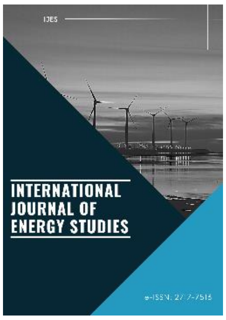
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article
Int J Energy Studies 2023; 8(3): 349-369
DOI: 10.58559/ijes.1306783

Received : 30 May 2023
Revised : 20 June 2023
Accepted : 21 June 2023

Investigation of the thermal performance and environmental impact of a forced circulation solar water heating system during the heating season

Gökhan Arslan[a]*, Seda Yüksel[b]

[a]Mersin University, Mechanical Engineering Department, garslan@mersin.edu.tr , Mersin, Turkiye. Orcid: 0000-0002-2611-1740
[b]Mersin University, Mechanical Engineering Department, sedayuksel0@gmail.com , Mersin, Turkiye. Orcid: 0000-0003-1327-6439
*(*Corresponding Author:garslan@mersin.edu.tr)*

Highlights

- 33 % reduction in greenhouse gas (GHG) emissions is achieved with this solar water heating system.
- 55% of the hot water requirement on the design day without requiring any auxiliary heater was met.
- the collector with black chrome absorber coating has the highest thermal efficiency

You can cite this article as: Arslan G, Yüksel S. Investigation of the thermal performance and environmental ımpact of a forced circulation solar water heating system during the heating season. Int J Energy Studies 2023; 8(3): 349-369.

ABSTRACT

A thermal analysis of a forced circulation solar water heating system (SWHS) was carried out. Three different models were analyzed: SWHS without an auxiliary heater, SWHS with an auxiliary heater, and electric heater only. The study was carried out for the province of Mersin-Turkiye. Flat plate collectors with different structural properties were used in simulations, the best results were obtained with the collector with black chrome absorber coating. This system met 55% of the hot water requirement on the design day without requiring any auxiliary heater. During the season, 18.7% of hot water needs were met in January, 20.42% in February, 37.6% in March, 31.2% in November, and 20.5% in December. SWHS with an auxiliary heater, consumed 1130.3 kWh of electrical energy during the heating season, resulting in 540.3 kg of CO_2 emissions. 33 % reduction in greenhouse gas (GHG) emissions is achieved with this system compared to a base system powered by electricity only. The hot water use profile is an essential factor in the design of the SWHS. Since the systems using fossil fuels can meet the needs of the users, energy storage techniques must be adapted to the SWHS to be an alternative.

Keywords: CO_2 emission, Flat plate collectors, Solar water heating, Solar fraction

1. INTRODUCTION

Energy is one of the basic needs of human beings. The rising population and developing technology lead to a significant increase in energy consumption. In the energy supply and consumption processes, negative influence occurs from the point of climate, ecosystem, and human health. In particular, the emphasis on fossil fuel consumption leads to climate change, one of the biggest ecological crises [1]. Turkiye has primary energy consumption in 2020 was approximately 1750 TWh. Of this energy need, 81.9% was obtained from fossil fuels, of which 29% was oil, 26.4% was coal, and 26.6% was natural gas [2]. A similar trend is observed in the sources used in electricity generation. Turkiye electricity generation in 2020 was approximately 300 TWh, and 59% was obtained from fossil fuels [3]. Energy consumption based on fossil fuels constitutes 80% of the annual greenhouse gas emissions. According to International Energy Agency statistics, Turkiye's CO_2 intensity has declined slightly in recent years as given in Figure 1 [4]. Compared to many other IEA countries, the growth in fossil fuel power generation leads to Turkiye's relatively high carbon intensity.

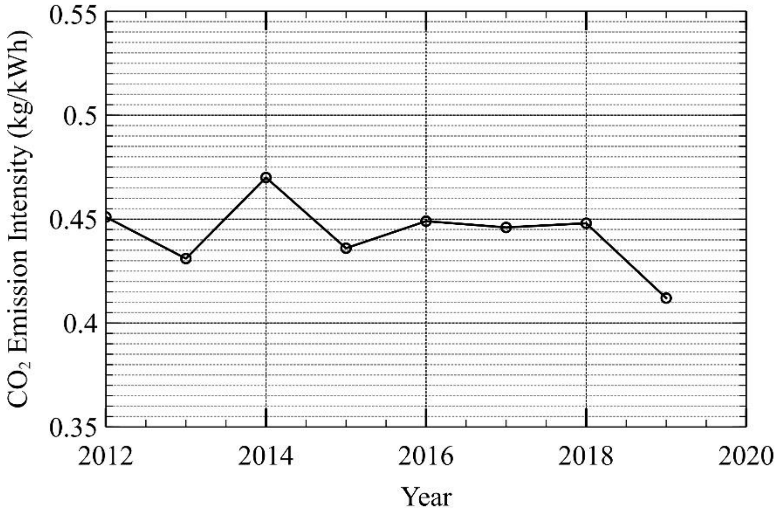


Figure 1. CO_2 intensity per unit of heat and power generation of Turkiye

Dividing each greenhouse gas emission by the amount of annual electricity energy production, the electricity emission factor of Turkiye is obtained. The emission factors parallel with IEA statistics are 0.498, 6.59E-06, 5.29E-06, and 0.001083 kg/kWh for CO_2, CH_4, N_2O, and NO_x, respectively [5]. Similiarly, emission factors based on electricity consumption of Erzincan Binali Yıldırım university was calculated according to IPCC Tier-1 method. Equivalent CO_2 emmision factor was determined 0.478 kg/kWh [6]. In another similar study, equivalent CO_2 emmision factor was determined 0.48 kg/kWh within the borders of the Electricity Generation Corporation (EÜAŞ) Main Campus [7]. In October 2021, Turkey ratified the Paris Agreement on climate change. To achieve the long-term targets of that agreement, clean energy additions and the use of low-carbon energy systems such as solar water heating systems (SWHS) are becoming more important. Turkiye had 18.9 GWth of solar thermal capacity and that is 4% of the overall capacity in the world in 2021. The payback periods are relatively short due to high irradiation. In the Mediterranean region, where sunshine duration is long, demand has increased significantly [8]. According to the Eurostat data, total solar collector area and household solar thermal final energy consumption have increased by 11 % and 9.6 %, respectively between 2012 and 2020. Figure 2 shows the change in these values over the years [9, 10].

