Energy and Economic Estimation for a Passive Solar Water Heating System Equipped with a Heat Pipe Evacuated Tube Collector – Case Study

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Abstract—The energy and the economic estimation for a passive solar water heating system under the Tirana climate conditions is performed. The trial system includes a heat pipe evacuated tube collector. To fulfil these objectives, measured values recorded every minute from the data logger of the system are used. The studied solar collector has a slope of 45° and is oriented 10° East from the South direction. The heat pipe evacuated tube collector has an aperture area of 1.476 m². For an annual time period the irradiation on tilted solar collector area, the extracted energy from the storage tank, the delivered energy to the thermal consumer and the system efficiency were defined. Also, the economic assessment of the system is performed.


I. INTRODUCTION

The idea of using the solar energy is gaining a foothold. By the end of 2017, the cumulative number of solar water heating (SWH) systems installed in Albania was 47449. The share of natural circulation systems was around 96.4%, whereas for the forced ones it was 3.6% [1].

The overall solar collector area installed in the country at the end of 2017 was 232215 m². Leaning on the statistical data they are all liquid collectors. Regarding the collector type, the installed area for glazed flat-plate collectors was \( A_{FPC} = 226969 \) m², whereas for the evacuated tube collectors was \( A_{ETC} = 5246 \) m² [1].

Maraj evaluated the long-term thermal performance for three types of SWH systems equipped with flat-plate and evacuated tube collectors. The trial systems were active and passive ones [2]. Lee and Sharma compared the thermal performance between a forced and a passive SWH system based on annual operation for a region with cold climate in South Korea. Monthly average values of collector efficiency for the passive system varied between (0.386 – 0.484) [3]. Gill et al. monitored the annual performance of an evacuated tube SWH system under the northern maritime climate. By excluding the energy losses from the storage tank, the obtained overall annual in-plane efficiency of the system was 0.628. Also, the simple payback period and the net present value methods are exploited to define the economic viability of the system [4]. Kalogirou performed the thermal performance, economic and environmental life cycle analysis for a single-family thermosiphon solar water heating system having a collector area of 2.7 m². The annual value of the useful energy was 1800 kWh/year. The simple payback period was 2.7 years for electricity backup and 4.5 years for diesel backup, respectively [5]. Ghorab et al. analyzed the performance of a domestic SWH installation. They defined domestic hot water energy load, solar energy delivered to hot water, gas energy consumption, etc. These values were shown on monthly basis [6].

Hernandez and Kenny analyzed several domestic SWH systems equipped with flat-plate and evacuated tube collectors under the climate conditions of Ireland. They defined the solar energy output, payback period, etc. The installation with the shortest payback period of 1.2 years was that with thermosiphon [7]. Kim et al. optimized the long-term performance of a solar water heating system leaning on the economic evaluation. Their analysis was based on simple payback period. They also optimized economically the total collector area, storage volume, and the daily demand [8]. Cost benefit analysis for SWH systems in Greece was performed by Diakoulaki et al. Their conclusion was that preparing hot water through the utilization of SWHS is more appropriate than using electricity and oil products [9]. Hazami et al. defined the thermal potential for two passive SWH equipped with flat-plate and evacuated tube collector installed in Tunisia. For the collector area of 2 m², the results showed that the annual savings of electricity was 1459 kWh/year and the simple payback period was 10 years [10].

Mathur and Bansal carried out the energy analysis of passive SWH systems in cities representing six climatic zones of India. They obtained the annual energy output of them and founded that the payback ranged from 0.73 to 4.16 years [11]. Asif et al. designed and developed two solar water heaters and undertook experiments during two months. The efficiency for the storage tank with stainless steel was 0.47, whereas for that with aluminium was 0.61. They obtained a payback period of 3.9 years and 1.4 years, respectively [12]. The magnitude of saved energy from SHW systems compared to conventional systems was provided from Crawford and Treloar. They showed that the payback period for the electric-boosted SWH system was 0.5 years, whereas for the gas-boosted one was 2 years [13]. Banik and Ganguly used capital budgeting techniques through the cash flow model to study a solar greenhouse. Their analysis was based on simple payback period and net present value [14].
II. SYSTEM DESCRIPTION

