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Comparison of simple methods for the design of central solar heating plants with seasonal storage

Mateo Guadalfajara[a]*, Miguel A. Lozano[a], Luis M. Serra[a]

GITSE-Aragon Institute of Engineering Research (I3A), University of Zaragoza, C/ María de Luna s/n, Zaragoza 50018, Spain

Abstract

The development of central solar heating plants with seasonal storage (CSHPSS) to cover part of the heating demand of buildings with district heating in the residential sector is becoming an economically viable option that can contribute significantly to the reduction of the consumption of fossil fuels. The calculation of CSHPSS systems, with a highly dynamic behaviour, is a complex process in which climatic, demand and design data are required. Simple calculation methods can be used to perform feasibility and pre-design studies enabling an estimation of the annual result. A review of several simple methods that have been proposed for the evaluation and design of the main components of CSHPSS is presented. The methods share some characteristics: main equipments considered, dependence with solar radiation and heating demand; and differ in other aspects: design parameters of the main equipments, secondary equipment considered, degree of detail of climatic and demand input data and equations of the model used to calculate the performance of the system. In this paper a description of each method is presented and results obtained for a base case (installation that produce 50% of the space heating demand for a community of 1000 dwellings in Zaragoza, Spain) are compared.

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

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* Corresponding author. Tel.: +34-976-761-913.
E-mail address: mateog@unizar.es; mlozano@unizar.es; serra@unizar.es

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1. Introduction

Renewable energies are becoming increasingly important all over the world. Particularly solar thermal energy presents a very important potential of development in the residential-commercial sector with many interesting and attractive benefits. The IEA expects that by the year 2050 will be produced 8.9 EJ (2472 TWh) of solar energy for space heating and domestic hot water [1]. The technical feasibility of covering an important part of the space heating and domestic hot water demands with solar thermal energy is nowadays a reality for central solar heating plants with seasonal storage (CSHPSS) systems [2-5]. Their commercial expansion will be supported by the usage of simple and validated tools to predesign, study and evaluate solar thermal alternatives. A review of several simple methods that have been proposed for the evaluation and design of the main components of CSHPSS is presented, a brief description of each method is done, and results obtained for a base case (installation that produces 50% of the space heating demand for a community of 1000 dwellings in Zaragoza, Spain) are compared.

2. Base case

The base case, that is completely described in [6], correspond to a CSHPSS system that produces 50% of space heating for a community of 1000 dwellings in multifamily buildings in Zaragoza (Spain). Main design parameters are given in Table 1. Detailed results are obtained using the dynamic simulation tool TRNSYS [7], which has been probed as a validated tool for these systems [8-10]. A summary of the results of the base case can be seen in this article but all the results can be found in the original paper [6].

A simplification of the CSHPSS system considered, for most simple models, is a system composed by a solar field, a seasonal thermal energy storage (STES) and an auxiliary energy source.

Table 1: Main parameters of the base case system [6]

Solar collector field; model Arcon HT-SA 28/10 [11])		STES, underground water tank		Demand
$A = 2854\ m^2$	$q = 20\ kg/(h\cdot m^2)$	$V = 22{,}829\ m^3$	$T_{min} = 30ºC$	$Q_d = 5488$ MWh/year
$\eta_0 = 0.817$	$HE_{eff} = 95\%$	$A_{acu} = 4604\ m^2$	$T_{max} = 90ºC$	$N_{houses} = 1000$
$k_1 = 2.205\ W/(m^2\cdot K)$	$c_{p,sf} = 3840\ J/(kg\cdot K)$	$U_{acu} = 0.06\ W/(m^2K)$	$c_p = 4180\ J/(kg\cdot K)$	$UA_{houses} = 100\ W/m^2K$
$k_2 = 0.0135\ W/(m^2\cdot K^2)$	$\rho = 1020\ kg/m^3$	$EA_{max} = 1590$ MWh	$\rho = 1000\ kg/m^3$	$T_{houses} = 21ºC$

3. Scheme of the CSHPSS plants

Fig. 1 shows the simplified system scheme and identifies the main energy flows that appear in simple models of CSHPSS plants.

The radiation received, Q_r, over the solar collector is harvested and the production of the solar field is Q_c. Simple models consider 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. 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.

