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DYNAMIC ANALYSIS OF SOLAR HOT WATER SYSTEMS: THE CASE STUDY OF A DWELLING LOCATED IN ITALY

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Abstract

The present paper is aimed at the energetic analysis of a solar hot water system performed on a dwelling located in different cities in Italy, precisely, from north to south: Bolzano, Turin, Bologna, Rome, Brindisi and Trapani. The study is focused on a group of apartments, where the domestic hot water is provided by a solar system coupled with a storage tank and a recirculation loop; it is worth to mention that the recirculation loop is obligatory on this kind of plants. Therefore, a dynamic energetic study is carried out, assigned the hot water load profiles and the set parameters of the solar collectors with reference to the configurations here tested (flat plane and evacuated tube). Thus, dynamic simulations have been performed by means of TRNSYS simulations tool, setting different parameters: collector configuration and mass flow rate. Several ideas and results emerged from this study, such as the sizing process of the whole system, according to the variation of the solar fraction for all the analyzed scenarios. A digression with simulation results regarding a specific case concludes the paper. More specifically, the study of water temperature oscillations in winter and summer time with reference to the climatic data of Bologna has been carried out under particular operating conditions: i) the pump of the recirculation loop is powered all time (24 hours a day) ii) the pump is switched off during the night, except when the water temperature in the loop falls below a certain threshold temperature.

Keywords: Flate plane and evacuated solar collectors; Dynamic simulations; Domestic hot water production;

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1. Introduction

In the last decades, environmental concerns and the relative depletion of fossil fuel reservoirs, have obliged researchers to develop alternative renewable energy sources such as solar, wind, and geothermal. Solar thermal systems are special kinds of energy converters which collect and transform the sun's energy to usable internal energy for buildings and industrials. In the residential sector, water heating is a significant user of energy. The European Union's renewable energy directive [1] sets a binding target of 20% final energy consumption from renewable sources by 2020. In this context, Solar Water Heating (SWH) is a well-known technology able to allow energy savings and reductions in CO_2 emissions in heating water for residential needs. The major component of these systems is the solar collector, whose performance is influenced by multiple factors such as surface area, temperature and weather conditions. Flat plate collectors (FPC) and evacuated tube collectors (ETC) have been here studied, because of their large use for solar domestic systems. Over the past several decades, the performance of SWH systems has been investigated theoretically and experimentally [2]. In order to study the performance of SWH and to evaluate the influence of design parameters, different computational tools have been developed. TRNSYS 17 [3] is an extensive software for transient simulation which provides good agreement with experimental data. Shrivastava et al. [4] pointed out a critical review of computations regarding SWH systems, with a comparative analysis of different simulation tools and their architecture in the perspective of TRNSYS. Hobbi and Siddiqui in Ref.[5] used TRNSYS to model a forced circulation SWH system for domestic hot water requirements in Montreal, Canada. In the study, system and collector parameters were optimized changing, among others, collector area and mass flow rate, storage tank volume, size and length of connecting pipes. The authors reported that by utilizing solar energy, the modeled system could provide 83–97% and 30–62% of the hot water demands in summer and winter, respectively. Solar fraction ratio is a key index and reference of solar hot water system design and is also a key factor to evaluate solar hot water system. Ref.[6] demonstrated that solar fractions close to 100% can be reached in the Mediterranean area (and other inter tropical territories) with reasonably-sized collector arrays and thermal storage capacity. Liu et al. in Ref. [7], by analyzing relevant inspection data of ongoing projects, found that using solar fraction ratio to evaluate the running systems has certain limitation, which cannot reasonably reflect the supplementation of conventional energy, especially with the residential buildings applying central solar hot water system. Valdiserri in Ref. [8] evaluated the entity of energy losses in the circulation loop between a hot water storage tank and the final hot water outlet both in term of solar fraction and heat loss fraction. The study demonstrated that i) neglecting pipe losses lead to an overestimation of the solar factor, ii) reducing the daily water consumption leads to a dramatic increase in heat loss fraction. Anyway, data of domestic hot water consumption are fundamental to compute the energy demand and to design the SWH system. Studies based on measured data or simulation are available to estimate DHW consumption focusing on a daily average, hourly average, appliance consumption, and occupant number [9,10]. In particular, Ahmed et al in Ref.[9] derived the hourly DHW profiles for 5 groups of different number of people as a function of the number of occupants. In the present study, assigned the hot water load profiles and the set parameters of the solar collectors (flat plane and evacuated tube), dynamic simulations have been performed by means of TRNSYS with reference to the climatic data of different locations in Italy. The aim is to investigate the sizing process of the whole system, according to the variation of the solar fraction and the heat loss fraction for all the analyzed scenarios.

