Solar collectors network map: shape and time dynamics of stored thermal energy for different user loads

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Abstract. Solar flat plate collectors are commonly used to transform solar energy into thermal one by heating a heat transfer fluid (HTF). The available thermal energy to the user is characterized by a certain thermal capacity and a certain temperature level. Comparing to the case of a single collector, when a higher thermal capacity is required in the user process, more collectors should be coupled in parallel, so that the HTF mass flow rate is increased, exiting the solar collector at the same temperature. Another case may be encountered when the user process requires the same mass flow rate of HTF, but at a higher temperature. In this last case, a series connection is considered. The aim of the present paper is to compare these cases and to build a solar panel map that could be used to choose the best arrangements for a specific user need. A study is performed regarding the map dynamics with respect to HTF consumption to the user for three storage tank capacities of 100L, 200L and 300L respectively. The results reveal a recommendation regarding collectors coupling function on user needs.

1 Introduction

Flat plate collectors (FPC) are commonly used to transform solar energy into thermal one by heating a heat transfer fluid (HTF). For domestic applications, the temperature and mass flow rates are limited to a relatively narrow range of values, but for industrial ones, the range might depend on the system operating conditions and might encounter more important fluctuations along a day. Thus, in some cases the HTF temperature level or mass flow rate might need to be adjusted depending on the required parameters or operating constraints. This is the aim of this paper, to study how such adjustment could be proceeded.

In the literature, there are numerous studies regarding the behaviour of solar collectors under different operating constraints such as input solar radiation or thermal loads delivered to the user, particularly for flat plate collectors.

A recent study regarding the flexible design of flat plate solar collectors for industrial applications is presented in [1] for two industrial processes. The paper proposes an approach

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for the collector network structure defined by adjusting the mass flow rate and the inlet temperature of the working fluid to achieve the smallest collector surface area, and thus minimum investment cost. The results reported regard the number of lines in parallel and the number of collectors in series in each line to answer the specific load defined for the two industrial processes under the above-mentioned optimisation criterion. Other similar works are described in [1], for industrial and agricultural applications. The great majority of them are regarding solar fields of FPC or other solar collectors types.

By “flexible design”, Martínez-Rodríguez et.al. referred to “the capability of the system to deliver the required thermal duties over the year as the ambient conditions vary” [1].

In a similar manner, the target of the present paper is to study the possibility of coupling more FPC either in series or in parallel in order to ensure the required thermal energy to the consumer, both in terms of mass flow rate and temperature level. Obviously the FPC operation is always constraint by the input solar energy or ambient conditions and by the user thermal energy load. Solar panel maps are built in order for the user to appropriately choose the best arrangement needed for a certain thermal load at a certain temperature level.

2 System description

The studied system is composed by a FPC, a uniform temperature storage tank and the output /return water network to the user, as sketched in Figure 1.

A fraction of the incoming solar radiation on the FPC area, $G_{T,t}$, is absorbed by the collector tubes and used to heat the HTF, water here, from an inlet temperature $T_{f,in}$ to an outlet temperature, $T_{f,o}$. The mass flow rate of HTF exiting the collector, $\dot{m}_{FPC}$, enters the storage tank where it instantaneously mixes with the HTF mass existing there. As a result, the entire HTF mass inside the storage tank volume is at the same temperature T_{ST}.

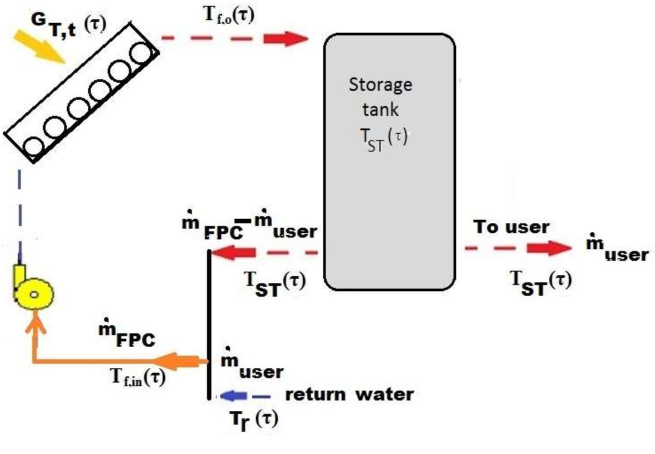

Fig. 1. Flat plate collector with uniform temperature water storage system and user delivery system.

