DYNAMIC SIMULATION OF CENTRAL SOLAR HEATING PLANT WITH SEASONAL STORAGE (CSHPSS) USING TRNSYS SOFTWARE

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1. Introduction

Solar energy is one of the renewable energies used for the heating or production of DHW (Domestic Hot Water) for buildings (residential, industrial, tertiary, etc.). Solar energy can be developed on a large scale, as for a district or a city, to meet the energy demand of several buildings connected to one another by a heating network. These thermal solar power plants integrated on heating networks can offer good performance, in particular because of the possible coupling with seasonal storage tanks: this makes it possible to store a surplus of produced energy in summer to restore in winter and thus take advantage of solar energy throughout the year. This is known as a Central Solar Heating Plant with Seasonal Storage (CSHPSS), (Novo and al., 2010; Mangold, 2007).

Few CSHPSS systems exist and the design rules are not well identified (Bauer D, 2010 ; Lund, 1989 ; Matrawy, 1996 ; Peltola and Lund, 1992 ; Peltola and Lund, 1992a). The main objective of this work is to better understand the operating mode and to explore the potential of the CSHPSS with water hot water storage tank by using numerical experiments with TRNSys software. We want to obtain recommendations for the design of low temperature heating networks. From a methodological point of view, this work consists of identifying the most favorable configurations. In this study, the costs are not related to real projects and the energy costs presented here are just used to define a methodology to identify key parameters and design rules by a modeling method with numerical experiments.

2. CSHPSS with hot water storage tank

2.1 Operating mode

Figure 1 shows a CSHPSS with a hot water storage tank. The solar energy collected by the thermal collectors is stored in the tank via the exchanger HX1. If the top tank temperature is higher than the return temperature of the heating network, stored energy is used via the exchanger HX2. An energy production method (such as a boiler) is used to increase the temperature of the water sent to the consumers if necessary.

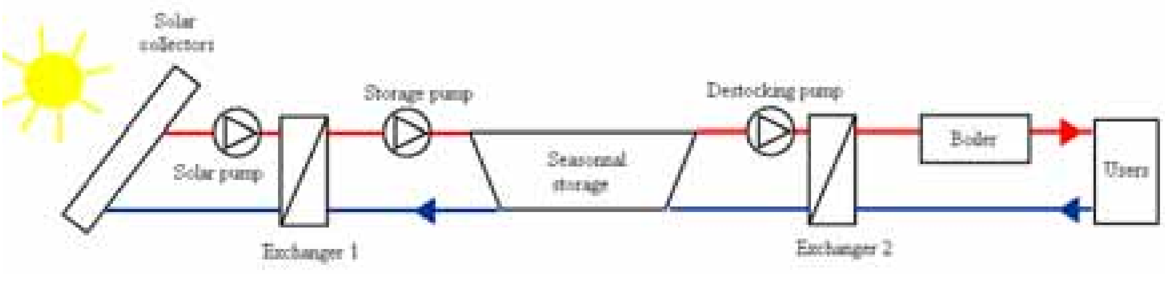


Fig 1 : General hydraulic diagram of a CSHPSS

The power plant shown in Figure 1 is one example to describe the general operating mode of a CSHPSS. There are several configurations for connecting the various elements together (collectors, seasonal storage, district heating, etc.), and each power plant has its own characteristics. There are no "standard" design rules for central solar heating plants with seasonal storage. The objective is to conduct a sensitivity study of various parameters to evaluate their influence and to obtain recommendations for the design. This sensitivity study using TRNSys software is performed with different parameters: the surface of the solar collectors, storage volume, solar and storage loop flow rates, annual energy production of the heating networks, temperature levels, relative fraction of domestic hot water, etc.).

2.2 Technical and economic evaluation

To evaluate the performance of such an installation, the following two parameters are studied: the Solar Fraction (SF) and the cost of the energy produced with the solar installation (€/MWh). The duration of the investment plan is 20 years. The cost of the produced annual heat takes into account the annual investment costs, maintenance and other operating costs. The investment is calculated at 300€/m^2 for the flat solar collectors (including the equipment and installation), with a storage cost represented below with existing plants (Mangold, 2007). Hypotheses have been taken to define a cost for solar collectors. This cost can seem to be low in comparison with other small solar plants dedicated to DHW production. But for this study, the collector surfaces are greater than 1000m^2 and the cost do not take into account the storage. This solar collector cost does not correspond to any existing plant but is used to present the methodology and to propose design rules. The efficiency of the flat solar collectors is shown in Figure 2.

