ENERGY EFFICIENCY CART MODELING OF SOLAR ENERGY COLLECTORS BY GENETIC PROGRAMMING

by

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A uniquely constructed technical solution of a solar energy collector is presented in this paper. It presents a great breakthrough in the field of energy efficiency and successful exploitation of renewable energy sources. The principle of this high-temperature energy storage enables the energy accumulated from the sun to be yielded when necessary and continuously, 24 hours a day and 365 days a year. Furthermore, this paper contains a modeling of Sun irradiance, generated energy intensity for flat solar panel and for a newly developed concentrator. The modeling is made with genetic programming which is found to be a suitable method for modeling energy intensity. It offers the results which are within the acceptable tolerances while maintaining the ease of use and short computational time. Genetic programming yielded the results of 12.97, 14.6 and 9.25% average percent error for the irradiance, the flat solar panel and the novel solar concentrator, respectively.

Key words: *energy efficiency, solar energy, collectors, modeling*

Introduction

Although the trend to upgrade solar energy harvesting devices is present, the progress in this field is relatively slow. There are a lot of solar thermal power plants constructed today, but none of them is able to provide a 24 hour electricity supply during the days when the sun shines with increased intensity, let alone during the winter months. The biggest success is achieved by power plants with parabolic mirrors, as well as by power plants with flat mirrors. As a temporary solution there are power plants with a storage made of potassium and sodium salt, which can store energy for five or six hours. These storages are extremely expensive with numerous technical problems which are still unsolved. It should also be pointed out that the efficiency factor of solar thermal power plants is a big issue; they are of low efficiency because solar water steam is low quality. The parameters like these are not present in the solar; here you can achieve the pressure of about 50 bar and the temperature of 350 °C. Based on these parameters the efficiency of 18-20% can be achieved (Abengoa and Andasol in Spain, and the solar power plants in California, USA).

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Throughout the last couple of years, very little has been done to make the utilization of solar energy purposeful, and to provide energy supply by solar energy. Various authors have made their contribution by research in this field.

Zheng *et al.* [1] conducted a study for the design of a centralized solar collection system based on the combination of a light funnel concentrator with a deflector. Sencan *et al.* [2] conducted a theoretical modeling of an absorption heat transformer for the temperature range obtained from an experimental solar pond. Different methods such as linear regression (LR), pace regression (PR), sequential minimal optimization (SMO), M5 model tree, M50 rules, decision table and back propagation neural network (BPNN) were used for modeling the absorption heat transformer. In [3] a hybrid solar concentrator (HSC) has been fabricated by doping a rare earth complex, Eu $(TTA)_3$ Phen, into a polymer optical fiber (POF). A methodological analysis to design and evaluate the technical feasibility of using a linear Fresnel reflector concentrator (LFRC) as a generator in an advanced absorption refrigeration system (Solar-GAX cycle) has been carried out by Velazquez *et al.* [4]. For this purpose, a detailed 1-D numerical simulation of the thermal and fluid-dynamic behavior of a LFRC is made. A new trapezoidal cavity receiver for a linear Fresnel solar collector is analyzed and optimized via raytrace and CFD simulations in [5]. A novel geometry of a 3-D static concentrator has been designed and coined the square elliptical hyperboloid (SEH) to be integrated in glazing windows or facades for photovoltaic (PV) application [6]. Evolution algorithm has been used in a mathematical model to effectively optimize the heliostat field on annual basis [7]. A beam-down solar tower (BST) system, equipped with three linear Fresnel heliostat modules, corresponding beam-down concentrators, and a central cavity receiver with a spiral tube, has been introduced, experimentally investigated and theoretically analyzed in [8]. A 2-D cone concentrator for sunlight was theoretically and experimentally studied by Somchai and Ekawit [9]. Babić and Djurišić [10] proposed a correlation index between average time diagram of PV power plant production and a typical diagram of the price of electrical energy at the open market. Gostimirovic *et al.* have previously studied energy efficiency in manufacturing processes [11]. Regarding evolution algorithms, they are used for numerical investigation of thermo-economic-environmental optimization of a micro turbine [12].