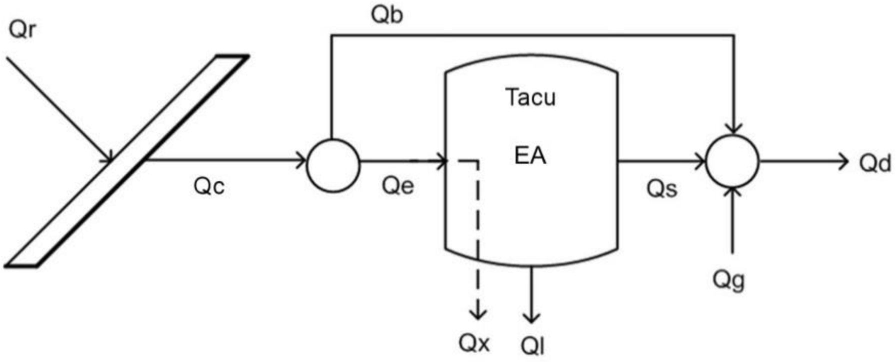

Fig. 1. Scheme of central solar heating plant with seasonal storage.

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 and the seasonal storage tank is discharged first, Q_s, and if it is still not enough, then the auxiliary system, Q_g, will provide the required heat to cover the demand. The thermal energy storage operation 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 to fulfil the demand. The thermal energy storage cannot 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. As the thermal energy storage is warm, the heat losses to the environment, Q_l, are also calculated. The thermal energy accumulated in the storage tank is denoted by the variable EA (Fig. 1).

The detailed base case was calculated with TRNSYS and the monthly results of the main energy flows are shown in Table 2. These results will be used as reference values to compare the results with the simple methods analyzed.

Table 2: Monthly results obtained with TRNSYS [6].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_r (MWh)	275	331	440	436	481	486	546	552	464	409	298	257	4978
Q_c (MWh)	165	210	289	289	326	317	335	304	160	143	166	152	2856
Q_g (MWh)	1130	659	347	162	0	0	0	0	0	0	0	389	2687
Q_d (MWh)	1309	865	632	366	80	0	0	0	0	142	807	1287	5488

4. Simple calculation methods

The methods presented use simple climatic and demand data and require low calculation effort to calculate CSHPSS systems. The methods agree (i) in the main equipment considered: solar collector field (SCF) and seasonal thermal energy storage (STES), and (ii) in the performance dependence with the local climatic and demand conditions. The methods disagree in the: (1) design parameters considered, (2) secondary equipment included, (3) detail of the climatic and demand input data, (4) equations required and (5) results obtained.

The following tables show an overview of the simple methods compared.

In Table 3 a comparison of the required or possible input data to introduce in each method is shown. The simple methods that require less input data variables might be easier to manage but present less opportunities to adjust the parameters to the real plant or to analyze the effect of different variables.

Table 3: Comparison of input data required in the different methods.

	A	V	η_0	k_1	k_2	β	γ	m_s	E_{ff}	T_{SH}	T_{ret}	T_{max}	UA_{acu}	UA_{houses}	T_{houses}	SF
Lunde method [12]	X	X	X	X	X*	-	-	-	-	-	X	X	X	-	-	-
BKM method [13]	X	X	X	X	X	X	-	-	-	X	X	X	X	X	X	-
DS method [14]	-	-	X	X	X	X	-	-	-	-	X	X	X	-	-	X
GLS method [15-18]	X	X	X	X	X	X	X	X	X	-	X	X	X	-	-	-
Feasibility tool [13]	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X

*With modifications from the original version in 1979 the second coefficient can be included

A: Solar field area; V: Seasonal storage volume; η_0, k_1, k_2: Efficiency collector coefficients; β, γ: Tilt and orientation of the collector; m_s: solar field flow; E_{ff}: Heat exchanger efficacy in the solar field; T_{SH}, T_{ret}: supply and return temperatures; T_{max}: STES maximum temperature; UA_{acu}: Heat transfer coefficient of the STES; UA_{houses}: Heat transfer coefficient of the consumer center; T_{houses}: Temperature of the consumer center; SF: solar fraction.

A summary of the calculation process considerations for each method is shown in Table 4.

Table 4: Main characteristics of the calculation process and results obtained

Method	Solar Collector field	Thermal Energy Storage	Results
Lunde method [12]	Organized climatic data	Thermal losses, charge discharge	Monthly performance
BKM method [13]	Utilizability correlation	Thermal losses, charge discharge + max demand	Monthly performance
DS method [14]	Utilizability correlation	Thermal losses, charge discharge	Size: Solar collector and Thermal Energy Storage
GLS method [15-18]	Hourly calculation of a typical day each month	Thermal losses, charge discharge	Monthly performance, solar collector hourly performance
Feasibility tool [19]	Area estimated, function of annual radiation	Volume estimated, function of solar fraction	Size: Solar collector and Thermal Energy Storage

