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Jasmina Skerlić[1)]
Milorad Bojić[1)]
Danijela Nikolić[1)]
Jasna Radulović[1)]
Dragan Cvetković[)]

1) Faculty of Engineering, University at Kragujevac, Serbia jskerlic@gmail.com milorad.bojic@gmail.com,, danijelan@kg.ac.rs, jasna@kg.ac.rs, dragan_cw8202@yahoo.com

ENVIRONMENTAL GAINS OF DHW SYSTEM THROUGH OPTIMUM SLOPE SOLAR COLLECTOR

Abstract: *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 in atmosphere. The emissions may be mitigated when part of energy needs is satisfied by using non-polluting energy sources such as solar energy, instead of fossil fuels. Also, 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, around 70% of electricity is produced by using coal with high greenhouse emission, it is important and the most rewarding to use solar energy for DHW heating instead of electrical energy. In addition it is important to have a high efficiency of conversion of solar energy to heat. Then, the highest amount of avoided primary energy, avoided electrical energy, and decrease in CO_2 emissions may be expected. In this paper, a use of Hooke-Jeeves algorithm is reported to obtain the maximum annual avoided CO_2 emission due to maximum avoided electrical energy use as a function of number of optimum tilt position of the solar collector in SDHWS during year for Belgrade, in Serbia. Also, the difference in annual avoided emission of CO2 of different solar collector system relates to the stationary optimally located solar collector that yearly operates at one tilt.
Keywords: *domestic hot water, slope angle, CO_2 emission, optimization*

1. INTRODUCTION

In Serbian households, the high amount of DHW is used for shower, tap, cloths-washing machines, and dish-washing (machines). It is customary to use electricity for heating of DHW. 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]. In addition it is important to have a high efficiency of conversion of solar energy to heat. Then, the highest decrease in CO_2 emissions may be expected.

To use SDHWS with the greatest benefit, SDHWS must have adequate design, installation, and operation. During its operation, the applied solar collector has to take the optimal position that will guarantee the highest generation of heat. The solar collector takes the north-south direction and the objective of this paper is to find the optimum solar collector slope. In literature, there is a lot of research with this objective. By using the equations for the global solar radiation by an empirical model, Nijegorodov and Jain calculated optimum slope of a north-south aligned absorber plate from the north to the south poles [4]. By determining the sunshine duration, Chang roughly estimated the optimal tilt angle of a solar collector in the northern hemisphere [3]. Based on the incident angles of the direct solar radiation, Skeiker calculated the optimum tilt angle and orientation for solar collectors in Syria [5]. By taking into account position of the sun at the sky and using the model of ASHRAE, Bari calculated the optimum orientation of domestic solar collectors for the low latitude countries [6]. By using the measured values of the global solar radiation, Ibrahim calculated the optimum tilt angle for solar collectors used in Cyprus [7]. Based on the measured data for solar radiation by meteorological station, Shariah et al optimized the tilt angle of solar collectors for the SDHW system where maximum solar fraction was used as an indicator for the optimum tilt angle [2] which is the case in the repoted investigations.

In this paper, a use of Hooke-Jeeves algorithm is reported to obtain the maximum annual avoided CO_2 emission due to maximum avoided electrical energy use as a function of number of optimum tilt position of the solar collector in SDHWS during year for Belgrade, in Serbia. Also, the difference in annual avoided emission of CO_2 of different solar collector system relates to the stationary optimally located solar collector that yearly operates at one tilt. The solar collectors of the SDHWSs are placed in north-south direction at roofs of houses. The used weather data were from the meteorological stations and software Meteonorm. These investigations use the computer codes: EnergyPlus and GenOpt and HJ search algorithm.

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 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

EnergyPlus Model for SDHWS: SDHWS serves to heat domestic hot water. The system heats the water by using solar energy and electric energy. The domestic hot water is used for heating of sink water, bath and shower water, and water for dish washing and cloth washing machines. Schematics of the solar hot-water system for heating of domestic hot water in EnergyPlus environment is shown in Figure 1. The system consists of the solar collector, storage tank, instantaneous heating tank, and tempering valve. 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.

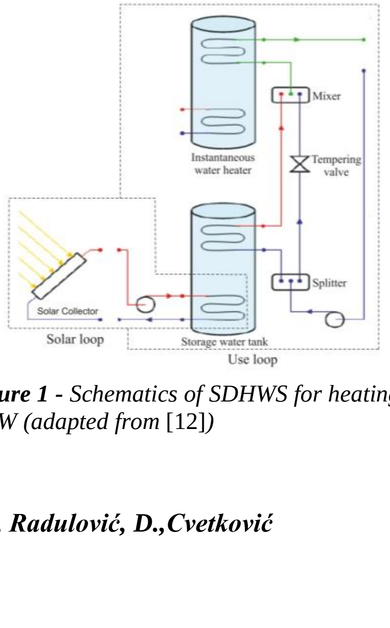

Figure 1 *- Schematics of SDHWS for heating of DHW (adapted from* [12]*)*

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 Figure 2) with its length designated as (a) and its width as (b). 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.

