Experimental Validation of a Forced-Circulation Solar Water Heating System Equipped with Flat-Plate Solar Collectors – Case Study

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Abstract—This paper represents the comparison and the validation of results obtained from the simulation, towards the measurements performed in a forced-circulation solar water heating system equipped with flat-plate solar collectors. Polysun tool is used to model and to simulate the considered system during an annual time period. Mathematical models are used to calculate the required sensible heat, thermal yield from the flat-plate collector area, delivered energy to the thermal consumer, efficiency of the collector area, efficiency of the system, and the solar fraction. To validate the model, experimental data recorded in time intervals of 5-minutes in a trial installation are utilized. Statistical test errors (ε, MBE, MPE, RMSE, and R²) are used to compare the values obtained from the simulation and measurements. Between them, a very good fit is noticed.

Index Terms—Active System, Flat-Plate Collector, Efficiency, Measurements, Simulation, Validation.

I. INTRODUCTION

Solar water heating (SWH) systems are mainly utilized in residential, services, and industrial sectors of a country. Generally, they are included in national action plans with the main aim to reduce the energy consumption. Their contribution depends mainly from their size, number, design, quality, and operation. Also, they contribute indirectly in the mitigation of greenhouse gas (GHG) emissions.

The installed collectors in Albania are all glazed and liquid ones. By the end of 2017, the flat-plate collectors covered around 97.7 % of the total installed area which was 232215 m². Forced-circulation installations constitute a very low percentage till now, which is around 3.6 % [1].

Different authors have performed their studies in various aspects related to the SWH installations. Many of them are focused on measurements, simulation, and validation of results.

Maraj et al. analyzed experimentally the performance of a forced-circulated installation equipped with flat-plate collectors for the Mediterranean climate conditions. They achieved experimental values for the annual system efficiency and solar fraction of 0.411 and 0.757, respectively [2].

Lee and Sharma defined experimentally the thermal performance of an active SWH installation based on annual operation for a region with cold climate in South Korea. Monthly values for the collector efficiency referred to the considered active system varied between (0.405 – 0.467) [3].

Ayompe and Duffy (2013) carried out the year-round energy analysis for a forced-circulation SWH system with flat-plate collector under the Dublin climate conditions. Results showed that the annual average solar fraction, collector efficiency and system efficiency were 0.322, 0.456 and 0.378, respectively [4].

Fertahi et al. optimized the thermal performance of a forced SWH system for a case study in Morocco. They optimized the useful energy gained and efficiency of the system. Through this optimization they achieved an annual system efficiency and a solar fraction higher than 0.6 and 0.5, respectively [5].

Badescu and Staiović modelled through TRNSYS an active solar system for a passive solar house. The system included space heating and domestic hot water preparation. The solar fraction values lied between (0.180 – 0.446), whereas the annual average was 0.446 [6].

Hobbi and Siddiqui optimally designed a forced circulation SWH system under the cold climate using TRNSYS. They defined the monthly and annual values for the solar fraction and the collector efficiency. The obtained results showed that the system provided (0.83 – 0.97) and (0.3 – 0.62) of the hot water demands in summer and winter, respectively [7].

Nogueira et al. developed a model to size small SWH systems through MATLAB platform. They defined the annual energy demand, solar system energy output, and solar fraction for five different systems. Also, the model allowed them to make optimization studies regarding the components [8].

Allouhi et al. used TRANSOL to simulate SWH systems with flat-plate collectors for six regions in Morocco. Also, they compared the obtained values of collected energy, losses, auxiliary energy and solar yield [9].

Bojić et al. modelled through FORTRAN a forced circulation SWH system using a time marching model. The model was used to evaluate the solar fraction of the system [10].

Abdunnabi et al. carried out the experimental validation of forced-circulation SWHS in TRNSYS. The discrepancy for the daily collected energy was less than 20.2 % [11].

Ayompe et al. validated the TRNSYS model for a forced circulation SWHS equipped with flat-plate collectors used in temperate climates. The percentage mean absolute errors for
the heat collected by the collectors and the heat delivered to the load were 14.1 % and 6.9 %, respectively [12]. Kalogirou evaluated the long-term performance prediction of three forced circulation SWHS using artificial neural networks for the climate conditions of three cities in Greece. The validation referred to the solar energy output from the system. The obtained value for the coefficient of determination was greater than 0.98 [13].

