OPTIMAL SLOPE OF A SOLAR COLLECTOR USING PARTICLE SWARM OPTIMIZATION ALGORITHM

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Abstract: In Serbia, it is customary to use electricity for domestic hot water heating. As around 70% of electricity is produced by using coal with high greenhouse emission, it is beneficial to environment to use solar energy for domestic water heating. In addition it is important to have the highest possible efficiency of this use that may be obtained for the solar collector placed at its optimal slope. To find the optimum slope, EnergyPlus software is used for modeling solar plant, Particle Swarm Optimization algorithm (PSO) and operation of these two software codes is connected by using Genopt optimization software. This paper reports that the descrepancied in the incident solar radiation (of the solar distribution models) with the applied calculation timestep are multiplied by the applied software when the final results are obtained such as the optimal slope, solar fraction of the installation and electrical energy used in the installation. The appled solar distribution models does not influence to the calculation.

Keywords: Solar Fraction, Storage tank, Solar collector, Collector slope, Timestep, Particle Swarm Optimization algorithm

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.

In Serbia, it is customary to use electricity for operation of solar domestic hot water systems (SDHWS). As around 70% of electricity is produced by using coal with high greenhouse emission, it is important to use solar energy for domestic water heating. In addition it is important to have a high efficiency of this use.

In households, the high amount of domestic hot water (DHW) is used for shower, tap, cloths-washing (machines), and dish-washing (machines). If this water is heated by electricity which is generated by coal burning, then the highest amount of CO_2 is released to atmosphere. Accordingly, the most rewarding application of solar energy is when it replaces this type of electrical energy for heating of hot water in households. Then, the highest decrease in CO_2 emissions may be expected. In renewable energy field, SDHWS have arisen a great research interest [1,2]. To use SDHWS with the greatest benefit, SDHWS must have adequate design, installation, and operation.

To obtain an optimum performance of SDHWS, the operation of the SDHWS may be investigated by using simulation and optimization. Then, the captured solar energy would be determined as a function of a position of the solar collector toward the sun. For energy simulation, EnergyPlus software would be used and for the optimization, Particle Swarm search algorithm (PSO). These two programs would be controlled by using GENOPT software.

This paper explains if there is different time step in calculation of the operation of the solar collector installation when using EnergyPlus with Genopt and Particle Swarm optimization routine how the errors of the solar distribution models reflect the final results such as the optimal slope, solar fraction of the installation and electrical energy used in the installation.

2.   SOFTWARE

Three software codes are used to optimize performance of SDHWS: EnergyPlus for simulation, Particle Swarm search algorithm for optimization, and GENOPT software for software execution control.

Simulation Software - EnergyPlus: In this study, the simulation software EnergyPlus (Version 7.0) was used. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA [3]. 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. 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[4].

To model, the solar hot water heating system in EnergyPlus environment, we used models of different components that are embedded in EnergyPlus such as that of flat-plate solar collector, storage tank, tempering valve, and instantaneous water heater. Water in the storage tank was heated by solar energy and water in the instantaneous water heater by electricity.

Optimization Methodology: Particle swam optimization is a new heuristic optimization method based on swarm intelligence. PSO algorithms exploit a set of potential solutions to the optimization problem. Each potential solution is called a particle, and the set of potential solutions in each iteration step is called a population. PSO algorithms are global optimization algorithms and do not require nor approximate gradients of the cost function. The first population is typically initialized using a random number generator to spread the particles uniformly in a user-defined hypercube. A particle update equation, which is modeled on the social behavior of members of bird flocks or fish, schools, determines the location of each particle in the next generation. [5,6]

Each particle keeps track of its coordinates in the problem space. They are associated with the best solution (fitness) it has achieved so far. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the neighbors of the particle. When a particle takes all the population as its topological neighbors, the best value is a global best.

Compared with the other algorithms, the method is very simple, easily completed and it needs fewer parameters, which made it fully developed.PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms. [7]

In past several years, PSO has been successfully applied in many research and application areas. It is demonstrated that PSO gets better results in a faster, cheaper way compared with other methods.

GENOPT software. GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program [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 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 a library with adaptive Particle Swarm optimization algorithm.

