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OPTIMIZATION SOLAR DOMESTIC HOT WATER SYSTEMS

Abstract: *In Serbia, it is customary to use electrical energy for heating of domestic hot water (DHW). As around 70% of electrical energy is produced by using coal with high greenhouse emission, it is beneficial to environment to use solar energy for heating of DHW in solar DHW system (SDHWS). During SDHWS operation, different SDHWSs generate different amounts of heat from solar energy, obtain different amounts of avoided electrical energy, avoided energy, and avoided fossil energy. These investigations use computer code EnergyPlus. The used weather data are from the meteorological station. In this paper, a use of Hooke-Jeeves algorithm is reported to obtain the maximum amounts these of performances for different SDHWS use as a function of number of optimum positions of the solar collector in SDHWS during year for Belgrade, in Serbia.*

Keywords: *Optimization; SDHWS; Simulation; Solar collector; avoided energy;*

1. INTRODUCTION

During the first years of the twenty-first century, extensive efforts have been undertaken to alleviate global warming of the earth caused by emission of CO_2 into atmosphere. These emissions are generated by intensive burning of fossil fuels to satisfy the growing energy needs of humanity. When part of energy needs is satisfied by using non-polluting energy sources such as solar energy, the emissions may be mitigated, and they are thus used instead of fossil fuels. Furthermore, another important advantage of the usage of solar energy is that it does not pollute the environment with nitrogen oxides and sulfur dioxide.

In Serbian households, the high amount of DHW is used for shower, tap, cloths-washing and dish-washing machines. It is customary to use electricity for heating of DHW. Considering the fact that around 70% of electricity is produced by using coal with high greenhouse emission, it is highly important and the most rewarding to use solar energy for DHW heating instead of electrical energy. Accordingly, in Serbia and worldwide, the most rewarding application of solar energy is when it replaces electrical energy for heating of DHW in households [1,2]. In addition it is important to have a high efficiency of conversion of solar energy to heat. As a result, the highest amount of avoided exergy is achieved.

In this paper, Hooke-Jeeves algorithm is used to obtain the maximum amounts of these performances for different SDHWS as a function of number of optimum positions of the solar collector in SDHWS during year for the city of Belgrade, Serbia. Also, it has been calculated the reduction of the solar fractions, as well as a deficit avoided exergy in the case when the solar collector are not at its optimal position [3,13].

2. SIMULATION SOFTWARES

In this investigation, simulation, and optimization are performed by using two separate software packages. The research of these installations was performed by using simulation by EnergyPlus and optimization by using Hooke-Jevees method. In this investigation, the Hooke-Jevees method was used to optimize energy flows in SDHWS. In this investigation, the solar collector slope angle is optimized to obtain the highest solar fraction. In this study, the building energy simulation software

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EnergyPlus (Version 7.0) was used to predict solar energy and electrical energy use in solar installation for heating of DHW in several cities in Serbia. EnergyPlus program is a very useful tool for modeling of energy and environmental behavior of buildings. The program is initially developed by Lawrence Berkeley National Laboratory, U.S. Army Construction Engineering Laboratory, and the University of Illinois [9]. GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program [10]. It has been developed for optimization problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. The software GenOpt is programmed for the introduction of appropriate objective functions and optimization methods using Hook Jeeves method. Hooke-Jeeves algorithm is a direct search and derivative free optimization algorithm [11]. In Hooke Jeeves algorithm, only the objective functions and the constraint values are used to guide the search strategy.

3. MATHEMATICAL MODEL

To obtain performance of SDHWS, the operation of the SDHWS was investigated by using simulation and optimization. The mathematical model was developed in EnergyPlus simulation environment and the optimization was performed by using Hooke-Jeeves search algorithm.

This part of the paper provides the mathematical model used to simulate the energy behavior of SDHWS and different parts of its installation: solar collector, thermal tanks (storage & heaters), tempering valve, and SDHWS-control devices. Schematics of the solar hot-water system for heating of domestic hot water in EnergyPlus environment is shown in Fig.1. Solar energy is captured by using solar collector. This energy heats water that flows through the collector. Furthermore, the water from collector heats water in the storage tank to some temperature that may be higher or lower than the needed (hot-water set-up) temperature. If this temperature is higher than the needed temperature, then this temperature is lowered by using cold water through the tempering valve. If this temperature is lower than the needed temperature, this water is heated by electric energy in the instantaneous water heater.