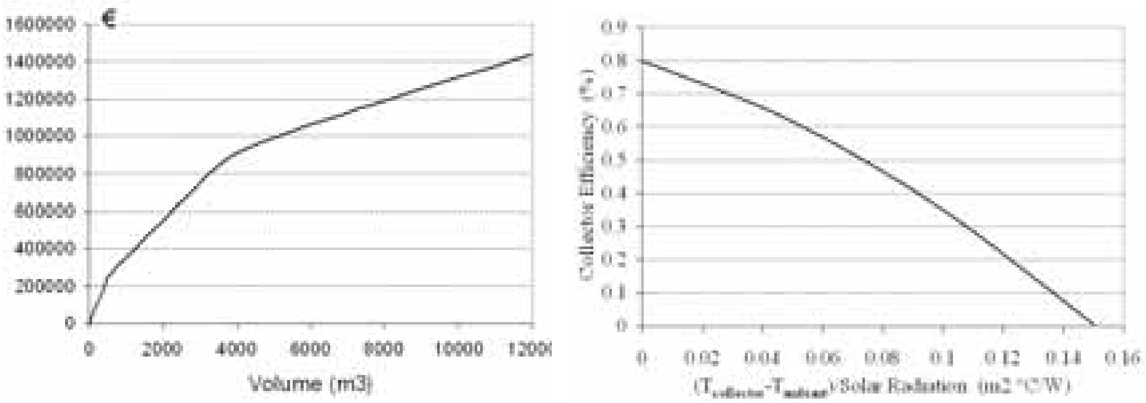


Fig 2. Cost of seasonal storage and efficiency of the flat solar collectors

The economic model is very simple and could be modified according to the particular studied cases.

$$K_{Solar\_Energy} = \frac{K_{invest} / n + K_{op} + K_{maint}}{E_{net}} \quad (€/MWh)$$

(eq. 1)

K_{invest} : total investment costs of the solar power plant (€).
n : project duration (20 years).
K_{op} : annual operating costs (€).
K_{maint} : annual maintenance costs (€).
E_{net} : solar energy provided to the heating network per year (MWh). Energy balance for exchanger 2.

K_{maint} is calculated by taking 0.25% of the amount of the total investment of the power plant $K_{invest.}$
Kop is calculated by taking a percentage of the cost of provided solar energy E_{net}.
$K_{op}= 0.05.E_{net}.K_{elec}$ where K_{elec} is the cost of electricity (70 €/MWh for this study).

3. Modeling using the TRNSys software

The CSHPSS is modeled using TRNSys software (Fig 3). The operating mode of a CSHPSS depends mainly on the energy demand and thus on the behavior of the heating network. This network demand is characterized by the return and supply temperatures with the power demand. These parameters are inputs for the model and are time-dependent values. The profiles of the studied heating networks come from data obtained from existing heating networks or are built from a model of the buildings energy demand (TRNSys software).

