The influence of climatic conditions on the efficiency of the solar system

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Abstract. The simulation analysis of the solar hot water preparation system for an apartment building is presented. The analyses investigated the effect of climatic conditions on the efficiency of the solar system. To demonstrate the influence of climatic conditions, four building locations (Stockholm, Prague, Milan, and Barcelona), six different solar collectors, and six different design areas of solar collector field were used. The aim was to verify how the efficiency of the solar system varies depending on the climatic and design conditions. Moreover, the influence of year-to-year fluctuations of climatic conditions was also explored. The analysis has been provided by using TRNSYS simulation software over the period of one year using the time step of 2 minutes. The simulation results clearly showed that the efficiency of the SDHW system is dependent on the climatic conditions, especially on the air temperature. On the other hand, year-to-year weather fluctuations do not strongly affect the efficiency of the SDHW system.

1 Introduction

Nowadays buildings consume more than 40 % of primary energy all over the world. The major part is spent for hot water production and space heating. Generally, water is heated by burning natural gas, coal or other fossil fuels. However, the use of fossil fuels creates serious environmental problems, including acid emissions, air pollution, and consequent climate changes. This calls for exploring all the possibilities of alternative energy sources that could potentially decrease noxious emissions and reduce the greenhouse effect. In this regard, utilization of solar energy through solar domestic hot water (SDHW) heating systems plays a big role in reducing energy amount required.

SDHW is probably the most popular application of solar system, allowing both fossil fuel savings and emission reductions. Based on the latest reports, 94 % of the energy provided by solar thermal systems worldwide was used for SDHW [1]. The big popularity of these systems is based on the direct conversion of solar energy, relative simplicity of such system and high lifetime of the main components. This is confirmed by the fact that, in the last years the installed capacity of SDHW systems worldwide has increased from 58 GW_{th} in 2000 to 450 GW_{th} at the end of 2018. This corresponds to the annual solar thermal energy yield of 372 TWh in 2018, which correlates to savings of 40 million tons of oil and 129 million tons of CO_2 [1].

Many studies analysed different solar hot water preparation system for different climatic conditions. Nikoofard et al. [2] presented an investigation of the technoeconomic feasibility of SDHW system for the Canadian housing stock. Naspolini and Rüther [3] investigated the technical and economic viability of low-cost SDHW system for residential dwellings on Brazil. In Greece, the feasibility analysis of SDHW system was conducted by Kaldellis et al. [4]. Based on China climate conditions, Chow et al. [5] provided the evaluation of the annual efficiency and the solar fraction of SDHW. Allouhi et al. [6] presented an energy analysis of SDHW for six different climatic zones of Morocco.

These studies give rise to two research questions to be addressed in the remainder of the paper:

1. Is the energy performance of SDWH strongly dependent on climatic conditions?
2. Do the year-to-year fluctuations of climatic conditions for the specific location affect energy efficiency of SDHW?

2 Solar water heating system

2.1 General information

The influence of climatic conditions on the efficiency of the solar system has been analysed by using TRNSYS simulation software over the period of one year using the time step of 2 minutes.

2.2 System design

A schematic diagram of a forced-circulation SDHW system is illustrated in Figure 1. This SDHW system consists of three parts. The first part is the solar part and it consists of solar collector field (SF), supply (SI and SE)