2. Description of the SHW under investigation

In the present work, a forced circulation system with a secondary flow loop and a storage tank (Figure 1) has been computationally studied using TRNSYS 17. The secondary flow, which absorbs and transports the solar energy collected by the solar collector (SC), circulates between a heat exchanger, inside a storage tank (SSD) and a collector. When the produced water is cooler than the desired set temperature in the tank (50 ± 2.5°C) or during overcast days, the water inside the tank is warmed up by a hot fluid circulating through a heat exchanger placed inside the tank (Aux). The produced hot water arrives at the final user through a system of pipes (HW). A tempering valve will add cold water (CW) to adjust the temperature in order to supply the water (WS) at the user's desired temperature (38°C). A recirculation flow loop (CS) is able to maintain the water warm from the storage tank to the final user.

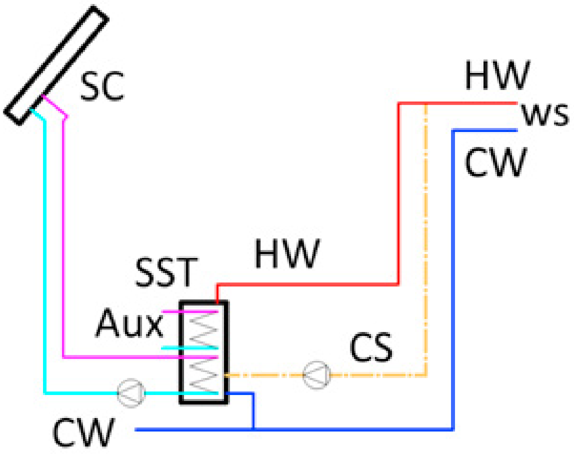

Fig. 1. Representation of the SWH system.

The study is applied to a residential building of 20 apartments (48 people) located in the following Italian cities (listed from north to south): Bolzano, Turin, Bologna, Rome, Brindisi and Trapani. The average daily consumption of hot water is set on 2400 liters (50 liters per person). All the climatic data as a function of time are deducted from Meteonorm [3].

2.1. Hot water load profile

Several factors affect the hourly distribution of domestic hot water consumption during a day. It varies from day to day, from season to season and from family to family. The daily water profiles adopted in this study are presented in Fig. 2(a): these consumptions are employed in Ref. [8] and they have been derived from Ref. [9] that it consider a community exceeding 50 people. In the graph, the hourly water consumption (l/h) is reported for an average daily amount of 2400 liters. Four different profiles are used in the present study according to: i) the period of year: winter (WIN), summer (SUM) and ii) the day of the week: weekday (WD), weekend day (WE). Winter period is considered from the last Monday in October till the last Sunday in March, whilst the summer season starts the last Monday in March and finishes the last Sunday in October. The monthly correction factor is the one employed in Ref. [8] where it was slighty modified from the one proposed by Ahmed et al. in Ref.[9], since the majority of people in Italy are on vacation in August and therefore the consumption of hot water drops in that period of the year. Figure 2(b) illustrates the monthly consumption factor.