Fig. 1 shows the outside and the inside part of the SWH system used in this work. It is a trial installation equipped with the appropriate sensors. The external part of the system is installed on the roof and the measuring devices are placed in the Laboratory of Thermal Energy, Department of Energy, Polytechnic University of Tirana (PUT). The building is situated in the city of Tirana, where the geographical coordinates are 41.33 °N and 19.82 °E [15]. The average altitude of the city is 110 m, whereas the annual averaged number of sunny hours is $\bar{n}_w = 2500$ h/year [16].

Fig. 1. View of the outside (a) and inside (b) parts of the system

The SWH system studied in this work is a passive system. The layout and the sensor configuration are depicted at Fig. 2. Measured parameters through the appropriate sensors include the global solar irradiance (SRS), the temperature of supply water (TS1), the temperature of sanitary water (TS2, TS3, TS), the temperature of the outside ambient air (ATS), and the flow rate of the sanitary water (FRS).

![Diagram of SWH System](image)

To carry out the energy and the economic evaluation of the studied system all necessary parameters are measured through these sensors: CS 10 type “E” (solar irradiance), FRP6 (temperatures of supply and sanitary water), FAP13 (temperature of outside ambient air), and RESOL V40 (flow rate of sanitary water) [17]. Resol DeltaSol BX plus controller is used to store data in time intervals of $\tau = 1$ min [17]. The recorded data are transferred to a personal computer through the Resol VBus cable and then are managed through the appropriate softwares.

The evacuated tube collector studied in this work is produced by Sunda. Its operation is based on the heat pipe principle. The collector slope is 45° and is oriented 10° East from the South direction. Principal technical specifications of the studied solar thermal collector are: the gross area is 2.1 m², the aperture area is 1.476 m², the zero-loss efficiency is 0.735, the first-order coefficient is 1.16 W/(m² K), and the second-order coefficient is 0.0053 W/(m² K) [18].

To perform the economic assessment of the SWH system several parameters are included: the required quantity of the heated water is 160 l/day, the electricity cost is 0.082 €/kWh, the installed cost of the system is 500 €, and the discount rate is 7%.

III. MATHEMATICAL MODEL

The mathematical model used in this case study is focused on the energy and the economic estimation of the considered SWH system.

A. Energy Analysis

The energy analysis is carried out by defining several quantities.

The required rate of addition of sensible heat will be [19]:

$$\dot{L}_w = \dot{m}_w \cdot c_{pw} \cdot (T_{req} - T_{sup})$$

where, $\dot{m}_w$ is the mass flow rate of water [kg/s], $c_{pw}$ is the specific heat of water [kJ/(kg K)], $T_{req}$ is the required temperature [K], and $T_{sup}$ is the supply temperature [K].

The rate of useful energy gain from the solar water heater is estimated as [19]:

$$\dot{Q}_u = \dot{m}_w \cdot c_{pw} \cdot (T_2 - T_1)$$

where, $T_2$ is the outlet temperature [K] and $T_1$ is the inlet temperature [K].

The rate of energy delivered from the solar water heater system is defined as [19]:

$$\dot{Q}_{del} = \dot{m}_w \cdot c_{pw} \cdot (T_3 - T_1)$$

The instantaneous efficiency referring to the solar water heater is given as [19]:

$$\eta_{swh} = \frac{\dot{Q}_u}{A_c G_t} = \frac{\dot{m}_w c_{pw} (T_2 - T_1)}{A_c G_t}$$

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

The instantaneous efficiency referring to the SWH system is calculated as [19]:

$$\eta_{sys} = \frac{\dot{Q}_{del}}{A_c G_t} = \frac{\dot{m}_w c_{pw} (T_3 - T_1)}{A_c G_t}$$

B. Economic Analysis

The economic analysis of the considered SWH system is based on the discounted payback period (DPBP), the net present value (NPV), and the internal rate of return (IRR).