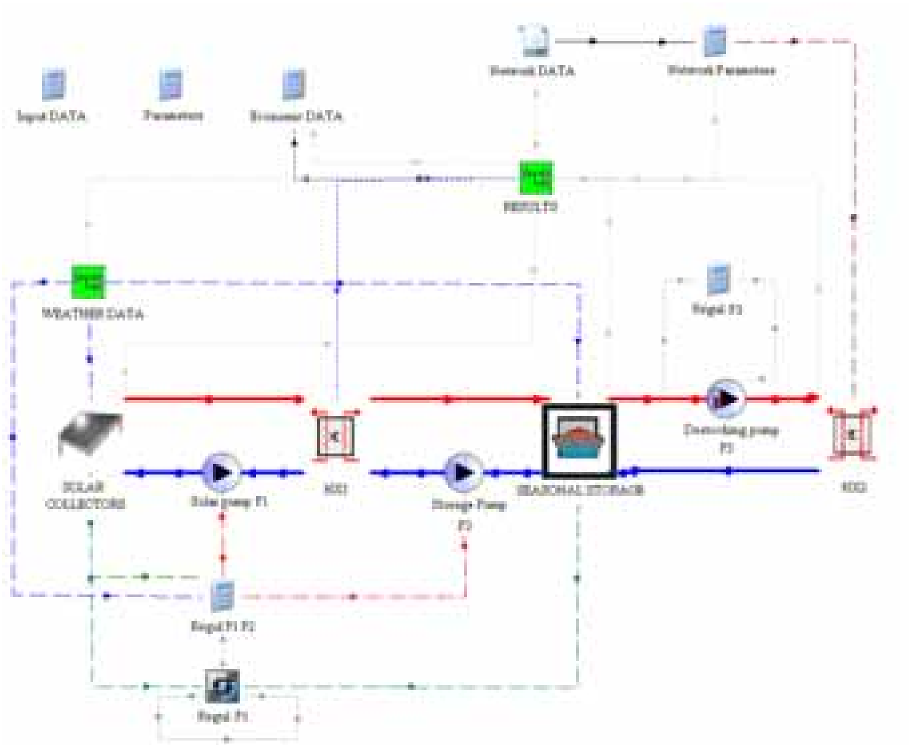


Fig 3: TRNSys model of a CSHPSS diagram

4. Numerical study of the influence of the various parameters for a particular case

For the whole study, only solar fractions SF higher than 15% are taken into account. The influence of the collector surface, storage volume, flow rate values, relative fraction of DHW, etc., is analyzed through parametric studies. Matlab software controls all of the TRNSys loop calculations. To study the influence of these various parameters, the case study defined in table 1 is used.

Tab. 1: Characteristics of the heating network studied (annual energy demand: 5GWh)

Characteristics of the heating network	Studied values
Geographical zone	A city near Paris (France)
Power	1.6MW (approximately 600 apartments)
Annual energy production	5GWh
DHW part (% of MWh)	26%
Supply and return temperature	70°/40°
Collector slope	45°
Flow rates (solar and storage loop)	15 l/m^2 ; 20 l/m^2 ; 25 l/m^2 of collector surface
Collector surface	1000m^2 ; 2000m^2 ; 3000m^2 ; 4000m^2 ; 5000m^2 ; 6000m^2
Ratio R= Storage Volume /Collector Surface	0.05 ; 0.1 ; 0.5 ; 1 ; 1.5 ; 2 ; 2.5 ; 3 ; 3.5

The return temperature of the heating network (40°C) is a constant value which is not very realistic but this value is used to present the methodology. The energy demand profile of the studied network is obtained using existing profiles. A factor was applied to each time step to obtain an annual production of 5GWh (with too large a production, it is not possible to obtain a significant solar fraction).

4.1. Influence of the ratio R (=storage volume/collectors surface)

162 calculations have been performed (6 surfaces × 9 volumes × 3 flow rates, table 1). Figure 4 shows results with a cost lower than 150€/MWh and a solar fraction FS higher than 15%. For a fixed surface, the lower

costs are obtained where ratio R (Volume/Surface) = 0.5. Nevertheless, for surfaces of 2000m^2 and 3000m^2, R=1 allows us to obtain a larger solar fraction at a slightly higher cost. The ratios R=0.5 and R=1 lead to the lowest cost (€/MWh) for this case study. It is observed that the solar fraction and the cost increase with volume.

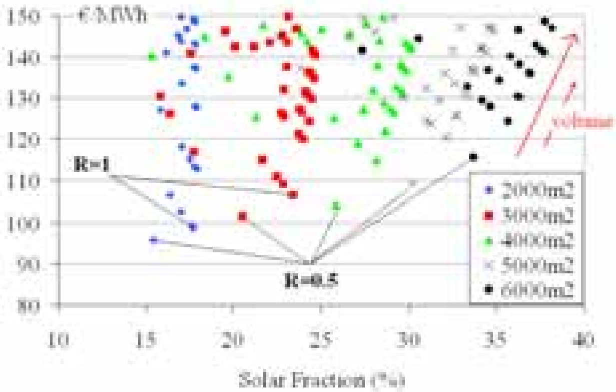
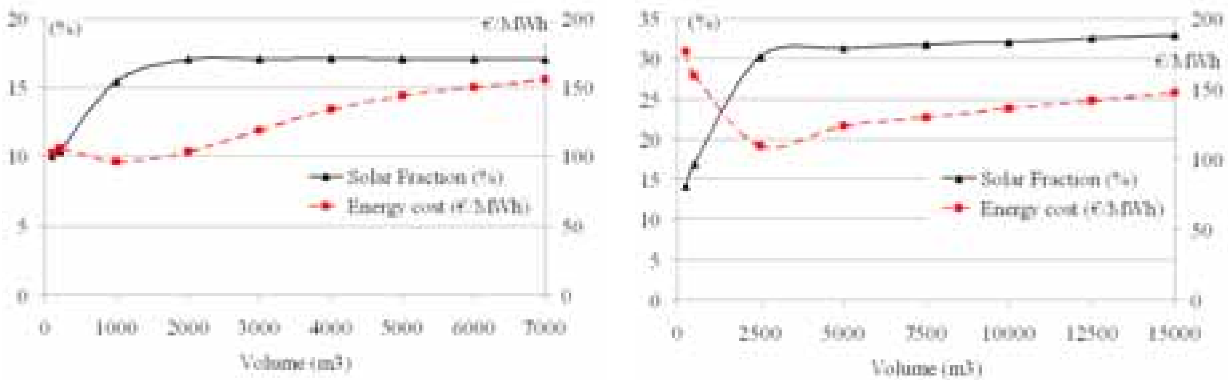