Soriga and Badescu validated a model used to simulate the dynamic behavior of a SHW system with two flat-plate collectors against experimental measurements. They employed RMSE, MBE, to validate useful heat gain from the solar collector [14]. This work represents the validation of results obtained both from measurements and the simulation. Measurements are obtained from a forced-circulation SWH installation. They refer to an annual time period, which is necessary to fulfill the validation of results.

II. MATERIAL AND METHOD

In this section, the trial installation used for the model validation, the mathematical model, and the model designed through Polysun are described. The installation is explained in terms of components, hydraulic layout, measuring and control equipment.

A. Description of the System

The system considered in this work is used for research purposes and is shown at Fig. 1. Components of the outside part are situated on the roof of the three stores building of the Faculty of Mechanical Engineering, Polytechnic University of Tirana (PUT). Whereas, the components of the inside part are placed in the Laboratory of Plants, Department of Energy. The structure is located in the city of Tirana, where the latitude is 41.33 °N, the longitude is 19.82 °E, and the average altitude is 110 m [15]. For this location, the annual averaged number of sunny hours is \( \bar{h}_Y = 2500 \) h/year [16].

Fig. 1. Views from the trial installation (a- outside and b- inside part)

Fig. 2 shows the layout of the trial installation and the sensor arrangement. It consists of five subsystems: collection, circulation, storage, control, and auxiliary energy source.

Two selective flat-plate solar collectors connected in parallel constitute the subsystem of collection. They are produced by Isofoton. The installed solar collectors have a gross area of 2.45 m² and an absorber area of 2.205 m². Also, the zero-loss efficiency is 0.773, the first-order coefficient is 3.243 W/(m²·K), and the second-order coefficient is 0.014 W/(m²·K)² [17]. Collectors have a slope of 45° and are oriented 10° East from the South direction [18].

The subsystem of circulation consists of insulated copper pipes having a diameter of 22 mm and a solar circulation pump. An assembled Resol “FlowCon B” is used [19].

The subsystem of storage includes a storage tank having a volume of \( V_{st} = 300 \) l. It is fabricated from Lapesa and its type is CV-300-M2 [20].

The subsystem of control includes the sensors, the controller, and the datalogger. To perform the energy evaluation and analysis of the installation all the required parameters are measured. The solar irradiance is provided through the CS10 type “E” sensor. The temperatures of heat transfer fluid and water are measured through the FRP6 sensors. Volume flow rates are obtained through the Resol V40 sensor. Outside air temperature is measured by FAP13 sensor [19]. All sensors are connected with the IsoControl Top controller [21]. The datalogger Resol DL2 is used to store the data in time intervals of \( \tau = 5 \) min. Whereas, the Resol VBus cable is utilized to transfer the recorded data to a personal computer [18].

B. Software Model

The Polysun tool is utilized to model the trial installation used in this work. The model is designed according to the characteristics of the considered installation. The layout of the modelled installation is provided at Fig. 3.

The characteristics of the pipes (number, material, length, insulation thickness) and their placement are given at Table I. They refer to the modelled system obtained through the utilization of the Polysun tool.
C. Mathematical Model

This case study is focused on the energy analysis of a trial installation. To obtain this goal, the following mathematical model is employed.

The solar collector is a heat exchanger. When the solar rays fall on the absorber area, the heat transfer fluid is going to be heated. When the required temperature difference is achieved, a circulation pump flows it through the collector and the hydraulic circuit. The rate of thermal yield from the flat-plate collector area is expressed as [22]:

$$\dot{Q}_u = \rho_f \cdot \dot{V}_f \cdot c_{pf} \cdot (T_o - T_i)$$  \hspace{1cm} (1)

where, $\rho_f$ is the density of heat transfer fluid [kg/m³], $\dot{V}_f$ is the volume flow rate of heat transfer fluid [m³/s], $c_{pf}$ is the specific heat of heat transfer fluid [kJ/(kg·K)], $T_o$ is the outlet temperature [K] and $T_i$ is the inlet temperature [K].

The solar collector field represents a key component for a SWH system. The instantaneous collector efficiency is given as [22]:

$$\eta_{coll} = \frac{\dot{Q}_u}{A_c \cdot G_t}$$  \hspace{1cm} (2)

where, $A_c$ is the aperture area of the solar collector [m²] and $G_t$ is the total solar irradiance [W/m²].

