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Maximizing performances of variable tilt flat-plate solar collectors for Belgrade (Serbia)

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In Serbia, for heating of domestic hot water (DHW) it is customary to use electricity. As around 70% of electricity is produced by using low quality coal with high greenhouse emission, it is beneficial to environment to use solar energy by flat-plate solar collectors for heating of DHW in a solar DHW system (SDHWS). The SDHWS with variable tilt flat-plate solar collectors placed in north-south direction at roofs of houses are investigated for their optimal operation in Belgrade, Serbia. The investigated variable-tilt collectors annually take 2 tilts, 4 tilts, and 12 tilts. The used weather data are from the meteorological station. These investigations use three computer codes: EnergyPlus, GenOpt, and Hooke-Jeeves search algorithm. For different solar collectors, the investigations revile their optimum tilts that maximize the solar fraction by the SDHWS. Then, the solar fraction and avoided fossil energy by the SDHWS are maximized. In addition, the deficit in the solar fraction is estimated when the solar collectors are not at their optimum tilt. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4819254]

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, instead by fossil fuels, the part of energy needs is satisfied by using non-polluting energy sources such as solar energy. 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 domestic hot water (DHW) is used for shower, tap, cloths-washing, and dish-washing. It is customary to use electricity for heating of DHW. As around 70% of electricity is produced by using low quality coal with high greenhouse emission, it is important and the most rewarding to use solar energy for DHW heating instead of electricity. Accordingly, in Serbia and worldwide, the most rewarding application of solar energy is that it replaces electricity 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 electricity and avoided fossil energy may be expected.

During its operation, the solar collector in some solar DHW system (SDHWS) has to take the optimal position to generate the highest amount of heat. The solar collector takes the north-south direction. Usually, the solar collector with only one optimal tilt during the year is used in practice, which is called stationary solar collector. Here, the variable tilt flat-plate solar collectors are investigated to enhance performance of stationary solar collectors. The investigated solar collectors are SC#2 (solar collector annually taking 2 tilts), SC#4 (solar collector annually taking 4 tilts), and SC#12 (solar collector annually taking 12 tilts). These tilts should be

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determined to be optimal and yield the highest amount of heat that will avoid electricity consumption.

Most of researchers investigated the optimum tilt for the solar collectors without taking into account that it is part of the entire SDHW. Consequently, the optimum tilt is determined for maximum amounts of different types of incident solar radiation on the solar collector: extraterrestrial,[2] global (the measured data),[3–6] global and diffuse (measured data),[7] and direct.[8] Furthermore, the optimal tilt is determined regarding the sunshine duration.[9] Some researchers optimized the solar collector tilt through the response of the SDHWS (the maximum solar fraction).[10,11] This literature shows that most of researchers investigated the optimum tilt for the stationary solar collector and the solar collector annually taking 12 tilts. However, they rarely studied variable-tilt flat-plate solar collectors performing in Serbia that annually take 2 and 4 optimal tilts. In this investigation, the tilts are also optimized through the response of the SDHWS as it is performed in Ref. 10. However, to stress that in Serbia the obtained heat in such an installation avoids use of electricity, the optimal tilt is obtained when the SDHWS achieves the maximum of the solar fraction. However, it is clear that in this case the solar fraction has the same value as solar fraction.

This paper reports an investigation of the energy performance for variable tilt flat-plate solar collectors in Belgrade, Serbia. The investigated solar collectors are SC#2, SC#4, and SC#12. These solar collectors are placed at roofs of houses in north-south direction. The used weather data were from the meteorological station. These investigations use computer codes in EnergyPlus and GenOpt software with the application of Hooke-Jeeves search algorithm. For the different variable tilt SCs, the investigations yield their optimum tilts that maximize the solar fraction, avoided electricity, and avoided fossil energy by the SDHWS. In addition the research will study the deficit in the solar fraction when the tilt in practice is not optimal. After that the values of the avoided electricity are compared for all cases in order to show the real need for SC#2, SC#4, and SC#12 in practice.

II. MODELLING AND SIMULATION

In these investigations, simulations and optimizations are performed. The simulations use EnergyPlus software. The optimizations use an optimization routine that is specially programmed around GenOpt computer code with implementation of the Hooke-Jeeves search algorithm.

A. Simulation software—EnergyPlus

In this study, the building energy simulation software EnergyPlus (Version 7.0) is used to predict solar energy and electricity use in solar installation for heating of DHW in several cities in Serbia. Then, the solar fraction is determined for its different design, installation, and operation parameters. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA.[12] 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.[13] 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.[14]

Modeling of the SDHWS in EnergyPlus requires models of different components embedded in EnergyPlus such as that of flat-plate solar collector, storage tank, tempering valve, and instantaneous water heater. Water in the storage tank is heated by solar energy and water in the instantaneous water heater by electricity.

B. GenOpt software

GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program.[15] 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.[16] 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.

C. Optimization algorithm

For optimization, the Hooke-Jeeves algorithm is used together with EnergyPlus simulation. These two programs are connected together by using GenOpt software.[15] In this research, the adaptive precision Hooke-Jeeves algorithm is used. Hooke-Jeeves algorithm is a derivative free optimization and direct search algorithm.[17–19] In direct search methods, only the objective functions and the constraint values are used to guide the search strategy.[18,19] The used Hooke-Jeeves algorithm is the adaptive precision algorithm. This algorithm progressively increases 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.

It should be recognized that the parametric runs may give the results because the optimization with one independent variable is performed; however, the Hooke-Jeeves algorithm gives more accurate result for the tilt that yields the maximum of f. Also, it is understood that the difference in f obtained by the both methods can be neglected.

III. MATHEMATICAL MODEL

This part of the paper provides the mathematical model used in EnergyPlus to simulate the energy behavior of SDHWS and its different parts: the flat-plate solar collector, thermal tanks (storage & heaters), tempering valve, and SDHWS-control devices.