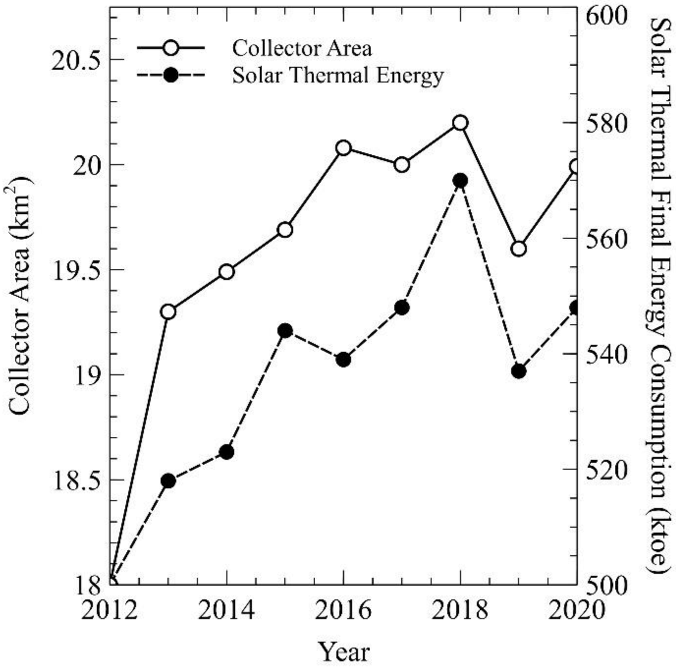


Figure 2. Solar collector area and the household solar thermal final energy consumption of Turkiye

61 % of households use solid fuel stoves for heating. Total household energy consumption and greenhouse emission could be reduced by around 13% and 8% when an SWHS is present [11]. Turkey meets most of its primary energy demand from fossil fuel energy sources. Replacing this energy source with solar energy will reduce greenhouse gas emissions.

Recently, many researchers are working on improving the performance of these systems to reduce fossil fuel consumption. A simple framework to determine the CO_2 emissions mitigation potential of SWHS technology was developed. An SWHS of 100 L tank volume emission was approximately 1237 kg of CO_2 per year [12]. The environmental effects of natural gas and SWHS in a textile factory located in the northeastern region of Brazil were investigated. While the total greenhouse gas emission caused by the systems during the construction and operation period is 33098.42 kg CO_2-eq / year for the natural gas system, this value has been determined as 642.87 kg CO_2-eq / year for the SWHS [13]. The energy used for obtaining hot water in South Africa constitutes 40% of the domestic energy consumption. It has been determined that the use of SWHS throughout the country will reduce 23.5 tons of $kgCO_2$ emissions annually [14].

Some research in this area has focused on simulation programs. In some cases, it is not possible to set test environments in laboratory conditions. Simulation tools are therefore an alternative to performance analysis of SWHS. [15]. A flat-plate collector SWHS in Montreal, Canada was modeled using TRNSYS. The designed system with a 6 m^2 collector surface area and 300 L storage tank volume could provide 30–62% of the demand in the heating period [16]. In a similar study, the Transol program was used to simulate the thermal performance of an SWHS with a flat plate under Moroccan conditions. According to the energy analysis results, the solar fraction ranged from 40% to 65% in the case of flat plate solar collector installation in the months: of December, January, February, and March for the most favorable region for solar water application [17]. An SWHS consisting of flat plate collectors was modeled by using TRNSYS and conducted experiments to validate the model for Nicosia, Cyprus. The temperature rise in the storage tank is used to test the accuracy of the model. The mean percentage difference between the model and experimental results was within 4.68% and the annual solar fraction was 79%. The auxiliary energy need of the system was calculated as 265 kWh in the months: December, January, February, and March [18]. Similarly, experimental results of the thermal performance of flat plate collectors were validated by using the TRNSYS model. Model results of the collector outlet temperature, heat gained by the collectors, and heat delivered to the load deviate from measured data by 16.9%, 14.1%, and 6.9%, respectively. It is stated that the TRNSYS model could be used to predict the long-term performance of the SWHS in different locations and system performances could be simulated [19]. A dynamic model for the collector of a thermosyphon SWHS was simulated by using the MATLAB Simulink program. Experiments were conducted in the northern region of

Iran. The thermal efficiency was determined as 68%. The obtained simulation results in clear sky conditions agreed well with the experiment results [20].

In some studies, the effect of surface coating techniques on collector performance has been investigated. 6%, 7%, and 21% increases in the auxiliary energy demand were reported for black chrome, thermochromic, and solar paint coatings, respectively when compared with the sputtered coating [21]. SWHS with black chrome coating was defined as high reliability due to its manufacturing quality that assures a well-sealed system. Experimental results of the flat plate solar collectors showed that the highest instantaneous and average thermal efficiencies were obtained with black coating collectors [22].

Recent innovations in flat plate solar collectors to improve thermal performance by using reflectors in SWHS showed that using basic geometry techniques like reflectors may be used to improve the performance of flat plate solar collectors rather than complex geometry techniques [23]. Investigation on the thermal performance improvement of flat plate SWHS by inserting different tube configurations inside the riser pipes showed that the best thermal performance was obtained with the model consisting of a straight tube inside the riser pipe rather than wavy and helical tubes. The straight model thermal performance was 12.3% higher than the conventional model [24]. Another investigation is about the use of fixed-volume tanks in SWHS that causes insufficient flexibility and incompatibility problem between solar energy supply and the required thermal load demand. With the two-stage variable volume tank model, it was calculated that the heat losses of the system decreased by 17.2% during the heating season in Beijing. During the year, auxiliary heater energy consumption decreased by 6.6% [25].

Combining bibliometric techniques and a systematic literature review, it can be stated that interest in SWHS remains high and current in the period from 1993 to 2020 [26]. SWHS is widely used in Mersin province and thermal performance of the SWHS was discussed in the literature. However, enviromental impact of this system is not discussed in detail. In practical application, electricity and natural gas is prefered for water heating in heating season in recent years. This study aims to examine the parameters that directly affect the thermal performance of the SWHS, taking into account the environmental effects. The ability of the system to meet the hot water demand will also be questioned. This is important in terms of demonstrating the preferability of the system over alternative systems that consume fossil fuels.

