MAXIMIZING PERFORMANCES OF A SOLAR DOMESTIC HOT WATER SYSTEM THROUGH OPTIMUM POSITION OF THE SOLAR COLLECTOR

MAKSIMIRANJE OSOBINA SOLARNOG SISTEMA ZA POTROŠNJU TOPLE VODE OPTIMALNIM POLOŽAJEM PRIJEMNIKA SUNČEVE ENERGIJE

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In Serbia, it is usually to use electrical energy for domestic hot water (DHW) heating. About 70% of electrical energy is produced by using coal with high greenhouse emission, so 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 exergy and avoided fossil energy. These investigations use software EnergyPlus. Used weather data are from the meteorological station. 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 where the solar collector are not at its optimal position.

Keywords: *Optimization, SDHWS, Solar fraction, Simulation, Solar collector, Avoided exergy.*

U Srbiji se najčešće električna energija koristi za zagrevanje sanitarne vode (SV). Kako je oko 70% električne energije dobija korišćenjem uglja koji oslobađa veliki broj gasova sa efektom staklene bašte, korišćenje solarne energije za zagrevanje sanitarne vode u solarnim sistemima za zagrevanje sanitarne vode (STV) ima povoljan uticaj na očuvanje životne sredine. Tokom rad solarni sistem za grejanje sanitarne tople vode generiše različite količine toplote iz solarne energije, dobijaju se različite količine izbegnute elekrične energije, izbegnute eksergije i izbegnute fosilne energije. U istraživanjma je primenjen softver EnergyPlus. Korišćeni vremenski podaci su iz ovlašćenih meteoroloških stanica. Hooke-Javes algoritam se koristi za dobijanje maksimalnih vrednosti performansi za različite STV u funkciji broja optimalnih položaja solarnog prijemnika u toku godine za grad Beograd, Srbija. Takođe, izračunato je i smanjenje solarne frakcije, kao i deficit izbegnute eksegije u slučaju kada solarni prijemnici nisu na svom optimalnom položaju.

Ključne reči: *Optimizacija, STV, Solarni udeo, Simulacija, Solarni prijemnik, Izbegnuta eksergija.*

I. 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.

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 [1,2]. In addition it is important to have a high efficiency of conversion of solar energy to heat. Then, the highest amount of avoided exergy is acchieved.

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].

II. MODELLING AND SIMULATION

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.

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 several cities 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 [9-4]. Its development began in 1996 on the basis of two widely used programs: DOE-2 and BLAST. The software serves to simulate building energy behavior and use of renewable energy in buildings [10-5]. The renewable energy simulation capabilities include solar thermal and photovoltaic simulation. Other simulation features of EnergyPlus include: variable time steps, user-configurable modular systems, and user defined input and output data structures. The software has been tested using the IEA HVAC BESTEST E100-E200 series of tests [11-6]. Modeling of the SDHWS in EnergyPlus environment required models of different components embedded in EnergyPlus such as that of flat-plate solar collector, storage tank, tempering valve, and instantaneous water heater [12-7]. Water in the storage tank was heated by solar energy and water in the instantaneous water heater by electricity.

Genopt Software: GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program [13-8]. 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 [14-9]. 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 [13-8]. In this research, the adaptive precision Hooke-Jeeves algorithm is used. Hooke-Jeeves algorithm is derivative free optimization algorithms [15, 16-10,11]. Hooke Jeeves algorithm is a direct search algorithm [17-12]. 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 [10,12] 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.

III. 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.

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.