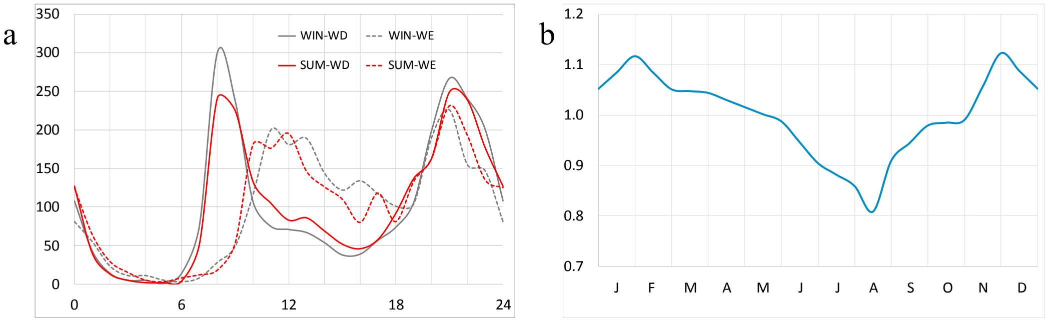

Fig. 2. (a) Daily water profiles (l/h) for winter and summer, weekdays (WD) and weekend (WE), deducted by Ref. [8]; (b) DHW monthly consumption factor for the apartment buildings, modified from Ref.[8].

2.2. Description of the system components

Solar collector (SC): Flat-plate and evacuated tube collectors have been considered. The set parameters, in terms of aperture area, are highlighted in Table 1, where η_0 indicates the optical efficiency of the collector, a_1 and a_2 represent the thermal loss parameters.

Table 1. Solar collector characteristics per aperture area.

Type of collector	η_0	a_1 ($Wm^{-2} K^{-1}$)	a_2 ($Wm^{-2} K^{-2}$)
Flat-plate	0.807	3.766	0.0059
Evacuated tube	0.675	0.6965	0.0029

Every single collector has an aperture area of 2.32 m^2 (flat plate) or 2.99 m^2 (evacuated tube) and it is oriented towards the south with different total area and slope depending on the city under examination.

Storage water tank (SST): A fully stratified storage tank (10 nodes) of different volume, depending on the city, has been employed in the simulation (Table 1). Two heat exchangers provide heat from the solar collector and from the auxiliary system.

Solar circuit: A pipe system connects the solar collector to the upper heat exchanger inside the storage water tank. A mixture of water and glycol flows in the circuit. The total length of the circuit is 50 m and the pipes are insulated with a material having thermal conductivity $k = 0.036\ Wm^{-1}K^{-1}$ and thickness equal to 25 mm.

Circulation system (CS): A pipe system connects the storage water tank to the apartments where the hot water is supplied. A mass flow of 500 kg/h is moved by a pump absorbing from the electrical grid the power of 50 W. The considered insulation thickness, with an insulation material having thermal conductivity $k = 0.036\ Wm^{-1}K^{-1}$, is set at 19 and 13 mm respectively for pipe of 1”1/4 (HW in Fig. 1) and 3/4 (CS in Fig. 1). The total length of the circuit is 60 m.

3. Results and Discussion

Monthly or annual solar fraction, which is the fraction of the total hot water energy (Q_{Load}) that is supplied by solar system, are calculated according to Ref.[11]:

$$f = \frac{Q_{Load} - Q_{Aux}}{Q_{Load}} \tag{1}$$

where Q_{Aux} is the energy supplied by the auxiliary system to integrate the part of the total load that is not provide by the solar energy.

Concerning all the localities taken into account in the simulations, Figure 3 and Figure 4 show, by means of a histogram, the monthly and annual solar fraction, respectively for flat-plane and evacuated tube collectors. Based on comparative observation, the f-values referred to evacuated tube collectors in winter period exceed the corresponding ones with reference to the flat plane configuration.