2. METHODS AND METHODOLOGY

The thermal analysis of the forced circulation SWHS was made by designing a system without the auxiliary heater using the EnergyPlus program. Simulations were carried out for the heating season of the region and the design day, separately. The heating season was determined according to the heating degree day (HDD) of the region. In addition, the coldest day with a clear sky of this season is determined as the design day. The daily hot water requirement of a typical family was taken according to the ASHRAE standard. With the hourly thermal analysis, it was determined at what time of the day the hot water need is met without using an auxiliary heater, both for the design day and for the heating season. In the next stage, an electric heater was added to the system as an auxiliary heater to demonstrate the environmental impacts. Finally, the environmental impacts of heating with only electrical energy without using solar energy in the water heating system are analyzed. Environmental impacts are compared in terms of GHG emissions for each system configuration.

The SWHS is modeled using a solar collector, water tank, heat exchangers, and pump. The inlet and outlet tubes of the solar collector are connected to a heat exchanger. In the SWHS, the hot water supply and the water circulation in the collector line are provided by pumps. The system is for domestic water heating purposes only. The system diagram is shown in Figure 3.

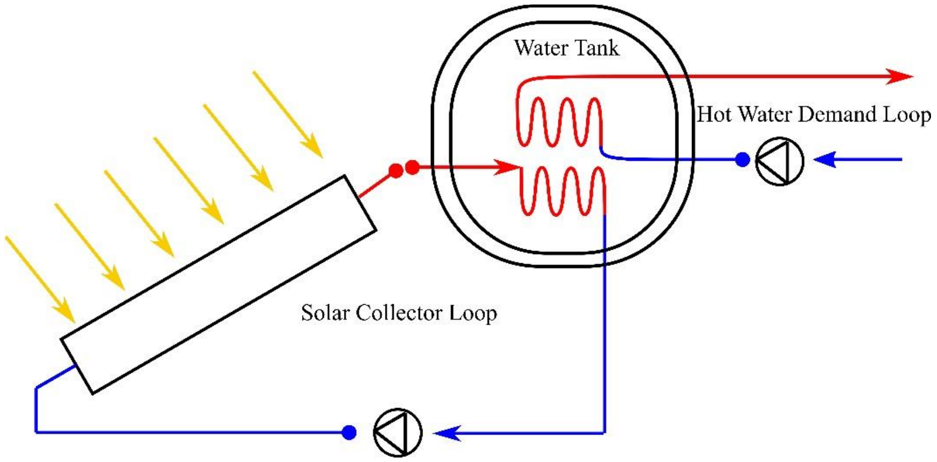


Figure 3. Diagram of the SWHS

The thermal model [27] of the flat-plate collector is developed according to the ASHRAE standards. The thermal efficiency of a collector is obtained by dividing the useful heat gain of the collector fluid by the total incident solar radiation on the surface area of the collector.

$$\eta = \frac{\dot{Q}_{useful}/A_{gross}}{I_{solar}} \tag{1}$$

A quadratic correlation which is given in Eq. (2) can be constructed for the efficiency given in eq. 1 by using test data from The Solar Rating & Certification Corporation (ICC-SRCC) [28]. Coeffients η_o, a_1, and a_2 of solar collectors used in the model are given in Table 1.

$$\eta = \eta_o + a_1 \frac{(T_{in} - T_{air})}{I_{solar}} + a_2 \frac{(T_{in} - T_{air})^2}{I_{solar}} \tag{2}$$

$$T_{out} = T_{in} + \frac{\dot{Q}_{useful}}{\dot{m} c_p} \tag{3}$$

$$\dot{Q}_{useful} = \dot{m} c_p (T_{out} - T_{in}) \tag{4}$$

The thermal stratified model based on the multi-node approach is applied inside the water tank. In this model, the energy balance on n number of nodes that has equal volume must be solved simultaneously. Node 1 is at the top and node n is at the bottom of the water tank. Calculations were made according to 12 layers. Complete mixing of the demand and collector-side fluid streams with the tank water is assumed. The system time step is divided into one-second substeps [29].

For the system with an auxiliary heater, the solar fraction is an important parameter and represents the percentage of energy required to drive a heating system fulfilled by solar energy.

$$SF = \frac{\dot{Q}_{useful}}{\dot{Q}_{useful} + \dot{Q}_{aux}} \tag{5}$$

In the system, the thermal performance of three different flat plate collectors with different surface coating properties was examined separately. Collectors certified by ICC-SRCC were used. The collectors were tested according to the ASHRAE 93-1986 “Methods of Testing to Determine the Thermal Performance of Solar Collectors” standard. Efficiency equation coefficients in these certificates were used in the thermal analysis [30]. Information about the collectors is given in Table 1.

In the designed system, a 250 L water tank was used in a horizontal position. The overall heat transfer coefficient of the tank used to calculate the heat loss to the external environment was taken as 0.846 W/m^2K. A pump with variable speed and 87% efficiency was used.

Table 1. Collectors technical data

	Model 1	Model 2	Model 3
Net Aperture Area (m^2)		1.765	
Collector Slope Angle (°)		45	
Outer Cover		Low Iron Tempered Glass	
Absorber Material		Tube – Cu / Plate - Cu	
Absorber Coating	Sputtered Al. Nitride	Selective Black Paint	Black Chrome
ηo: Intercept Max. Efficiency (Eq. 2)	0.633	0.638	0.702
a1: 1st order loss coefficient (W/m^2K) (Eq. 2)	-3.2437	-4.2645	-3.2828
a2: 2nd order loss coefficient (W/m^2K^2) (Eq. 2)	-0.0153	-0.0297	-0.0099
Maximum Flowrate (L/s)	0.0327	0.0385	0.0317

According to ASHRAE standards, the hourly average hot water usage profile of a typical family is introduced to the designed system. It needs a total of 237.5 liters of hot water per day. Currently, water heating system manufacturers recommend that the initial set point be approximately 50°C to minimize the potential for scalding. Decreased set points generally reduce standby losses and increase the efficiency and recovery capacity of the water heater, but can also reduce the amount of hot water available. The average bath temperature for an adult is 40°C to 45°C [30]. In this study, the required hot water temperature was taken as 40ºC. System analysis was done without an auxiliary heater. During the simulation period, when the temperature of the tank water is 40ºC and above, how much hot water is needed is calculated and it is determined that the system meets the need at that moment, otherwise, the system is insufficient. Accordingly, how much of the daily hot water need is met was determined by defining the coverage ratio.

The heating season for Mersin province is between 1 January – 30 March and 1 November – 31 December according to the HDD values and the thermal analysis of the system was made between these dates. The monthly average values of the meteorological data, including the HDD, which is important in the system design, are presented in Table 2. Long term average temperatures (1991-2019), solar radiation (1983-1992), sunshine duration, HDD and CDD values (2020) are obtained from Turkish State Meteorological service.