A. EnergyPlus model for SDHWS

The SDHWS heats DHW by using solar and electricity. The DHW is used for sink, bath, shower, dish washing and cloth washing. The SDHWS is schematically shown in Figure 1 in EnergyPlus. The SDHWS consists of the following main elements explained separately in the

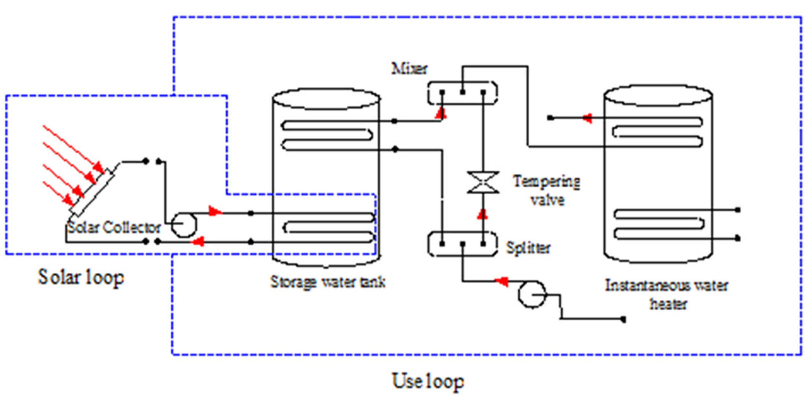

FIG. 1. Schematics of SDHWS model for heating of DHW.

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 to capture solar energy. The use loop is to consume DHW. 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. The solar energy heats water that flows through the solar collector. Furthermore, this hot water heats DHW in the storage water tank. Directly from water supply network in the use loop, the water reaches the splitter. From the splitter, the domestic water may go to the storage water tank or to the tempering valve. In the storage water tank, the domestic water 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 domestic water through the tempering valve. If this water temperature is lower than the needed DHW temperature, this water is heated by electricity in the instantaneous water heater to the needed DHW temperature.

B. Solar collector

1. Surface geometry

The solar collector described by vertices 1, 2, 3, and 4 with its supporting construction is placed to the building roof (Figure 2). The solar collector faces south. The solar collector is rectangular in shape with its length designated as (a) and its width as (b). The solar collector height is designated as h_{12}. Its tilt angle (β) is the angle between the Z-axis and the normal to its surface (or between its surface and the horizontal). The assumed convention is that $-90° < \beta < 90°$. The surface with positive β faces south and with negative β faces north.

2. Thermal performance

The thermal efficiency of a solar collector is defined as the ratio of the useful heat gain of the solar collector fluid versus the total incident solar radiation on the gross surface area of the solar collector

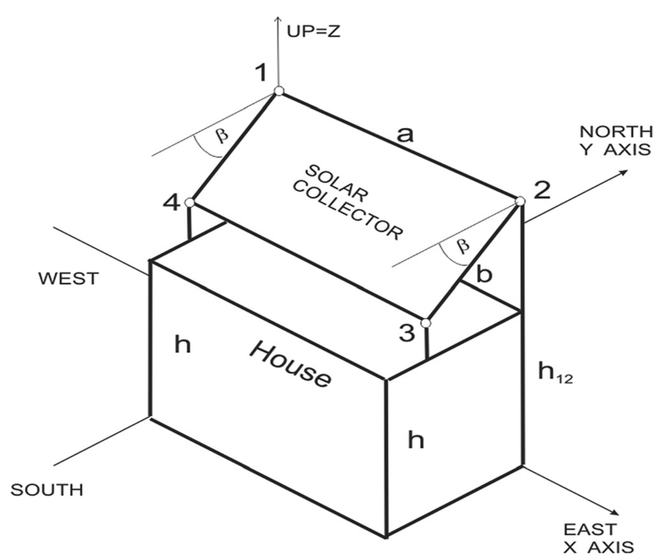

FIG. 2. The simple house model with the solar collector designated as 12341 at the house roof.

$$\eta = (q/A)/I_{\rm solar} = c_0 + c_1(T_{\rm in} - T_{\rm air})/I_{\rm solar} + c_2\,(T_{\rm in} - T_{\rm air})^2/I_{\rm solar}. \quad (1)$$

Here, q stands for the useful heat gain, A stands for the gross area of the solar collector, and $I_{\rm solar}$ stands for the total incident solar radiation. Note that η is only defined for $I_{\rm solar} > 0$. For η, the quadratic correlation is used where c_0, c_1, and c_2 are coefficients obtained by investigation for each used solar collector. Here, $T_{\rm in}$ stands for the temperature of the water entering the solar collector and $T_{\rm air}$ stands for the temperature of outside air.

3. Incident angle modifiers

The transmittance of the solar collector glazing varies with the incidence angle of radiation. Usually the transmittance is highest when the incident radiation is normal to the glazing surface. The test conditions determine the efficiency coefficients for the normal incidence. For off-normal angles, the transmittance of the glazing is modified by the incident angle modifier coefficient. Its relationship is fit to a second-order, quadratic correlation

$$K_{\tau\alpha} = 1 + b_0[(1/\cos\theta) - 1] + b_1[(1/\cos\theta) - 1]^2. \quad (2)$$

The incident angle modifier coefficients b_0 and b_1 are usually negative. They are obtained by measurement for each used solar collector. The obtained coefficients are only valid for incident angles of 60° or less. Then, the EnergyPlus model cuts off solar collector gains for the incident angles greater than 60°.

4. Investigated solar collector

The used solar collector AE-32 is manufactured by Alternate energy technologies. Its gross area is 8.892 m^2. Test fluid is water with the test flow rate 0.0002328 m^3/s. Test correlation type is inlet. The coefficients of the efficiency equation are $c_0 = 0.691$, $c_1 = -3.396$ W/m^2 K, $c_2 = -0.00193$ W/m^2 K^2. The coefficients of the incident angle modifier are $b_0 = -0.1939$ and $b_1 = -0.0055$.

C. Storage water tank

The storage water tank stores thermal energy in water. EnergyPlus provides a model that simulates a storage water tank (as a well-mixed water tank). It has volume of 0.75 m^3, UA = 5 W/K, its ambient temperature = 22 °C, and heat exchangers effectiveness = 1. The water supply temperature to the tank is the water mains temperature (T_{mains}) that is a function of outdoor climate conditions and varies with time of year. A correlation is used to predict this temperature based on two weather inputs: $T_{out,avg}$ = (dry-bulb) average annual outdoor air temperature, and $\Delta T_{out,maxdiff}$ = maximum difference in monthly average outdoor air temperatures[22]

$$T_{mains} = (1.8\,T_{out,avg} + 38) + {\rm ratio}((1.8\Delta T_{out,{\rm max}diff} + 32)/2)\ \sin[0.986({\rm day} - 15 - {\rm lag}) - 90], \quad (3)$$

where day = Julian day of the year (1–365), ratio = 0.4 + 0.01 (1.8 $T_{out,avg}$ − 12), and lag = 35 − (1.8 $T_{out,avg}$ − 12). Values for $T_{\rm out,avg}$ and $\Delta T_{\rm out,maxdiff}$ are easily calculated from annual weather data using a spreadsheet. For the Belgrade, $T_{\rm out,avg}$ = 9.69 °C and $\Delta T_{\rm out,maxdiff}$ = 28.1 °C.