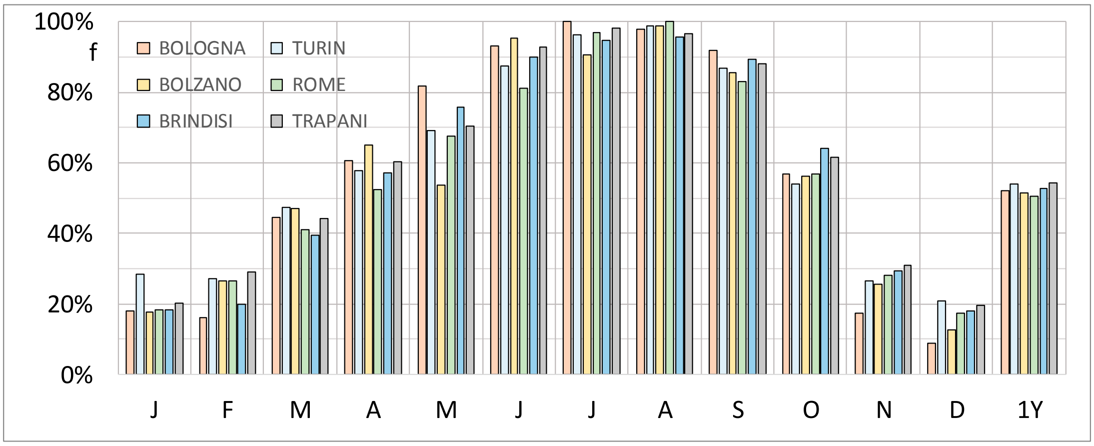

Fig. 3. Monthly and annual solar fraction with reference to all the localities under investigation using flat-plane collectors.

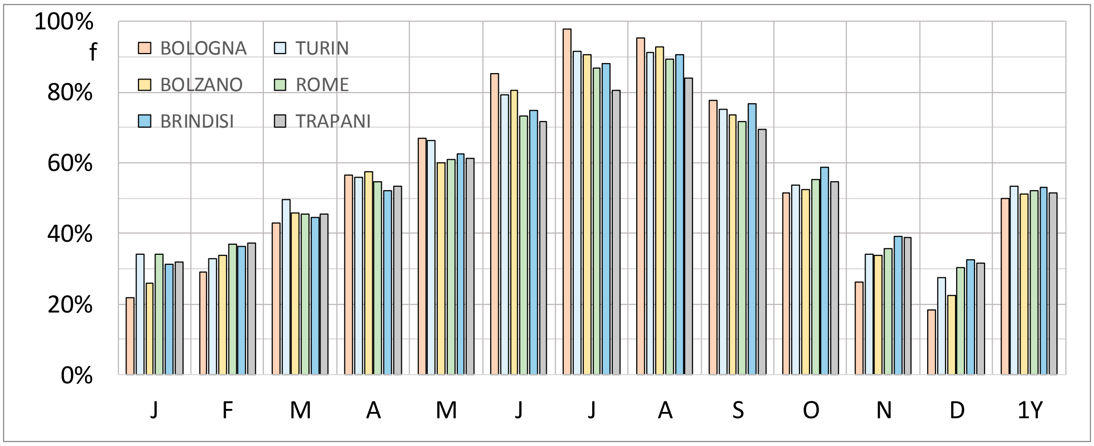

Fig. 4. Monthly and annual solar fraction with reference to all the localities under investigation using evacuated tube collectors.

Table 2 and Table 3 summarize the main output results of the simulations, respectively referred to flat-plane and evacuated tube collectors. The total collectors surface, the number of collectors, the angle of inclination, the water tank volume and the annual solar fraction are highlighted with reference to each locality. It is worth to mention that such values have been tested so as to meet both the following instances: to cover at least the 50% of the annual hot water energy need and to obtain obviously an integer (not decimal) number of collectors.

Tables 2 and 3 demonstrate that, for all the analyzed cities, the collector surfaces needed to obtain a solar fraction exceeding 50% referred to the evacuated tube configuration is practically half of the corresponding collector surfaces of the flat-plane geometry.