Taking into consideration the above mentioned research work, the absence of genetic programming modeling procedure for energy intensity was noticed. One of the purposes of this paper is to partially fill this gap and study the possibility of using genetic programming for modeling the energy change during the day.

Energy efficiency of solar systems

The newly developed solution represents a great breakthrough in the field of energy efficiency and successful exploitation of renewable energy sources. As it is widely known, the problem with renewable sources of energy is their constancy. Solar systems, concentrated solar power (CSP) or PV modules alike, can fulfill one third of daily needs for energy because of the fact that the sun shines for eight hours a day on average. This value of irradiance is taken for the geographical location of Eastern Europe [13]. In order to close the gap of 16 hours, many companies (ABENGOA, ANDASOL, SES…), have installed gas power plants besides the solar plants. There is a small number of solar power plants with heat storages based on the principle of accumulating the phase transition heat. Molten salt is utilized in this process, but such storages can ensure the production of energy for only three more hours after the sunset.

Figure 1 presents a schematic representation of Petrović [14] system. Air is circulated, driven by the fan V1, through pipes into the concentrator's C1 focus point, where it is heated and then stored in the storage container S1.

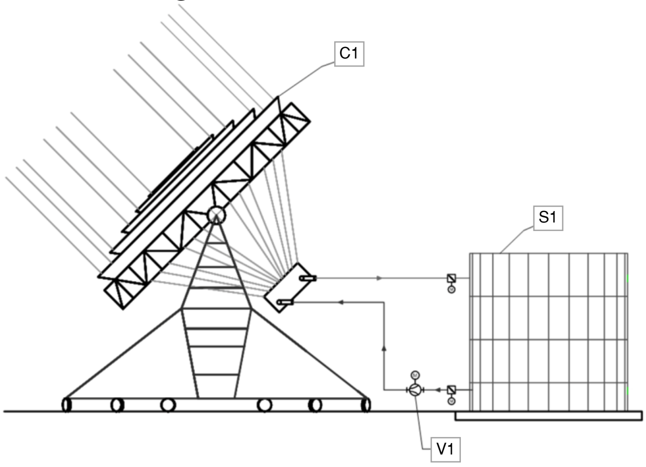

Figure 1. Schematic of solar system [14]; C1 – concentrator, S1 – storage, V1 – fan

Figure 2 shows a mini version of a solar collector [14] which is used for heating the water and storing it in a small tank. This solution is mobile, which makes it highly practical because it can be used on remote locations and can be relocated with ease. The principle of this variation of solar collector is identical to that in Fig. 1, except that in this case the heating medium is water instead of air.

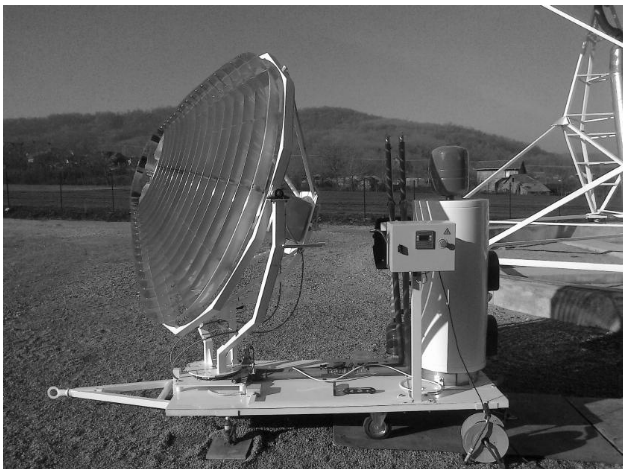

Figure 2. Small version of the collector for water heating [14]

The high-temperature storage [14] enables the energy accumulated from the Sun to be produced when necessary and continuously, 24 hours a day and 365 days a year. This makes it the first ever company in the world that managed to utilize solar energy continuously throughout the day and year.