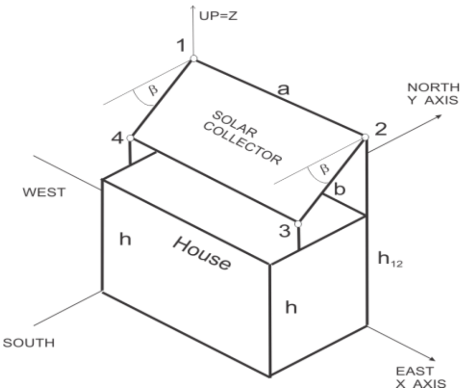

***Figure 2** - The buiding with the solar collector at its roof. The surface area of the solar collector 1234 is equal to that of the building roof.*

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

$$\eta=(q/A)/I_{solar} \quad (1)$$

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

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

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 (WaterHeater: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 (60^0C), High temperature turn on in solar loop (0^0C), Temperature difference on limit (differential thermostat) (10^0C), Temperature difference off limit (differential thermostat) (2^0C).

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).

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. Figure 3 provide hot water characteristics: temperatures, maximum flow rates and daily schedules that may be valid for family of four in Serbia.

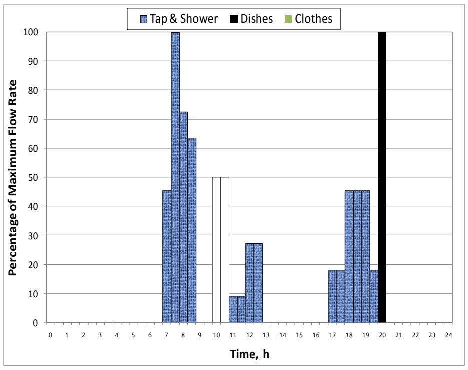

Figure 3 *- Schedule of hot water use for (a) tap and shower (0.0000945 m3/s maximum with 43.3^{0}C) (b) dish and clothes washer (0.000063 m3/s maximum with 50^{0}C). Dish-washer operates daily, while cloth washer on Sundays).*

Weather: The location of the facility under analysis is critical for the determination of energy consumption. In EnergyPlus, both external (i.e, weather files supplied from others) and internal weather data is used during simulations. The "Site:Location" input object includes parameters that allow EnergyPlus to calculate the solar position (using Latitude, Longitude and Timezone) for any day of the year as well as supply the standard barometric pressure (using elevation).

SDHWS simulation and optimization procedure: To operate the SDHWS, EnergyPlus software is used to simulate and the Hooke Jeeves algorithm to optimize its performance. The SDHWS is simulated for different operation duration that may last 1, 3, 6, and 12 months.

EnergyPlus calculates the electrical energy consumption of the SDHWS during its run. The obtained results are Ei,e and Ei,tot. The variable Ei,e is the electrical energy consumed by the SDHWS if the solar collector operates. As variable Ei,e =Ei,hr+Ei,wp, the electrical energy is consumed by the electric heater to heat the DHW (Ei,hr) and by the circulation pump to run water inside the solar loop (Ei,wp). The variable Etot,i is the electrical energy consumed by the electric heater to heat DHW if the solar collector does not exist. Energy Ei,s=Ei,tot-Ei represents the generated heat from the solar energy that heats DHW instead of the electrical energy from the electrical network. Consequently, Ei,s represents the amount of electrical energy that is not consumed from the electricity network as it would be consumed if the SDHWS did not capture solar energy. This is the avoided electrical energy designated as Ei,ae = Ei,ax= Ei,s. This means that other needs for electrical energy may be covered without constructing new generating capacities for electrical energy.
The amount of the avoided (use of) fossil energy by the electricity network is also proportional to the avoided electrical energy as

Ei,af =Cf Ei,ae, (3)

where Cf stands for the fossil fuel energy factor[13].
The avoided emission of CO_2 by the electricity network is also proportional to the avoided electrical energy as

Pi = Cc Ei,ae (4)

Here, Cc stands for the CO2 equivalent for the EPS electrical network of Serbia[13].

The performance of the SDHWS is evaluated by calculating the solar fraction (fi). This is the objective function used by the Hooke Jeeves algorithm:

SO= fi = 100(Ei,tot -Ei)/Ei,tot =f(βi) (5)

If fi is larger, the SDHWS better protects the environment. The variable fi also represents the fraction of avoided electrical energy (avoided electrical energy, avoided fossil fuel, and avoided CO_2 emission). Variable fi is a function of tilt βi. It should be maximized in the constrained region of βi. As a result of the optimization, we obtain the maximum solar fraction (fi,max), and the optimum tilt (βi,opt) [14].