D. Tempering valve

The tempering valve is useful when the water in the storage water tank becomes warmer than is necessary for safe use of the DHW. Then, the tempering valve diverts the cold water flow through its branch to adjust the temperature of DHW at the outlet of the mixer (see Figure 1).

E. SDHWS controls

By using several temperature controls inside the installation, the control equipment manages the SDHWS. These controlled temperatures are inside the solar and use loop. The solar loop has the following controlled temperatures: the loop temperature (60 °C), the high temperature turn off (60 °C), the high temperature turn on (0 °C), the temperature difference on limit (differential thermostat) (10 °C), and the temperature difference off limit (differential thermostat) (2 °C). The use loop has the following controlled temperatures: the hot water set-point temperature (50 °C) and the maximum temperature limit for storage tank (82.2 °C).

IV. SIMULATION AND OPTIMIZATION

To run simulations and optimizations, it is necessary to know the hot water consumption and climate.

A. Hot water consumption

This installation generates four types of DHW: that of tap, shower, dish-washer, and cloth-washer. Figure 3 provides DHW characteristics: temperatures, maximum flow rates and daily schedules that may be valid for family of four in Serbia. Regarding its applications, the DHW would be heated to two temperatures: 43.3 (tap and shower) and 50 °C (dish and clothes washer). For DHW with lower temperature and for DHW with higher temperature used in dish washer, the daily schedule is the same for each day throughout entire year. The cloth washer operates only on Sunday. For DHW with higher temperature used in the cloth washer, the daily schedule is the same for each Sunday throughout the entire year.

B. Climate

The investigated SDHWS is located in the city of Belgrade in Balkan Peninsula in the state of Serbia. Its height is 99 m, latitude N 44.82, and longitude E 20.27. The meteorological data

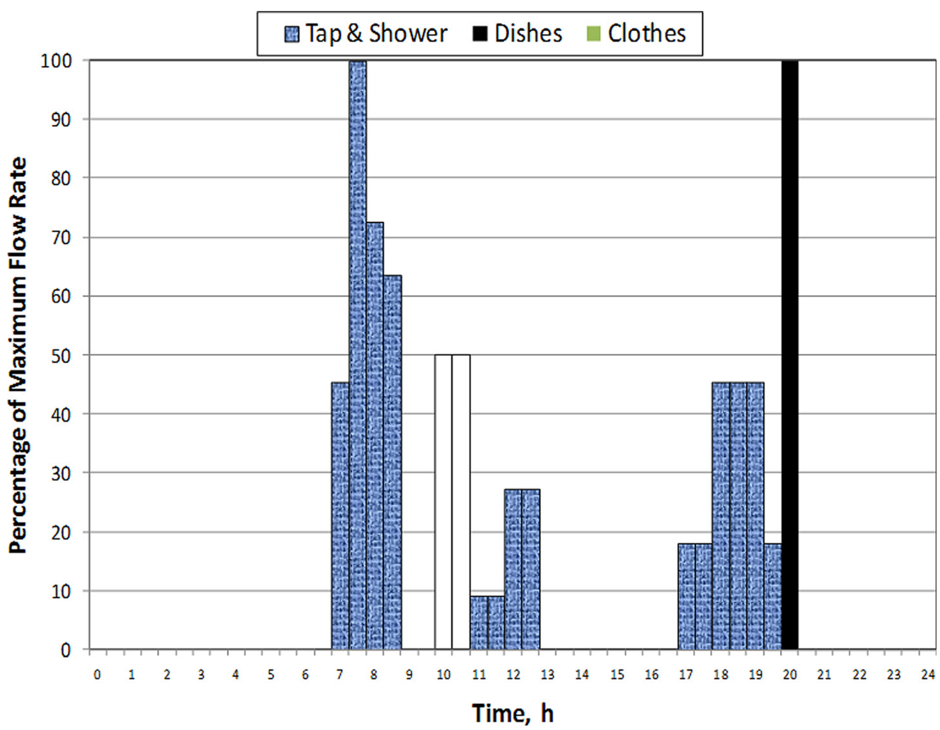

FIG. 3. Schedule of DHW use for (a) tap and shower (0.0000945 m^3/s maximum with 43.3 °C) (b) dish and clothes washer (0.000063 m^3/s maximum with 50 °C). Dish-washer operates daily, while cloth washer on Sundays.

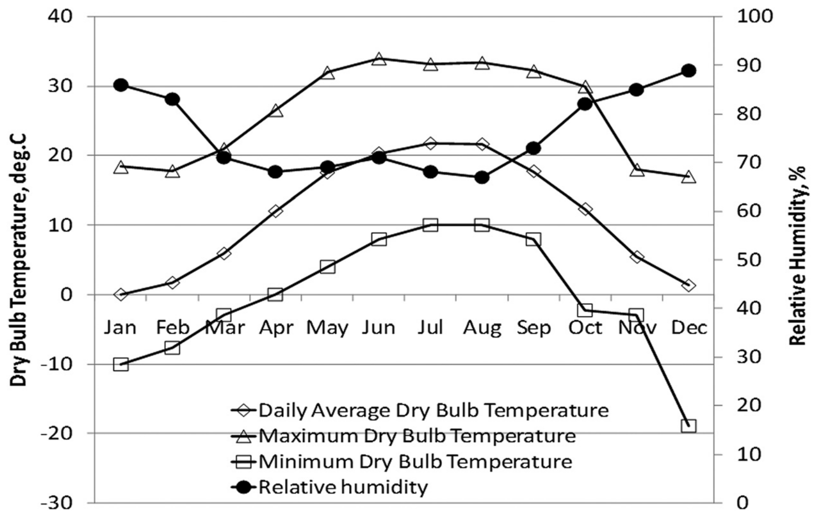

FIG. 4. Relative humidity and dry bulb temperature (minimum, daily average, and maximum) from the monthly statistics for Belgrade, Serbia from the Belgrade weather file.

are measured by the meteorological station designated by World Meteorological organization as 132720.[20] The metrological data for Belgrade used in this paper are the ASHRAE International Weather data for Energy Calculations (IWEC). They are used in the form of EnergyPlus weather files with hourly data.