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 Fig.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.
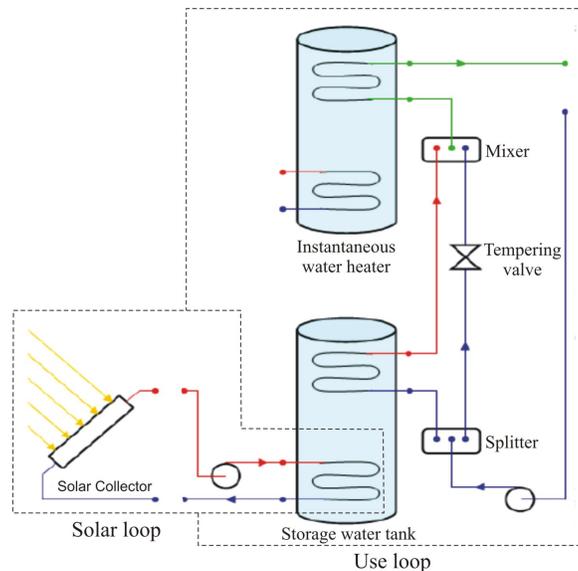

Fig.1 *Schematics of the solar hot-water system for heating of domestic hot water (taken from [9])*

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:

$$f = 100 \ (R-E)/R \tag{1}$$

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. The thermal efficiency of a collector is defined as

$$\eta=(q/A)/I_{solar} \tag{2}$$

where q = useful heat gain, A = $8.89m^2$ 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

$$\eta = c_0 + c_1 \frac{(T_{in} - T_{air})}{I_{solar}} + c_2 \frac{(T_{in} - T_{air})^2}{I_{solar}} \tag{3}$$

Both first- and second-order efficiency equation coefficients from [10] 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:

$$K_{\tau\alpha} = (\tau\alpha)/(\tau\alpha)_n = 1 + b_0(-1+\cos\theta) + b_1 (-1+\cos\theta)^2 \tag{4}$$

The incident angle modifier coefficients b_0= -0.1939 and b_1= -0.0055 are usually negative [10]. 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.

Collector Surface Geometry: Calculations require that the collector surface is described geometrically. Here, the collector is placed to the building roof that is rectangular in shape (see Fig.2). Its size and shape is the same as that of the roof, where the length of the collector is designated as (a) and the width of the collector as (b). The building height is designated as h. Finally, the 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 surface of the solar collector is rectangular and defined by 4 vertices. Vertex 1 has coordinates $x_1=0$, $y_1=0$, $z_1=h$. Vertex 2 has coordinates: $x_2=a$, $y_2=0$, $z_2=h$. Vertex 3 has coordinates: $x_3=a$, $y_3= b \cos \beta$, $z_3 =h + b \sin \beta$. Vertex 4 has coordinates: $x_4 = 0$, $y_4 = b \cos \beta$, $z_4 =h + b \sin \beta$.

The collector is south facing. Its tilt angle (β) is the angle between the Z-axis and the normal to the surface of the collector (or between the 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.

Hot Water Consumption: This installation generates four different types of hot water: that of tap, shower, dish-washer, and cloth-washer. Fig.2 provide hot water characteristics: temperatures, maximum flow rates and daily schedules that may be valid for family of four in Serbia. Regarding its application, the water would be heated to two temperatures: 43.3 (tap
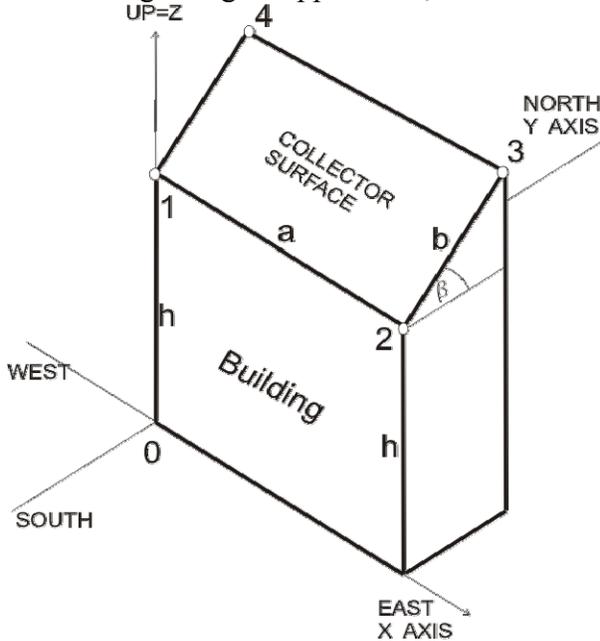
Fig.3 *The buiding with the solar collector at its roof. The surface area of the solar collector 1234 is equal to that of the building roof.*
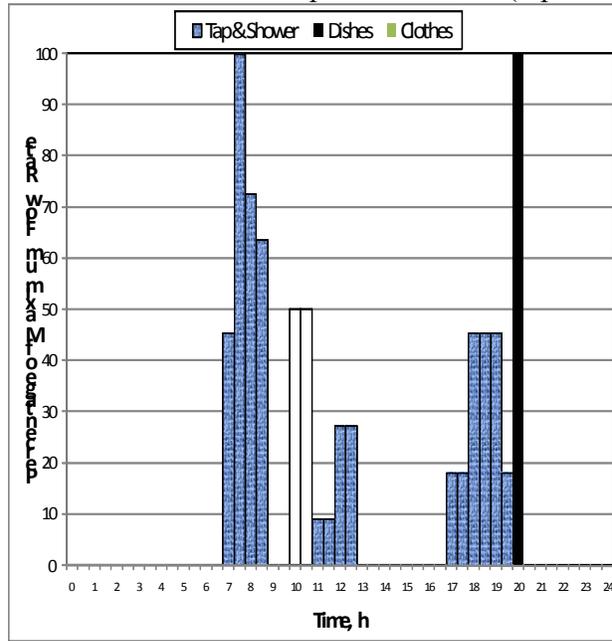