DPBP defines how many years are required to recover the investment, by considering the time value of money. During
the evaluation phase of an investment, it is preferred to have a minimum value of DPBP and below the fixed target period. It is given as [20]:

\[ DPBP = A + \frac{B}{C} \]  

(6)

where, \( A \) is the last period with a negative discounted cumulative cash flow [years], \( B \) is the absolute value of discounted cumulative cash flow at the end of the period \( A \) [€], and \( C \) is the discounted cash flow during the period after \( A \) [€/year].

NPV is widely regarded as the most representative measure of the financial performance of an investment. It measures the economic value of an investment as the sum of all discounted future net cash flows. All future cash inflows, cash outflows and investment cash flows are discounted to the base year using a discount rate and summed. In the case of a standalone project, it is preferred to accept it only if the NPV is positive. It is given as [21]:

\[ NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} - I_0 \]  

(7)

where, \( C_t \) is the cash flow at the end of year \( t \) [€/year], \( r \) is the discount rate [-], \( n \) is the system duration [years], and \( I_0 \) is the initial investment, €

IRR is the discount rate which equates the present value of future cash flows of a project with its initial investment. In the case of a standalone project, it is preferred to accept it only if the IRR is not less than the targeted IRR. It is given as [21]:

\[ \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} = I_0 \]  

(8)

IV. RESULTS AND DISCUSSIONS

The aim of the paper is the energy and economic estimation and analysis for a passive SWH system under real weather conditions and operations during a 12-months period. To obtain the goals, the database of measured parameters from a passive SWH system is utilized. The considered parameters include the irradiation on solar collector plane, the mean ambient air temperature, the volume flow rate of the heated water, the temperature of the supply water, the temperature of the heated water at the storage tank outlet, and the temperature of the delivered water to the thermal consumer. Then, the energy and the economic evaluation and analysis are carried out based on the mathematical model.

Fig. 3 shows monthly values of irradiation on solar collector plane. Its values increase gradually towards the summer months and vice versa. Their variation represents the effects of the season, latitude, and local climate conditions. The magnitude of irradiation on the tilted solar collector plane varies between \( H_{\min}^s = (98 - 255.8) \) kWh/month. The minimum value refers to the month of December, whereas the maximum to that of July. The annual value is \( H_{year}^s = 2065 \) kWh/year.

Also, at Fig. 3 is shown the variation of mean monthly values of ambient air temperature near the studied solar collector. The minimum value refers to the month of December with \( T_{\min} = 7.9 ^\circ C \), whereas the maximum is in August with \( T_{\max} = 28.3 ^\circ C \). The effect of the season and that of the local climate conditions is quite clear. The values are lower during the winter period. Its annual value is \( T_{air} = 17.9 ^\circ C \).

In Fig. 4 the monthly values of hot-water load for this trial field solar water heating system are shown. It is evident that the hot-water load is lower in the months, where the ambient air temperatures are higher. The how-water load ranged between the \( L_{min} = 153.5 \) kWh/month and \( L_{max} = 203.1 \) kWh/month in September and March, respectively. The results also show that the annual hot-water load for this trial field solar water heating system was \( L_{year} = 2129 \) kWh/year.

Considering the connection of the heat pipe evacuated tubes with the storage tank, then their unity will be mentioned as the solar water heater. This, because the heat exchanger of the solar collector is placed inside the storage tank. Fig. 5 shows the variation of useful energy gain from the solar water heater. It is evident that this quantity is lower in the months with lower values of insolation and vice versa. The useful energy gain from the solar water heater ranged between the \( Q_{min} = 27.3 \) kWh/month and \( Q_{max} = 145.8 \) kWh/month in December and July respectively. The results also show that the annual useful energy gain from the solar water heater is \( Q_{year} = 1006 \) kWh/year.

In Fig. 5 the values of delivered energy to the thermal consumer are shown also. This quantity was lower during the period where lower values of insolation are present and vice versa. The minimum value of the delivered energy to the thermal consumer is \( Q_{min} = 2.7 \) kWh/month, which
corresponds to the month of December. While, its maximum is noticed in the month of July, where $Q_{\text{det}}^{\text{max}} = 142$ kWh/month. The annual delivered energy to the thermal consumer is $Q_{\text{det}}^{\text{year}} = 983$ kWh/year.