To familiarize with the Belgrade climate, Figures 4 and 5 are given by using monthly statistics for the Belgrade weather file. For each month during entire year, Figure 4 gives the dry bulb temperature (minimum, daily average, and maximum), and relative humidity. For each month during entire year, Figure 5 shows the 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 warm and humid, with temperatures as high as 34 °C. The winters are cool and snowy, with temperatures as low as −19 °C. The collectors are protected from freezing by using adequate glycol water solution as heat carrier inside them.

C. SDHWS simulation and optimization procedure

To study the SDHWS, EnergyPlus software is used to simulate its operation and the Hooke-Jeeves algorithm to optimize its performance. The SDHWS is simulated for different

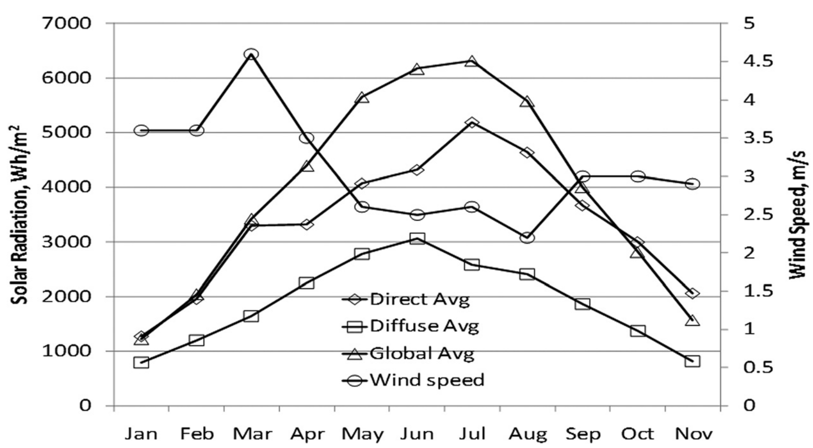

FIG. 5. Direct, diffuse, and global average solar radiation, and daily average wind speed from the monthly statistics for Belgrade, Serbia from the Belgrade weather file.

continual runs that may last 1, 3, and 6 months. During each continual run, the SDHWS will have the solar collector with one value for its tilt β_i. Here, "i" designates the run duration. If the run lasts one month i = m, three months i = q, and six-months i = h.

EnergyPlus calculates the electricity consumption by the SDHWS during its run. The obtained results are $E_{i,e}$ and $E_{i,tot}$. The variable $E_{i,e}$ is the electricity consumed by the SDHWS if the solar collector exists.

As variable $E_{i,e} = E_{i,hr} + E_{i,wp}$, the electricity is consumed by the electric heater to heat the DHW ($E_{i,hr}$) and by the circulation pump to run water inside the solar loop ($E_{i,wp}$). The variable $E_{i,tot}$ is the electricity consumed by the electric heater to heat DHW if the solar collector does not exist. Energy $E_{i,s} = E_{i,tot} - E_{i,hr}$ represents the generated heat from the solar energy that heats DHW instead of the electricity from the electrical network. Consequently, $E_{i,s}$ represents the amount of electricity 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 electricity designated as $E_{i,ae} = E_{i,s}$. This means that other needs for electricity may be covered by using electricity without constructing new generating capacities for electricity based on the fact that electricity is replaced by the solar-origin heat.

The amount of the avoided (use of) fossil energy by the electricity network is also proportional to the avoided electricity as $E_{i,af} = C_f E_{i,ae}$, where C_f stands for the fossil fuel energy factor.

The performance of the SDHWS is evaluated by calculating the solar fraction (f_i). This is the objective function used by the Hooke-Jeeves algorithm that should be maximized,

$$f_i = 100(E_{i,tot} - E_{i,ae})/E_{i,tot} = f(\beta_i). \quad (4)$$

If f_i is larger, the SDHWS better protects the environment. The variable f_i also represents the solar fraction and avoided fossil energy fraction. Variable f_i is a function of tilt β_i. It should be maximized in the constrained region of β_i. As a result of the optimization, we obtain the maximum solar fraction ($f_{i,max}$) and the optimum tilt ($\beta_{i,opt}$). Figure 6 shows how f_i and β_i approach to $f_{i,max}$ and $\beta_{i,opt}$ with number of iterations.

Each solar collector that stays at $\beta_{i,opt}$ generates the highest amount of heat $(E_{i,s})_{max}$ from the incident solar energy. Then, the SDHWS uses this heat for the DHW heating instead of the electricity from the electricity network. This means that such a SDHWS avoids use of the highest amount of electricity from the electricity grid for the DHW heating. In addition, this avoids the highest amount of electricity generation by the national power plants.

If the SC does not stay at the optimum tilt due to some reason, then it will generate smaller amount of heat for the DHW heating than the maximum amount it would generate when it

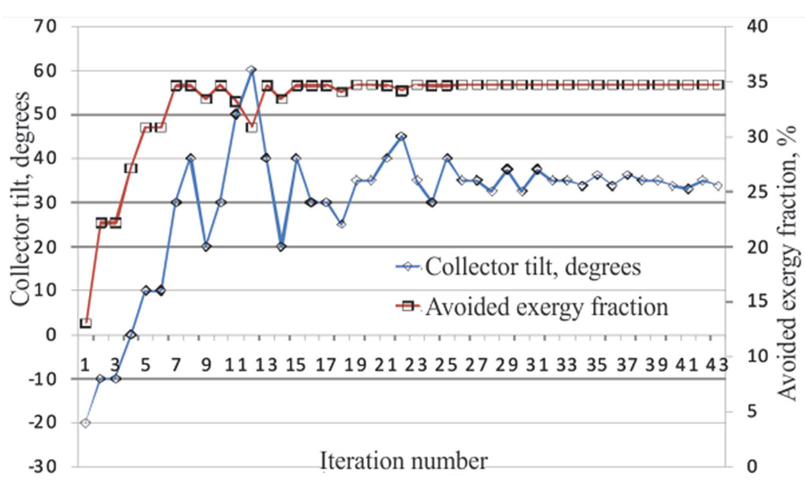

FIG. 6. History of f_i and β_i with the iteration number.

stays at the optimum tilt. As the heating of DHW uses the electricity, the solar collector will use more electricity for the DHW heating than that when the SC has its optimum tilt. This means that the solar collector will lose the electricity. For this case, the deficit in solar fractions defined as

$$D_i = 100(f_i - f_{i,max})/f_{i,max}. \quad (5)$$

V. RESULTS AND DISCUSSION

The paper reports the investigations of SDHWS with SC#2, SDHWS with SC#4, and SDHWS with SC#12. Note that in the text, Latin numerals represent the months such as I (January), II (February), III (March), IV (April), V (May), VI (June), VII (July), VIII (August), IX (September), X (October), XI (November), and XII (December).