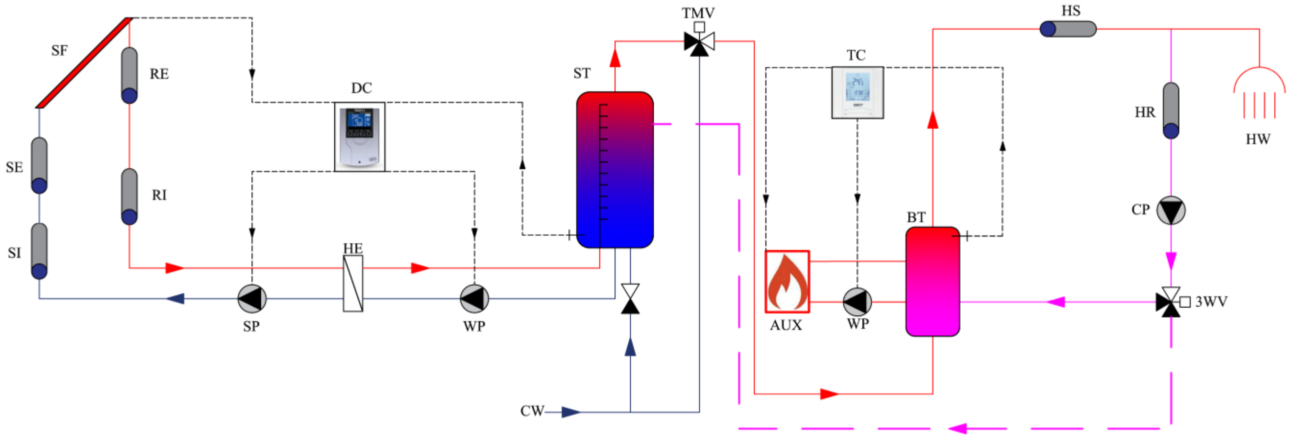

Fig. 1. Schematic of the considered SDHW system.

and returns pipes (RI and RE), solar pump (SP), solar heat exchanger (HE), and differential controller (DC). The second part is the domestic hot water part which includes a solar storage tank (ST), backup hot water tank (BT) with auxiliary heater (AUX), water pump (WP), temperature controller (TC), and a thermostatic mixing valve (TMV) to control the temperature after the solar tank. The third one is recirculation part and it includes supply (HS) and return water circulation pipes (HR), DHW circulation pump (CP), and 3-way valve (3WV) to redirect return circulation water from the backup hot water tank to the solar hot water tank and increase an annual specific solar energy yield of the system. Detailed parameters of the presented SDHW system are listed in Table 1.

Table 1. Detailed parameters of SHDW system.

Parameter	**Description**
Building occupancy	91 persons
Collector orientation	South, slope 45°
Collector mass flow rate	15 l/m^2.h
Heat transfer medium	Propylene Glycol / Water (50 % / 50 %)
Solar pump control strategy	Pump switching on/off temperature difference collector-storage 8 K / 2 K
Collector piping	Supply and return pipes are located in the interior and exterior: 50 m each, DN 20, with 25 mm outside thermal insulation
Heat exchanger efficiency	80 % for 42 °C / 32 °C (inlet temperature/tank storage temperature)
Solar tank volume	50 l/m^2
TMV control temperature	55 °C
Backup hot water tank volume	500 l

Table 1. Continued. Detailed parameters of SHDW system.

Parameter	**Description**
Supply and return water circulation pipes	173 m each, DN 50, with 25 mm thermal insulation
3WV control	3WV valve diverts water from the backup hot water tank to the solar tank if the temperature difference between hot water in the solar tank and return circulation water is higher than 3 °C and diverts it back to the backup hot water tank when the difference becomes lower than 0 °C.

2.3 Weather data

As previously mentioned, the analysis has been performed for four climatic conditions – Prague, Stockholm, Milan, and Barcelona. The meteorological data were taken from the Meteonorm (TMY) database. The climatic conditions of the considered locations are listed in Table 2.

2.4 Hot water consumption

One of the key elements of SDHW dimensioning is the determination of daily hot water consumption. Based on EU statistic data, the average daily domestic hot water consumption varies from 10 litres to 50 litres at 60 ºC. This wide range could be described by difference in several parameters like climatic conditions and people habits. An average EU-28 daily domestic hot water consumption is 24 litres at 60 ºC [7]. In the present investigation, an average daily domestic hot water consumption of 40 l at 55 °C per person has been used.

2.5 Hot water load profile

In all simulations presented in the study, the characteristic load profile for an apartment building has

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been considered [8]. The daily hot water load profile and profile of circulation operation are presented in Figure 2.

Table 2. Climatic conditions of considered locations (Meteonorm).

Parameter	**Prague (Czech Republic)**	**Stockholm (Sweden)**	**Milan (Italy)**	**Barcelona (Spain)**
Latitude	50.10° N	59.65° N	45.43° N	41.39 ° N
Annual average ambient temperature	7.9 °C	5.3 °C	11.7 °C	16.27 °C
Minimum ambient temperature	-15.2 °C	-19.9 °C	-7.7 °C	0.4 °C
Maximum ambient temperature	30.7 °C	28.3 °C	32.1 °C	31.3 °C
Global solar horizontal irradiation	999 kWh/m^2	981 kWh/m^2	1255 kWh/m^2	1446 kWh/m^2
Global solar irradiation on tilted surface (South, 45°)	1114 kWh/m^2	1231 kWh/m^2	1392 kWh/m^2	1629 kWh/m^2

The cold water temperature considered in the analysis was 10 ºC and is constant during the year. The hot water is provided at temperature of 55 °C. Annual heat energy demand without heat losses is 67.6 MWh/a. The total annual heat energy demand (including heat losses of hot water distribution system) is 119 MWh/a.