This solar technology consists of:

– a solar concentrator capable of focusing solar energy to very high temperatures,
– a solar thermal energy storage unit,
– a solar receiver which transforms solar radiation into heat, and
– a combined solar cycle which provides high efficiency electricity production from the stored solar energy.

Solar concentrator capable of focusing solar energy to very high temperatures

The solar concentrator is made of coned shape mirrors which reflect the Sun`s rays into one focal point with very high concentration and achieving very intense energy flux. The concentrator tracks the sun with the preprogrammed equations so that it is always directed towards the sun. The tracking angles are azimuth and elevation. There are two solutions for concentrator design: one with fixed focus and one with adjusting focus. For electric energy production fixed focus design is more favorable. The main advantage of this system is direct accumulation of solar energy into the storage without any heat transfer fluid. The mirrors are cleaned automatically and at certain time intervals so that the water is recycled and used several times. Very high temperatures can be achieved in the range up to 3000 °C.

Solar thermal energy storage unit

The thermal energy storage has been designed so that it can store energy for a long time with minimum heat loss. The thermal storage can keep energy for 180 days if necessary so that the energy could be used for heating or cooling cities. The energy is stored at very high temperatures, up to 800 °C and it can be cooled down to 100 °C. The specific heat capacity in the mentioned range of temperatures is 450 kWh/m^3 and the heat loss is less than 6% for a 180 day period. If the storage is used for power production, then the temperature ranges from 600-800 °C and the specific heat capacity is 250 kWh/m^3. The concept for electric power production from solar energy anticipates a daily storage unit with an integrated absorber and both of them incorporated into a long time thermal storage. The focused solar energy enters the daily storage directly and the daily storage has the capacity to receive solar energy during 12 hours of sunshine per day. If the thermal output of the concentrator is 350 kW, then for the time span of 12 hours the collected energy is 4200 kWh. This energy can be stored and distributed equally for 24 hours. Considering that Serbia has 2200 hours of sunshine annually (Belgrade) we get approximately 6.2 hours of sunshine every day. Based on that, the average storage capacity will be 6.2 h times 350 kW equals 2170 kWh and the average thermal power distributed for 24 hours is 2170 kWh divided by 24 h equals 90.4 kW. The value of direct normal irradiation (DNI) in Serbia is approx. 1400 kWh/m^2 a year and, having this value, we can easily calculate the energy collection from the concentrator [14] which has 430 m^2. The annual yield from the concentrator is 602000 kWh$_{\text{thermal}}$. If combined cycle were realized, then the electric energy produced for one year would be 301000 kWh$_{\text{electric}}$ with the efficiency of the cycle of 50%.

Solar receiver (absorber) which transforms solar radiation into heat

The solar concentrator mentioned above has the possibility to focus the beam to 1000 times smaller surface achieving very high temperature on the surface. Transforming such high flux into thermal energy presents a great technical challenge. This problem has been successfully solved with the help of a specially designed absorber. The absorber is installed into the thermal storage unit so that heat losses are minimal because there is no need for heat transfer medium.

Combined solar cycle which provides high efficiency electricity production from the stored solar energy

Present solar technologies work with very low efficiency *i.e*. PV modules have only 10% efficiency and best CSP plants have maximum 20% efficiency. The fact is that such low efficiencies affect the economics of the solar plant itself. The goal of the system is to solve those problems and in that sense a combined solar cycle has been developed which can produce relatively high efficiency. The combined solar cycle consists of a turbo compressor, an air turbine and a steam turbine. All thermodynamic measures are applied so that the cycle has high efficiency. The efficiency of the cycle depending on air temperature can be seen in tab. 1. The physical characteristics of all solar collectors have been measured using UV analyzer PV-KLA (Ingenieur buero Mencke & Tegtmeye, Germany) and the device for automatic control of measurements SolarUsb. The intensity of solar irradiance has been measured by wireless meteorological station Davis Vantage Pro 2 (USA).