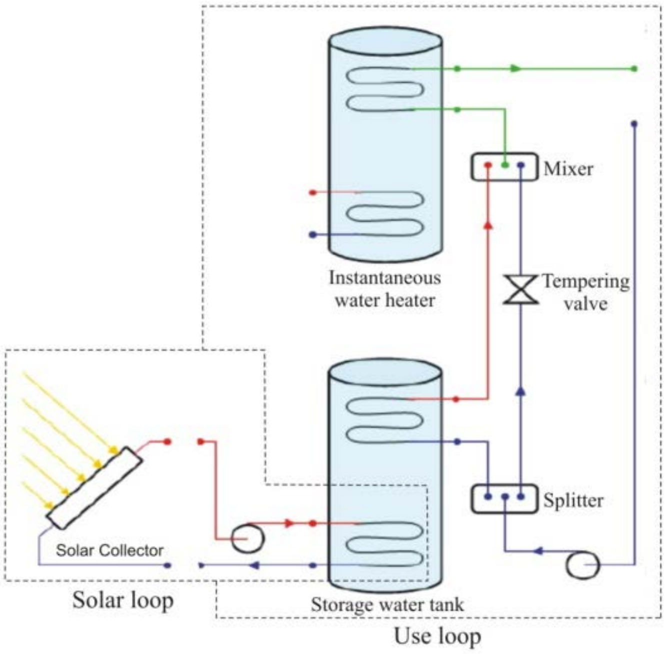

Figure 1. Schematics of SDHWS for heating of DHW (adapted from [12])

Surface geometry. Calculations require that the solar collector surface is described geometrically. Here, the solar collector is placed to the building roof. The solar collector is rectangular in shape (see Fig.2) with its length designated as (a) and its width as (b). The building height is designated as h.

Finally, the solar collector surface is described by the coordinates of their vertices 1, 2, 3, and 4 in a three dimensional Cartesian coordinate system. This right-hand coordinate system has the *X* axis pointing east, the *Y* axis pointing north, and the *Z* axis pointing up that is characteristics of EnergyPlus Cartesian coordinate system. The vertices are recorded in counter-clockwise sequence (as the surface is viewed from outside its zone).

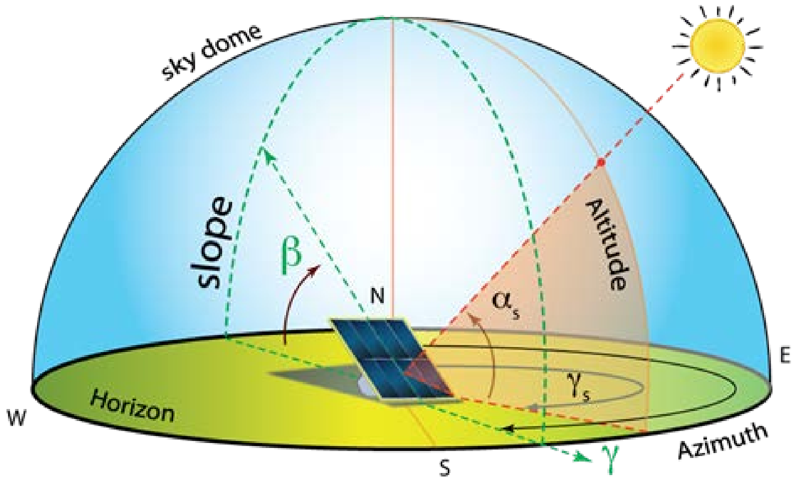

Figure 2. Collector-Sun Orientation

The solar collector is south facing. Its tilt angle (β) is the angle between the *Z*-axis and the normal to the surface of the solar collector (or between the solar collector surface and the horizontal). The convention assumed here is that $-90^0<\beta<90^0$. The surfaces with positive β face south and with negative β face north. Its azimuth angle (γ) is defined as the displacement angle between the projection on a horizontal plane of the normal to the collector surface and due north. The convention assumed here is that $-180^0 < \gamma < 180^0$.