Table 2. Simulation results with reference to flat-plane collectors.

City	Total collectors surface [m^2]	Number of collectors	Angle of inclination [°]	Water tank volume [m^3]	Annual solar fraction [%]
Bolzano	37.12	16	45	5	51.4
Turin	37.12	16	45	5	54.1
Bologna	46.4	20	45	5	52.0
Rome	20.88	9	40	3.5	50.6
Brindisi	23.2	10	40	4	52.8
Trapani	18.56	8	40	4	54.2

Table 3. Simulation results with reference to evacuated tube collectors.

City	Total collectors surface [m^2]	Number of collectors	Angle of inclination [°]	Water tank volume [m^3]	Annual solar fraction [%]
Bolzano	17.94	6	45	4.5	51.2
Turin	17.94	6	45	4.5	53.4
Bologna	17.94	6	45	4.5	50.1
Rome	11.96	4	40	4.5	52.2
Brindisi	11.96	4	45	4.5	53.1
Trapani	8.97	3	40	4.5	51.4

The following part of the treatment is aimed at the study of the simulation results regarding a specific case, i.e. the water temperature oscillations in winter and summer time with reference to the climatic data of Bologna, under particular operating conditions: i) the pump of the recirculation loop is powered all time (24 hours a day) ii) the pump is switched off during the night, except when the water temperature in the loop falls below a certain threshold temperature (40°C in the case here studied). The analysis is performed employing the flat plate collector under investigation. Figures 5(a) and 5(b) display the variation of the water temperature respectively during one week in winter (end of February) and summer (middle of June) when the pump of the recirculation loop is powered all time. Three different sections have been depicted: the red curve represents the hot water temperature exiting the tank, the grey curve is the temperature of water leaving the hot pipes at the three-way valve with the circulation pipes and the light blue curve is referred to the water temperature at the user's tap after mixing with the cold water.

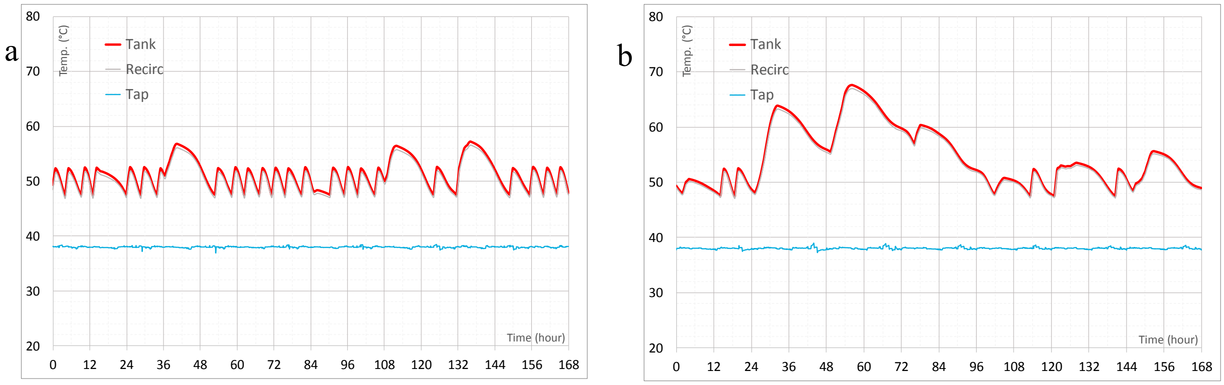

Fig. 5. (a) Water temperature oscillation during one week in winter time when the pump of the recirculation loop is powered; (b) Water temperature oscillation during one week in summer time when the pump of the recirculation loop is powered.