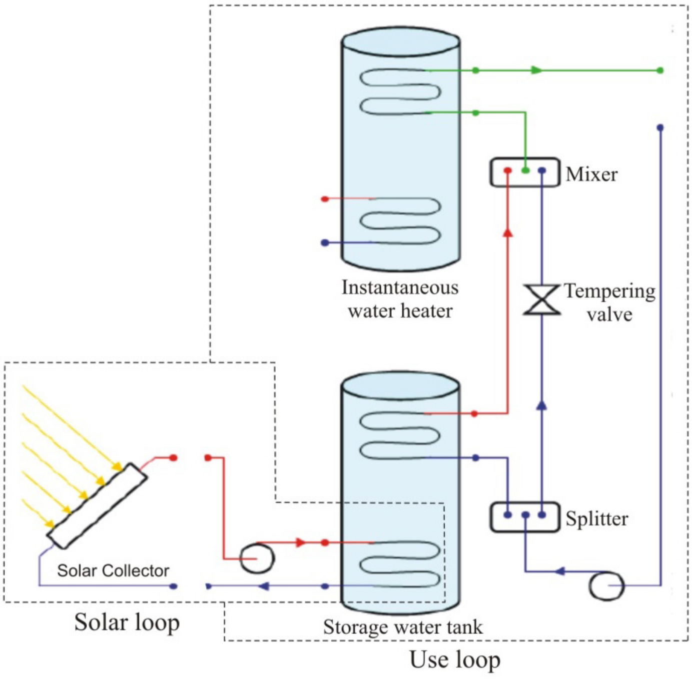

Fig.1 *- Schematics of SDHWS for heating of DHW (adapted from [7])*

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).

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:

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

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.

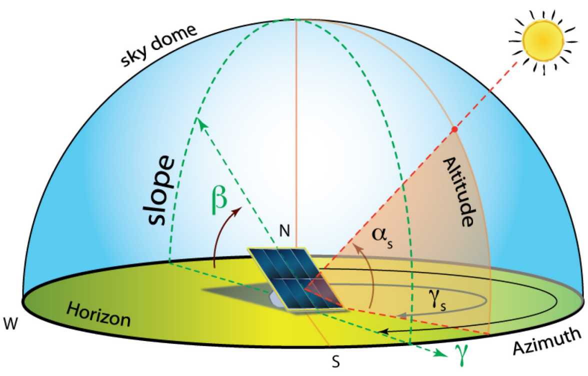

Fig. 2*- Collector-Sun_Orientation*

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 solar fraction is defined as

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

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

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

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 the ratio of the useful heat gain of the collector fluid versus the total incident solar radiation on the gross surface area of the collector.

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

where:q = useful heat gain
A = 8.89m^2 = gross area of the collector
H_{solar} = total incident solar radiation

Notice that the efficiency η is only defined for $H_{solar} > 0$.

An energy balance on a solar collector with double glazing shows relationships between the glazing properties, absorber plate properties, and environmental conditions.

$$\frac{q}{A} = H_{solar}\tau_{g1}\tau_{g2}\alpha_a - \frac{T_{abs}^4 - T_{g2}^4}{R_{rad}} - \frac{T_{abs} - T_{g2}}{R_{conv}} - \frac{T_{abs} - T_{air}}{R_{cond}} \tag{4}$$

where:
τ_{g1} = transmittance of the first glazing layer
τ_{g2} = transmittance of the second glazing layer
α_{abs} = absorptance of the absorber plate
R_{rad} = radiative resistance from absorber to inside glazing
R_{conv} = convective resistance from absorber to inside glazing

R_{cond} = conductive resistance from absorber to outdoor air through the insulation
T_{abs} = temperature of the absorber plate
T_{g2} = temperature of the inside glazing
T_{air} = temperature of the outdoor air

The equation above can be approximated with a simpler formulation as:

$$\frac{q}{A} = F_R\left[I_{sol}(\tau\alpha) - U_L(T_{in} - T_{air})\right] \tag{5}$$

where:
F_R = an empirically determined correction factor
$(\tau\alpha)$ = the product of all transmittance and absorptance terms
U_L = overall heat loss coefficient combining radiation, convection, and conduction term.
T_{in} = inlet temperature of the working fluid.

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{(T_{in} - T_{air})}{I_{sol}} \tag{6}$$

For η, the following linear correlation can be constructed by treating $F_R(\tau\alpha)$ and $-F_RU_L$ as characteristic and quadratic correlation:

$$\eta = c_0 + c_1 \frac{(T_{in} - T_{air})}{I_{sol}} \tag{7}$$

$$\eta = c_0 + c_1 \frac{(T_{in} - T_{air})}{I_{sol}} + c_2 \frac{(T_{in} - T_{air})^2}{I_{sol}} \tag{8}$$

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^2K^2.