A. SDHWS with SC#2

The SC#2 is the solar collector would operate by using two tilts $\beta_{q,opt}$ per year - one tilt per six months. The SC#2 would operate at one $\beta_{h,opt}$ from 15th October to the 14th April, and at other $\beta_{h,opt}$ from the 15th April to the 14th October.

In Figure 7, two curves (designated as X-IV and IV-X) refer to the SDHWS with SC#2. Each curve represents the solar fraction f_h by the SDHWS as a function of SC#2 tilt β_h. The curve X-IV refers to the operation of SC#2 from 15th October to the 14th April (182 days). The curve IV-X refers to the operation of SC#2 from the 15th April to the 14th October (183 days). Each curve has its maximum value of f_h (labeled as $f_{h,max}$ furthermore in the text) at $\beta_{h,opt}$. If the SC#2 does not have $\beta_{h,opt}$, $f_h < f_{h,max}$. The curves in Fig. 7 are made by using the calculated results (f_h vs. SC#2 tilt β_h) during the approaching procedure to the optimum solution guided by Hooke-Jeeves optimization algorithm. Value of $f_{h,max}$ is obtained by using this procedure as the result of the Hooke-Jeeves optimization algorithm; however, these curves are given to assess discrepancy f values when the tilt is different from the optimal tilt.

For the city of Belgrade, during the first period (that includes winter months), the SC#2 has $\beta_{h,opt} = 48.8°$ and the SDHWS has $f_{h,max} = 19.3\%$. During the second period (that includes the summer months), the SDHWS has $f_{h,max} = 50.9\%$ with $\beta_{h,opt} = 26.9°$. During the second

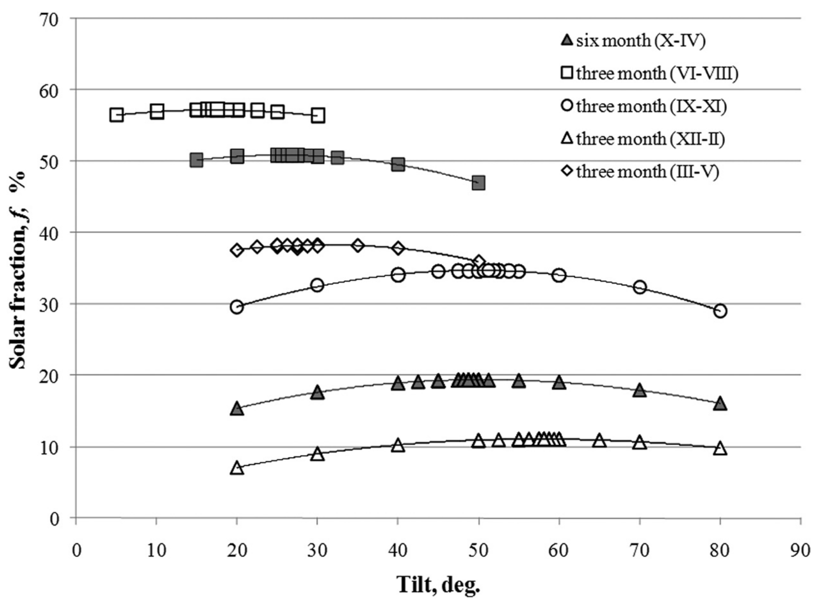

FIG. 7. The solar fraction as a function of the tilt of SC#2, and SC#4 in Belgrade.

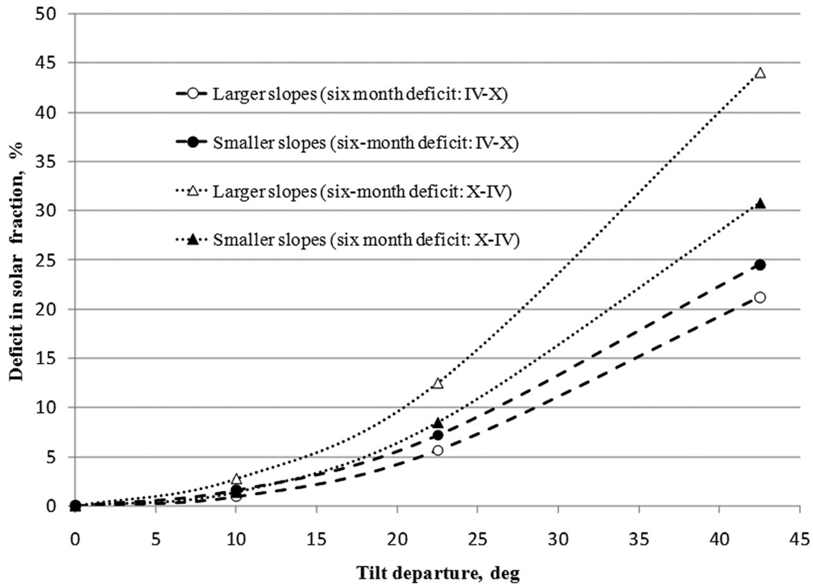

FIG. 8. Deficit in solar fraction vs the tilt departure from the optimum tilt for Belgrade, Serbia. The diagrams are given for SC#2. IV-X stands for 15th April to 14th October and X-IV stands for 15th October to 14th April.

period, $\beta_{h,opt}$ is 21.9° lower than that during the first period, and $f_{h,max}$ is around 2.6 times higher than that during the first period.

For the SC#2 for period IV-X, Figure 8 shows that when β_h departs below $\beta_{h,opt}$ for $\Delta\beta_h$, the solar fraction is lower than that when β_h departs above $\beta_{h,opt}$ for $\Delta\beta_h$. For $\Delta\beta_h = 10°$, the deficit in the solar fraction is around 2% for the both cases. For $\Delta\beta_h = 42°$, the deficit in the solar fraction is around 25% for the departure of β_h below $\beta_{h,opt}$, while for the deficit in the solar fraction is around 21.5% for the departure in β_h above $\beta_{h,opt}$.