Depending on the user demand, a mass flow rate $\dot{m}_{user}$, is delivered at the storage tank fluid temperature and returns at a certain temperature T_r towards the inflow section of FPC. At the same time, a HTF mass flow rate $\dot{m}_{FPC}$-$\dot{m}_{user}$ is extracted from storage tank. Before entering the FPC, the two streams are mixed, and the inflow HTF temperature $T_{f,in}$ is obtained. The return fluid temperature T_r can be the ambient temperature T_a or a higher value resulting from the user consuming network.

When a higher thermal energy is required to the user, coupling more collectors could be advantageous. Two arrangements are studied in this regard.

The first one is a series coupling of two or more collectors, as presented in Figure 2.

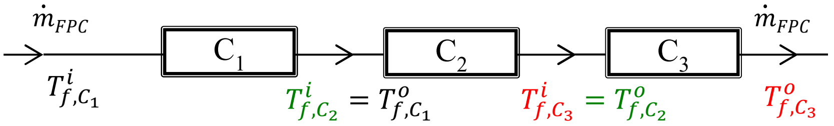

Fig. 2. Series coupling of flat plate collectors.

The same mass flow rate of HTF passes through all collectors. Due to the fact that the inlet HTF temperature to the second collector is equal to the outlet one from the first collector, the outlet temperature from the second collector will be higher. Thus, at the end of the coupling, the HTF temperature is significantly higher compared to the case of using a single collector. Consequently, the available thermal energy is higher.

The second case represents a parallel coupling of two or more collectors, as presented in Figure 3.

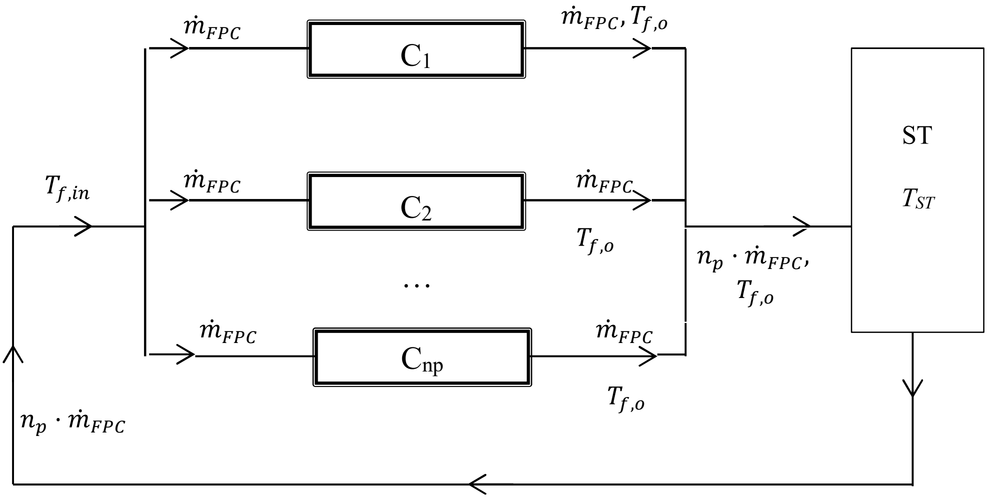

Fig. 3. Parallel coupling of flat plate collectors.

In this case, the outlet HTF temperature is the same as compared to the case of one collector, but the mass flow rate is increased proportional to the number of coupled collectors. Consequently, the available thermal energy is increased in this case, too.

3 Mathematical modelling

The total solar incoming radiation (beam and diffuse) under the chosen tilt angle, $G_{T,t}$ and ambient air temperature, T_a, are generated using METEONORM V7.1.8.29631 software [2]. These data represent 10-years measured average values and were extracted for Bucharest location (44.25°N latitude), on July 15th.

The heat transfer mechanisms inside the FPC is presented in Figure 4. The overall heat flux incident on the collector surface is $\dot{Q}_s = A_{FPC} G_{T,t}$, where A_{FPC} represents the surface area of FPC. The heat flux passing the FPC cover towards the absorber plate is expressed as $\dot{Q}_{Ab} = (\tau\alpha)\dot{Q}_s$ computed as function of the absorbance - transmittance property $(\tau\alpha)$ of the glass cover. Further, this heat flux is divided into two parts. The useful heat flux, $\dot{Q}_u$, is taken over by HTF, while the heat flux loss, $\dot{Q}_{loss,p-c} = \dot{Q}_{loss,c-a}$, is transferred to the environment.