Calculation of energy consumption: Calculation of energy consumption during the calculation period gives two electrical energies *E* and *R* consumed for DHW production. The energy *E* is consumed by the electric heater when the solar collector is present and operating, and energy *R* is consumed when no solar collector is employed. The objective function is the performance of the installation is evaluated by calculating the solar fraction (*f*) by:

$f = 100\ (R-E)/R = f\ (\beta_i, \gamma_i)$ (1)

If $f=f_i$ is larger, the SDHWS better protects the environment. Variable f_i is a function of tilt β_i and azimuth angle γ_i.

It should be maximized in the constrained region of β_i and γ_i. As a result of the optimization, we obtain the maximum solar fraction $f_{i,max}$, and the optimum tilt $\beta_{i,opt}$, and optimum azimuth angle $\gamma_{i,opt}$.

Each solar collector that stays at optimal position generates the highest amount of heat from the incident solar energy. Then, the SDHWS uses this heat for the DHW heating instead of the electrical energy from the electricity network. This means that such a SDHWS avoids use of the highest amount of electrical energy from the electricity grid for the DHW heating. In addition, this avoids the highest amount of electrical energy generation by the national power plants.

If the solar collector of a SDHWS does not stay at the optimum position due to some reason, then it will generate smaller amount of exergy for the DHW heating than the maximum amount it would generate when it stays at the optimum position. As the heating of DHW uses the electrical energy, the SDHWS will use more electrical energy for the DHW heating than that when the SDHWS has its solar collector at the optimum position [13, 14].

For this case, the deficit in avoided energy is defined as

$$DE_{xi} = \frac{100 \cdot (E_{x,i} - E_{i,max})}{E_{i,max}} . \quad (2)$$

Solar Collector (Thermal Performance): Solar Collector is of Flat Plate type produced by, Alternate Energy Technologies (AE-32) with length of 3.66m and width of 2.43m. The thermal efficiency of a collector is defined as

$$\eta = \frac{(q/A)}{H_{solar}} \quad (3)$$

where q = useful heat gain, A = 8.892m^2 gross area of the collector, and H_{solar} = total incident solar radiation. Note that the efficiency η is only defined for H_{solar} > 0.

For η, the following quadratic correlation is used

$$\eta = c_0 + c_1 \frac{(T_{in} - T_{air})}{I_{solar}} + c_2 \frac{(T_{in} - T_{air})^2}{I_{solar}} \quad (4)$$

Both first- and second-order efficiency equation coefficients from [12] are given as c_0 = 0.691, c_0 = 3.396 W/m2-K, and c_0 = 0.00193 W/m^{2}K^2.

Thermal tanks (storage & heaters): Water thermal tanks are devices for storing thermal energy in water from the SDHWS. The input object of EnergyPlus (Water Heater: Mixed) provides a model that simulates a storage water tank (well-mixed water tank), and also instantaneous water tank (tankless water heater). The storage water tank has volume of 0.75 m^3.

SDHWS-Control temperatures for solar loop: To control use of this installation, several temperatures will be supported in the solar loop by using the control equipment inside this installation. Its maximum flow rate is 0.00006 m3/s. Main parameters of solar heating installation for water loop through the solar collector are the following Loop temperature (T_L=60^{0}C), High temperature turn off in solar loop (60^{0}C), High temperature turn on in solar loop (0^{0}C), Temperature difference on limit (differential thermostat) (10^{0}C), Temperature difference off limit (differential thermostat) (2^{0}C).

SDHWS-Control temperatures for use loop: To control use of this installation, several temperatures will be supported in the use loop by using the control equipment inside this installation. Main supported temperatures are are the hot water setpoint temperature (T_H=50^{0}C) and the maximum temperature limit for storage tank (82.2 ^{0}C).

Tempering Valve: In certain solar hot water and heat recovery situations, a thermal storage tank may become warmer than is necessary or allowable for safe use of the hot water. The tempering valve acts to divert flow through the branch it is on in order to adjust the temperature at the outlet of the mixer (see Fig. 3).