Fig 4 : Influence of R (=Storage Volume /Collector surface)

4.2. Influence of the storage volume on the solar fraction and energy cost

Figure 5 shows changes in the solar fraction and the energy cost according to the volume of seasonal storage for a surface of 2000m^2 and 5000m^2. In both cases, the solar fraction reaches a maximum, which is dependent on the surface of the thermal collectors but not on the storage volume. This result provides an optimum (maximum solar fraction at the lowest possible cost) which is close to R=0.5 for both cases.



(a) : S = 2000 m^2 *(b) : S = 5000 m^2*

Fig 5: Influence of the storage volume on the solar fraction and energy cost

4.3 Influence of flow rates (solar and storage)

The solar and storage loop flow rates are the same for this study. The values of the studied flow rates (l/m^2 of collector surface) are as follows: 15; 20; 25; 30; 40; 50; 60. Various collector surfaces (m^2): 1000; 2000; 3000; 4000; 5000; 6000 are studied with the constraint R = Volume/Surface = 0.5. Figure 6 shows the results where the cost of produced energy is lower than 200€/MWh with a solar fraction SF higher than 15%. The collector surface flow rate of 15 l/m^2 is the design that makes it possible to obtain the lowest cost for all surfaces.

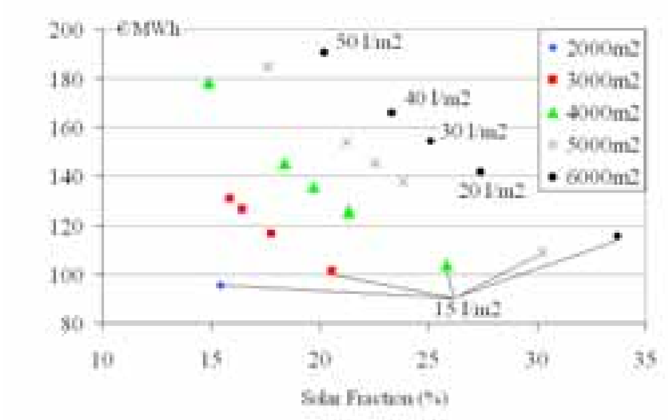


Fig 6: Influence of solar and storage flow rates on the study case

Another series of calculations showed that for R=1, a flow rate of 20 l/m2 is the best design. Consequently, there are no reference flow rates; the flow is also related to the volume of storage which thus needs to be taken into account.

5. Generalization of the parametric study

The preceding section highlights the influence of parameters such as the surface of the collectors, the volume of storage and the solar loop and storage loop flow rates on a particular heating network with a heat production of 5GWh per year. The objective is now to try to generalize these first results for several types of heating networks, with a heat production of 1GWh, 5GWh and 10 GWh per year and a relative fraction of domestic hot water of 17%, 25% and 30% of the total energy consumption. This energy demand was obtained from existing networks or from the modeling of buildings using the TRNSys software. The supply and return temperatures of the heating network are 70°C/40°C and the climate considered is near Paris.