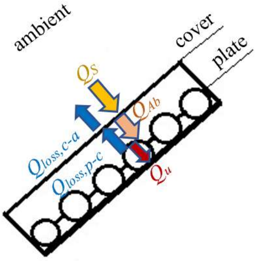

Fig. 4. Losses in the considered flat plate collector.

The losses between collector's plate and cover $\dot{Q}_{loss,p-c}$ occur by both free convection and radiation mechanisms. The free convection losses are computed by using the Hollands correlation [4] , which links the Nusselt number, $Nu_{cv,p-c}$ to the Rayleigh number $Ra_{L,p-c}$ and the collector tilt angle β. Accordingly, the convection heat transfer coefficient is expressed by:

$$h_{cv,p-c} = Nu_{cv,p-c} \cdot k/L_{p-c} \tag{1}$$

where $L_{p\text{-}c}$ represents the distance between the plate and the cover and k is the air thermal conductivity. The radiation heat transfer coefficient between the collector plate and cover is computes as:

$$h_{rad,p-c} = \sigma\left(T_p + T_c\right)\left(T_p^2 + T_p^2\right)\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)^{-1} \tag{2}$$

These losses are further transmitted from the cover towards ambient by the same heat transfer mechanisms (convection and radiation). The corresponding heat transfer coefficients are:

$$h_{cv,c-a} = 5.7 + 3.8w \tag{3}$$

$$h_{rad,c-a} = \varepsilon_c \sigma (T_c + T_a)(T_c^2 + T_a^2) \tag{4}$$

At each time moment the two heat flux losses are equal. Assuming that the plate and cover areas are the same, the corresponding equation looks like:

$$\dot{q}_{loss} = \left(h_{cv,p-c} + h_{rad,p-c}\right)\left(T_p - T_c\right) = (h_{cv,c-a} + h_{rad,c-a})(T_c - T_a) \tag{5}$$

The useful heat rate transformed into thermal energy carried by the HTF can be expressed in two ways. One way is to apply the balance energy equation to the plate surface, and another is to consider the forced convection heat transfer between the tubes wall and the HTF. Neglecting the conduction through tubes wall, one obtains the following equation:

$$\dot{Q}_u = \dot{Q}_{Ab} - A_{FPC}\dot{q}_{loss} = N_{tube}(\pi D_{tube} L_{tube}) h_{HTF}(T_p - \bar{T}_f) \tag{6}$$

where N_{tube} represents the number of tubes inside FPC through which the HTF flows, D_{tube} and L_{tube} are the tube inner diameter and length respectively, while $\bar{T}_f = (T_{f,o} + T_{f,in})/2$ is the mean temperature of the HTF between inlet and outlet of FPC tubes. Assuming that the convection heat transfer occurs under constant heat flux boundary condition and that the flow through tubes is laminar and fully developed, the value of Nusselt number considered to compute h_f is Nu_f=4.36. Further, the outflow HTF temperature is computed as:

$$T_{f,o} = T_{f,in} + \frac{\dot{Q}_u}{(\dot{m}_{FPC} c_{p,FPC})} \tag{7}$$

The mean plate temperature T_p, cover temperature T_c, and HTF temperature at the collector's outlet $T_{f,o}$ are unknown and determined by solving the system of equations at each time step. The inlet fluid temperature to the collector $T_{f,in}$ is computed after each time iteration, resulting from the mixing of two HTF streams, as presented in Figure 1:

$$T_{f,in} = T_{ST} - \frac{\dot{m}_{user}}{\dot{m}_{FPC}} (T_{ST} - T_r) \tag{8}$$

The storage tank temperature T_{ST} is computed by integrating the expression resulting from the First Law of Thermodynamics applied in transient conditions:

$$T_{ST} = T_{ST}^{(\tau-1)} + \frac{\dot{m}_{FPC} c_{p,FPC} (T_{f,o} - T_{ST}^{(\tau-1)}) - (UA)_{ST} \left(T_{ST}^{(\tau-1)} - T_a\right)}{m_{ST} c_{p,ST}} \Delta\tau \tag{9}$$

where m_{ST} represents the mass of fluid stored in the storage tank. Capacities of 100L for each squared meter of FPC are recommended [3].

