{T - T_m}{T_{max} - T_{min}} = \sum_{k=1}^{4} a_k \cos(k \cdot \tau - b_k) \qquad (A1)$$

$$\tau = \frac{2\pi(\theta - 1)}{24} \qquad (A2)$$

being θ solar hour, θ = 12 at noon and τ angular solar hour.

Table A.1: Coefficients for the Erbs' correlation to calculate the hourly temperature [A1]

k	1	2	3	4
a_k	0.4632	0.0984	0.0168	0.0138
b_k	3.805	0.360	0.822	3.513

If it is only known T_m then ($T_{max} – T_{min}$) can be calculated as

$$T_{max} - T_{min} = 25.8 \cdot K_t - 5.21 \qquad (A3)$$

In Table A.2 is shown the calculated hourly temperature for Zaragoza, Spain in a typical day of January from minimum average and maximum average daily temperature in January

Table A.2: Hourly temperature from 7:00-21:00 in January estimated with Erbs' correlation for Zaragoza, Spain

Hour	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21
T (ºC)	3.6	4.7	6.1	7.5	8.6	9.5	10.1	10.5	10.5	10.2	9.8	8.4	7.4	6.6

Solar radiation over tilted surface

With the average daily horizontal radiation and the extraterrestrial radiation, which depends on the city latitude and the date, the sky clearness index can be calculated [A3]. This index is used to calculate the daily diffuse radiation [A4]. The total horizontal radiation is hourly distributed with the Collares-Pereira & Rabl correlation [A5], and the diffuse radiation is hourly distributed with Liu & Jordan correlation [A6]. The difference between total radiation and diffuse radiation is the direct (beam) radiation. The hourly radiation over tilted surface (beam, diffuse and total) can be calculated using the isotropic sky model [A3].

Table A.3 shows the calculated horizontal radiation in Zaragoza (latitude 41º), total (I), direct (I_b) and diffuse (I_d) from average horizontal radiation (H_0). It is also shown the calculation for Zaragoza of hourly radiation over tilted surface (I_t) at 45º using isotropic sky model with ground reflectance 0.2.

Table A.3: Hourly radiation from 5:00-12:00 in January estimated with Erbs' correlation for Zaragoza, Spain

Hour	6-7	7-8	8-9	9-10	10-11	11-12
I (W/m^2)	0	10	100	190	270	310
I_d (W/m^2)	0	0	50	90	110	130
I_b (W/m^2)	0	10	50	100	160	180
I_t (W/m^2)	0	71	196	325	431	490

Underground temperature

Kusuda and Achenbach [A7] proposed a correlation to determine the ground temperature at a given depth, along the year. The underground temperature depends on the annual average ambient temperature, the daily average temperature, amplitude along the year, the day of the year and on the soil thermal diffusivity. Soil thermal diffusivity can be calculated using the equation proposed by ASHRAE [A8]. This model does not consider the soil thermal inertia and the effect of the seasonal storage over the soil temperature.

Using these correlations the authors have noticed that the average underground temperature in the range of large underground hot water tank (deep > 5 m) is almost constant and in average, equal to the annual average ambient temperature.

Degree days

Degree days in a determined month, can be calculated with the average ambient temperature T_{amb} for a determined base temperature T_{base}, [A1, A2] with the correlation proposed by Erbs, Klein and Beckman. In Table A.4 are presented the monthly degree days for Zaragoza calculated with T_{base} = 15 ºC.

Table A.4: Monthly degree days with T_{base} = 15 ºC, for Zaragoza, Spain

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_m (ºC)	6.4	8.4	10.9	13.0	17.2	21.3	24.5	24.4	20.7	15.5	10.0	7.1
DD_{15} (ºC·dia)	270	190	142	87	23	3	0	0	4	43	160	250

Water supply network temperature

The monthly average temperature of the water supply network can be calculated as a function of the monthly ambient temperature and the annual average ambient temperature using the Equation A10, that has been built based on the values of the cold water temperature of different cities in Spain (A = 10/3, B = 2/3) [A9]. Usually a minimum distribution temperature is used for locations with very low temperature. The authors use a limit in the cold water distribution temperature of 4 ºC.

$$\mathrm{T}_{\mathrm{net}}(n) = T_{ave} - A + B \cdot (T_{amb}(n) - T_{ave}) \qquad (A10)$$

The monthly average cold water temperature values for the city of Zaragoza are shown in Table A.5

Table A.5: Monthly average temperature of the water supply network for Zaragoza, Spain

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{net} (ºC)	6.7	8.1	9.8	11.2	14.0	16.7	18.8	18.8	16.3	12.8	9.2	7.2

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