Cold water enters the storage tank at a volume flow rate of $\dot{V}_w$, where is heated gradually and leaves it at as hot water with temperature $T_{hw}$. The rate of energy delivered to the thermal consumer is defined as [22]:

$$\dot{L}_{hw} = \rho_w \cdot \dot{V}_w \cdot c_{pw} \cdot (T_{hw} - T_s)$$  \hspace{1cm} (3)

where, $\rho_w$ is the density of water [kg/m³], $\dot{V}_w$ is the volume flow rate of water [m³/s], $c_{pw}$ is the specific heat of heated water [kJ/(kg·K)], $T_{hw}$ is the hot water temperature [K], and $T_s$ is the supply temperature [K].

The rate of sensible heat required to heat the cold water is obtained through [22]:

$$\dot{L}_{req} = \rho_w \cdot \dot{V}_w \cdot c_{pw} \cdot (T_{req} - T_s)$$  \hspace{1cm} (4)

where, $T_{req}$ is the required temperature [K].

For each SWH installation, it is very important to obtain high values of system efficiency. It expresses the conversion of solar energy to useful heat gain from the storage tank. The last term refers to the thermal energy which is delivered to the consumer. For this reason, the system efficiency includes even the thermal losses, which take place in the hydraulic circuit. Also, it considers the thermal losses in the storage tank as well. It is expressed as [22]:

$$\eta_{sys} = \frac{\dot{L}_{hw}}{A_c \cdot G_t}$$  \hspace{1cm} (5)

One of the indicators necessary for the estimation and comparison of SWH systems is named as solar fraction. This quantity indicates the portion of the required energy covered from the system operating through the solar part only. It is important to note that it doesn’t consider additional parasitic electrical energy (circulation pump, controller, etc.) and the heat losses from the storage. In this case, the trial installation is a small plant and the additional parasitic electrical energy is small. For this reason, the monthly solar fraction becomes important and it can be defined as [23]:

$$f_i = \frac{\dot{Q}_{u-i}}{\dot{Q}_{req-i}}$$  \hspace{1cm} (6)

where, $f_i$ is the monthly solar fraction [-].

The annual solar fraction expresses the contribution of solar energy in covering up the load. It is given as [22]:

$$F = \frac{\sum_{i=1}^{12} f_i \cdot \dot{Q}_{req-i}}{\sum_{i=1}^{12} \dot{Q}_{req-i}}$$  \hspace{1cm} (7)

where, $F$ is the annual solar fraction [-].

III. RESULTS AND DISCUSSIONS

The objective of the paper is the experimental validation of results achieved through the simulation of a forced-circulation SWH installation equipped with flat-plate collectors. To fulfill the objective, several steps are followed. Firstly, a trial installation is considered and its database of operating parameters is used. The recorded data obtained during an annual period are utilized. Secondly, the considered installation is designed and simulated by utilizing a simulation tool. In this case the Polysun tool is employed. Thirdly, the mathematical model is built. It created the possibility to perform the energy analysis of the trial installation. And fourthly, obtained results from the simulation are validated through the utilization of measured and calculated data.

To avoid the confusion between the compared quantities are used the following subscripts. Monthly values of quantities obtained from measurements are indexed by (m) and those from the simulation by (s).

At Fig. 4, the monthly values of irradiation on solar collector’s plane are shown. It is observed that its values rise up in the summer months. The contrary happens in the winter months, where the maximum reduction noticed is till 2.7-times. For the selected location, it is evident the significant effect of the season. Its lowest value of $H_{min}^{sw} = 291.6$ kWh/month refers to the month of December.
Whereas, the highest one of $H_r^{\text{max}} = 814.2$ kWh/month refers to the month of July. The annual measured value is $H_r^{\text{year}} = 6474$ kWh/year.

Fig. 4 shows the monthly average values of outside air temperature nearby the flat-plate collectors, also. From the graph, it is noticed that its values vary between $\bar{T}_{\text{air}} = (7.7 - 28.2)$ °C. The lowest value refers to the month of December and the highest one to that of August. The season’s influence is clearly identified. After achieving higher values in the summer months, its values decrease progressively towards the winter ones.