4.1. Lunde method

Lunde (1979) proposed a method to calculate the performance of large solar thermal systems including a finite thermal energy storage in which the storage temperature rises or falls monotonically [12]. The method predicts with an integrated equation, which introduces the effect of the monthly demand and thermal losses, the performance over an entire month of the solar collector using elaborated climatic data. Hourly ambient temperature and radiation over tilted surface during the year are required. Monthly climatic data are classified by levels of radiation so that the total radiation received (MJ/month) and the average ambient temperature (ºC) is known for a radiation range (W/m^2). The base case has been calculated with this method. To explain the calculation Lunde method, the production in May of the solar collector, calculated with this method, is presented. Elaborated climatic data by ranges of radiation of 80 W/m^2 has been prepared with hourly values obtained from TRNSYS simulation (see Table 5).

Table 5: Climatic parameters by ranges of radiation in May, critical radiation range in grey.

Radiation range (W/m^2)	< 2	2 - 80	80 - 160	160 - 240	240 – 320	320 - 400	400 - 480	> 480
q_r (kWh/m^2)	0	2.9	8.2	5.3	9.6	15.6	10.9	116.0
t (h)	291	92	68	26	34	45	24	164
T_{amb} (ºC)	13.7	16.3	17.0	18.8	17.1	19.6	19.4	21.0

The average radiation in the ranges <80 is lower than the minimum required to produce net energy in the solar collector field according to the efficiency coefficients, ambient temperature and average tank temperature. Therefore the operation period t_{op} = 361 h is calculated in the upper ranges. Radiation received in the operation range (sum of radiation received with a level higher than 80W/m^2) is q_{op} = 165.6 kWh/m^2. STES thermal losses are calculated at the average ambient temperature in the upper ranges $T_{amb,op}$ = 19.4 ºC. An energy balance in the STES between solar production, thermal losses and demand determines the variation of energy in the STES and its final temperature each month. This calculation is performed sequentially, month by month (see Table 6), considering the following limits in the STES: i) when the system reaches the minimum temperature an auxiliary source gives the thermal energy required, and ii) when the STES temperature overpass the maximum temperature the final temperature is reset to the maximum temperature.

Table 6: Results obtained with the Lunde method.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_r (MWh)	275	331	440	435	481	486	546	552	465	409	299	257	4978
Q_c (MWh)	182	231	316	317	347	332	350	321	229	173	130	146	3075
Q_l (MWh)	4.9	4.1	4.0	3.4	3.7	5.0	7.0	9.7	12.0	14.3	12.5	7.9	88.5
Q_g (MWh)	1132	638	320	53	0	0	0	0	0	0	0	359	2501
Q_d (MWh)	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
EA (MWh)	0.0	0.0	0.0	0.0	264	591	933	1245	1462	1479	790	0.0	---
T (ºC)	30.0	30.0	30.0	30.0	39.9	52.2	65.1	76.9	85.0	85.7	59.7	30.0	---

4.2. BKM method

To calculate the monthly performance of a CSHPSS with simpler initial data than Lunde method, Braun et al. [13] proposed to use the utilizability factor to estimate the monthly performance of the solar collector field [20]. This method requires daily horizontal radiation and average ambient temperature for each month on the location of the system. The utilizability factor estimates the fraction of radiation from the daily average that can be transformed into useful thermal energy considering the minimum radiation required. The utilizability correlation and other climatic correlations required for this method can be found widely explained in common literature of solar systems [21]. BKM method proposed to introduce a heat transfer limit between the seasonal storage and the demand, $Q_{d,max}$, according to the house heat transfer coefficient (UA_{houses}) and the STES temperature (T_{acu}). For systems with high delivering water temperature (of supply) this condition is very appropriate and limits the discharge of thermal energy in months with high demand and low STES temperature.

An energy balance is used each month to calculate the system performance, as in the Lunde method. However to calculate the performance by this method it is required an iterative process because the monthly performance of the SCF is calculated with an estimated temperature value for the STES (unknown temperature of the STES is necessary to calculate the utilizability factor of the month). Final results obtained for the base case are shown in Table 7. As this method introduces a limit in the discharge capacity, auxiliary energy can be required even when the STES is still charged (EA>0). In the base case auxiliary energy is used in December while the energy accumulated at the end of the month is 126 MWh.