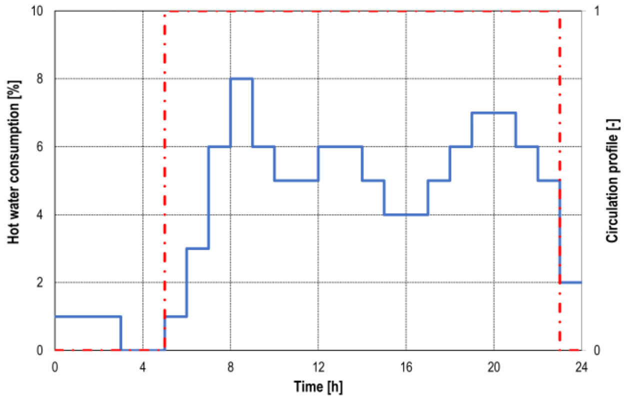

Fig. 2. Daily hot water profile and circulation operation profile.

2.6 Solar thermal collectors

A mathematical modelling of solar thermal collectors is based on the standard second-order collector performance equation expressed as

$$\eta = \eta_0 - a_1 \frac{T_\mathrm{m} - T_\mathrm{a}}{G} - a_2 \frac{\left(T_\mathrm{m} - T_\mathrm{a}\right)^2}{G} \qquad (1)$$

where η_0 parameter indicates the optical efficiency of the collector [-]; a_1 [W/m^{2}K] and a_2 [W/m^{2}K^2] represents the thermal loss parameters. G is the incident solar irradiance [W/m^2], T_m is the fluid mean temperature across the solar collector [K] and T_a is the ambient temperature [K].

In the present study, six different flat plate solar collectors were chosen. In Table 3 are listed the characterizing parameters of the selected solar thermal collectors related to the gross area of the collectors.

2.7 Solar thermal collectors

In order to analyse the effect of climatic conditions on the efficiency of the solar system, six different solar collector field areas in the range between 0.25 and 1.5 m^2 of solar collectors per person were chosen.

Table 3. Collector performance characteristics.

Collector	**η_0 [-]**	**a_1 [W/m^{2}K]**	**a_2 [W/m^{2}K^2]**
1	0.702	3.930	0.007
2	0.737	3.128	0.010
3	0.728	3.055	0.014
4	0.754	3.669	0.012
5	0.769	3.411	0.010
6	0.749	3.040	0.006

3 Energy performance

The SDHW system performance is evaluated using efficiency of solar system η_{ss} [-]. System efficiency is defined as the total useful solar energy delivered to the building $Q_{ss,u}$ divided by the total energy incident on the collector filed Q_s:

$$\eta_\mathrm{ss} = \frac{Q_\mathrm{ss,u}}{Q_\mathrm{s}} = \frac{Q_\mathrm{ss,u}}{H_\mathrm{T} A} = \frac{q_\mathrm{ss,u}}{H_\mathrm{T}} \qquad (2)$$

where H_T is total solar energy yield on the collector surface [kWh/m^{2}a], A is the area of collector field [m^2], q_{ss} is an annual specific solar energy yield [kWh/m^{2}a].

Annual specific solar energy yield describes the annual amount of usable heat supplied to load the from 1 m^2 of collector surface area

$$q_{\mathrm{ss,u}} = \frac{Q_{\mathrm{ss,u}}}{A} \qquad (3)$$

4 Results and discussion

4.1 Influence of climatic conditions

To demonstrate the influence of climatic conditions on the efficiency of DHW system, four different locations (Stockholm, Prague, Milan, and Barcelona), six different flat plate collectors, and six different design areas of solar collector field were chosen for comprehensive analysis. The SDHW system efficiency for every case was determined by detailed simulation in TRNSYS. The results of the simulation for the collector alternatives 1 and 6 are shown in Table 4. The simulation results for the other collector variants are identical. The results of the simulation for all collector alternatives (coloured dots) are shown in Figure 3.

Firstly, the results of the simulation indicate that the efficiency of solar system is dependent on the climatic conditions or, to be more precise, on the ambient air temperature. On the one hand, it is evident, that the colder climate cases higher heat losses of the outdoor part of the solar system and therefore lower efficiency of the whole system. On the other hand, in the well-insulated SDHW system the influence of the heat losses could be minimised and, as a result, the influence of climatic conditions could be also minimised.