Table 2. Monthly meteorological data of Mersin province

	T_{avg} (°C)	$T_{max\ avg}$ (°C)	$T_{min\ avg}$ (°C)	$T_{mains\ water}$ (°C)	$t_{sunshine\ duration}$ (hour)	G_{total} (kWh/m^2)	HDD (T<15°C)	CDD (T>22°C)
Jan.	10.1	14.5	6.2	14.8	4.7	75	218	0
Feb.	11	15.4	6.8	13.8	5.6	91	177	0
March	13.7	18.1	9.1	15.4	6.7	141	50	0
April	17.4	21.6	12.8	17.7	7.6	171	0	0
May	21.2	24.9	16.8	20.9	8.4	213	0	59
June	25	28.1	20.8	24.6	9.8	235	0	95
July	27.7	30.7	23.9	27.5	9.9	230	0	237
August	28.3	31.5	24.2	29.3	9.8	208	0	252
Sept.	25.7	30	20.8	28.9	9.1	170	0	228
Oct.	21.4	26.6	16.2	26.2	7.5	121	0	121
Nov.	16.1	21.5	11.5	21.5	5.7	81	7	1
Dec.	11.8	16.4	7.8	17.7	4.7	68	71	0
Annual						1804	523	993

In practical applications, the optimum value of the collector inclination angle for all year conditions is the same as the latitude of the region. However, since the heating season is prioritized in the design, the angle of inclination of the collector is taken as 45°. In the heating season, the average daily total radiation per unit surface with an angle of inclination of 45° was determined as 4.04 kWh/m^{2}day. The daily average temperature was determined as 13°C. In Figure 4, the variation of daily average temperature values and daily total radiation values during the heating season is given.

January 15, the coldest day of the heating season with clear sky conditions, was chosen as the design day, and the thermal performance of the system was carried out for that day. On that day, the total daily radiation falling on the collector unit surface is 6.1 kWh / m^{2}day, and the daily average temperature is 4.9 °C.

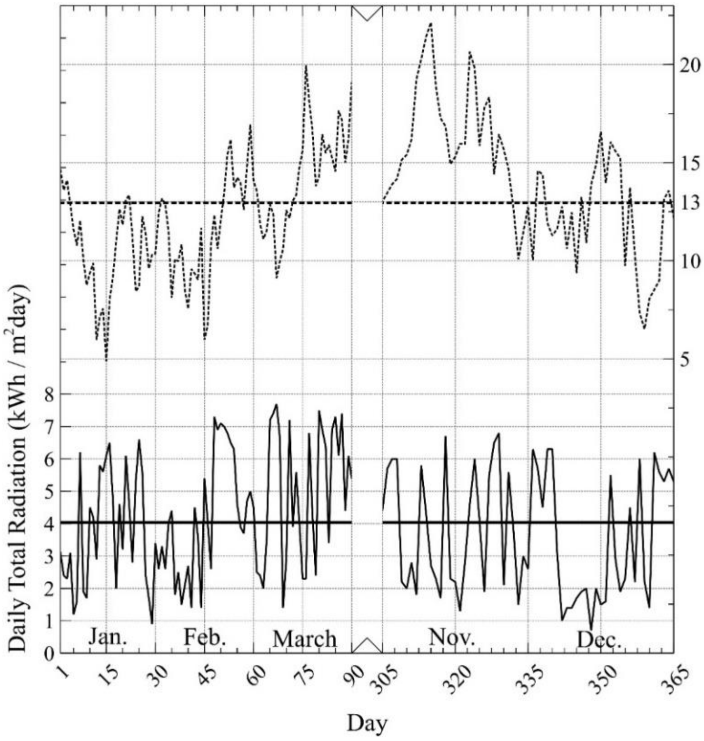


Figure 4. Variation of daily average temperature and total radiation values during the heating season

3. RESULTS

The data obtained as a result of the thermal analysis of the heating season and the design day are presented in this section. First of all, hourly data obtained on the design day were evaluated. These data include the 24-hour tank water and domestic water temperatures, the temperature distribution of the 12 layers in the tank, and the collector efficiency. In addition, since the set temperature of the domestic water is 40°C, the amount of mains water to be added to cool the domestic water in case the tank water temperature rises above this temperature has also been examined. In the designed system, the thermal performance of 3 different flat plate collectors was analyzed. These collectors have been selected with different absorber surface coatings. The surfaces of the collectors used in model 1, model 2, and model 3 are coated with sputtered Aluminum Nitride, partially selective black paint, and black chrome respectively. In Figure 5, the variation of the thermal efficiencies of the collectors during the design day is given. Accordingly, the highest thermal efficiency was obtained from model 3 and it varies in the range of about 45%-60%. The highest efficiency was obtained in the middle of the day.

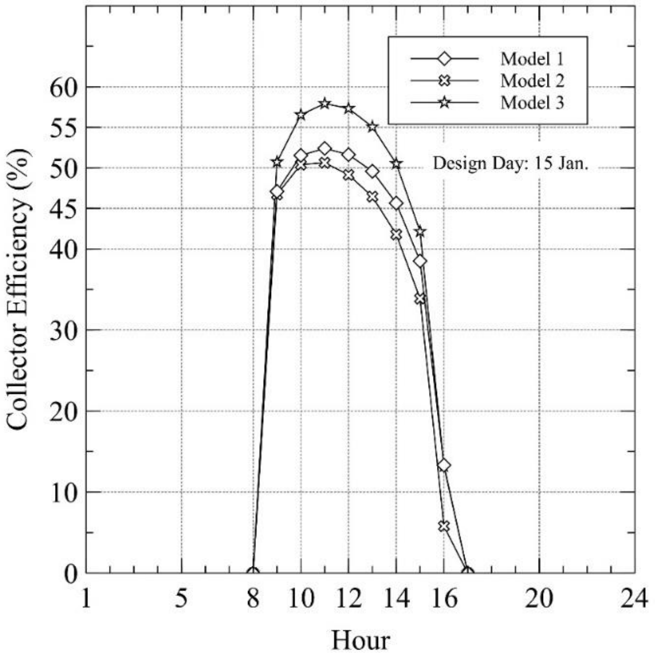


Figure 5. Variation of the thermal efficiencies of the collectors during the design day

The detailed thermal analysis of the designed system was made with model 3, in which the most efficient collector coated with black chrome was used. In Figures 6-7-8, hourly thermal analysis results of the design day are given. Figure 6 shows the tank water and domestic water temperatures. Likewise, data showing how much hot water is needed at which time of the day are shared. For example, approximately 7 L of hot water is needed at 01:00 on the design day. The tank temperature (average value of the layers) is about 27°C. At this hour, the domestic water temperature is approximately 34°C and cannot meet the need. The reason for the difference in the temperature of the tank water and the domestic water is due to the thermal stratification in the tank. While the hot water requirement is met from the upper layers of the tank, there are lower-temperature water layers at the bottom of the tank. During the night, the tank water temperature decreased due to heat losses to the environment. After 08:00 in the morning, the tank temperature increased with the effect of solar radiation. Between 11:00 and 12:00, the tank water temperature has risen above 40°C. Until this hour, the system could not provide the required amount of hot water. Until 22:00, the system met the need.

