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ANALYSIS AND EVALUATION OF SOLAR ENERGY SYSTEMS

Jasmina Skerlic[1], Danijela Nikolic[2], Vanja Šušteršić[3], Jasna Radulovic[4], Aleksandar Mišković[5], Blaža Stojanović[6]

Summary: *In Serbia, it is usually to use electricity for domestic hot water (DHW) heating. As about 70% of electrical energy is produced by using coal, with high greenhouse emission, it is beneficial to environment to use solar energy for DHW heating in solar DHW system (SDHWS).*
This paper represents the optimization of design, implementation in practice and operation of the solar collectors in space and time, as elements of solar installations, in order to determine the feasibility of the proposed concept modern methods of energy monitoring and energy diagnostics. These investigations use computer software 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 of performances for different SDHWS use as a function of number of optimum positions of the solar collector in SDHWS during year for Belgrade, Serbia.
Solar energy systems have been improved, whereby we obtain minimum consumption of fossil energy, reduction of the use of energy resources, maximizing energy security, as well as the minimum impact on the environment.
Key words: *Optimization; Solar system for heating of DHW; simulation; solar collector; solar fraction*

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 in atmosphere. These emissions are generated by intensive burning of fossil fuels to satisfy the growing energy needs of humanity. 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.

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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. As 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. 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 amount of avoided primary energy, avoided electrical energy, avoided exergy, and de- crease in CO_2 emissions may be expected.To use SDHWS with the greatest benefit, SDHWS must have adequate design, installation, and opera- tion. 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 and azimuth angle. 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 reported investigations. Talebizadeh, reported investigation, the optimum slope and azimuth angles for hourly, daily, monthly, seasonally and yearly bases were found using the Genetic Algorithm (GA) respectively. The percentages of heat gain of a solar collector under these optimum angles were obtained [8]. In this paper, we compared the results of all cases exploration of the solar system. Use of Hooke-Jeeves algorithm is reported to obtain of solar fraction, where their difference are observed if it is optimized the values fi (βi), fi (βi,ɣi) and fi (βi=βa,opt, ɣi), i.e. when the slope has optimal value (βi =βa,opt = 37.5°) for SDHWS in Belgrade.

SIMULATION SOFTWARES

Simulation Software – EnergyPlus: 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 Serbia. Then, the solar fraction was determined for its different design, installation and operation parameters. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA [9]. The software serves to simulate building energy behavior and use of renewable energy in buildings. The software has been tested using the IEA HVAC BESTEST E100-E200 series of tests [10,11]. Modeling of the SDHWS in EnergyPlus environment required models of different components embedded in EnergyPlus [12].

Genopt Software: GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program [13]. 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. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files. The independent variables can be continuous variables (possibly with lower and upper bounds), discrete variables, or both, continuous and discrete variables. Constraints on dependent variables can be implemented using penalty or barrier functions. GenOpt has a library with local and global multi-dimensional and one dimensional optimization algorithms, and algorithms for doing parametric runs [14]. An algorithm interface allows adding new minimization algorithms without knowing the details of the program structure. GenOpt is written in Java so that it is platform independent. The platform independence and the general interface make GenOpt applicable to a wide range of optimization problems. GenOpt has not been designed for linear programming problems, quadratic programming problems, and problems where the gradient of the cost function is available. For such problems, as well as for other problems, special tailored software exists that is more efficient.

Optimization Algorithm: For optimization, the Hooke–Jeeves algorithm is used together with EnergyPlus simulation. These two programs are connected together by using Genopt software [13]. In this research, the adaptive precision Hooke-Jeeves algorithm is used. Hooke Jeeves algorithm is a direct search algorithm [14,15]. In direct search methods, only the objective functions and the constraint values are used to guide the search strategy. The methodology of search is given in [16,17] in sufficient details. The used Hooke Jeeves algorithm is the adaptive precision algorithm. This algorithm progressively increase the precision of the approximating cost functions as the sequence of iterates approaches a stationary point. In addition, the algorithm only accepts iterates that reduces the cost sufficiently. It reduces the computation time up to a factor of four compared to the standard Hooke–Jeeves algorithm.

2. MATHEMATICAL MODEL

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.