The available thermal energy in the storage tank at each time step is:

$$Q_{ST} = m_{ST} c_{p,ST} (T_{ST} - T_a) \tag{10}$$

assuming that the ambient temperature is used as reference.

In all above equations, the material properties and geometric parameters are known: cover absorbance-transmittance property ($\tau\alpha$) = 0.8, plate emittance ε_p = 0.05, cover emittance ε_c = 0.89, plate-cover distance $L_{p\text{-}c}$ = 0.04m, collector tilt angle $\beta=30°$, FPC receiving area A_{FPC}=2m^2, tube diameter and length D_{tube} = 0.00881 m and L_{tube} = 2m respectively, number of tubes N_{tube} = 12. Fluid properties (air conduction coefficient k, HTF specific heat $c_{p,FPC}$, etc) are determined as temperature dependent, using EES software [5]. A HTF mass flow rate $\dot{m}_{FPC} = 0.035$kg/s was considered inside the tubes. For the storage tank, constant overall losses were considered as $(UA)_{ST}$=11W/K. A wind velocity of w=1 m/s was also considered for computing the forced cover-ambient convection.

In order to obtain the necessary thermal load and HTF temperature to the consumer, different coupling schemes of FPC are studied. The useful heat rate to the user $\dot{Q}_{user}$ is directly proportional to the mass flow rate $\dot{m}_{user}$ and the temperature difference between delivery and return streams:

$$\dot{Q}_{user} = \dot{m}_{user} c_{p,ST} (T_{ST} - T_r) \tag{11}$$

When user needs a higher thermal energy rate at a certain temperature level T_{ST}, the only way to increase it is by increasing the mass flow rate. Thus, a parallel coupling of more collectors could be useful. In case of higher temperature level needs, a series coupling could be sought.

3.1 Series collectors coupling

When two or more collectors are coupled in series, as presented in Figure 2, the mass flow rate passing through each FPC is the same, but the inlet temperature in a collector is equal to the outlet temperature from the previous one. Thus, the HTF temperature is gradually increased along the FPC series and checked at each time for safety operating conditions.

In this case, the computing algorithm is the same as the one presented for the single FPC case, the difference consisting in successively repeating it for each collector. Consequently the same mass flow rate of HTF $\dot{m}_{FPC}$ is entering the storage tank, but at a higher temperature $T_{f,o}$ compared to the single FPC case.

3.2 Parallel collectors coupling

The parallel connection is presented in Figure 3. When a certain number n_p of collectors are coupled, the storage tank is fed by n_p streams of HTF existing each collector at the same final temperature $T_{f,o}$. Consequently, the thermal energy rate available in the storage tank for consumer use is:

$$\dot{Q}_{ST,FPCp} = n_p \dot{m}_{user} c_{p,ST}(T_{ST} - T_r) = n_p \dot{Q}_{ST} \tag{12}$$

Results are further presented.

4 Results and discussions

The numerical simulation was firstly performed for a single FPC connected to a storage tank of 100L capacity. In this case, a constant volume flow rate of 5L/h is delivered to the user at the storage tank temperature. Water was chosen as heat transfer fluid. The return temperature to the FPC was considered the ambient one. Results in terms of inlet and outlet fluid temperatures, storage tank one and available thermal energy in the storage tank were obtained.

For this particular case, it was noticed that the temperature in the storage tank, initially equal to the ambient one, began increasing at sunrise. It reached the value of 60°C at 11:10 AM and continued increasing until 15:40 when the maximum value of 84.53°C was reached. After this time, it began decreasing, as the solar radiation decreased as well. It reached again 60°C at 21:00. When performing this calculation for different storage tank capacities (200L and 300L) and for the same constant user consumption of 5L/h from the storage tank, Figure 5 was obtained. One may notice some important aspects regarding the whole system behaviour:

- Firstly, the maximum storage tank temperature decreases as the storage tank capacity increases. Obviously, heating a more important quantity of HTF with the same available solar energy conducts to a lower temperature.
- Another observation is the fact that the same fluid temperature in the storage tank is reached later in the case of higher capacities. For example, when a 100L storage tank was used, a temperature of 60°C was reached at 11:20 AM, while in the case of 200L this value was reached at 13:40. In the last case of 300L, the maximum temperature reached by the storage tank fluid was 58.83°C at 17:30. In conclusion, the storage tank capacity should be correctly linked to the size of the system (FPC area and mass flow rates) in order to reach a desired value for the HTF temperature.
- The third notice regards the capacity of the storage tank to ensure a longer use of the stored thermal energy. One may observe that the decrease in thermal energy Q_{ST} in larger storage tanks is slower and more damped after the maximum value was reached.