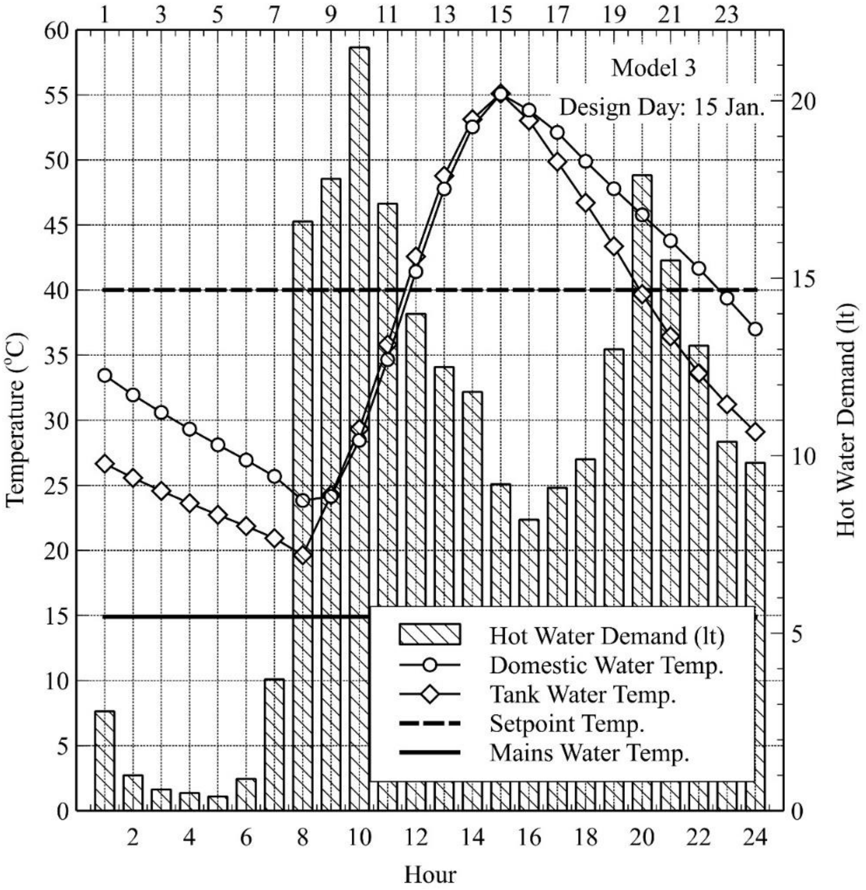


Figure 6. Tank water and domestic water temperature profiles with hot water demand

Figure 7 shows the hourly variation of the total mass flow rate and tank water mass flow rate. Mains water is mixed with in the flow of hot water drawn from the tank during the intervals when the tank water temperature is above 40°C. In cases where the tank water temperature is high, 40°C domestic water is obtained by mixing the mains water into the total water flow. In the other case, since no auxiliary heater was used, the tank water was transferred as total demand water.

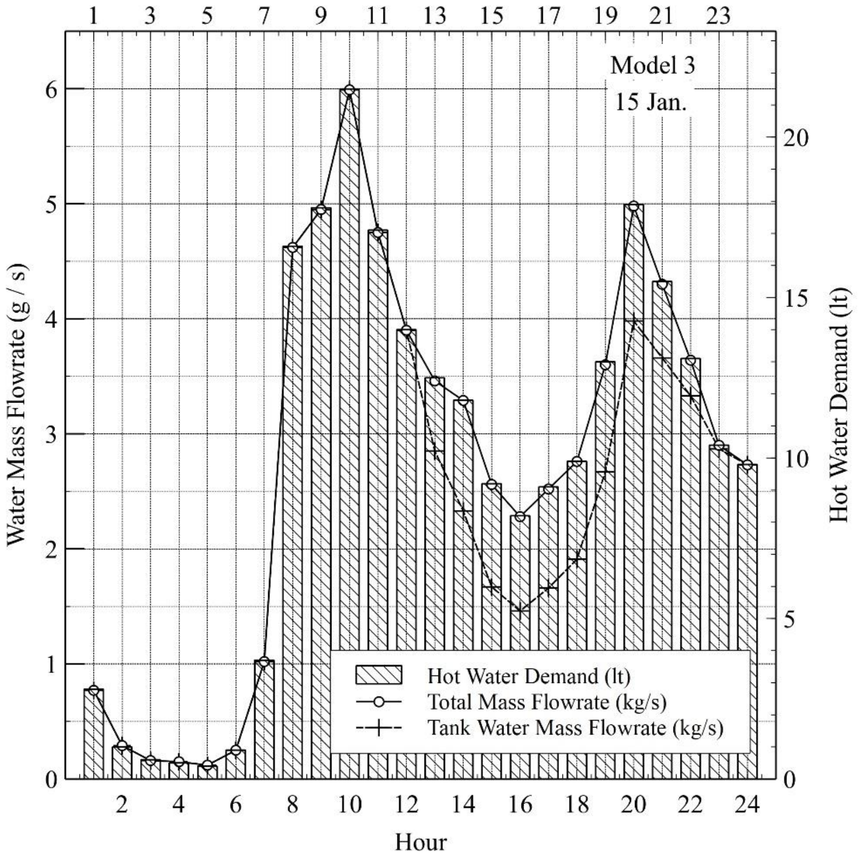


Figure 7. Variation of the total mass flow rate and tank water mass flow rate

In Figure 8, the temperature changes of the layers due to thermal stratification in the tank are given. Layer 1 shows the top point of the tank, and the temperature values coincide with the domestic water temperature. Temperature values decrease in the lower layers of the tank. It was observed that the temperature difference between the layers decreased as a result of the warming of the tank water due to the radiation coming to the collectors during the day. The lowest temperature difference between the layers was approximately 2°C at noon when the collector efficiency has the highest value. The highest temperature difference is about 23°C at night.