For the SC#2 for period X-IV, Figure 8 shows that when β_h departs below $\beta_{h,opt}$ for $\Delta\beta_h$, the lost six-month amount of the solar fraction is lower than that when β_h departs above $\beta_{h,opt}$ for $\Delta\beta_h$. For $\Delta\beta_h = 10°$, the deficit in the solar fraction is around 3% for the both cases. For $\Delta\beta_h = 42°$, the deficit in the solar fraction is around 31% for the departure of β_h below $\beta_{h,opt}$, while for the deficit in the solar fraction is around 44% for the same departure in β_h above $\beta_{h,opt}$.

B. SDHWS with SC#4

For the SC#4, the four curves (one for each period) are shown in Figure 7 for Belgrade. The curves represent f_q as a function of β_q of the solar collector. Each curve has its maximum value that corresponds to $\beta_{q,opt}$ and $f_{q,max}$ of the SDHWS.

The SC#4 takes four tilts per year - one tilt per three months. It means that it would operate with four $\beta_{q,opt}$ during year. The SC#4 would operate with one $\beta_{q,opt}$ during period XII-II (90 days from 1st December to 28th February), with other $\beta_{q,opt}$ during period III-V (92 days from 1st March to 31th May), with other $\beta_{q,opt}$ during period VI-VIII (92 days from 1st June to 31th August), and with other $\beta_{q,opt}$ during period IX-XI (91 days from 1st September to 30th November). During the period XII-II, the SDHWS would produce $f_{q,max}$ of 11.1% with $\beta_{q,opt}$ of 58.1°. During the period III-V, the SDHWS should produce $f_{q,max}$ of 38.2% with $\beta_{q,opt} = 26.9°$. During the period VI-VIII, the SDHWS should produce $f_{q,max} = 57.3\%$ with $\beta_{q,opt} = 17.5°$. During the period IX-XI, the SDHWS should produce $f_{q,max} = 34.7\%$ with $\beta_{q,opt} = 51.2°$. It can be noted that during period VI-VIII, $\beta_{q,opt}$ is 40.6° smaller and $f_{q,max}$ is around 5.16 times larger than that during period XII-II.

For the SC #4, the four curves (one for each period) are shown in Figure 7 for Belgrade. The curves represent f_q as a function of β_q of the solar collector. Each curve has its maximum value that corresponds to $\beta_{q,opt}$ and $f_{q,max}$ of the SDHWS.

TABLE I. The deficit in solar fraction for different three month periods and for the tilt departure of $|\beta - \beta_{opt}| = 42°$ for SC#4 in Belgrade, Serbia.

			Deficit in solar fraction (%)	
Periods	Optimum tilt (deg)	Optimum solar fraction (%)	β_q departs below $\beta_{q,opt}$	β_q departs above $\beta_{q,opt}$
XII-II	60	11.2	37.6	45.3
III-V	27.5	44.5	29.3	27.9
VI-VIII	27.5	57.1	16.0	16.3
IX-XI	51.2	34.1	34.3	27.0

The deficit in the solar fraction for all periods is given in Table I for the β_q departure of 42° from $\beta_{q,opt}$ for the SC#4 in Belgrade, Serbia. For the period IX-XI, the deficit in the solar fraction is higher when β_q departs below $\beta_{q,opt}$ than that when β_q departs above $\beta_{q,opt}$ for 42°. For the period XII-II, the situation is opposite. For the periods III-V and VI-VIII, the deficit in the solar fraction is almost the same when β_q departs either below or above $\beta_{q,opt}$ for 42°. The angle of 42° is selected arbitrarily in order to obtain high enough values of discrepancies in f to differentiate them for the use of solar collector in different seasons.

C. SDHWS with SC#12

The SC#12 annually takes twelve tilts - one tilt $\beta_{m,opt}$ per each month. Then, $\beta_{m,opt}$ generates the monthly maximum amount of heat from the solar energy to obtain $f_{m,max}$. In Fig. 9, the maximum solar fraction is given as a function of the optimum tilt for each month. This figure is designed in this way to give a design energy signature for this collector. Figure 9 shows that the range of $\beta_{m,opt}$ is between 11° (for the summer month of June) and 64° (for the winter month of December). The maximum annual difference in $\beta_{m,opt}$ is 53°. The $f_{m,max}$ is between 59% (in the summer month of August) and 8% (in the winter month of December). This means that $f_{m,max}$ in August is around 51% higher than that in December.

For the SDHWS with SC#12 operating in Belgrade, twelve curves (are given in Figure 10. The curves represent the solar fractions that will be obtained if SC#12 takes different tilts during its application. Each curve is given for each month. The curves in Fig. 10 are obtained by

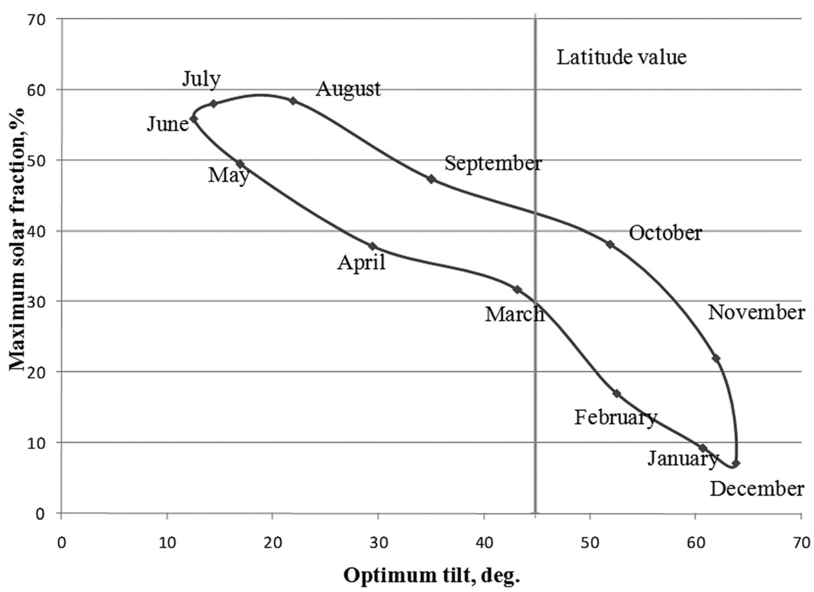

FIG. 9. The monthly β_{opt} of the solar collector and the monthly f_{max} in Belgrade, Serbia, for SDHWS with SC#12.

