Evaluation and control of thermal losses and solar fraction in a hot water solar system

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Abstract

Water heating for domestic needs contributes significantly to energy demands in the residential sector. The paper reports an energetic analysis of a solar hot water system performed on a dwelling located in different European cities. 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. A recirculation loop, composed by a pump and a system of pipes from the tank to the more distant apartment is also considered in the study. The loop overcomes the problem of long waiting times for hot water for the user by keeping it flowing inside the system. Since the recirculation loop is compulsory in this kind of plants, a dynamic energetic analysis is performed in order to analyze the pipe heat loss influence on the solar fraction. Dynamic simulations are performed using TRNSYS by interrupting the flow in the recirculation loop during the night and monitoring the temperature in the circulation loop. The study shows the sizing process of the whole system, the variation of the solar fraction and heat loss fraction for all the analyzed cases.

Keywords: solar collector; energy saving; circulation loop; dynamic simulation; TRNSYS

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1 INTRODUCTION

Water heating for domestic needs contributes significantly to the energy demands in the residential sector. The Member States of the European Union have to achieve at least 20% of renewable sources in the final energy consumption by 2020 [1]. Solar water heating (SWH) is a well-known technology able to allow energy savings and reductions in CO_2 emissions in water heating for residential needs. The performance of SWH systems has been studied theoretically and experimentally over the past several decades [2–7]. Different computational tools have been developed to numerically evaluate the long-term performance of solar systems and to study the effect of the design parameters. TRNSYS 17 [8] is an extensive software for transient simulation that provides good agreement with experimental data. Shrivastava *et al.* [9] provide a critical review of the SWH system simulation, a comparative analysis of popular simulation tools and their architecture in the TRNSYS perspective.

Hobbi and Siddiqui [10] used TRNSYS to model a forced circulation SWH system for domestic hot water requirements in Montreal, Canada. In their study, they optimized the system and collector parameters by 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 modelled system could provide 83–97% and 30–62% of the hot water demands in summer and winter, respectively.

For circulation of the hot water in the system piping a big amount of energy is required [11]. Once the hot water leaves the storage tank and flows through the pipes, the water temperature drops due to the travel distance and ambient air temperature. The solution for the problem, without using a circulation loop, is to reheat the water before use.

Since water circulation in pipes has an energetic cost, it is desirable to interrupt the hot water flow in the pipes when the water requirement is low. For this reason, it is important to know the hourly hot water consumption. Moreover, data of domestic hot water consumption are pivotal to compute the energy demand and to design the SWH system. Studies based on measured data or simulations are available to estimate DHW consumption focusing on a daily average, hourly average, appliance consumption and number of occupants [12, 13]. Ahmed *et al.* [12] derived the hourly DHW profiles for five groups of a different numbers of people as a function of the

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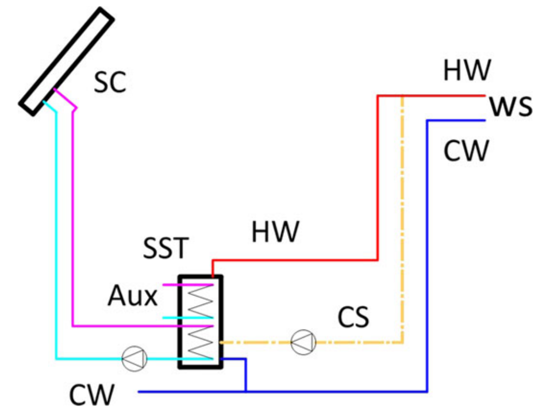

Figure 1. *Sketch of the SWH system.*

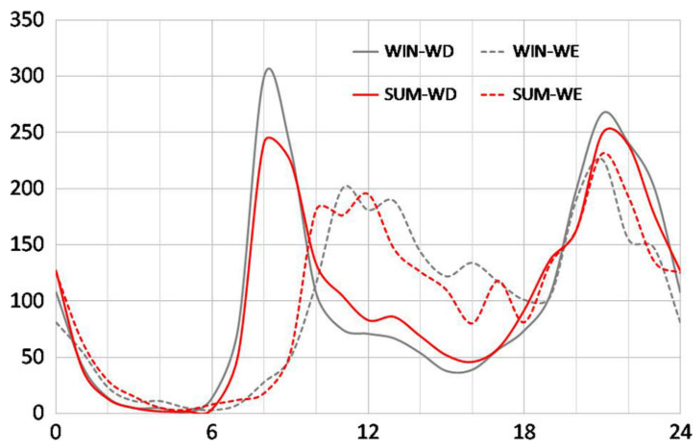

Figure 2. *Daily water profiles (l h^{-1}) for winter (WIN) and summer (SUM), weekdays (WD) and weekend days (WE) (from Ahmed* et al. *[12]).*

number of occupants. In the study, weekday (WD) and weekend (WE) consumption variations were reported.