![Fig. 4. Irradiation on the tilted solar collector and the mean outside air temperature](http://example.com/fig4)

The variation of the thermal yield from the flat-plate collector area is shown at Fig. 5. It shows that this quantity is proportional to the solar radiation. Also, its values depend even from the outside air temperature nearby the flat-plate collectors. It is observed, that during the months where the outside air temperature is lower, the heat gains are lower too. This reduction is related to thermal losses from the installed collectors. Another contributing factor is the number of the days for each month.

From the graphs related both to measurements and to the simulation is observed that this quantity has higher values in the summer months. Also, values obtained from the simulation are higher compared to them obtained from the measurements. As result, the simulation software slightly overestimates this quantity. Leaning on values obtained from measurements and the simulation, it is calculated that the statistical test errors for the thermal yield from the flat-plate collectors area are $\epsilon_{\text{min}} = -11.48 \%$, $\epsilon_{\text{max}} = 3.620 \%$, $\text{MBE} = 11.18$ kWh/month, $\text{MPE} = -5.206 \%$, $\text{RMSE} = 14.65$ kWh/month, and $R^2 = 0.964$. As result, a very good fit for this quantity is observed.

Annual estimations of the thermal yield from the flat-plate collector area for the considered period obtained from the measurements and the simulation are respectively $Q_u^{\text{year}} = 3159$ kWh/year and $Q_u^{\text{year}} = 3293$ kWh/year.

![Fig. 5. Thermal yield from the flat-plate collector area](http://example.com/fig5)

Fig. 6 shows the values of delivered energy to the thermal consumer. Its magnitude depends from the thermal consumer characteristics, the temperature of the cold water entering the storage tank and the storage tank quality of insulation. During the summer months it is noticed that this quantity is higher compared to the winter months. The curve shows the same shape as that of the thermal yield from the flat-plate collector area, but its values are lower. This difference is related with thermal losses which take place in the pipeline between the collector area and the storage tank.

Comparing the obtained values from the measurements and the simulation, it is noticed that the first are lower in the months where lower values of solar radiation are present. From the comparison it results that during these months the simulation tool overestimates the values of the delivered energy to the thermal consumer. Statistical test errors for this quantity are respectively $\epsilon_{\text{min}} = -18.61 \%$, $\epsilon_{\text{max}} = 4.824 \%$, $\text{MBE} = 13.12$ kWh/month, $\text{MPE} = -8.028 \%$, $\text{RMSE} = 16.60$ kWh/month, and $R^2 = 0.921$. From the achieved results, a moderate fit for the delivered energy to the thermal consumer is observed.

The annual values of the delivered energy to the thermal consumer obtained through measurements and the simulation are $L_{\text{hw-m}}^{\text{year}} = 2427$ kWh/year and $L_{\text{hw-s}}^{\text{year}} = 2584$ kWh/year, respectively.

![Fig. 6. The energy delivered to thermal consumer and the required sensible heat](http://example.com/fig6)

Fig. 6 shows also the variation of required sensible heat. During the months with low values of ambient temperature, its values are higher and vice versa. Another effect on the magnitude of its values is represented from the cold water temperature entering the storage tank, which is lower during
the colder months. This is associated with higher values of the required sensible heat. Also, its value is influenced even from the day number of the month. The maximum value of this quantity is observed in March, where $L_w^{\text{max}} = 380.7$ kWh/month. Whereas, the minimum is on September, where $L_w^{\text{min}} = 287.8$ kWh/month. The annual value of the required sensible heat is $L_w^{\text{year}} = 3993$ kWh/year.

Monthly values of efficiency related to the collector area and the system are shown at Fig. 7. It is noticed that these quantities have lower values during the summer months. The contrary is observed during the winter months, where the season impact is evident.

From the graphs is observed that solar collector efficiency values obtained from measurements are lower compared to them obtained from the simulation. Also, another interesting occurrence is noticed. This is related to fact, that during the summer months the magnitude of their discrepancies diminishes. For the considered annual time period the simulation tool overestimates this parameter during the period with low or medium values of insolation. Regarding to the efficiency of the collector, the statistical test errors are $\epsilon_{\text{min}} = -8.858$ %, $\epsilon_{\text{max}} = -2.733$ %, $MPE = 0.030$, $MPE = -5.956$ %, $RMSE = 0.032$, and $R^2 = 0.981$. As result, a very good fit for the solar collector field efficiency is observed.

Annual average value of the collector efficiency for the whole study period obtained both from measurements and the simulation are $\eta_{\text{coll}}^{\text{year}} = 0.495$ and $\eta_{\text{coll}}^{\text{year}} = 0.524$, respectively.