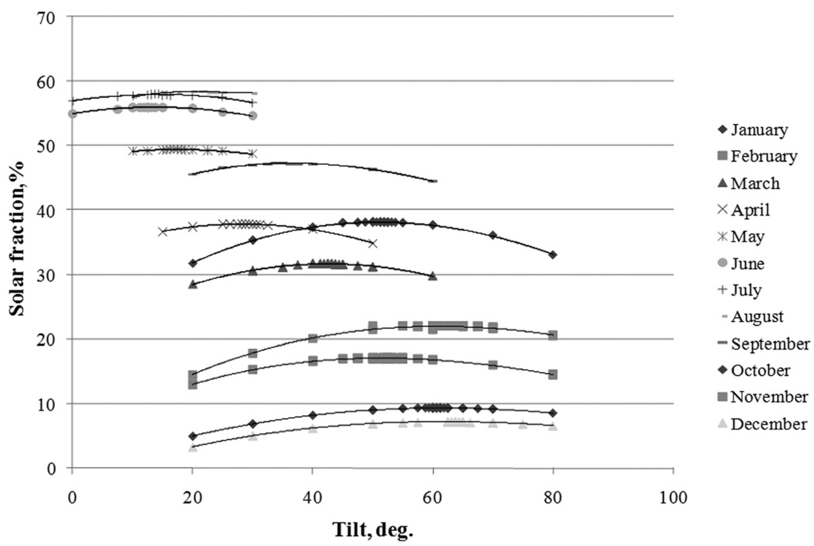

FIG. 10. The solar fraction as a function of the solar collector tilts for the SC#12 in Belgrade. Then, the solar collector surface is directed south-north.

using the calculated results (f_h vs. *tiltangle* β_h of collector SC#12) during the approaching procedure to the optimum solution guided by Hooke-Jeeves optimization algorithm. If the collector SC#12 does not take the optimum tilts during its application, lower amount of electricity will be avoided by the SDHWS.

For the SDHWS with the SC#12 in Belgrade, Serbia, Figure 11 shows the deficit in the solar fraction for the situation that the tilt of the SC#12 during some month is either higher or lower than β_{opt} by 42°. There are two situations. (1) For the months of January, February, May, June, August, September, and December, when β is higher than β_{opt} by 42°, the deficit in the

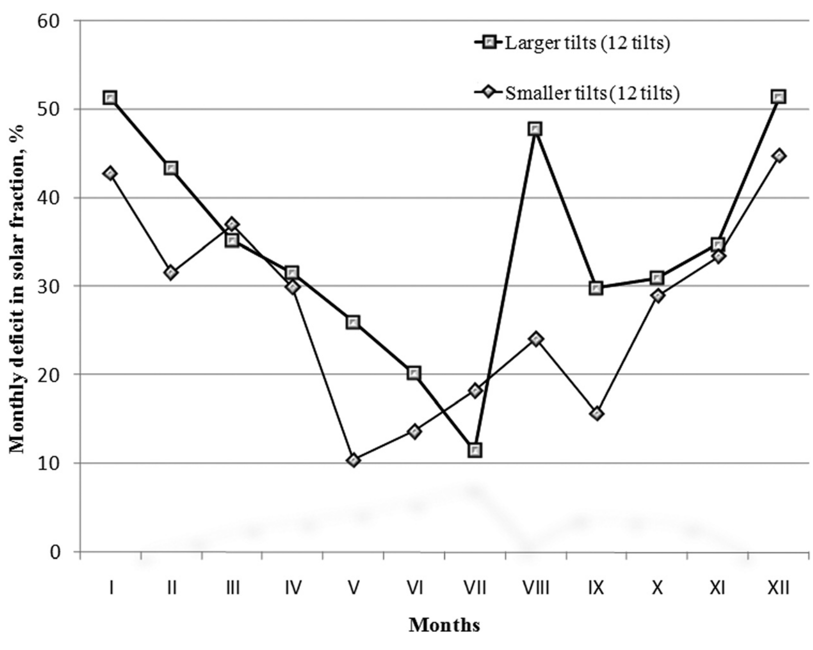

FIG. 11. The deficit in solar fraction for the tilt departure of $|\beta - \beta_{opt}| = 42°$ as a function of month for the SDHWS with SC#12 in Belgrade, Serbia.

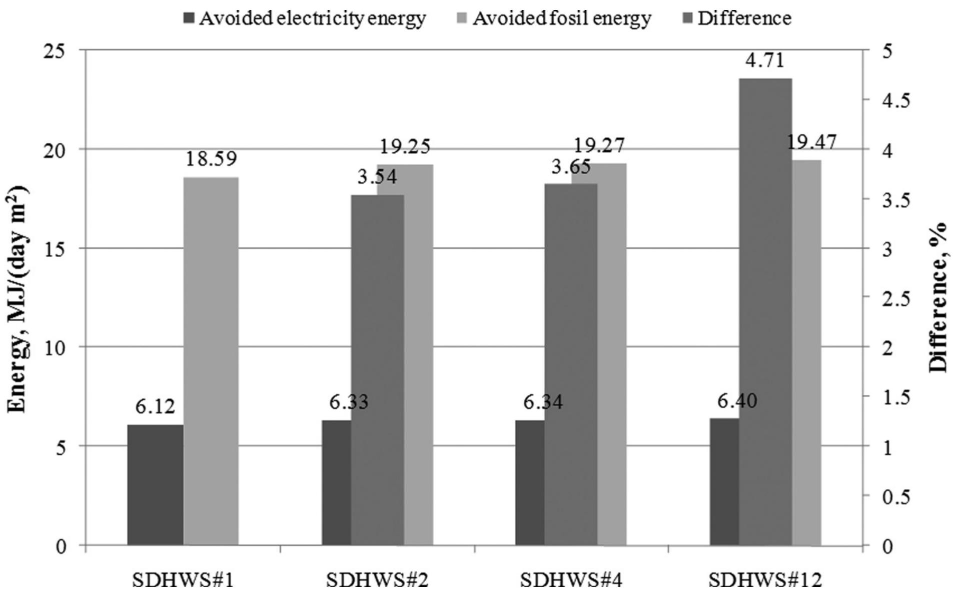

FIG. 12. Maximum annual amounts of avoided electricity, and avoided fossil energy for different SCs for Belgrade. Also, the difference of these variables compared to the stationary solar collector is given.

solar fraction is higher than that when β lower than β_{opt} by 42°. The highest difference in the deficit of around 24% exists for the month VIII. For the months of XII, I, and VIII, when β_m is higher than β_{opt} by 42°, the highest deficit in f of about 50% exists. (2) For the month of July, when β is higher than β_{opt} by 42°, the deficit in the solar fraction is lower than that when β lower than β_{opt} by 42°. (3) For the months of March, April, October, and November, the deficit in the solar fraction is the same as when β_m departs either above or below β_{opt}.