Solar Collector (Incident Angle Modifiers): As with regular windows the transmittance of the collector glazing varies with the incidence angle of radiation. Usually the transmittance is highest when the incident radiation is normal to the glazing surface. Test conditions determine the efficiency coefficients for normal incidence. For off-normal angles, the transmittance of the glazing is modified by incident angle modifier coefficients by the equation:

$$K_{\tau\alpha} = \frac{(\tau\alpha)}{(\tau\alpha)_n} \tag{9}$$

$$K_{\tau\alpha} = 1 + b_0\left(\frac{1}{\cos\theta} - 1\right) \tag{10}$$

$$K_{\tau\alpha} = 1 + b_0\left(\frac{1}{\cos\theta} - 1\right) + b_1\left(\frac{1}{\cos\theta} - 1\right)^2 \tag{11}$$

The incident angle modifier coefficients b_0= -0.1939 and b_1= -0.0055 are usually negative [12]. and only valid for incident angles of 60 degrees or less. Because these curves can be valid yet behave poorly for angles greater than 60 degree, the EnergyPlus model cuts off collector gains for incident angles greater than 60 degrees.

Solar Collector (Outlet temperature): Outlet temperature is calculated using the useful heat gain q, the inlet fluid temperature T_{in}, and the mass flow rate available from the plant simulation:

$$\frac{q}{A} = \dot{m}c_p(T_{out} - T_{in}) \tag{12}$$

where:
$\dot{m}$ = fluid mass flow rate through the collector
c_p = specific heat of the working fluid

Solving for T_{out}:

$$T_{out} = T_{in} + \frac{q}{\dot{m}c_p A} \tag{13}$$

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.

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).

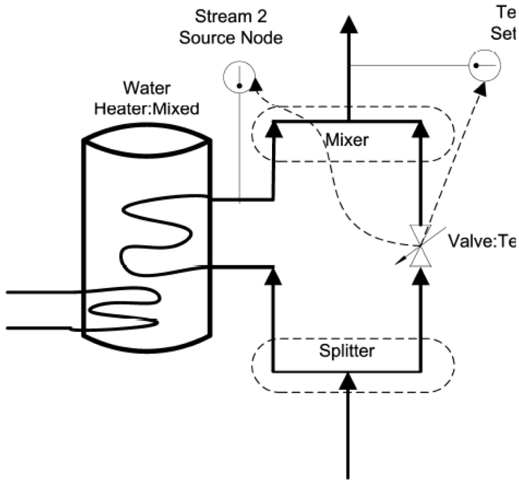

Fig. 3*- SDHWS –tempering valve (adapted from [7])*

SDHWS control: By using several temperature controls inside the installation, the control equipment ménages the SDHWS. These controlled temperatures are inside the solar loop and in the use loop. The controlled temperatures inside the solar loop are the following: the loop temperature, the high temperature turn off, the high temperature turn on, the temperature difference on limit (differential thermostat), and the temperature difference off limit (differential thermostat). The controlled temperatures inside the use loop are the following: the hot water set-point temperature, and the maximum temperature limit for storage tank. The values of controlled temperatures are given in Table 1.

Table 1 - Main parameters of solar heating installation

#	Loop	Quantity	Value	Unit
1	Solar	Solar loop water temperature	60	^0C
2	Solar	High water temperature turn off in the solar loop	60	^0C
3	Solar	High water temperature turn on in the solar loop	0	^0C
4	Solar	Temperature difference on limit (differential thermostat)	10	^0C
5	Solar	Temperature difference off limit (differential thermostat)	2	^0C
6	Use	Hot water setpoint temperature	50	^0C
7	Use	Maximum water temperature limit for storage tank	82.2	^0C

IV. 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. For each month, Fig.4 gives the dry bulb temperature (minimum, daily average, and maximum), and relative humidity. For each month, Fig.5 shows direct, diffuse and global daily average solar radiation, and daily average wind speed. These figures show that the city has a moderate continental climate with a gradual transition between the four distinct seasons (winter, spring, summer, and autumn). The summers are worm and humid, with temperatures as high as 34°C. The winters are cool, and snowy, with temperatures as low as -19°C.