Also, from Fig. 7 is noticed that during the summer months, the system efficiency values obtained from the simulation are lower compared to them obtained from measurements and vice versa. Thereby, the simulation tool overestimates this parameter during the months with lower values of insolation. Statistical test errors for the system efficiency are $\epsilon_{\text{min}} = -12.81$ %, $\epsilon_{\text{max}} = -2.733$ %, $MPE = 0.034$, $MPE = -8.820$ %, $RMSE = 0.038$, and $R^2 = 0.981$. As result, a very good fit for the system efficiency values is observed.

Annual averaged value of the system efficiency obtained from measurements and the simulation are $\eta_{\text{sys}}^{\text{year}} = 0.380$ and $\eta_{\text{sys}}^{\text{year}} = 0.414$, respectively.

It is observed that obtained values from the simulation generally are higher compared to them from the measurements. An exception is noticed in the months of January, July, and December when the contrary happens. Also, during the months with higher values of insolation their discrepancies increase slightly. The month of July constitutes an exemption, where they are nearly the same. It results that the simulation tool slightly overestimates this parameter during periods with higher insolation values and vice versa. Statistical test errors for the solar fraction are $\epsilon_{\text{min}} = -11.43$ %, $\epsilon_{\text{max}} = 3.624$ %, $MPE = 0.033$, $MPE = -5.180$ %, $RMSE = 0.044$, and $R^2 = 0.995$. Referring to the solar fraction it results that a very good fit is achieved.

Annual solar fraction for the considered period obtained both from measurements and the simulation were $F_m = 0.809$ and $F_s = 0.842$, respectively.

Annual energy flows obtained from measurements/calculations and the simulation of the considered installation are shown at Table II. The absolute percentage error for each quantity is respectively $|\epsilon_{\text{th}}| = 4.24$ %, $|\epsilon_{L_{\text{wp}}} = 6.47$ %, $|\epsilon_{\text{coll}} = 5.86$ %, $|\epsilon_{\eta_{\text{sys}}} = 8.95$ %, and $|\epsilon_{\eta_s} = 4.08$ %. These differences are related to the fact that exploited data refers to a time period of 1-year. For a multiyear analysis, smaller differences and an improved accuracy could be achieved.

| Parameter | From measurements/calculations | From the simulation |
|-----------|-------------------------------|--------------------|
| Thermal yield from the solar collector area, kWh/year | 3159 | 3293 |
| Delivered energy, kWh/year | 2427 | 2584 |
| Efficiency of the collector, - | 0.495 | 0.524 |
| Efficiency of the system, - | 0.380 | 0.414 |
| Solar fraction, - | 0.809 | 0.842 |

Fig. 7. Efficiencies for the collector and the system

Fig. 8. Solar fractions for the considered SWH system

Monthly values for the solar fraction of the SWH installation are shown at Fig. 8. They are obtained both from measurements and the simulation. It is noticed that the solar fraction is proportional to the insolation. A particular occurrence is observed in June, July, August, and September, where its values are higher than one. Whereas, the minimum value in both cases refers to the month of December.
IV. CONCLUSIONS

In this work, the comparison and validation of results obtained both from the simulation towards the measurements/calculations is performed. To perform this task a forced-circulation SWH system operating under the Tirana climate characteristics is analyzed. The database of recorded data during a 12-months period are utilized.

Between the obtained results several discrepancies were observed. Leaning on the coefficient of determination values, it was noticed that:

a) The thermal yield from the flat-plate collectors area has a $R^2 = 0.964$.

b) The delivered energy to the thermal consumer showed a $R^2 = 0.921$.

c) For the collector efficiency is obtained a $R^2 = 0.981$.

d) With regard to the collector efficiency, a $R^2 = 0.981$ is achieved.

e) Referring to the solar fraction, a very good fit is observed with $R^2 = 0.995$.

Referring to the annual values, it is observed that the absolute percentage error for all compared parameters respectively is $|\varepsilon_{\text{th}}| = 4.24\%$, $|\varepsilon_{\text{hru}}| = 6.47\%$, $|\varepsilon_{\text{cole}}| = 5.86\%$, $|\varepsilon_{\text{dys}}| = 8.95\%$, and $|\varepsilon_d| = 4.08\%$.

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