Table 2: Maximum solar fraction value and energy cost for different heating networks

Production (GWh)	*Surface (m^2)*	*Maximum possible value for the Solar Fraction (%)*	*Energy Cost (€/MWh)*
1 GWh	1000	25 – 30	138 – 158
	2000	40 – 45	162 – 187
	3000	50 – 55	190 – 216
	4000	55 – 60	220 – 244
	5000	60 – 65	245 – 272
5 GWh	2000	15 – 20	96 – 116
	3000	20 – 25	101 – 136
	4000	25 – 30	104 – 146
	5000	30 – 35	109 – 156
	6000	35	115 – 166
10 GWh	4000	15 – 20	87 – 105
	5000	15 – 20	92 – 128
	6000	20 – 25	95 – 127

For each of these 9 heating networks, 162 calculations were carried out, corresponding to the various possible combinations defined in table 1. Only the results corresponding to a solar fraction higher than 15% are taken into account.

All the calculations show similar results to the preceding section with the 5GWh network: the best designs (the lowest energy cost with a solar fraction higher than 15%) are always obtained for a ratio R (storage volume / collector surface) equal to 0.5 or 1 and for flow rates between 15 and 20 l/m^2. This result seems significant because of the diversity of networks studied here. In addition to these design results, calculations allow us to make links between the collector surfaces available with a solar fraction and an optimum possible energy cost (table 2) for the three categories of heating networks (1GWh, 5GWh and 10GWh).

Logically, the costs decrease with the size of the heating network because solar energy is more easily used when the energy demand is greater. Moreover, the storage cost decreases when the volume increases.

The best results in the preceding section are obtained for the highest fractions of DHW, from 25% to 30%. The influence of the relative fraction of DHW is a determining factor on the performance of the central solar system. The networks with the most energy potential are those in which the fraction of DHW is the highest because there is more solar valorization in summer. Figure 7 provides an example of this, where calculations correspond to a heating network with an energy production of 5GWh per year with three different DHW profiles, leading to fractions of 17%, 25% and 30% of the total energy consumption. These different profiles are built using the TRNSys software, by modeling the time energy demand of several residential and tertiary buildings. The best configurations (the lowest energy cost with a solar fraction higher than 15%) are obtained when the relative fraction of DHW is the highest (30%).

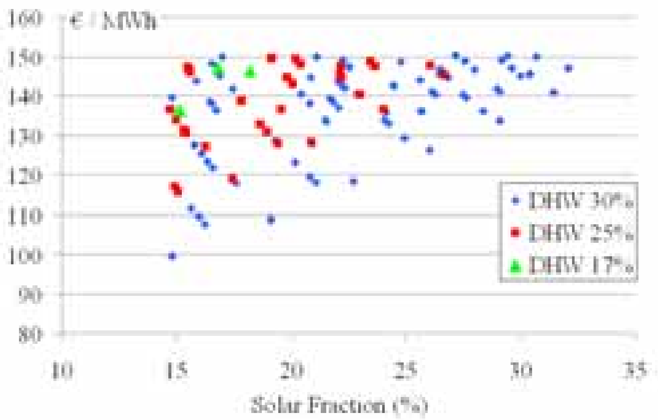


Fig 7: Influence of the relative fraction of domestic hot water demand

6. Conclusion

The results from this study show that the technical and economic performance of a CSHPSS depend on many parameters, and that the most important for the design are the collector surface, the ratio R (= Storage volume/Collector surface), the flow rates (solar and storage), the energy production of the heating network, and the fraction of DHW. Even if this was studied here, the influence of the return and supply temperature can be taken into account and analyzed using a numerical approach.

For a given project, a parametric study with numerical experiments can allow us to take into account the project constraints (limits of investment, surface and volume available, etc.), to define the optimal configuration. With the economic assumptions chosen here, and for heating networks with an energy demand ranging from 1GWh to 10GWh, the results of the experimental plans show that it is possible to define some design rules. The more profitable configurations (lowest energy cost in €/MWh) are always obtained for a ratio R (= volume/surface) equal to 0.5 or 1 and for variable flow rates (solar and storage) ranging from 15 to 20 l/m^2.

A modeling approach for this problem with multi-parameters phenomena allows us to define design rules and study the technical and economic potential of this type of energy production. Other CSHPSS configurations could be tested with this modeling approach.

The value of the return temperature of the heating network (40°C) is a constant value and it is not very realistic. This value has an effect on the CSHPSS performances and it will be interesting to use values measured on an existing heating network. The next step could be the improvement of the economic model (with accurate costs for the solar collectors), the test of the impact of the return temperature of the heating network and a validation with experimental data.

7. References

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