Table 1. Efficiency of the cycle depending on air temperature

The temperature at which the solar energy is used [°C]	The overall level of efficiency of *Combined Solar Cycle* η[%]
1200	61.8
1100	59.5
1000	57.3
900	54.4
800	51.4
700	48.6
600	43.2

The storage core insulation system is also a patent solution [14] which enables heat losses to be less than 6% annually. The advantages of the systems are:
– the continuous production of energy from the accumulated sun energy is 24 hours a day for 365 days,
– the accumulation capacity is 4-5 times higher than with the existing systems,
– there are no restrictions concerning location selection for installing the plant, and
– the concentrator's design is made in a special software simulation which enables the construction to withstand all atmospheric influences with considerable savings in material, unlike the similar existing systems.

The diameter of the concentrator which is D = 10 m, has the surface of the concentrator 66.7 m^2, and can achieve the maximum temperature in focus of 1450 °C.

Modeling procedure

Based on the natural principle of evolution and survival of the fittest, genetic programming is one of the most used evolutionary based algorithms [15]. It uses selection, crossover and mutation to yield the fittest individual. In mathematical language, genetic programming is a very capable tool for finding a suitable model function. Genetic programming is used to model membership function using available data [16, 17]. For the purpose of data modeling, GPdotNET software was used [18]. Because three independent cases were observed, the number of functions generated was also three. The operators that were included in the creation process are +, –, *, /, x^2, 1/x, and abs. Each generation contained 500 individuals and the whole process took 3000 generations for every individual case. The whole procedure is measured in minutes and is fully acceptable taking in consideration only average computational equipment. The probability for crossover was 0.7, mutation 0.1 and reproduction 0.2. The number of elite individuals was 5 which meant that the top five solutions from every generation will be automatically transferred into the next one. At the beginning of the process 6 constants (marked R_i in tab. 2 for the irradiance model, tab. 3 for the flat solar panel and in tab. 4 for the concentrator data model) are generated randomly and later used in the creation process. As a fitness function, in this case, mean square error was used. It has been found that this type of function will yield the best results. The final function generated for the irradiance data is presented in eq. (1), for the flat solar panel in eq. (2) and for the concentrator in eq. (3).

$$M_I = \left(R_5 \cdot R_2 - h_i + R_2 + R_1 - R_6{}^2 + (R_3 - h_i)\cdot(R_3 - R_1)\right)\cdot\left(\frac{h_i{}^2 \cdot R_4}{\dfrac{R_5{}^2}{2\cdot h_i} + \dfrac{R_5}{R_1}}\right) + \left(\frac{R_3 - R_4{}^2}{R_5 - h_i + R_1}\right) + \left(\frac{(R_3 \cdot R_4 - h_i + R_1)^2}{R_5 - h_i + R_3}\right) \tag{1}$$

$$M_F = \left(\frac{h_i \cdot (R_5 \cdot R_3 - h_i + R_6)}{R_6} - R_4\right)\cdot\left(\frac{(R_2 \cdot h_i)^2}{\dfrac{2\cdot h_i}{R_6} + \dfrac{1}{R_3 - R_5}}\right) + \left(\frac{R_1 + R_4 - h_i \cdot R_1}{(h_i - R_6)^2}\right) - \left|\frac{R_5{}^3}{h_i}\right|\cdot\left(\frac{R_5 \cdot R_1}{h_i{}^2 - R_4 + R_5}\right) \tag{2}$$

$$M_C = (R_1 + h_i \cdot R_6)\cdot\left(\frac{1}{h_i - R_4}\right) + \left(\frac{R_5}{h_i - R_3}\right) + (R_3 + h_i + R_5)^2 - \left|(2\cdot R_3 + R_5)\cdot(R_5 - h_i)\cdot\left(h_i - R_6 - \frac{1}{R_5} + R_5 - R_2\right)\right| \tag{3}$$