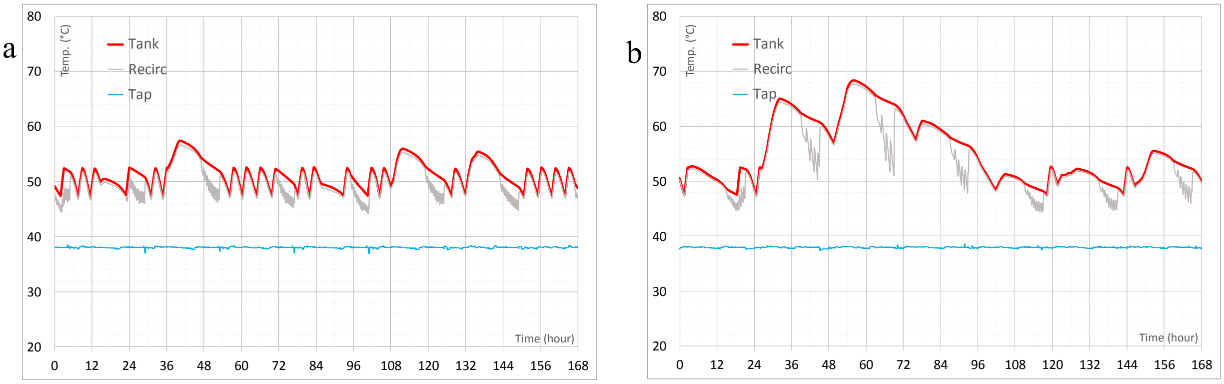

Fig. 6. (a) Water temperature oscillation during one week in winter time when the pump of the recirculation loop is switched off during the night, except when the water temperature in the loop falls below the threshold value; (b) Water temperature oscillation during one week in summer time when the pump of the recirculation loop is switched off during the night, except when the water temperature in the loop falls below the threshold value;

Based on pure observation with reference to both the diagrams, the temperature of water at the end of the circuit before the mixing with the cold water (i.e. the grey curve) strictly approaches the temporal trend of the hot water exiting the tank (red curve), falling itself a little below. This discrepancy is due to thermal losses inside the pipes.

In a similar way, Figures 6(a) and 6(b) show the oscillation of the water temperature respectively during one week in winter (end of February) and summer (middle of June) when the pump of the recirculation loop is switched off during the night, except when the water temperature in the loop falls below the value of 40°C. Correspondingly, three sections have been highlighted; the legend with colored curves is the same as Figures 5(a) and 5(b) and for sake of conciseness it is here not repeated.

A comparative analysis between Figs. 5(a)-6(a) and Figs. 5(b)-6(b) shows that in the morning period the water temperature inside the tank when the pump is switched off normally exceeds the corresponding temperature referred to the case of priming the pump. Moreover, it is possible to observe that the required use of auxiliary energy for heating the tank is less frequent when the pump is not working continuously. Finally, it is worth to mention that the water temperature at the user's tap after mixing with the cold water remains almost constant approaching the value of 38°C.

4. Conclusions

The present paper in concerned with a solar hot water system performed on a dwelling located in different cities in Italy, precisely, from north to south: Bolzano, Turin, Bologna, Rome, Brindisi and Trapani. The domestic hot water need is provided by a solar system coupled with a storage tank and a recirculation loop. Thus, dynamic simulations have been performed by means of TRNSYS simulations tool. Several results and ideas for further developments emerged from this study. The output results of the simulations are arranged in terms of total collectors surface, number of collectors, angle of inclination, water tank volume and annual solar fraction with reference to each locality. In the second part, the study of water temperature oscillations in winter and summer time with reference to the climatic data of Bologna has been carried out under particular operating conditions: i) the pump of the recirculation loop is powered all time (24 hours a day) ii) the pump is switched off during the night, except when the water temperature in the loop falls below a certain threshold temperature. Basing on a comparative analysis, in the morning period the water temperature inside the tank when the pump is switched off normally proves to exceed the corresponding temperature referred to the case of priming the pump. Furthermore, it is possible to notice that the required use of auxiliary energy for heating the tank is less frequent when the pump is not working continuously.

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