Table 7: Results obtained with the BKM method.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$\bar{H}$ (MJ/(m^2·day))	6.4	9.8	13.8	17.4	21.5	23.8	25.3	22.5	16.5	11.6	7.5	5.7	---
$\bar{K}_t$	0.45	0.50	0.52	0.51	0.54	0.57	0.62	0.62	0.56	0.54	0.48	0.45	---
$\bar{H}_t$ (MJ/(m^2·day))	11.2	14.9	17.9	18.3	19.6	20.5	22.2	22.5	19.5	16.6	12.5	10.5	---
Φ	0.78	0.85	0.87	0.88	0.88	0.83	0.78	0.70	0.57	0.48	0.48	0.64	---
Q_r (MWh)	275	331	441	436	481	486	547	552	464	409	298	257	4978
Q_c (MWh)	175	229	313	313	345	329	349	315	217	160	117	134	2996
Q_l (MWh)	5.3	3.9	4.0	3.5	3.9	5.2	7.3	9.9	12.1	14.4	12.4	8.3	90.2
Q_g (MWh)	985	647	375	89	0	0	0	0	0	0	0	517	2614
Q_d (MWh)	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
$Q_{d,max}$ (MWh)	324	218	257	277	433	754	1153	1516	1744	1919	1477	770	---
EA (MWh)	-28	-20	0	32	293	617	959	1264	1469	1472	770	126	---
T (ºC)	31.9	29.1	29.6	30.6	35.6	47.3	59.8	72.1	81.7	85.6	72.4	47.0	---

4.3. DS method

Drew and Selvage proposed a method to calculate the area of the solar field and the volume of the seasonal storage to obtain a determined behavior [14]. This method calculates the performance of the solar field with the utilizability factor, similarly to the method proposed by Braun, but do not considers a heat transfer limit between the STES and the demand.

Two equations are solved simultaneously for the two unknown variables: area of solar collectors and volume of the seasonal storage. The first equation is the energy balance along the charging period (April-September) and the second equation is the energy balance along the discharging period (October-March). This method requires the knowledge of the STES temperature profile for a desired behavior. The temperature profile along the year for a 100% solar fraction is a sine function as Drew and Selvage proposed in 1980 [14].

Solving the system of equations for the demand of the base case and its climatic conditions, the optimum area and volume required to reach 100% solar fraction can be obtained. The solution is $V = 46{,}690\ m^3$ and $A = 5794\ m^2$. This method cannot be used to design systems with different solar fraction unless the temperature profile is known for each optimum solar fraction.

4.4. GLS method

The method proposed by the authors of this paper calculates the performance of the solar collector according to the hourly radiation and ambient temperature of a typical day each month [15-18]. The climatic hourly data for the typical day is obtained with common climatic correlations [21]. The production of the solar collector field is calculated hourly with the efficiency equation of the solar collector and the efficacy equation for the heat exchanger between the SCF and STES. The SCF inlet temperature is the STES temperature at the end of the previous month. This method introduces the effect of temperature rise in the solar collector which is very typical for large applications with low flow rates. The hourly climatic parameters and the hourly production per square meter of solar collector are shown in Table 8, for May month.

Table 8: Hourly climatic parameters and heat collected per square meter of solar collector in May

Hour	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
I_t (W/m^2)	30	110	250	400	540	650	710	710	650	540	400	250	110	30
T_{amb} (ºC)	11.8	12.0	13.0	14.6	16.7	18.8	20.6	21.9	22.8	23.4	23.5	22.9	21.8	21.3
q_c (W/m^2)	0	46	155	274	385	471	520	524	482	402	296	180	70	4

The hourly production per square meter is used to calculate the monthly production of the solar field. The simple method calculates the system energy flows and the temperature of the thermal energy storage at the end of the month to calculate the performance of the solar field the following month. Monthly results are shown in Table 9 for the base case.

Table 9: Results obtained with the GLS method.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Q_r (MWh)	271	319	407	418	477	483	542	538	445	397	300	256	4853
Q_c (MWh)	162	210	279	296	349	330	341	294	186	128	69	99	2744
Q_l (MWh)	4.8	3.7	3.3	2.4	1.3	3.3	5.8	9.1	12.3	15.2	15.2	9.9	87
Q_g (MWh)	1147	655	353	70	0	0	0	0	0	0	0	606	2830
Q_d (MWh)	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
EA (MWh)	-5	-9	-12	-14	254	581	916	1201	1375	1345	592	0	---
T (ºC)	29.8	29.7	29.5	29.4	40.2	53.4	66.9	78.4	85.4	84.2	53.8	30.0	---

4.5. Feasibility tool

The platform SDH proposed a method to perform feasibility studies of CSHPSS plants based on empirical design correlations and investment estimations [21]. This method requires the annual radiation, the annual demand, and the solar collector area or the desired solar fraction. The production of the SCF is estimated according to the annual radiation, supply temperature and type of solar collector. According to the desired solar fraction, the appropriate ratio V (STES) / A(SCF) is proposed.