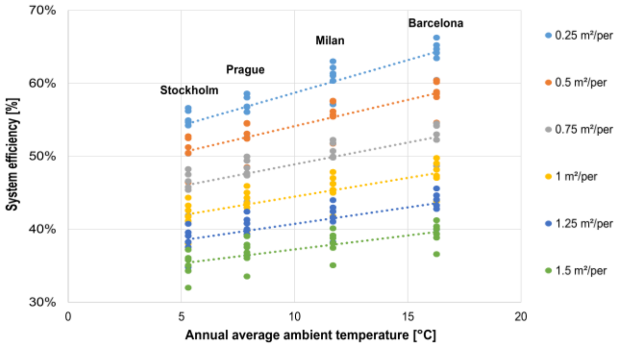

Fig. 3. Annual efficiency of considered SDHW systems.

Secondly, the mean system efficiency for the different areas of solar collector field could be calculated based on the simulation results. Figure 4 shows the mean system efficiency as a function of solar collector field area. It is important to note that the efficiency value varies in the range between 37 % and 59 %. Moreover, this figure may be further used for the quick estimation of an annual specific solar energy yield of the solar thermal system in Europe.

Table 4. The simulation results of the annual efficiency for the collector alternatives 1 and 6.

Specific solar collector area [m^2/per]	**Prague (Czech Republic)**	**Stockholm (Sweden)**	**Milan (Italy)**	**Barcelona (Spain)**
Collector 1				
0.25	53 %	50 %	57 %	60 %
0.50	49 %	46 %	52 %	55 %
0.75	44 %	42 %	46 %	49 %
1.00	40 %	38 %	42 %	44 %
1.25	36 %	35 %	38 %	40 %
1.50	34 %	32 %	35 %	37 %
Collector 6				
0.25	58 %	56 %	62 %	65 %
0.50	55 %	53 %	58 %	60 %
0.75	50 %	48 %	52 %	54 %
1.00	46 %	44 %	48 %	50 %
1.25	42 %	41 %	44 %	46 %
1.50	39 %	37 %	40 %	41 %

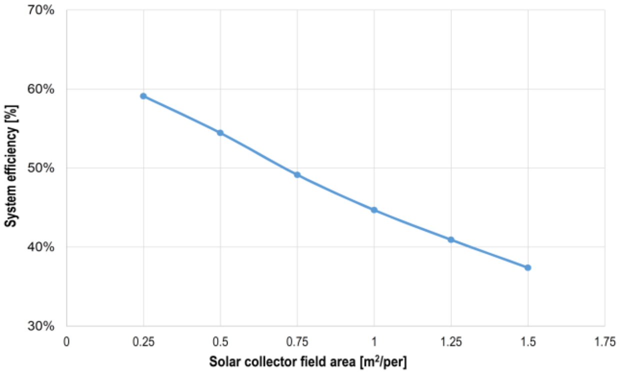

Fig. 4. The mean calculated efficiency values for the different solar collector field areas.

Finally, it can be observed that the efficiency of the solar system is strongly influenced by the ratio between solar collector area and heat demand, here represented as a number of occupants. The higher this value is, the higher mean water temperature in the solar tank is, consequently, the operation temperature in the collector field is higher, and finally, the collector field operates with lower efficiency and the SDHW efficiency is lower. Moreover, the high value of solar collector field area may cause frequent stagnation in summer period and, as a result, unused solar gains during the summer. This leads to decrease in the annual energy yield of the solar system, and, as a result, to lower efficiency of whole SDHW system.

4.2 Year-on-year weather fluctuations

To demonstrate the influence of year-to-year fluctuations of climatic conditions on the efficiency of SDHW system, the simulation analysis was provided for Prague climate conditions, for solar collector field of 1 m^2/per and for solar collector variant 3. The hourly climatic data from 2007 to 2016 used in the analysis were taken from PVGIS weather database and compared with reference climatic year for Prague (RCY, Czech Hydrometeorological Institute) and typical meteorological year (TMY, Meteonorm). The results of the simulation are shown in Table 5 and in Figure 5.