In the present study, the entity of energy losses in the circulation loop between the hot water storage tank and the final hot water outlet has been analyzed both in terms of solar fraction and heat loss fraction.

2 SWH SYSTEM UNDER INVESTIGATION

In the present study, a forced circulation system with a secondary flow loop and a storage tank is modelled (Figure 1). The secondary flow that 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 through a heat exchanger placed inside the tank (Aux). The produced hot water reaches the final user through a system of pipes (HW). A tempering valve adds cold water (CW) to adjust the temperature in order to supply the water (ws) at the user's desired temperature (38°C).

Figure 3. *DHW monthly consumption factor for the apartment buildings.*

A recirculation flow loop (CS) can keep the water warm from the storage tank to the final user. The described system is simulated using the TRNSYS simulation program.

The solar heating plan is able to provide hot water for a residential building of 20 apartments (48 people). The average daily consumption of hot water is set to 2400 l (50 l per person). The solar radiation and ambient temperature data as a function of time are from Meteonorm. The simulations are conducted for seven European cities: Lisbon, Rome, Madrid, Milan, Wien, Paris and London.

3 HOT WATER LOAD PROFILE

The hourly distribution of domestic hot water consumption during a day is affected by several factors. It varies from day to day, from season to season and from family to family. The daily water profiles used in this study are presented in Figure 2 and are derived from Ahmed *et al.* [12] in the case of a community having more than fifty people.

In the graph, for each hour of the day the hourly water consumption (l h^{-1}) is reported for an average daily consumption of 2400 l. 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: WD, WE day . The winter period goes from the last Monday in October to the last Sunday in March, while the summer season starts on the last Monday in March and ends on the last Sunday in October.

The monthly correction factor was modified from the one proposed by Ahmed *et al.*, 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 3).

4 DESCRIPTION OF SYSTEM COMPONENTS

SC: flat-plate collectors have been employed. The set parameters, in terms of aperture area, are summarized in Table 1:

Table 1. *SC characteristics per aperture area*

η_0	a_1 (Wm^{-2} K^{-1})	a_2 (Wm^{-2} K^{-2})
0.807	3.766	0.0059

Table 2. *Dimension of SCs and storage water tanks*

	SC—total area (m^2)	SC—slope	SST—volume (m^3)
Lisbon	20.0	40°	3
Rome	22.5	45°	4
Madrid	25.0	45°	4
Milan	50.0	50°	5
Wien	75.0	55°	5
Paris	80.0	50°	6
London	85.0	50°	6

η_0 indicates the optical efficiency of the collector; a_1 and a_2 represent the thermal loss parameters.

Every single collector has an aperture area of 2.5 m^2 and they are oriented towards the south with different total areas and slopes depending on the city under examination (Table 2). The values in Table 2 are computed to cover at least the 50% of the annual hot water energy need.

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

Solar circuit: a pipe system connects the SC 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 $\lambda = 0.036\ W\,m^{-1}\,K^{-1}$ and thickness of 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 $kg\,h^{-1}$ is moved by a pump absorbing 50 W from the electrical grid. The considered insulation thickness, with an insulation material having thermal conductivity $\lambda = 0.036\ W\,m^{-1}\,K^{-1}$, is set at 19 and 13 mm, respectively, for pipe of 1″1/4 (HW in Figure 1) and 3/4 (CS in Figure 1). In the present work, these insulation parameters are considered as a standard insulation. The total length of the circuit is 60 m.