When considering two or three collectors connected in series, the results are revealed by Figure 6. The same behaviour is met, but higher storage tank fluid temperatures are reached. One may notice that 120°C could be achieved when connecting two FPC in series to a 100L storage tank. The results require the following observation: the HTF circuit in the FPC and ST is pressurized at 3bar in order to avoid steam production and system damage, while keeping the ability to produce hotter fluid. These results show the ability of the network to cover different thermal energy values at different fluid temperatures. It's importance is revealed when choosing the correct size of the network for a certain application.

In Figure 7 the results are plotted for the 200L storage tank, but for all considered collector networks. Parallel couplings are mentioned by “*FPCp*”, while series ones by “*FPCs*”. This chart reveals that when connecting two or three collectors in parallel, the same temperature level is reached in the storage tank in the same delay from start-up, but the thermal energy stored is more important due to a larger mass flow rate of fluid feeding the storage tank.

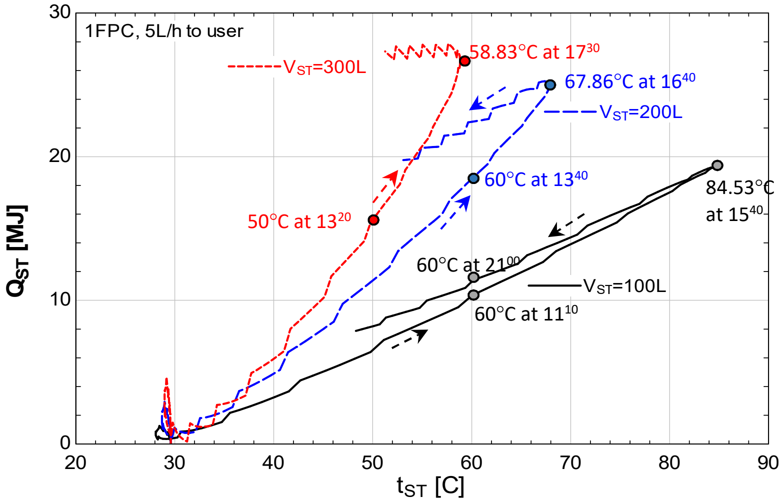

Fig. 5. Available thermal energy stored in the storage tank (5l/h volume flow rate for user delivery); sensitivity study with respect to storage tank capacity.

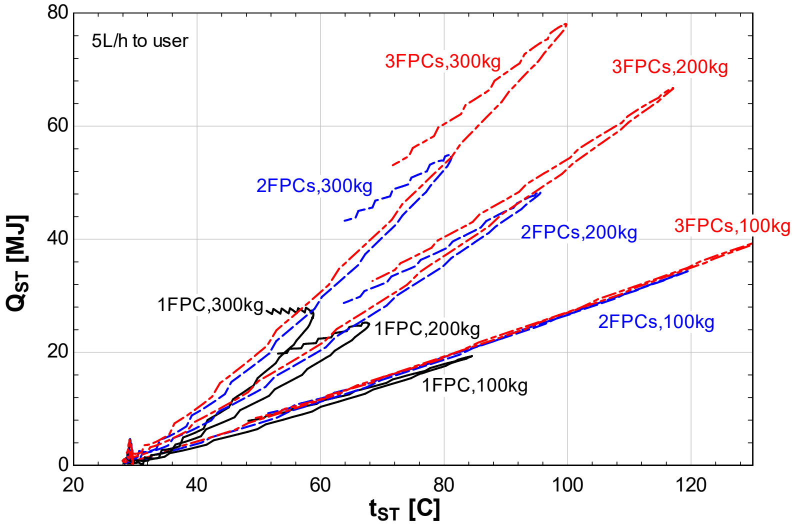

Fig. 6. Available thermal energy stored in the storage tank (5l/h volume flow rate for user delivery); sensitivity study with respect to storage capacity and number of collectors in series.