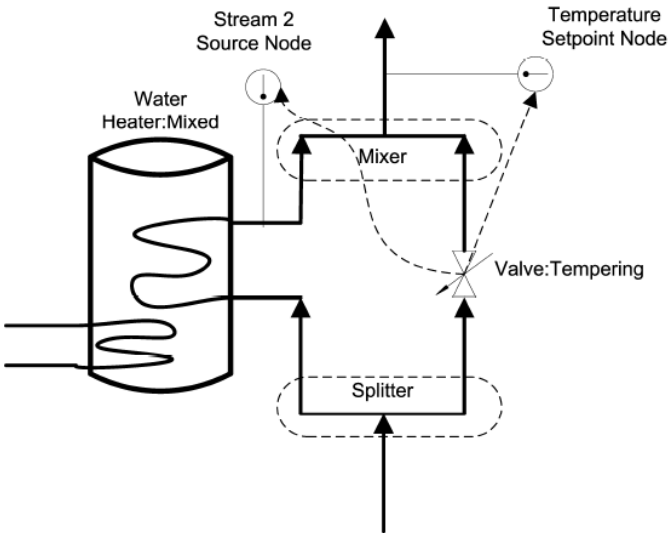

Figure 3. SDHWS –tempering valve (adapted from [7])

4. SIMULATION AND OPTIMIZATION

For simulation and optimization to run, it is necessary to know the hot water consumption and climate.

Hot Water Consumption: This installation generates four different types of hot water: that of tap, shower, dish-washer, and cloth-washer. Regarding its application, the water would be heated to two temperatures: 43.3 (tap and shower with the maximum flow rate of 0.0000945 m^3/s) and 50^0C (dish and clothes washer with the maximum flow rate of (0.000063 m^3/s). For water with lower temperature and for water with higher temperature used in dish washer, the daily schedule is the same for each day throughout entire summer. The cloth washer operates only on Sunday. For water with higher temperature used in the cloth washer, the daily schedule is the same for each Sunday throughout the entire summer.

Weather data: The investigated SDHWS is located in the city of Belgrade. Their meteorological data are used in the form of EnergyPlus weather files. These are either measured by the meteorological stations or calculated by the software Meteonorm for sites where data from meteorological stations are not available. Belgrade has the average height above sea-level of 99 m. Its latitude is 44.82°N, longitude 20.27°E, and time zone GMT +1.0 Hours. To familiarize with the Belgrade climate, Figs.4 and 5 are given by using monthly statistics for the Belgrade weather file.

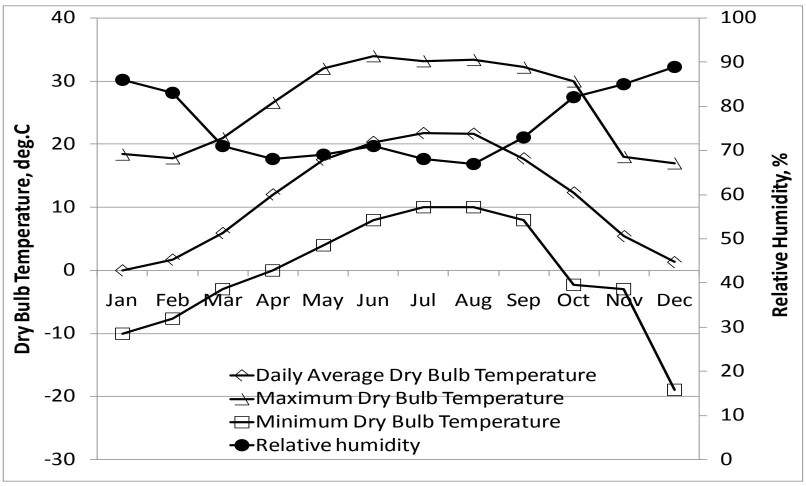

Figure 4. Relative humidity and dry bulb temperature (minimum, daily average and maximum) from the monthly statistics for Belgrade, Serbia from Belgrade weather file.