5 RESULTS AND DISCUSSION

Monthly or annual solar fraction, which is the fraction of the total hot water energy (QLoad) that is supplied by solar system, are calculated using the equation from Buckles and Klein [14],

$$f = (Q_{Load} - Q_{Aux})/Q_{Load}$$

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

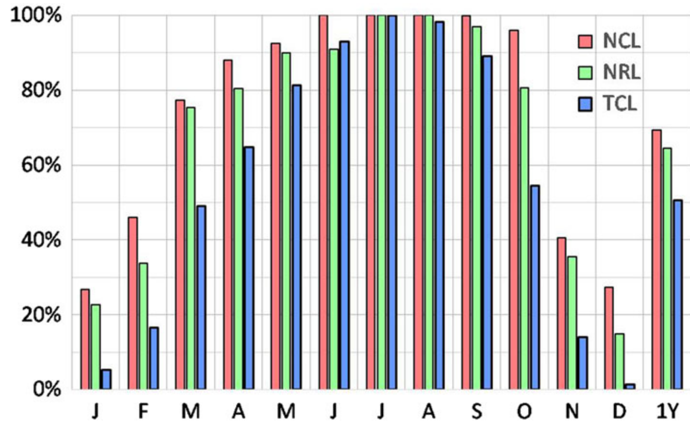

Figure 4. *Solar fraction for each month of the year and annual average in three different cases for the city of Milan (see text for more details).*

Table 3. *Yearly solar fraction for different cases*

	Case 1 (%)	Case 2 (%)	Case 3 (%)
Lisbon	52.9	53.9	53.2
Rome	49.9	51.0	50.3
Madrid	53.1	54.0	53.4
Milan	50.6	51.4	50.8
Wien	50.4	51.8	51.2
Paris	50.0	51.2	50.5
London	49.9	51.3	50.6

Regarding the city of Milan, the solar fraction in three different cases is shown in Figure 4: (i) without taking the heat losses from the tank and the pipes of both the solar and the recirculation system into account (no circuit losses, NCL); (ii) considering only the losses of the solar circuit and the tank but not the recirculation flow loop (no recirculation loop losses, NRL); (iii) considering the three heat losses mentioned above (total circuit losses, TCL). Figure 4 shows the yearly solar fraction fall from 69.5% (NCL) to 64.4% (NRL) and 50.6% (TLC). The difference among the three cases is more evident in the winter months, owing to pipe heat losses that are not counteracted by the solar energy. Neglecting pipe losses may lead to overestimate the solar factor.

Table 3 shows the yearly solar fraction for three different cases: Case 1, the pump of the circulation system was powered all time (24 h a day—365 days a year); Case 2, the recirculation pump was switched off every day between 11 p.m. to 5 a.m. In this case, during the night, when the hot water demand is lower than that during daytime, no water is circulating through CS pipes and in HW flows only the hot water required by the users; Case 3, the pump was generally switched off every day between 11 p.m. to 5 a.m. except when the temperature of water inside the recirculation loop falls below the value of 40°C. In this case, when this value is reached, the pump was switched on for a short period of time (around 5 min) in order to reheat the water inside the pipes. As expected, the solar

Table 4. *Heat loss fraction for different cases (A—through the entire system; B—through the circulation loop)*

	Case 1A (%)	Case 2A (%)	Case 3A (%)	Case 1B (%)	Case 2B (%)	Case 3B (%)
Lisbon	47.8	45.9	47.2	26.8	25.0	26.2
Rome	47.8	45.8	47.0	25.6	23.7	25.0
Madrid	48.7	46.8	48.0	25.8	23.9	25.2
Milan	51.5	49.4	50.8	26.4	24.4	25.7
Wien	50.2	48.0	49.4	25.8	23.8	25.2
Paris	55.5	53.3	54.7	26.5	24.4	25.8
London	52.0	49.8	51.2	25.9	23.8	25.2

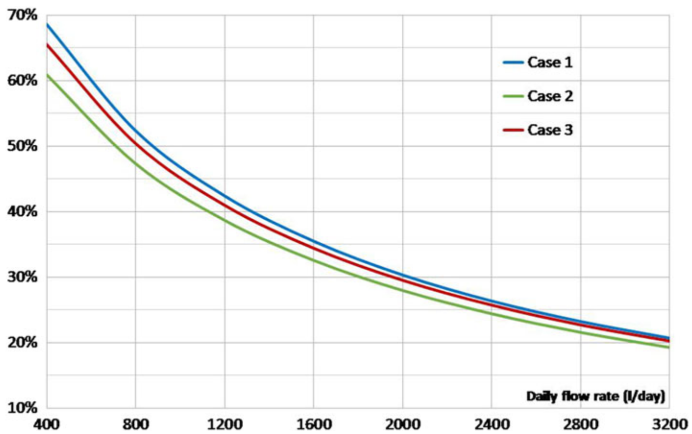

Figure 5. *Heat loss fraction vs different daily water consumption (l/day) by the occupants of the apartments (Milan).*