D. Comparison between different SCs

During their operation, the SDHWS with different SCs may generate different amounts of heat from solar energy. This may result in different amounts of avoided electricity, and avoided fossil energy.

Maximum annual amounts of avoided electricity, and avoided fossil energy for different the SDHWS is given in Figure 12 for their application in Belgrade. The fossil energy factor $C_f = 3.04$ is estimated from Ref. 21. Also, this figure gives the annual difference in the maximum annual avoided electricity of different SDHWS and that SDHWS with the stationary solar collector. The investigated SDHWS with SC#1 is the stationary solar collector that yearly operates at one tilt. The values of $\beta = \beta_{opt} = 37.5$ and corresponding $f = f_{max} = 32.9$ are given for Belgrade.

For the SC#2, the amount of the avoided electricity is 3.54% higher than that by the stationary solar collector. For the SC#4, the amount of the avoided electricity is 3.65% higher than that by the stationary solar collector. For the SC#12, the amount of the avoided electricity is around 4.75% higher than that by the stationary solar collector. Taking into account these data, it may be promising to construct the SC#2 instead of the stationary solar collector. The SC#4 and SC#12 do not generate much more avoided electricity than the SC#2. In these analyses, the cost of tracking is not taken into account.

Almost the same comments relate to the maximum avoided fossil energy as this variable is proportional the avoided electricity.

VI. CONCLUSION

This paper reports the investigation of three SDHWS that have different types of collectors (SC#2, SC#4, and SC#12) in Belgrade, Serbia. SC#2 annually takes 2 tilts; SC#4 annually takes

4 tilts; and SC#12 annually takes 12 tilts. These solar collectors are placed in north-south direction at roofs of houses. The optimum tilts of these solar collectors are found. For this research, EnergyPlus software and Hooke-Jeeves search algorithm in GenOpt software serve using weather data from the meteorological stations. For the different SDHWSs, the investigations yield the optimum tilts of their solar collectors that maximize the avoided electricity. The following results are reported.

Regarding SC#2 during period IV-X, it is found that the $\beta_{h,opt}$ is 21.9° lower and the $f_{h,max}$ is around 2.6 times higher than that during period X-IV. For period IV-X, when β_h decreases below $\beta_{h,opt}$ for $\Delta\beta_h$, the deficit in the solar fraction is smaller than that when β_h increases above $\beta_{h,opt}$ for $\Delta\beta_h$. The opposite is valid for period X-IV.

Regarding SC#4 during period VI-VIII, it is found that $\beta_{q,opt}$ is 40.6° lower and $f_{q,max}$ is around 5.16 times larger than that during period XII-II. For period IX-XI, the deficit in the solar fraction is higher when β_q decreases below $\beta_{q,opt}$ for $\Delta\beta_q$ than that when β_q increases from $\beta_{q,opt}$ for $\Delta\beta_q$. For period XII-II, the situation is opposite. For periods III-V and VI-VIII, the deficit in the solar fraction is almost the same as when β_q either increases or decreases from $\beta_{q,opt}$ for $\Delta\beta_q$.

Regarding SC#12, the maximum difference in the monthly $\beta_{m,opt}$ annually is 53°. The $f_{m,max}$ in August is around 51% higher than that in December. When β_m departs above $\beta_{m,opt}$ for $\Delta\beta_m$, the lost amount of the solar fraction is higher than that when β_m departs below $\beta_{m,opt}$ for $\Delta\beta_m$ for the months: January, February, May, June, August, September, and December. For the month of July, when β_m departs below $\beta_{m,opt}$ for $\Delta\beta_1$, the lost amount of the solar fraction is higher than that when β_m departs above $\beta_{m,opt}$ for $\Delta\beta_m$. For the months of March, April, October, and December, the lost amount of the solar fraction is the same as when β_m departs either below or above $\beta_{m,opt}$ for $\Delta\beta_m$.

When SC#2 is used, the avoided electricity is 3.54% higher than that generated by the stationary solar collector, which is slightly lower than that for SC#4 and SC#12. Then, it may be promising to have the SC#2 in SDHWSs in Serbian cities.

In the future research, the cost of tracking as well as energy used to produce tracking device will be taken into account to calculate the optimum tilt for the collectors.

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NOMENCLATURE

A	surface area of the solar collector, m^2
C_f	fossil energy factor, J of the fossil energy per J of the final consumer electricity
c_p	stands for the specific heat of water, J/kg K
D	deficit in avoided electricity, %
$E_{i,e}$	electricity consumed for DHW during period "i," J
$E_{i,tot}$	electricity for DHW heating if SC does not operate during period "i," J
$E_{i,hr}$	Electricity for operation of the heater during period "i," J
$E_{i,s}$	Heat generated from solar energy during period "i," J
E_{wp}	Electricity for operation of the water pump, J f = solar fraction, %
T	temperature of the tank water, °C
t	time, h
V	volume of the tank, m^3
β	tilt, degree
ρ	density of water, m^3/kg
$T_{out,avg}$	average annual outdoor air temperature (dry-bulb), °C

$\Delta T_{out,maxdiff}$	maximum difference in monthly average outdoor air temperatures, °C
T_{mains}	water mains temperature, °C

Indices

a	annually
hr	operation of heater
i	operation duration
m	daily average for each month
m	monthly
h	half-yearly
q	quarterly
max	maximum
t	operation of heater and water pump
wp	operation of water pump

Abbreviations

DHW	domestic hot water
SC	solar collector
SDHWS	system for solar domestic hot water heating

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