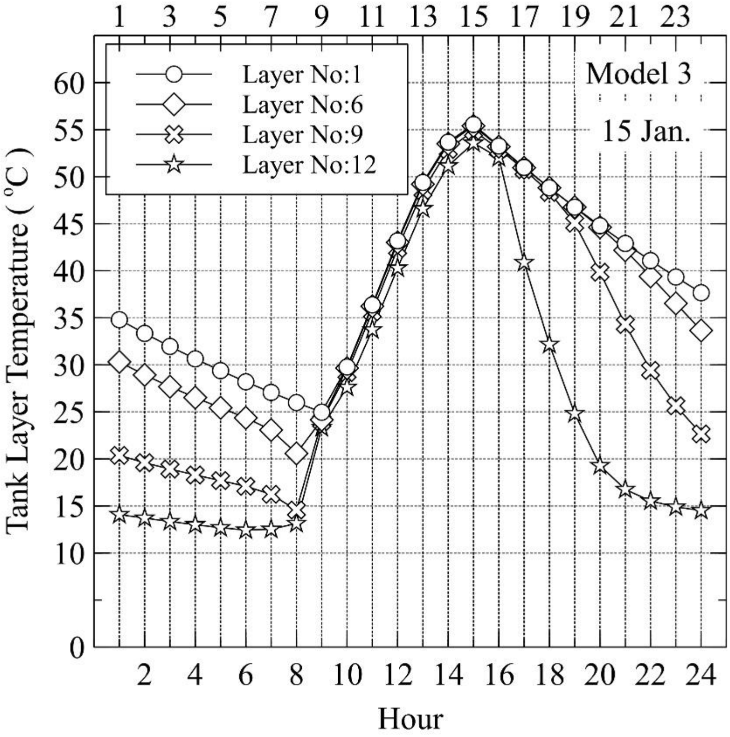


Figure 8. Temperature changes of the layers

If the temperature of the water drawn from the tank is above the set point value, the tank water is mixed with the mains water. As the tank water temperature rises, the amount of mains water used increases. Accordingly, the solar water heating system could meet the desired hot water without needing any auxiliary heater during the hours when the main water was mixed with the water coming from the tank. Since the temperature of the water drawn from the tank between 12:00 and 22:00 was above 40°C, this system met the need in this period without any auxiliary heater. 130.7 L of hot water is needed in this period. This constitutes 55% of the daily hot water need and this is defined as the coverage ratio. For this system to be an alternative to fossil fuel-consuming systems, the coverage ratio must be higher. However, in the absence of solar radiation, the low ambient temperature reduces the temperature of the water in the tank. The application of energy storage techniques in a well-insulated tank may be a solution to increase the coverage ratio.

The daily total values (pump power consumption, useful energy obtained from the collector, heat lost from the tank to the environment, the total amount of water requirement, the amount of water drawn from the tank and the water network, the amount of hot water supplied without auxiliary heater, the coverage ratio) obtained from the analysis for the design day are given in Table 3.

Table 3. The daily total values obtained from the thermal analysis

Pump Power Consumption (kWh/day)	0.336
Useful energy obtained from the collector (kWh/day)	16.07
Heat lost from the tank to the environment (kWh/day)	9.81
The total amount of water requirement (L)	237.6
Amount of water drawn from the tank (L)	209.1
Amount of water drawn from the water network (L)	28.5
Amount of hot water supplied without an auxiliary heater (L)	130.7
Coverage ratio (%)	55

Figure 9 shows the variation in daily coverage ratios during the heating season. The water temperature in the system was always below 40°C for 12 days in November, 18 days in December, 17 days in January, 17 days in February, and 9 days in March. Monthly average coverage ratio values are obtained as 18.7%, 20.4%, 37.6%, 31.2%, and 20.5% for January, February, March, November, and December, respectively. During the entire heating season, only 26% of the hot water need is met.

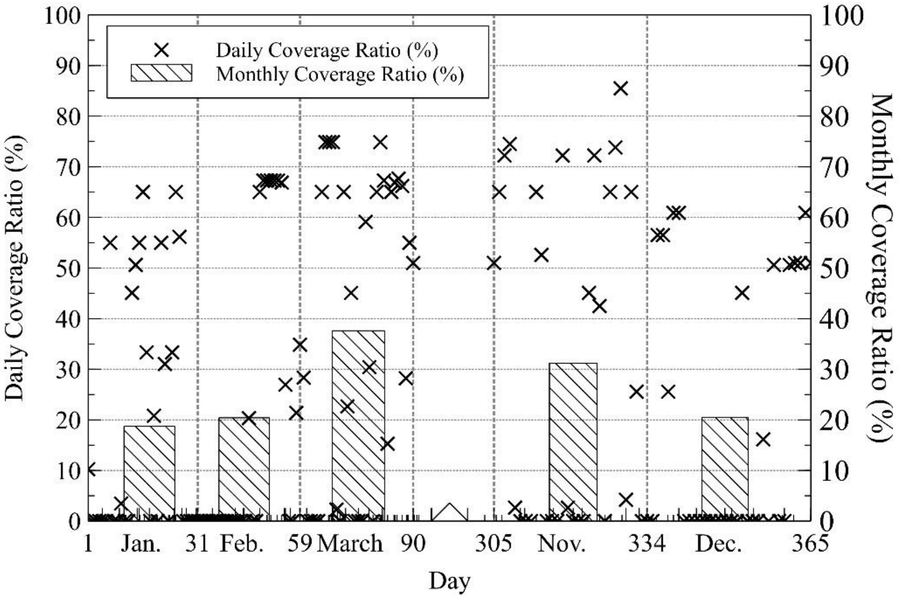


Figure 9. Variation of daily coverage ratio during the heating season

Researchers compare the environmental impact of the designed systems with alternatives not only in terms of their energy performance but also in terms of their environmental performance. Accordingly, more sustainable designs can be achieved. Within the scope of this study, the environmental effects of the solar water heating system were examined lastly. For this purpose, an electric heater has been placed in the system as an auxiliary heater and has been adjusted to provide the required hot water demand at all times. Thermal analyzes were repeated. The SWHS, in which electrical energy is used as the auxiliary heater, consumed a total of 1130.3 kWh of electrical energy during the heating season, resulting in 540.3 kg of CO_2 emissions.