Fig. 2 *Schedule of hot water use for (a) tap and shower, (b) dish and clothes washer.*

and shower with the maximum flow rate of 0.0000945 m³/s) and 50^0C (dish and clothes washer with the maximum flow rate of (0.000063 m³/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.

Thermal tanks (storage & heaters): Water thermal tanks are devices for storing thermal energy in water from solar hot water systems. The input object of EnergyPlus (WaterHeater:Mixed) provides a model that simulates a well-mixed water tank (the thermal tank) with volume of 0.75 m³, and also instantaneous, tankless water heater. The equations that govern these models are given in [10].

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.

SDHWS-Control temperatures for solar loop: To control use of this installation, several temperatures will be supported in the solar loop by using the control equipment inside this

installation. Its maximum flow rate is 0.00006 m3/s. Main parameters of solar heating installation for water loop through the solar collector are the following Loop temperature (T_L=60^{0}C), High temperature turn off in solar loop (60^{0}C), High temperature turn on in solar loop (0^{0}C), Temperature difference on limit (differential thermostat) (10^{0}C), Temperature difference off limit (differential thermostat) (2^{0}C).

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

Climate Calculations: 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). Weather files have hourly or sub-hourly data for each of the critical elements needed during the calculations (i.e., Dry-Bulb Temperature, Dew-Point Temperature, Relative Humidity, Barometric Pressure, Direct Normal Radiation, Diffuse Horizontal Radiation, Total & Opaque Sky Cover, Wind Direction, Wind Speed) as well as some auxiliary data such as Rain or Snow.

Timestep: The timestep object in EnergyPlus specifies the "basic" time-step for the simulation. The value entered here is usually known as the zone timestep. This is used in the zone heat balance model calculation as the driving timestep for heat transfer and load calculations. The value entered here is the number of timesteps to use within an hour. Longer length of time-steps has lower values for number of time-steps per hour.

4.   RESULTS AND DISCUSSION

This paper explains if there is variation in the optimal slope for installation of a solar collector when there is different time step in calculation of the operation of the solar collector installation when using EnergyPlus with Genopt and Particle Swarm optimization routine. As an example, these software tools are applied to SDHWS in Belgrade, Serbia.

This investigation is performed with two solar distribution models: (1) full interior and exterior, (2) full exterior with reflections. Their applications gave the same results.
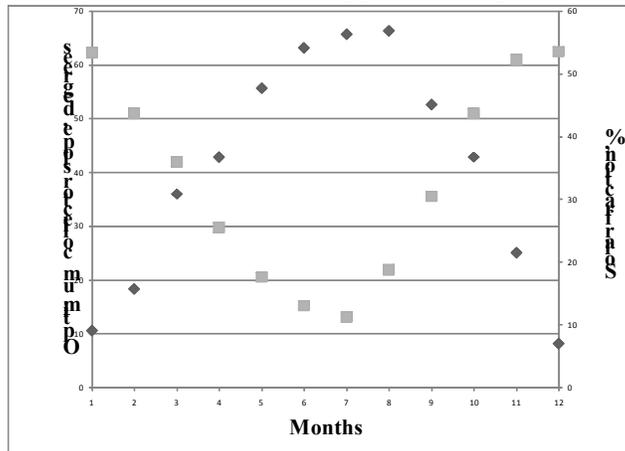
Fig.4 *Optimal collector slope and solar fraction for different months for the collector located in Belgrade, Serbia*