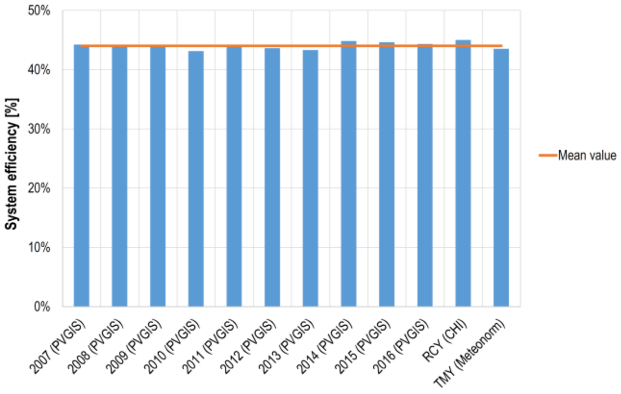

Fig. 5. The influence of year-to-year climate fluctuations on the efficiency of SDHW system.

Using the data gathered, one may support that the efficiency of the considered solar system is not strongly dependent on the year-to-year fluctuations of climatic

Table 5. The simulation results of the annual efficiency of SDHW system for individual years.

Climate data	$T_{a,av}$ [°C]	H_T [kWh/m^{2}a]	$q_{ss,u}$ [kWh/m^{2}a]	η_{ss} [%]
2007 (PVGIS)	10.4	1229	543	44.2
2008 (PVGIS)	10.1	1199	529	44.1
2009 (PVGIS)	9.8	1194	524	43.9
2010 (PVGIS)	8.5	1200	517	43.1
2011 (PVGIS)	10.0	1339	587	43.8
2012 (PVGIS)	9.7	1321	576	43.6
2013 (PVGIS)	9.4	1166	505	43.3
2014 (PVGIS)	10.8	1219	547	44.8
2015 (PVGIS)	10.9	1297	578	44.6
2016 (PVGIS)	10.1	1233	546	44.3
RCY (CHI)	10.4	1215	546	45.0
TMY (Meteonorm)	7.9	1114	485	43.5

conditions. According to the simulation results, the mean SDHW efficiency value is 44 %. The highest efficiency value of 45 % demonstrated SDHW system simulated using the reference climatic year (RCY, Czech Hydrometeorological Institute), which had been calculated according to measured data from the last decade. On the other hand, the lowest efficiency of 43.5 showed SDHW system simulated using the typical meteorological year (TMY, Meteonorm). Moreover, it is also important to note that the TMY, which is commonly used in simulation software, also demonstrated the lowest annual ambient temperature $T_{\mathrm{a,av}}$, the lowest total solar energy yield on the collector surface H_{T}, and consequently the lowest annual specific solar energy yield $q_{\mathrm{ss,u}}$.

5 Conclusion

Detailed simulation analysis of the influence of climatic conditions on the efficiency of SDHW system has been provided. To demonstrate the influence of climatic conditions, four different locations across Europe, six different collectors and six different areas of solar collector field have been investigated. Based on the simulation results, the following can be concluded:

- The efficiency of solar system is dependent on the climatic conditions. The main parameter which affects the efficiency of the solar system is an ambient air temperature,
- The efficiency of the solar system is strongly dependent on the ratio between area of solar collector field and heat demand. The higher ratio is, the lower is annual efficiency of the SDHW system. The efficiency values for the different design conditions, different collector alternatives, and different climate conditions vary in the range between 37 % and 59 %,
- The year-to-year fluctuations of climatic conditions at given location do not strongly affect the efficiency of SDHW system. According the simulation results, the mean SDHW efficiency value for Prague climate is 44 % with a variation of maximum 1 % due to climatic fluctuations. The design conditions have much stronger impact than climatic conditions fluctuation.

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References

1. W. Weiss, M. Spörk-Dür, *Solar heat worldwide* (IEA Solar Heating & Cooling Programme, 2019)
2. S. Nikoofard, V. I. Ugursal, I. Beausoleil-Morrison, Sol. Energy **101**, 308 (2014)
3. H. F. Naspolini, R. Rüther, Renew. Energy **48**, 92 (2012)
4. J. K. Kaldellis, K. El-Samani, P. Koronakis, Renew. Energy **30**, 659 (2005)
5. T. T. Chow, K. F. Fong, A. L. S. Chan, Z. Lin, Appl. Energy **83**, 42 (2006)
6. A. Allouhi, A. Jamil, T. Kousksou, T. El Rhafiki, Y. Mourad, Y. Zeraouli, Energy Convers. Manag. **92**, 105 (2015)
7. R. Kemna, M van Elburg, W. Li, R. van Holsteijn, *Eco-design of Boilers, Task 1, Final* (VHK for European Comission, 2007)
8. EN 12831-3:2017, *Energy performance of buildings—Method for calculation of the design heat load—Part 3: Domestic hot water systems heat load and characterisation of needs,* (2017)