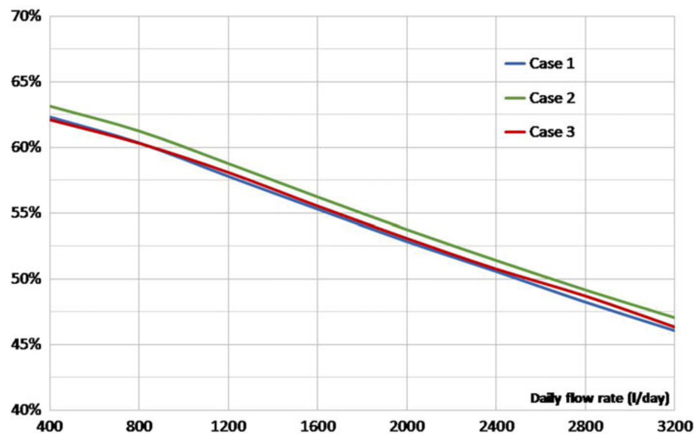

Figure 6. *Solar fraction vs different daily water consumption (l/day) by the occupants of the apartments (Milan).*

fraction increases in the case of the night interruption of the flow.

The same cases are evaluated in terms of heat loss fraction (Table 4). Two different heat loss fractions are defined:

$$h_{A,lf} = Q_{A,Loss}/Q_{Load}; \qquad h_{B,lf} = Q_{B,Loss}/Q_{Load}$$

where $Q_{A,Loss}$ is the energy waisted through the entire system, while $Q_{B,Loss}$ in the energy lost through the pipes from the tank to the final user and in the recirculation circuit.

The table shows that, for all the analyzed cities, the heat loss fraction has a value around 50% when it is evaluated in terms of energy lost through the entire system, whilst it is about 25% when the heat loss fraction is taking into account only the energy lost through the pipes from the tank to the final user. As expected, the heat loss fraction decreases when the night interruption of the flow occurs.

Figures 5 and 6 show the heat loss fraction and the solar fraction for different values of daily water consumption. The three curves with circulation operating 24 h per day (Case 1), only during the daytime (Case 2) and in addition for some short period during the night (Case 3) are reported in the graph. Reducing the daily water consumption leads to a dramatic increase in heat loss fraction, whereas the solar fraction is increasing.

Table 5 shows for all cities the annual auxiliary energy necessary to heat the water inside the tank and the electrical energy required by the circulation pump. An overall energy efficiency of 85% for the boiler-to-tank heating system, and a coefficient of 0.46 for converting the electrical energy in primary energy were considered. Table 6 reports the values of primary energy and the energy saving (in percentage) in two scenarios: Case 2 vs Case 1 and Case 3 vs Case 1.

Despite the advantages in energy saving obtained switching the circulation pump off, in Case 2 (when the pump is working only during the day), the system is not able to provide the warm water (i.e. 38°C, the temperature required by the users, during the night period as seen in Figure 7 for the city of Milan). This figure displays the variation of the water temperature during 1 week in winter (middle of February) in three different sections. The red curve represents the temperature of the hot water exiting from the tank, the dotted curve is the temperature of the water leaving the hot water pipes at the three-way valve with the circulation pipes (end of the circuit before the mixing with the cold water); the light blue curve is the temperature of the water at the user's tap after mixing with the cold water.

The control of the auxiliary system starts to provide energy to the tank water when the temperature falls below 47.5°C and ends when it reaches 52.5°C. The two peaks (i.e. $T > 52.5$°C) of

Table 5. *Auxiliary energy provided at the tank and electrical energy for circulation pump*

	Auxiliary energy provided at the tank (kWh)			Electrical energy for circulation pump (kWh)		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Lisbon	11 693	11 252	11 565	438	329	340
Rome	13 390	12 835	13 212	438	329	342
Madrid	13 400	12 908	13 255	438	329	342
Milan	15 746	15 163	15 592	438	329	343
Wien	16 860	16 050	16 518	438	329	344
Paris	16 242	15 509	15 966	438	329	343
London	16 786	16 012	16 457	438	329	344