Figure 5 shows collector slope as a function of the applied time step per hour. The figure shows that the optimum slope mean value is 36.84^0 and the standard deviation $\sigma = 1.34^0$.
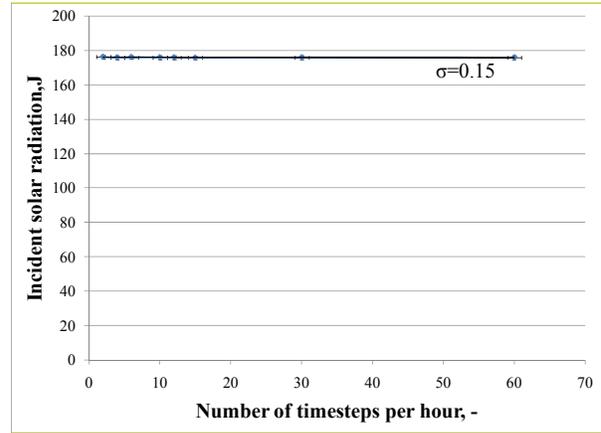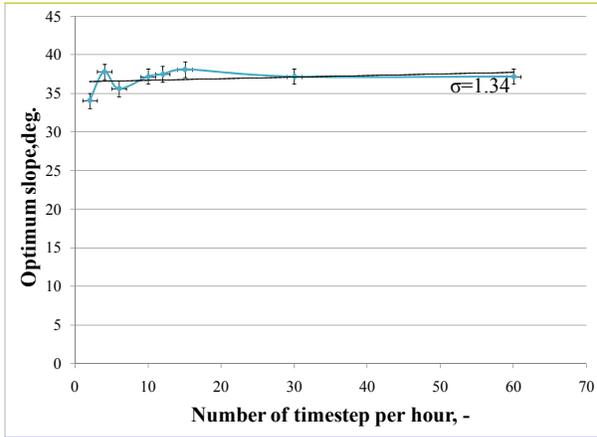

Fig.5 *Collector slope as a function of the applied time step per hour.*

Fig.6 *Incident solar radiation as a function of the applied time step per hour.*

Figure 6 shows the incident solar radiation to the collector as a function of the applied time step per hour. The figure shows that the mean value of the incident solar radiation is 176.045 J and the standard deviation is 0.15 J that is 0.084% of the mean value. This shows that the incident solar radiation is not responsible for the variation of the optimum collector slope with the time step.
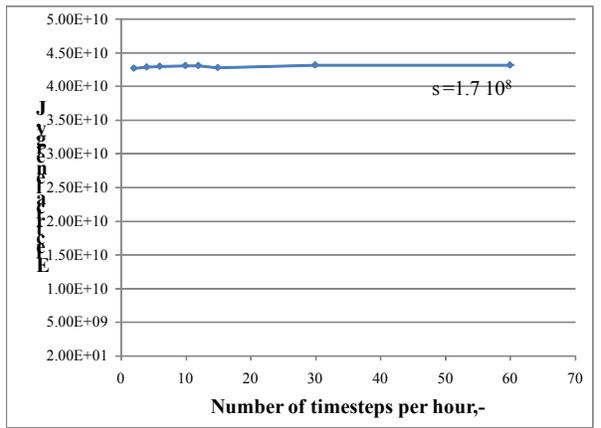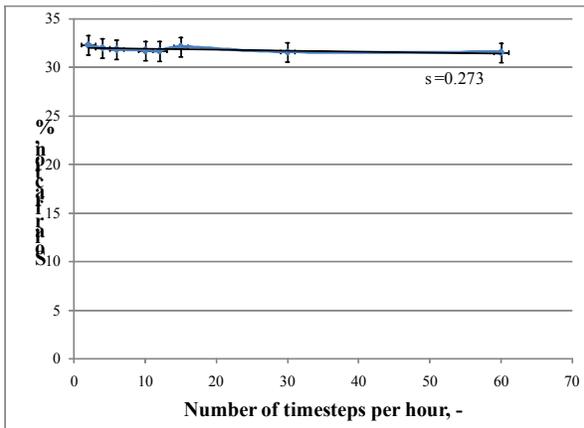

Fig.7 *Solar fraction as a function of the applied time step per hour.*

Fig.8 *Electrical energy as a function of the applied time step per hour.*

Figure 7 shows the solar fraction to the collector as a function of the applied time step per hour. The figure shows that the mean value of the solar fraction is 31.848 and the standard deviation is $\sigma = 0.273$ that is 0.855% of the mean value.

Figure 8 shows the electrical energy to the collector boiler as a function of the applied time step per hour. The figure shows that the mean value of the electrical energy is 4.3 10^{10} and the standard deviation is $\sigma = 1.7$ 10^8 that is 0.4% of the mean value.

5. CONCLUSION

This paper reports how the selection of the timestep in EnergyPlus software with the modified, Particle Swarm optimization algorithm methodology influences the determination of the optimal slope for installation of a solar collector and the optimum solar fraction. As an example, the optimum slopes of solar collector due to south and the collected solar energy are calculated for each month during entire year that enable the maximum amount of the solar energy and the solar fraction for SDHWS in Belgrade, Serbia.

The collector slope depends slightly on the applied time step per hour. The incident solar radiation to the collector does depend slightly on the applied time step per hour (0.084% of the mean value). The solar fraction to the collector varies with the applied time step per hour by around 0.855% of the mean value. The electrical energy to the collector varies with the applied time step per hour by around 0.4% of the mean value.

This means that the final variables (the solar fraction, the optimum collector angle and the electrical energy to the collector boiler) have the larger discrepancies with the timestep than that of the incident solar radiation.

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