EnergyPlus Model for SDHWS

The SDHWS heats DHW by using solar and electric energy. The DHW is used as water for sink, bath, shower, dish washing and cloth washing. The SDHWS is schematically shown in Fig.1 in EnergyPlus environment. The SDHWS consists of the following main elements explained separately in the text below: the solar collector, storage water tank, instantaneous water heater, tempering valve, and temperature controls. These elements are located in two inner loops of the SDHWS: the solar loop and the use loop. The solar loop is a loop through the solar collector. The use loop is a loop for DHW consumption. The solar loop consists of the solar collector, water pump, and spiral pipe heat exchanger (inside the hot water storage tank). The use loop consists of the splitter, storage water tank, instantaneous water heater, tempering valve, and mixer. Inside the solar loop, the solar collector captures solar energy. This energy heats water that flows through the solar collector. Furthermore, the hot water heats DHW in the storage water tank. In the use loop, the cold DW reaches the splitter. From the splitter, the DW may go to the storage water tank or to the tempering valve. In the storage water tank, DW is heated from the solar loop via the spiral pipe heat exchanger. From the storage water tank, the hot water goes to the instantaneous water heater where can be additionally heated. Then the hot water from the instantaneous water heater and the cold water from the tempering valve go to the mixer and after that as DHW to the consumers. The water temperature in the storage tank may be higher or lower than the needed (hot-water set-up) DHW temperature. If this water temperature is higher than the needed DHW temperature, then this water temperature is lowered in the mixer by using the cold DW through the tempering valve. If this water temperature is lower than the needed DHW temperature, this water is heated by electric energy in the instantaneous water heater to the needed DHW temperature. The investigated solar collector is of flat plate type.

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 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).

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 $-180^0 < \gamma <180^0$.

The surface of the solar collector is rectangular and defined by 4 vertices. Vertex 1 has coordinates: $x_1= b \cos \beta \sin \gamma$, $y_1 = b \cos \beta \cos \gamma$, $z_1 = b \sin \beta + h_{12}$. Vertex 2 has coordinates $x_2=0$, $y_2=0$, $z_2=h_{12}$. Vertex 3 has coordinates: $x_3= a \cos \gamma$, $y_3= b \sin \gamma$, $z_3 = h_{12}$. Vertex 4 has coordinates: $x_4 = b \cos \beta \sin \gamma + a \cos \gamma$, $y_4 = b \cos \beta \cos \gamma +a \sin \gamma$, $z_4 = h_{12} + b \sin \beta$.

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:

$$f = 100\ (R-E)/R= f\ (\beta_{\mathrm{i}}, \gamma_i)$$

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 $\gamma_{i,\ opt}$.

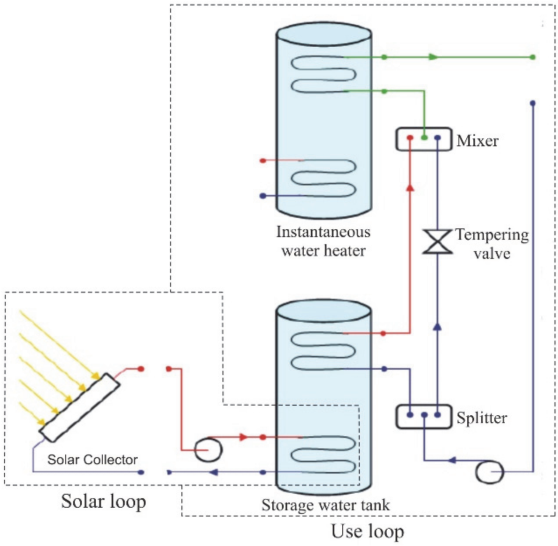

Fig. 1 *Schematics of SDHWS for heating of DHW (adapted from [12])*

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 [18,19].

For this case, the deficit solar fraction is defined as

$$D_i = \frac{100 \cdot (f_{i,tot} - f_{i,max})}{f_{i,max}} \tag{1}$$

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, A = 8.89m^2 = gross area of the collector.

3. 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.2 and 3 are given by using monthly statistics for the Belgrade weather file.

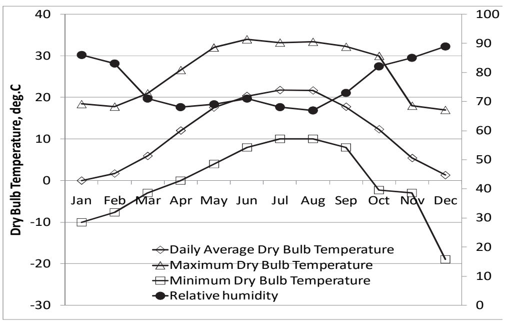

Fig. 2 *Relative humidity and dry bulb temperature (minimum, daily average and maximum) from the monthly statistics for Belgrade, Serbia from Belgrade weather file.*

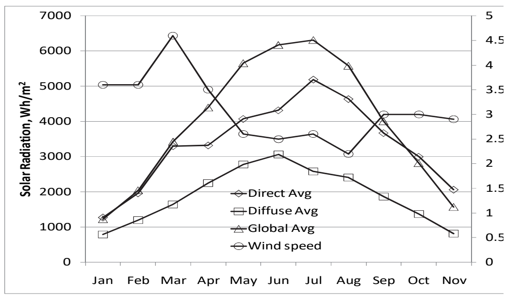

Fig.3 *Direct, diffuse, and global average solar radiation, and daily average wind speed from the monthly statistics for Belgrade, Serbia from Belgrade weather file.*

4. RESULT AND DISCUSSION

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. As an example, these software tools are applied to SDHWS in Belgrade, Serbia.