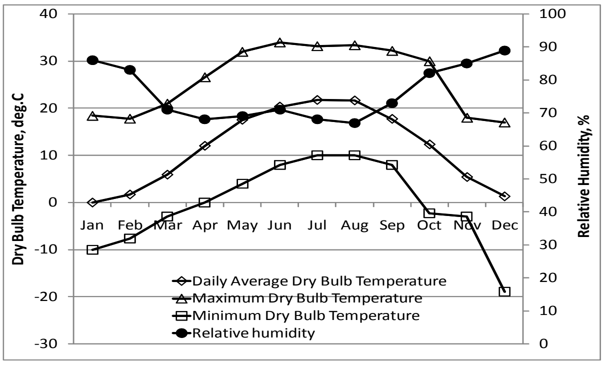

Fig.4 - Relative humidity and dry bulb temperature (minimum, daily average and maximum) from the monthly statistics for Belgrade, Serbia from Belgrade weather file.

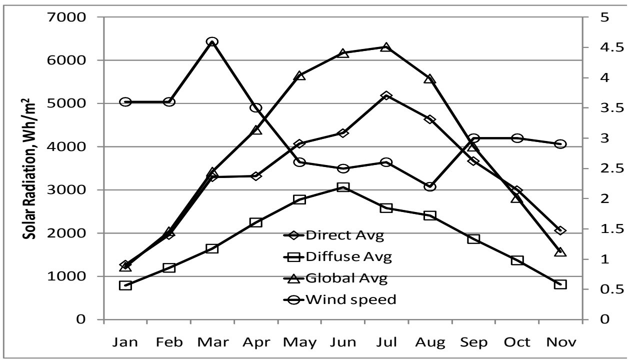

Fig.5 - Direct, diffuse, and global average solar radiation, and daily average wind speed from the monthly statistics for Belgrade, Serbia from Belgrade weather file.

V. RESULTS 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. Figure 6 shows the annual deficit solar fraction versus angle deviation from the optimal position of the solar collector for SDHWS in Belgrade, Serbia. Figure 6 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 solar fraction is lower than that when β_a и γ_a departs above $\beta_{a,opt}$ and $\gamma_{a,opt}$ for $\Delta\beta_a$, respectively $\Delta\gamma_a$. 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 lower than that when β_a и γ_a departs above $\beta_{a,opt}$ and $\gamma_{a,opt}$ for $\Delta\beta_a$, respectively $\Delta\gamma_a$.

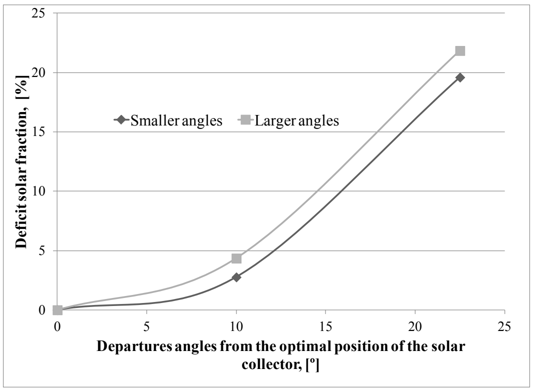

Fig. 6 - Deficit solar fraction versus departures angles from the optimal position of the solar collector for SDHWS in Belgrade, Serbia

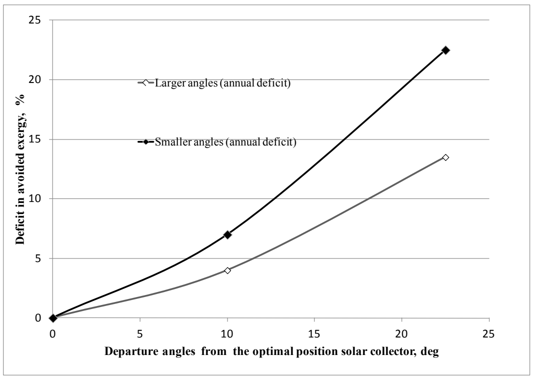

Fig. 7 - Deficit avoided exergy versus departures angles from the optimal position of the solar collector for SDHWS in Belgrade, Serbia

VI. 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 the reduction of the solar fractions, as well as a deficit of avoided exergy in the case when the solar collector are not at its optimal position.

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