Table 6. *Primary energy (for heating the water and to power the circulation pump) and energy Saving in two scenarios*

	Primary energy			Energy saving (%)	
	Case 1	Case 2	Case 3	Case 2 vs Case 1	Case 3 vs Case 1
Lisbon	14 709	13 953	14 345	5.1	2.5
Rome	16 705	15 815	16 287	5.3	2.5
Madrid	16 717	15 901	16 338	4.9	2.3
Milan	19 477	18 554	19 089	4.7	2.0
Wien	20 787	19 598	20 181	5.7	2.9
Paris	20 060	18 961	19 529	5.5	2.6
London	20 700	19 553	20 109	5.5	2.9

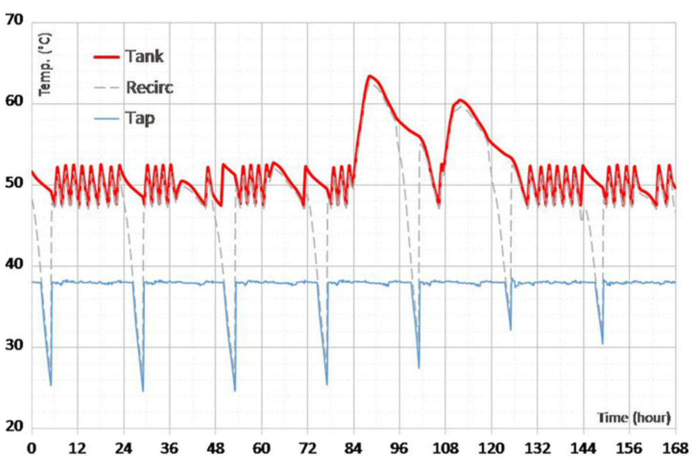

Figure 7. *Water temperature oscillation (°C) during 1 week (168 h) in winter time, with circulation pumps switched off during the night (Milan).*

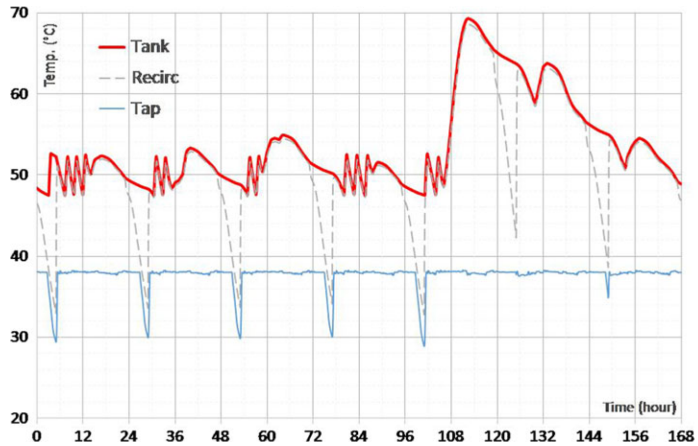

Figure 8. *Water temperature (°C) oscillation during 1 week (168 h) in summer time, with circulation pumps switched off during the night (Milan).*

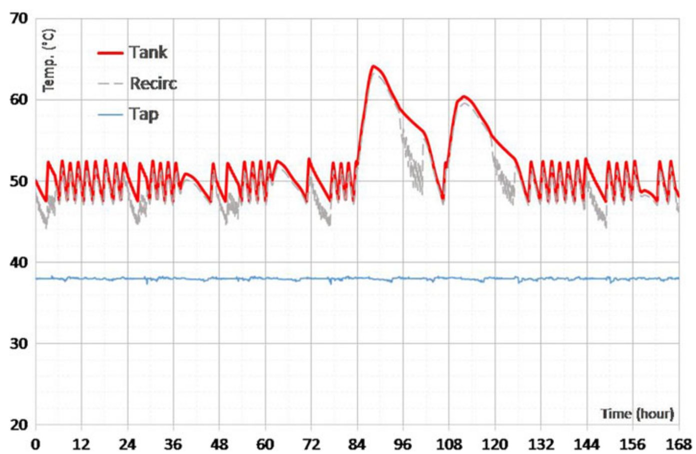

Figure 9. *Water temperature oscillation (°C) during 1 week (168 h) in winter time, with circulation pumps switched off during the night except when water temperature <40°C (Milan).*

the red curve in Figure 7 are due to energy from SCs, whilst the sharp oscillations around 50°C derive from the auxiliary energy. During the night, the hot water at the user's tap falls below the setting point of 38°C about 2 h after the circulation pump is switched off. So, in order to have water at 38°C in the apartments, it is necessary to reheat the water locally (e.g. with an electric boiler).