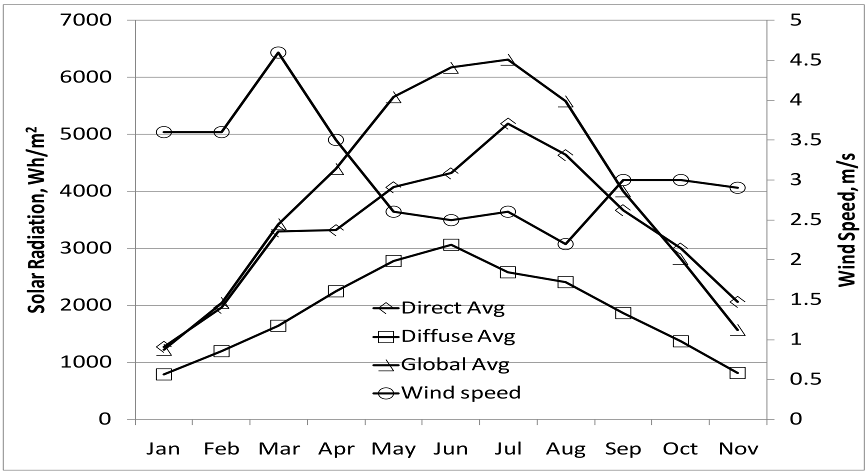

Figure 5. Direct, diffuse, and global average solar radiation, and daily average wind speed from the monthly statistics for Belgrade, Serbia from Belgrade weather file.

5. RESULTS AND DISCUSION

To use SDHWS adequately, it must be satisfactory designed, installed, and operated. In this paper, we report how the optimal installation of the SDHWS can be achieved by using EnergyPlus software with the modified Hooke Jeeves direct search algorithm.

Analyzed domestic hot water solar systems with SDHWS#1 is a stationary solar collector which operates on one slope during the year. The values of $\beta = \beta_{opt} = 37.5$ ° and according to that $f = f_{max} = 32.9\%$ are given in Belgrade, Serbia. Figure 6 shows the annual deficit avoided exergy versus angle deviation from the optimal angle slope of the solar collector for SDHWS in Belgrade, Serbia. Figure 7 shows that when β_a departs below $\beta_{a,opt}$ for $\Delta\beta_a$, the avoided exergy is lower than that when β_a departs above $\beta_{a,opt}$ for $\Delta\beta_a$.

Analyzed domestic hot water solar systems with SDHWS#1 is stationary solar collector that working on one position (slope and azimuth) during the year. The values of $\beta = \beta_{opt} = 28.75°$ and $\gamma_{opt} = 25°$ and according $f = f_{max} = 35.8\%$ are given in Belgrade, Serbia. Figure 7 shows the annual deficit avoided exergy versus angle deviation from the optimal position of the solar collector for SDHWS in Belgrade, Serbia. Figure 7 shows that when β_a and $\gamma_{a,}$ departs below $\beta_{a,opt}$ and $\gamma_{a,opt}$ for $\Delta\beta_a$ and $\Delta\gamma_{a,}$,the avoided exergy is higher than that when β_a и γ_a departs above $\beta_{a,opt}$ and$\gamma_{a,opt}$ for $\Delta\beta_a$, respectively$\Delta\gamma_a$.

Analyzed domestic hot water solar systems with SDHWS#1 is stationary solar collector that working on one position (slope and azimuth) during the year. The values of $\beta = \beta_{opt} = 37.5°$ and $\gamma_{opt} = 25.625°$ and according $f = f_{max} = 35.5\%$ are given in Belgrade, Serbia. Figure 8 shows the annual deficit avoided exergy versus angle deviation from the optimal position of the solar collector for SDHWS in Belgrade, Serbia. Figure 7 shows that when $\gamma_{a,}$ departs below $\gamma_{a,opt}$ for $\Delta\gamma_{a,}$,the avoided exergy is higher than that when γ_a departs above and $\gamma_{a,opt}$ for $\Delta\gamma_a$.

CONCLUSION

To use SDHWS with benefit, it has to be optimally designed, installed, and operated. In this paper, it is analyzed how the SDHWS can be optimally installed by using EnergyPlus software with the modified Hooke Jeeves direct search methodology. As an example,Hooke-Jeeves algorithm is used to obtain the maximum amounts of these performances for different SDHWS as a function of number of optimum positions of the solar collector in SDHWS during year for the city of Belgrade, Serbia. Also, it has been calculated deficit of avoided exergy in the case when the solar collector are not at its optimal position.