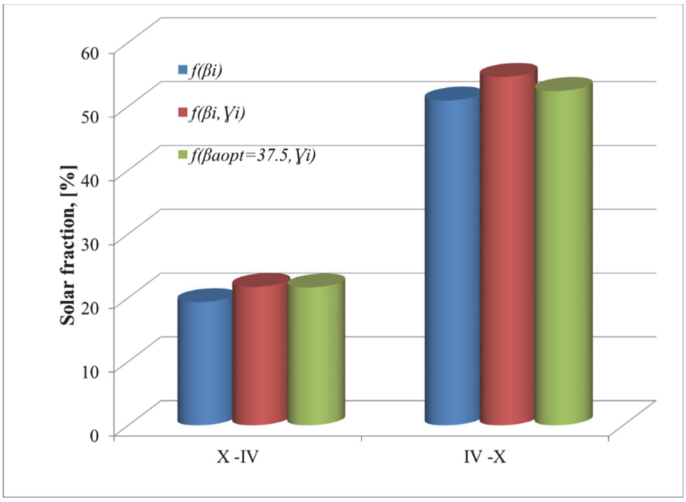

Fig. 4 *Solar fraction, optimized fi (1) fi(βi), (2) fi(βi,ɣi), (3) fi(βi = βa,opt = 37.5°, ɣi), for solar system to heat the hot wather with SC#2*

Comparison of results for all cases of research solar system. The figures (Fig. 4,5,6) shows the values of solar fraction where their difference are observed if optimize fi (βi), for the case of optimization of fi (βi,ɣi), for the case of optimization of fi(βi=βa,opt,ɣi), ie. when the slope is optimal to βi = βa,opt = 37.5°, the solar system for heating hot water with SK # 2, SK # 4, SK # 12 in Belgrade.

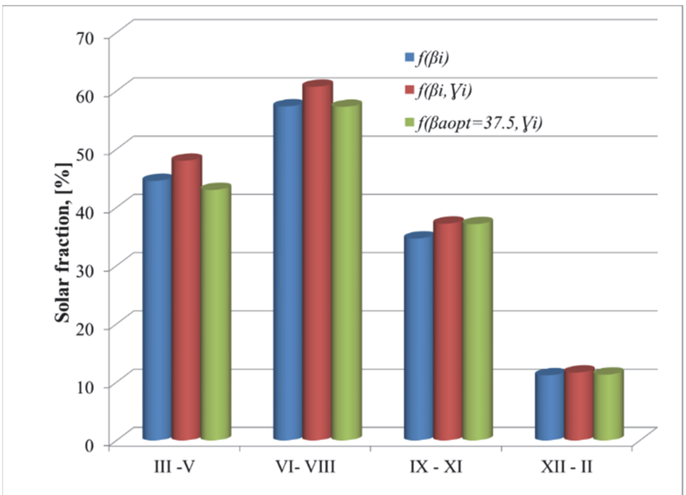

Fig. 5 *Solar fraction, optimized fi (1) fi(βi), (2) fi(βi,ɣi), (3) fi(βi = βa,opt = 37.5°, ɣi), for solar system to heat the hot wather with SC#4*

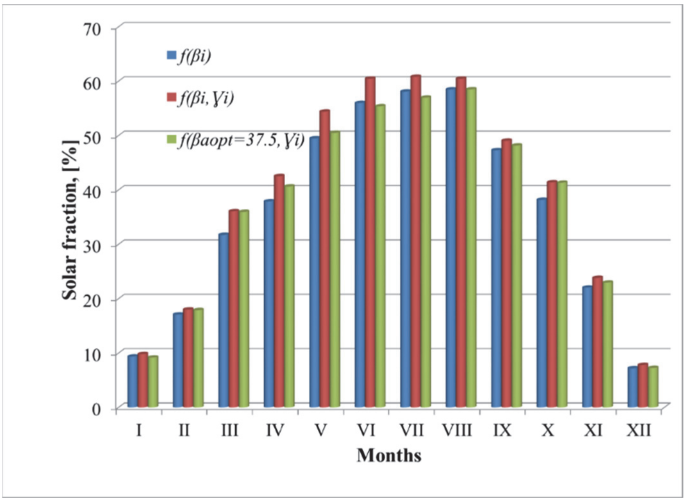

Fig. 6 *Solar fraction, optimized fi (1) fi(βi), (2) fi(βi,ɣi), (3) fi(βi = βa,opt = 37.5°, ɣi), for solar system to heat the hot wather with SC#12*

5. CONCLUSION

SDHWS must be optimally designed and installed, if the user want to SDHWS operates with benefits. In this paper, it is analyzed how SDHWS can be optimally installed, by using EnergyPlus software with the modified Hooke Jeeves direct search methodology. The results shows that the values of solar fraction, where their difference are observed if it is optimized the values *fi* (*βi*), *fi* (*βi,ɣi*) and *fi* (*βi=βa,opt, ɣi*), i.e. when the slope has optimal value (*βi =βa,opt* = 37.5°), the solar system for heating hot water with SK # 2, SK # 4, SK # 12 in Belgrade. It can be concluded that the optimization *fi (βh, ɣh)* is favorable, either for maximize utilization of solar energy, or for its use in order to realize the concept of zero net-energy building.

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