Compared to the other regions of Turkiye, the solar radiation values are high in the Mersin province where the study was conducted. One of the most important parameters defined for the SWHS with an auxiliary heater is the solar fraction which is defined in eq. 5. The monthly average solar fraction of the system varies between 46% and 65% and is given in Figure 10. In the designed system, high solar fraction values were obtained due to the use of efficient flat plate solar collectors and adequate insulation. Despite this, the reason for the low coverage ratio values in the heating season is related to the hot water use profile.

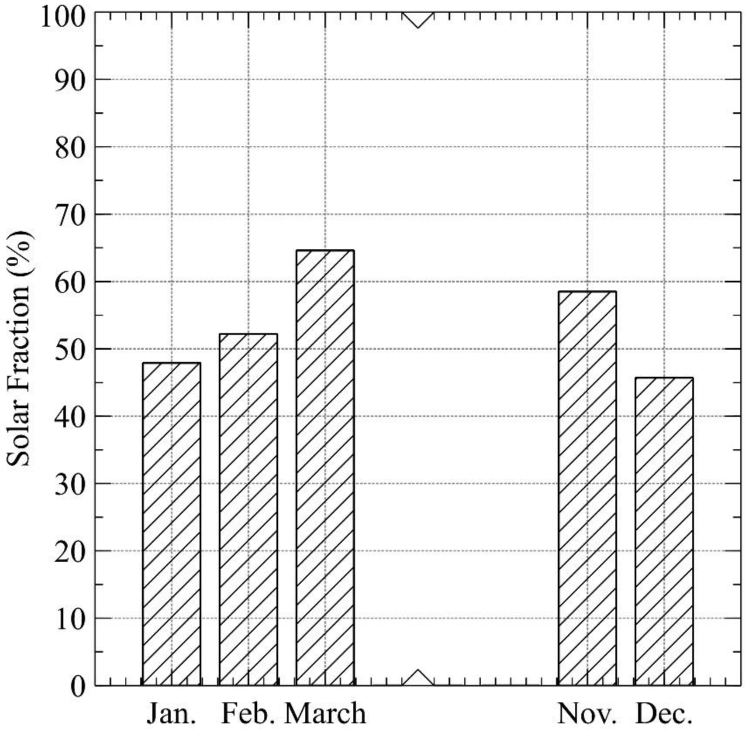


Figure 10. Monthly solar fraction values of SWHS with auxiliary heater

Although the SWHS with the auxiliary heater has high solar fraction values, the low coverage ratio leads many users to systems that only use fossil fuels in the heating season. In this case, to determine how much energy is needed and to compare its environmental effects, the electric water heating system with the same tank dimensions is modeled. When the electric water heating system is used instead of the SWHS, a total of 1681.9 kWh of electrical energy was consumed during the season, while 804 kg of CO_2 was emitted. As a result, the use of SWHS with an auxiliary heater saves 33% in electrical energy and 263.7 kg less CO_2 has been emitted. Detailed data are presented in Table 4.

Table 4. Electrical energy consumption, CO_2 emission values for the heating season

	Electrical Energy Consumption (kWh)		CO_2 Emission (kg)	
	SWHS + Aux. Heater	Electric Heater	SWHS + Aux. Heater	Electric Heater
Jan.	269.1	370.4	128.6	177.1
Feb.	229.1	336.2	109.5	160.7
March	188.8	349.9	90.2	167.3
Nov.	179	291.7	85.6	139.4
Dec.	264.3	333.7	126.3	159.5
Total	**1130.3**	**1681.9**	**540.3**	**803.9**

3. CONCLUSION

The thermal performance of a solar water heating system with a total collector surface area of 5.34 m^2, with a 250 L water tank and without instantaneous heaters, during the heating season, was examined in detail.

During the design day, 55% of the hot water needs were met. The rate of meeting the hot water need during the heating season was calculated as 26%. The monthly average solar fraction of the system varies between 46% and 65%. This is due to the high thermal efficiency of the system and the high solar radiation values of the region. However, the hot water usage profile indicates that there is a need for hot water, especially in the early hours of the day. The low outdoor and mains water temperatures cause the water that is heated in the tank during the day to cool down at night. This reduces the coverage ratio. The most important result obtained in the study is that thermal storage is mandatory in that type of system.

To reveal the environmental effects of the designed system, an electric water heater was integrated into the system as an auxiliary heater. When compared with the system powered by electricity, a 33 % reduction in greenhouse gas (GHG) emissions is achieved by using SWHS without an auxilary heater.

It can be concluded that the hot water use profile is an important factor in the design of the SWHS. Systems operated with fossil fuels could meet the needs of the users at all times. Considering that the hot water use profile has not changed, energy storage techniques must be adapted to the system for SWHS to be an alternative.

NOMENCLATURE

η: Thermal Efficiency

A_{gross}: Gross Area Of The Collector (m^2)

CDD: Cooling Degree Day

c_p: Specific Heat of the Collector Fluid (J/kg°C)

G_{total}: Monthly Total Solar Radiation (kWh/m^2)

HDD: Heating Degree Day

I_{solar}: Total Incident Solar Radiation (W/m^2)

$\dot{m}$: Fluid Mass Flow Rate (kg/s)

$\dot{Q}_{aux}$: Energy Delivered by the Auxiliary Heater (W)

$\dot{Q}_{useful}$: Useful Heat Gain of Collector Fluid (W)

SF: Solar Fraction (%)

T_{air}: Ambient Temperature (°C)

T_{avg}: Monthly Average Outdoor Temperature (°C)

T_{in}: Fluid Inlet Temperature (°C)

$T_{mains\ water}$: Monthly Average Mains Water Temperature (°C)

$T_{max\ avg}$: Maximum Monthly Average Outdoor Temperature (°C)

$T_{min\ avg}$: Minimum Monthly Average Outdoor Temperature (°C)

$t_{sunshine\ duration}$: Monthly Average Sunshine Duration (h)

T_{out}: Fluid Outlet Temperature (°C)

ACKNOWLEDGMENT

No financial support was received for this article from any institution, organization or company.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Gökhan Arslan: The author was the thesis supervisor of the second author and wrote the manuscript. Main simulation scheme was designed and required data was obtained by the author.
Seda Yüksel: The author performed the analyses and evaluated the result section.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://doi.org/ 10.1017/9781009157940.