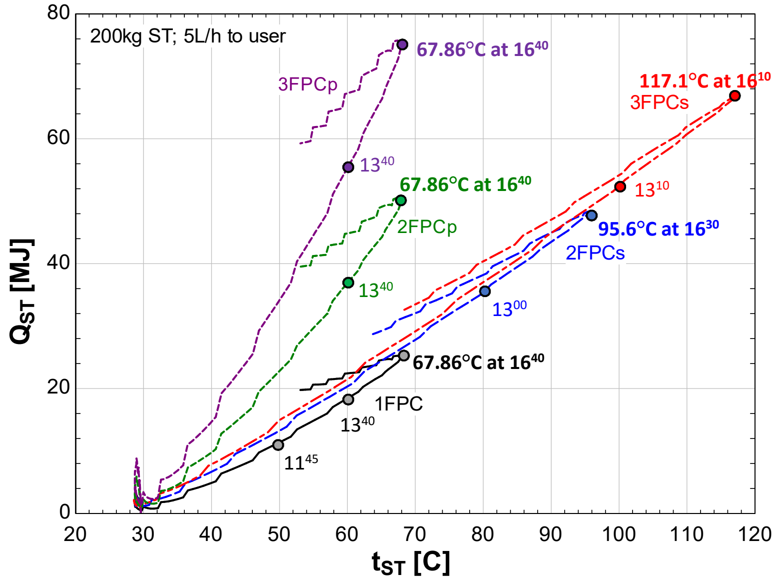

Fig. 7. Solar collector network optimization chart: available thermal energy stored in the 200kg storage tank (5l/h volume flow rate for user delivery) - comparison of different collector couplings.

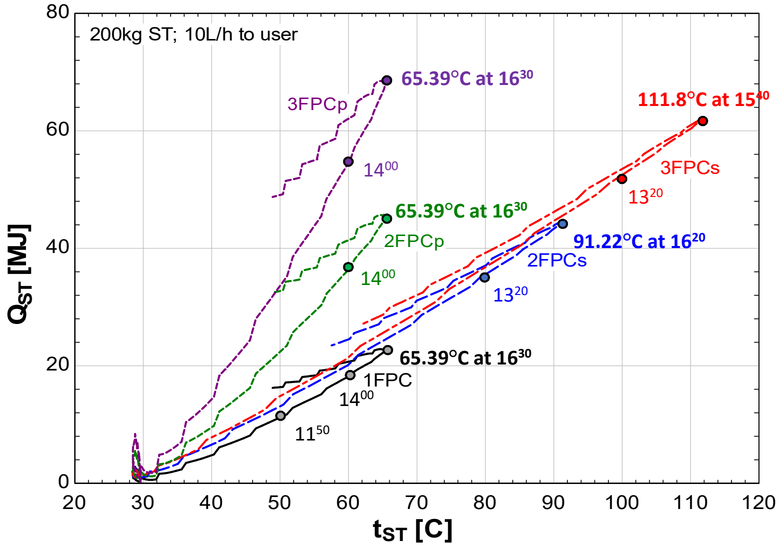

Fig. 8. Solar collector network optimization chart: available thermal energy stored in the 200kg storage tank (10l/h volume flow rate for user delivery) - comparison of different collector couplings.

When increasing the consumption to the user to 10L/h of HTF from the storage tank, the results are similar, but lower temperature values are reached, as revealed by Figure 8. Also, the value of the thermal energy available in the storage tank is lower, due to an increased flow rate constantly delivered to the user.

One may conclude that the solar collector maps built serve as selection charts for the user depending on the necessary thermal energy level and also on the temperature at which this energy is delivered.

5 Conclusions

The paper presents the results of a numerical simulation performed in the case of water solar heating using a flat plate collector provided with uniform storage tank. The results obtained are compared in terms of available thermal energy to the user, characterized by a certain thermal capacity and a certain temperature level. Few solar collector networks maps are built when comparing the use of a single collector to the cases in which more collectors are coupled in parallel or in series. These maps might be of interest when choosing the best arrangements for the system components. This choice depends on the thermal capacity and HTF temperature level required by the user. The results revealed the dynamic behaviour of these networks with respect to HTF consumption.

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