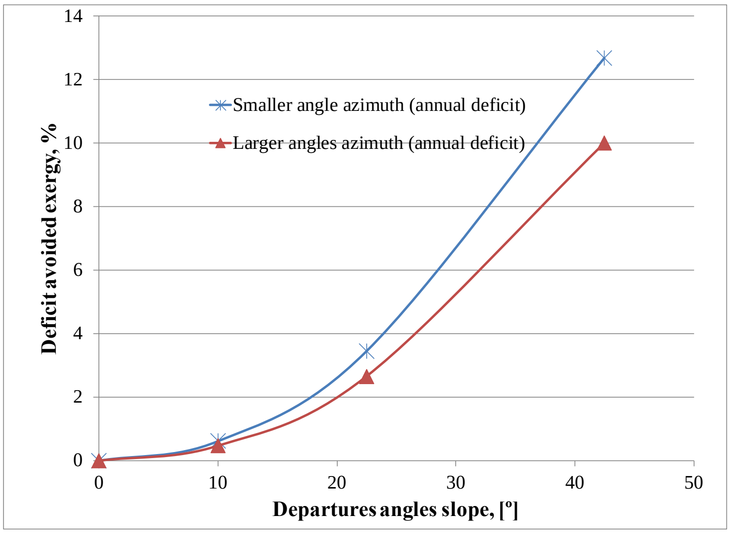

Figure 6. Deficit avoided exergy versus departures angles slope from the optimal slope of the solar collector for SDHWS in Belgrade, Serbia

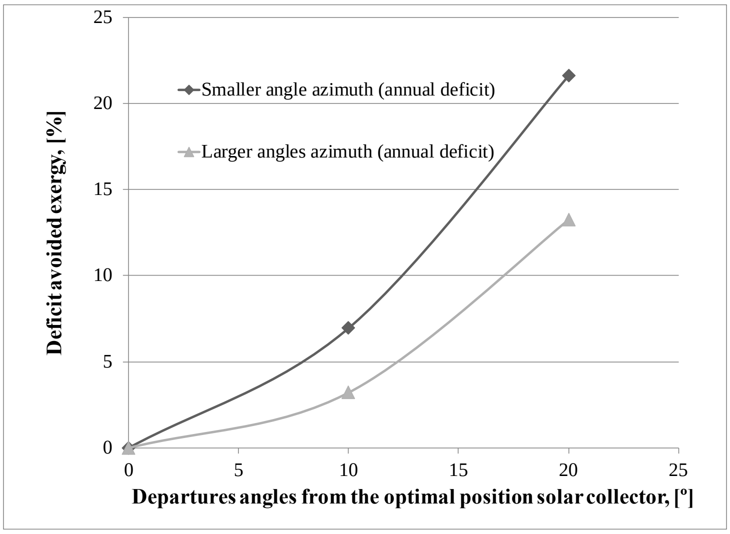

Figure 7. Deficit avoided exergy versus departures angles from the optimal position of the solar collector for SDHWS in Belgrade, Serbia

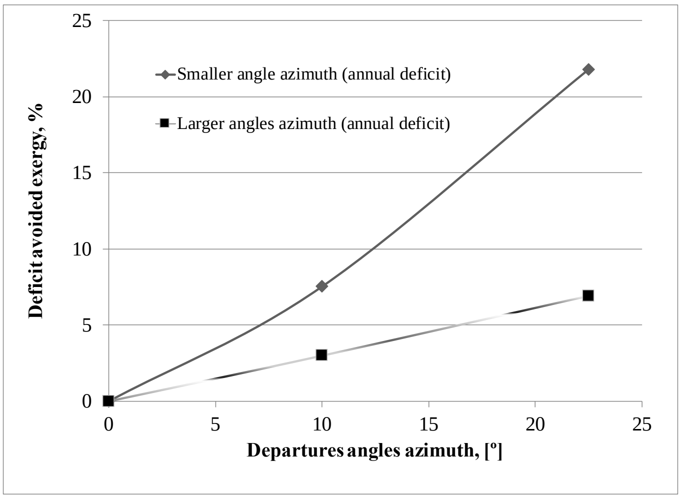

Figure 8. Deficit avoided exergy versus departures angles azimuth from the optimal position of the solar collector for SDHWS in Belgrade, Serbia

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