[2] Our World In Databased on BP Statistical Review of World Energy, 2023. [Online]. [Accessed 21.03.2023]. Available: https://ourworldindata.org/grapher/primary-sub-energy-source?country =~TUR

[3] Republic of Turkiye Energy Market Regulatory Authority, Activity Reports. [Online]. [Accessed 21.03.2023]. Available: https://www.epdk.gov.tr/Detay/Icerik/1-2335/emra-activity-reports

[4] IEA (2020), CO_2 Emissions from Fuel Combustion 2020, [Online]. [Accessed 21.03.2023]. Available: www.iea.org/statistics.

[5] Yatarkalkmaz MM, Ozdemir MB. The calculation of greenhouse gas emissions of a family and projections for emission reduction. Journal of Energy Systems 2019; 3(3): 96-110. https://doi.org/10.30521/jes.566516

[6] Seyhan AK, Çerçi M. IPCC Tier 1 ve DEFRA Metotları ile Karbon Ayak İzinin Belirlenmesi: Erzincan Binali Yıldırım Üniversitesi'nin Yakıt ve Elektrik Tüketimi Örneği . Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi 2022; 26(3): 386-397. DOI: 10.19113/sdufenbed.1061021

[7] Alagöz İ, Coşkun E, Babaoğlu S, Kaykaç R, Cidacı A. EÜAŞ Merkez Kampüs 2021 Yılı Karbon Ayak İzinin Hesaplanması . Çevre İklim ve Sürdürülebilirlik 2022; 23(2): 161-166.

[8] REN21 Renewables 2022 Global Status Report. ISBN 978-3-948393-04-5.

[9] Eurostat Statistics, Data Browser. [Online]. [Accessed 21.03.2023]. Available: https://ec.europa.eu/eurostat/databrowser/view/NRG_INF_STCS/default/table?lang=en&category=cli.cli_mit

[10] Eurostat Statistics, Data Browser. [Online]. [Accessed 21.03.2023]. Available: https://ec.europa.eu/eurostat/databrowser /view/ten00125/default/table?lang=en

[11] Aydin E, Eichholtz P, Yönder E. The economics of residential solar water heaters in emerging economies: The case of Turkey. Energy Economics 2018; 75: 285–299.

[12] Kumar A, Kandpal TC. CO_2 Emissions Mitigation Potential of Some Renewable Energy Technologies in India. Energy Sources, Part A 2007; 29 (13): 1203-1214. https://doi.org/10.1080/009083190965343.

[13] Barbosa RR, Schultz HS, Garcia LC, Martins DD, Carvalho M. Economic and greenhouse gas assessments for two hot water industrial systems: Solar vs. natural gas. Cleaner Engineering and Technology 2022; 6: 100365. https://doi.org/10.1016/j.clet.2021.100365

[14] Tang A, Alsultany FH, Borisov V, Mohebihafshejani A, Goli A, Mostafaeipour A, Riahi R. Technical, environmental and ranking analysis of using solar heating: A case study in South Africa. Sustainable Energy Technologies and Assessments 2022; 52: Part D, 102299. https://doi.org/10.1016/j.seta.2022.102299.

[15] Shrivastava RL, Kumar V, Untawale SP. Modeling and simulation of solar water heater: A TRNSYS perspective. Renewable and Sustainable Energy Reviews 2017; 67: 126–143.

[16] Hobbi A, Siddiqui K. Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS. Solar Energy 2009; 83: 700–714.

[17] Allouhi A, Jamil A, Kousksou T, El Rhafiki T, Mourad Y, Zeraouli Y. Solar domestic heating water systems in Morocco: An energy analysis. Energy Conversion and Management 2015; 92: 105–113.

[18] Kalogiroua SA, Papamarcou C. Modelling of a thermosyphon solar water heating system and simple model validation. Renewable Energy 2000; 21: 471–493.

[19] Ayompe LM, Duffy A, McCormack SJ, Conlon M. Validated TRNSYS model for forced circulation solar water heating systems with flat plate and heat pipe evacuated tube collectors. Applied Thermal Engineering 2011; 31: 1536-1542.

[20] Taherian H, Rezania A, Sadeghi S, Ganji DD. Experimental validation of dynamic simulation of the flat plate collector in a closed thermosyphon solar water heater. Energy Conversion and Management 2011; 52: 301–307.

[21] Müller S, Giovannetti F, Reineke-Kocha R, Kastner O, Hafner B. Simulation study on the efficiency of thermochromic absorber coatings for solar thermal flat-plate collectors. Solar Energy 2019; 188: 865–887. https://doi.org/10.1016/j.solener.2019.06.064

[22] Sakhrieh A, Al-Ghandoor A. Experimental investigation of the performance of five types of solar collectors. Energy Conversion and Management 2013; 65: 715–720.

[23] Kumar Y, Verma M, Ghritlahre HK, Verma P. Recent Developments in the Thermal Performance of Flat Plate Solar Water Heaters with Reflectors-A Review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 2022; 44(4): 9448-9475. https://doi.org/10.1080/15567036.2022.2131940

[24] Freegah B. Numerical and experimental analysis of the flat plate solar water heater systems' thermal performance. Heat Transfer 2022; 1-24. https://doi.org/10.1002/htj.22732

[25] Xiaoge L, Xin W, Pengfei S, Xiangyang R. Energy and energy analysis of two-stage water tanks variable-volume thermal heat storage system for solar heating. Energy Storage Science and Technology 2022; 11(2): 538-546.

[26] Da Silva Júnior OE, De Lima JA, Abrahão R, De Lima MHA, Santos Júnior EP, Coelho Junior LM. Solar Heating with Flat-Plate Collectors in Residential Buildings: A Review. Energies 2022; 15: 6130. https://doi.org/10.3390/en15176130

[27] Duffie JA, Beckman WA. Solar Engineering of Thermal Processes, 2d ed. New York: John Wiley & Sons, 1991.

[28] Directory of SRCC Certified Solar Collector Ratings, 2006, [Online]. [Accessed 21.03.2023]. Available: www.solar-rating.org

[29] EnergyPlus version 8.7. Documentation Input Output Reference, 2016.

[30] Ashrae Handbook Heating, Ventilating, and Air-Conditioning Applications, SI Edition, ASHRAE, 1791 Tullie Circle, N.E., Atlanta, GA 30329, www.ashrae.org, 2015.