5. RESULTS AND DISCUSION

During their operation, different SDHWSs generate different amounts of heat from solar energy, obtain different amounts of avoided electrical energy, and emit different amounts of CO_2.

Maximum amounts of avoided electrical energy for different SDHWSs. Figure 4 gives maximum amounts of the avoided electrical energy for annual application of different SDHWSs in Belgrade.

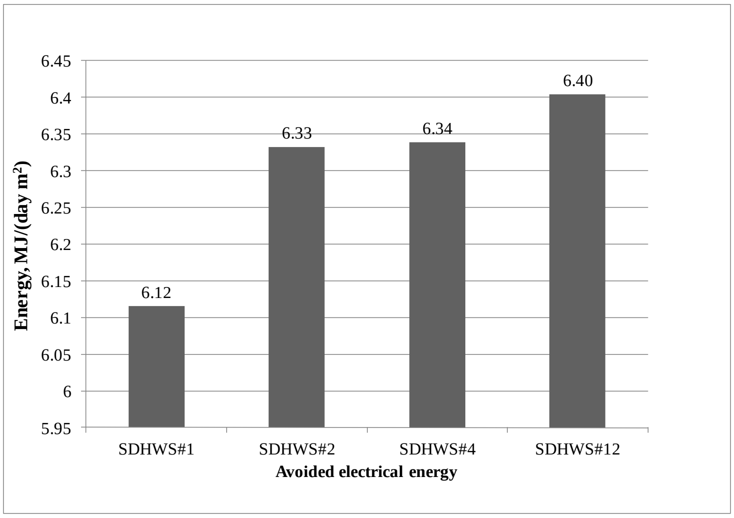

Figure 4 *- Maximum avoided electrical energy, for different SDHWSs during year for Belgrade.*

Environmental gains for different SDHWS assembles. The maximum annual avoided CO2 emissions are shown in Figure5 for different SDHWSs during year for Belgrade.

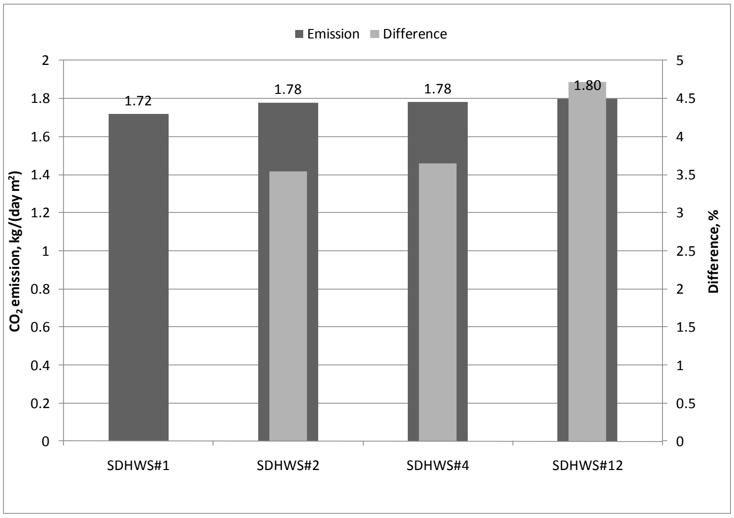

Figure 5 *- Maximum annual avoided CO_2 emission due to maximum avoided electrical energy use as a function of number of optimum tilt positions of the solar collector in SDHWS during year for Belgrade. Also, the difference in annual avoided emission of CO_2 of different solar collector system relates to the stationary optimally located solar collector in SDHWS#1.*

Also, the difference in the annual maximum avoided emission of CO2 of different SDHWSs compared to the SDHWS#1. When the SDHWS system has the solar collector with two optimal tilts per year, the difference is 3.54% higher than that generated by the optimal one-tilt solar collector. When the SDHWS system has the solar collector with four optimal tilts per year, the difference is 3.65% higher than that in the first case. When the SDHWS system has the solar collector with twelve optimal tilts per year, the difference is around 4.75%.

6. CONCLUSION

To use SDHWS with benefit, it has to be optimally designed, installed, and operated. In this paper, we report how the SDHWS can be optimally installation achieved by using EnergyPlus software with the modified Hooke Jeeves direct search methodology.

As an example, use of Hooke-Jeeves algorithm is to obtain the maximum annual avoided CO_2 emission due to maximum avoided electrical energy use as a function of number of optimum tilt position of the solar collector in SDHWS during year for Belgrade, in Serbia. Also, the difference in annual avoided emission of CO_2 of different solar collector system relates to the stationary optimally located solar collector that yearly operates at one tilt.

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