Table 2. Values of constants generated by the software for irradiance model

R_1	R_2	R_3	R_4	R_5	R_6
0.79399	5.75754	0.47018	8.14488	6.44630	2.56077

Table 3. Values of constants generated by the software for flat solar panel model

R_1	R_2	R_3	R_4	R_5	R_6
4.94484	1.16938	3.95977	8.96811	7.21380	7.37327

Table 4. Values of constants generated by the software for concentrator model

R_1	R_2	R_3	R_4	R_5	R_6
2.25255	3.07489	7.05716	7.63340	9.75992	5.01137

In eqs. (1)-(3) and tabs. 2-4, R stands for the constants generated at the start of the modeling process. Also in eqs. (1)-(3) h_i stands for the hour values in which the measurement of energy intensity took place. The calculated modeled values for the intensity in the three mentioned cases are shown in tab. 5. Average percent error was used to evaluate the success of the proposed model and it was calculated using one formula eq. (4) for each of the three cases:

$$\Delta = \sum_{i=1}^{13}\left|\frac{E_i - M_i}{E_i}\right| 100\% \tag{4}$$

where E_i represents the experimentally obtained value for energy intensity and M_i the modeled value from eqs. (1)-(3).

The average percent error, shown in tab. 5, does not exceed 15% for any of the cases. In authors' opinion these values are in the acceptable range. The results of the yielded models compared with the experimental data are presented in fig. 3 for the irradiance, in fig. 4 for the flat solar panel and in fig. 5 for the developed concentrator.

Table 5. Data presentation for measured and modeled energy intensity with calculated errors in deviation

Hour	Measured energy intensity of irradiance [Wm^{-2}]	Modeled energy intensity of irradiance [Wm^{-2}]	Measured energy intensity of flat panel [Wm^{-2}]	Modeled energy intensity of flat panel [Wm^{-2}]	Measured energy intensity of concentrator [Wm^{-2}]	Modeled energy intensity of concentrator [Wm^{-2}]
6	0	–10.4138	0	5.59828	0	–28.9374
7	215	246.5715	0	–17.1758	0	21.3948
8	705	734.5099	105	150.8388	570	582.1298
9	875	800.3207	300	272.4361	695	655.419
10	920	884.0864	370	331.9894	740	734.2905
11	965	949.8995	395	370.8843	770	769.6588
12	975	985.4818	405	389.4068	780	835.9306
13	965	981.6086	395	384.7522	770	810.3476
14	920	929.8292	370	353.3819	740	739.6548
15	875	821.9597	280	291.4868	695	623.5948
16	705	649.9259	95	195.1341	570	462.0324
17	215	405.7042	0	60.32606	150	254.8894
18	115	81.2964	0	–116.972	0	2.117672
Average percent error [%]		**12.97**		**14.59**		**9.25**

Discussion

As can be seen, it is possible to use genetic programming for obtaining the model function of energy intensity. It is mentioned that this technique offers great flexibility and is capable of constructing function from grounds up. With an average percent error of maximum 14.6%, the obtained results show the potential for use in this area. Observing the shape of the measured data dependency in figs. (3)-(5), one can see that its shape is fairly regular and with that in mind only basic operators were selected to take place in function creation. More improvements could be done by implementing more data and by attempting to combine all data in one universal function.