Clearly, when the pump is maintained switched on during the night, it is not necessary to reheat the water at the user's site, but the tank water is heated in the storage tank by the auxiliary system (data not shown).

Figure 8 shows the variation of the water temperature during 1 week in summer (beginning of June) in the three different positions previously described. Like in winter (Figure 7), in the summer week (Figure 8) during the night, when the circulation pump is switched off, the hot water at the user's tap falls below the setting point of 38°C, so it is necessary to reheat the water locally.

Figures 9 and 10 show the variation of the water temperature during the same week in winter and summer shown in Figures 7 and 8, respectively (when the circulation pump is mainly off during the night (h 11 p.m.–5 a.m.)), except when the temperature of the water in the circulation loop falls below

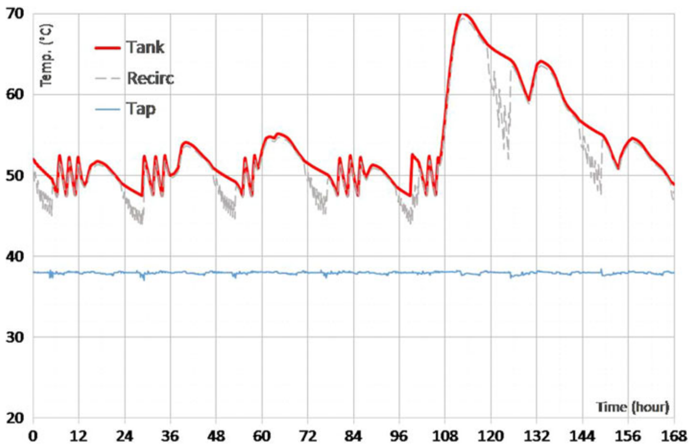

Figure 10. *Water temperature oscillation (°C) during 1 week (168 h) in summer time, with circulation pumps switched off during the night except when water temperature <40°C (Milan).*

40°C. In this latter case, the pump was switched on for a short period of time (about 5 min) to reheat the water inside the pipes. As indicated by the light blue curves in Figures 9 and 10, the user's site is always provided by hot water at the temperature of 38°C.

6 CONCLUSION

In the present study, the TRNSYS software was used to model a forced circulation SWH system for domestic hot water requirements in different cities in Europe. The entity of energy losses in the circulation loop between a hot water storage tank and the final hot water outlet has been analysed both in terms of solar fraction and heat loss fraction.

The study demonstrates that neglecting pipe losses leads to an overestimation of the solar factor. In addition, reducing the daily water consumption leads to a dramatic increase in heat loss fraction.

To improve the solar fraction, the strategy of interrupting the recirculation flow when the mass flow rate is low (i.e. during the night) has been applied. It was found that switching the circulation flow off during the night improves the solar fraction and reduces the heat loss fraction. However, in this case, the system is not able to provide the warm water (38°C) to the user level, so the water has to be reheated.

The domestic hot water is heated by SCs and an auxiliary system. Since in sunny summer days, the energy to heat the water is totally provided by the SC, in order to save auxiliary energy, it might be not necessary to switch off the pump, to save the energy provided by the auxiliary system. To decide whether it is economically convenient, to interrupt the circulation flow during summer nights, it is necessary to monitor if the heat is provided by either the SC or by the auxiliary system. Anyway, the best solution is to switch the pump off when the mass flow rate is low and monitor the temperature of the water in the circulation loop. When the temperature falls below 40°C, it is possible to switch the pump on for a short period of time (i.e. 5 to 10 min depending on the length of the pipes). The study demonstrates that applying this strategy it is always possible to provide warm water at the temperature of 38°C to the user and it is possible to save the auxiliary energy provided at the tank and electrical energy for powering the pump of the circulation loop.

The proposed solution is in line with the possible strategies of energy saving requested by the European Union's directives which hope for a reduction of the final energy consumption in buildings and a target of 20% final energy consumption from renewable sources by 2020.

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