For the base case (location Zaragoza, space heating demand of 1000 dwellings) to obtain a 50% solar fraction the feasibility tool estimates a solar collector area A = 3960 m^2. According to this solar fraction and the estimated design area of solar collector the feasibility tool estimates a STES volume V = 6732 m^3.

With TRNSYS [6] to obtain a solar fraction of 50% for Zaragoza was required an area of solar collector A=2854 m^2 and a volume of STES V = 22,829 m^3. The feasibility tool recommends 40% more area than the case base and almost 70% less volume of accumulation. Therefore, use of correlations to design a CSHPSS is only recommended for countries or locations with similar climatic and demand characteristics than the place where coefficients for sizing were fitted. The feasibility tool is the simpler tool to use and is useful in preliminary studies. It could be adapted to different climates increasing its accuracy.

5. Comparison of simple methods

In this paper different methods have been explained and applied to evaluate a CSHPSS system. The methods have been implemented in the software Engineering Equation Solver [22] and have been used to calculate the annual performance of a base case that was previously calculated with dynamic simulations with TRNSYS [6]. Comparable results are shown in Table 10.

Table 10: Monthly and annual results.

		Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Input Data	Q_r MWh	275	331	440	436	481	486	546	552	464	409	298	257	4978
	$\bar{H}$ MJ/(m^2·day)	6.4	9.8	13.8	17.4	21.5	23.8	25.3	22.5	16.5	11.6	7.5	5.7	
	T_{amb} ºC	6.2	8.0	10.3	12.8	16.7	21.0	24.3	23.8	20.7	15.4	9.7	6.5	
	Q_d MWh	1309	865	632	366	80	0	0	0	0	142	807	1287	5488
TRNSYS [6]	Q_c MWh	165	210	289	289	326	317	335	304	160	143	166	152	2856
	Q_g MWh	1130	659	347	162	0	0	0	0	0	0	0	389	2687
	SF %	14%	24%	45%	56%	100%	100%	100%	100%	100%	100%	100%	70%	51%
Lunde [12]	Q_c MWh	182	231	316	317	347	332	350	321	229	173	130	146	3075
	Q_g MWh	1132	638	320	53	0	0	0	0	0	0	0	359	2501
	T_{acu} ºC	30	30	30	30	39.9	52.2	65.1	76.9	85.0	85.7	59.7	30.0	---
	SF %	14%	26%	49%	86%	100%	100%	100%	100%	100%	100%	100%	72%	54%
BKM [13]	Q_c MWh	175	229	313	313	345	329	349	315	217	160	117	134	2996
	Q_g MWh	985	647	375	89	0	0	0	0	0	0	0	517	2614
	T_{acu} ºC	31.9	29.1	29.6	30.6	35.6	47.3	59.8	72.1	81.7	85.6	72.4	47.0	---
	SF %	25%	25%	41%	76%	100%	100%	100%	100%	100%	100%	100%	60%	52%
GLS [15-18]	Q_c MWh	162	210	279	296	349	321	333	287	180	123	72	95	2708
	Q_g MWh	1147	655	353	70	0	0	0	0	0	0	0	606	2830
	T_{acu} ºC	29.8	29.7	29.5	29.4	43.4	54.2	69.3	80.5	87.2	82.8	55.3	30.0	---
	SF %	14%	23%	36%	71%	100%	100%	100%	100%	100%	100%	100%	59%	48 %

The monthly results obtained are very similar in all the cases, although in the BKM method a demand limit has been introduced and in the GLS method different tilted radiation is introduced. The TRNSYS model estimates an annual solar fraction of 51%, the Lunde method estimates an annual solar fraction slightly higher, 54%, and the BKM method estimates an annual solar fraction of 52%. The GLS method proposed by the authors of this paper estimates the more conservative value of annual solar fraction, 48%.

The feasibility tool proposed by the platform SDH can be useful in very preliminary studies but the estimated design parameters do not properly fit to different climates. The GLS method can be used to perform feasibility studies according to specific climatic and demand parameters from available public climatic and demand sources in Spain and other locations.

The simple methods explained do not pretend to substitute the dynamic simulations for the calculation of CSHPSS but can become valid tools to predesign and evaluate alternatives in early stages of the decision-making process. To become a valid tool it is a requirement to compare with real operating plants for its validation and acceptation. The use of simple and validated tools to design CSHPSS can be as useful as the F-Chart method for the design of domestic hot water systems and could foster the development of these clean and renewable energy supply systems.

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