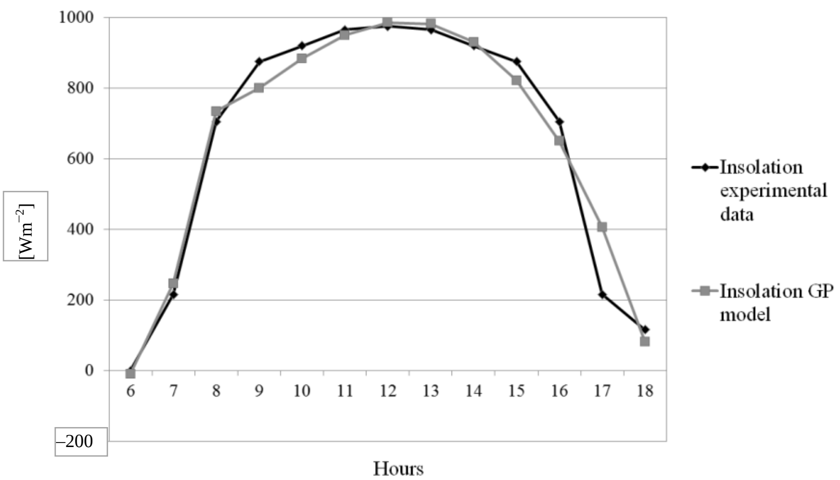

Figure 3. Graphical comparison between measured and modeled data for irradiance

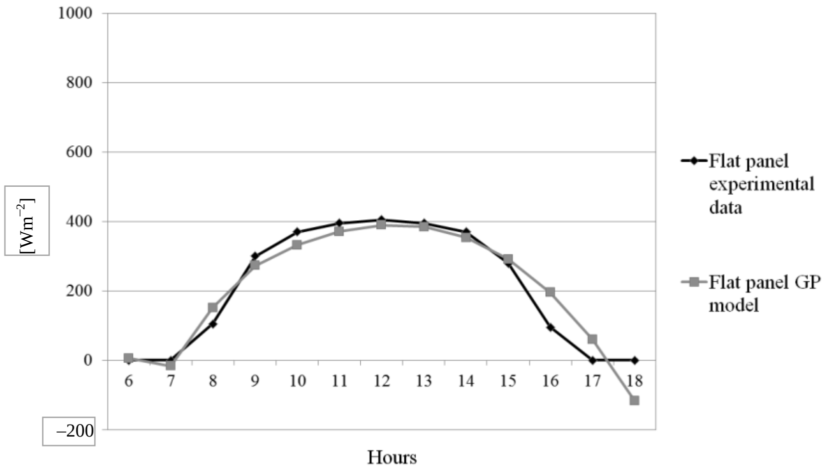

Figure 4. Graphical comparison between measured and modeled data for flat solar panel

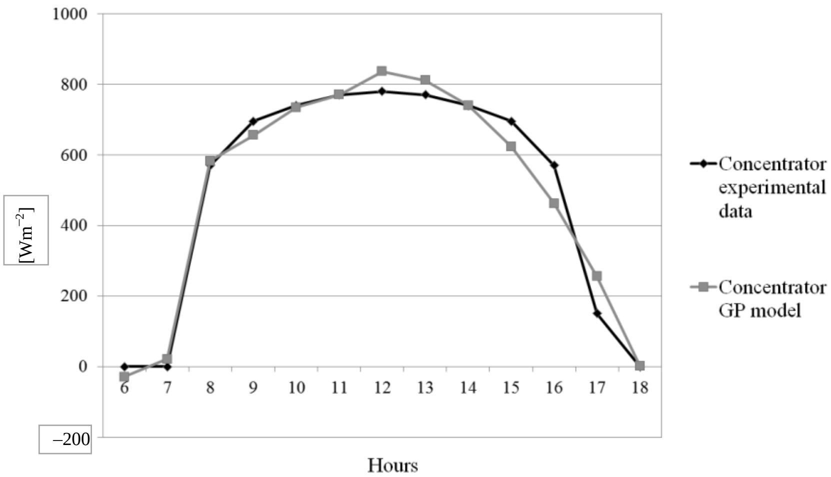

Figure 5. Graphical comparison between measured and modeled data for newly developed concentrator [14]

Conclusion

Genetic programming yielded results of 12.97, 14.6, and 9.25% average percent error for the irradiance, the flat solar panel and the novel solar concentrator [14], respectively. In authors' opinion, genetic programming offers greater flexibility without excessively prolonged computational time. More improvements could be done by implementing more data and attempting to combine all data in one universal function.

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