![Figure 5](image1)

Fig. 5. The useful energy gain and the delivered energy

Variations of efficiency referring to the solar water heater are shown at Fig. 6. From the graph it is evident that the efficiency referring to the solar water heater is lower during the period associated with lower insolation and vice versa. Its monthly values varied between $\eta_{\text{swh}} = (0.476 \pm 0.556)$. The minimum value was noticed during the month of January, while the maximum during that of July. Also, it is observed that the fluctuation of monthly values of efficiency referring to the solar water heater shows a maximum difference of 8 %. These fluctuations are related with many factors, such as the irradiation, ambient air temperature, vacuum presence, heat pipe technology applied in the tubes of the studied solar collector, etc.

Also, in Fig. 6 is shown the variation of efficiency referring to the solar water heating system. The curve has the same shape as that of the efficiency referring to the solar water heater, but the values are something lower. This is related with thermal losses which happen in the pipeline between the storage tank and the thermal consumer. The minimum value of the efficiency referring to the solar water heating system is $\eta_{\text{sys}}^{\text{min}} = 0.457$ and it refers to the month of January. Whereas, the maximum value of $\eta_{\text{sys}}^{\text{max}} = 0.530$ refers to the month of July.

![Figure 6](image2)

Fig. 6. Efficiencies referring to the heater and to the system

Net Present Value is the second method employed to perform the economic estimation for the considered SWH system. Leaning on expression (7), it is calculated that at the end of the considered period the $NPV_{20} = 375$ €. Taking into account that it is a standalone system and the NPV is positive, it results that the studied system is economically viable under the climate conditions of Tirana.

The third method utilized in this work for estimating the feasibility of the considered SWH system is the Internal Rate of Return. From the results obtained through the expression (8) and the Fig. 8, it results that NPV equals zero when the rate is 15.62 %. For this reason, it results that the return rate is greater than the discount rate (IRR > r) and the investment related to the considered SWH system type is economically acceptable.

![Figure 7](image3)

Fig. 7. Cumulative discounted cash flow for the considered system

![Figure 8](image4)

Fig. 8. NPV vs. IRR for the considered SWH system

V. CONCLUSIONS

The energy and economic estimation and analysis for a passive SWH system under the Tirana climate conditions are carried out. To achieve the objectives, recorded data from a trial installation are used. They refer to an annual time period. The passive system is equipped with a heat pipe evacuated tube collector. The obtained conclusions for this case study are as follows:

a) The annual irradiation on the tilted solar collector plane was $H_{T}^{\text{year}} = 2065$ kWh/year, whereas the mean annual ambient air temperature was $T_{\text{air}} = 17.9$ °C.

b) The annual hot-water load was $L_{w}^{\text{year}} = 2129$ kWh/year.
c) The annual useful energy gain from the solar water heater and the annual delivered energy to the thermal consumer were \( Q_u^{\text{year}} = 1006 \text{ kWh/year} \) and \( Q_{\text{del}}^{\text{year}} = 983 \text{ kWh/year} \), respectively.

d) The monthly values of efficiency for the passive SWH system fluctuated between \( \eta_{\text{sys}} = (0.457 \div 0.530) \).

e) The economic estimation showed that \( DPBP = 8.1 \) years, \( NPV_{20} = 375 \text{ €} \), and \( IRR = 15.62 \% \).

ACKNOWLEDGMENT

The author acknowledges the grant provided from the National Agency for Science Research, Technology, and Innovation- Albania through the project “Water and Energy 2010-2012”. The trial installation used in this paper was the third system provided through this project. The measured data are obtained from my doctorate thesis.

REFERENCES


Altin Maraj was born in Tirana, Albania (June 1976). The author holds a Ph.D. degree on solar thermal applications since December 2014. He obtained his degree from the Faculty of Mechanical Engineering (FME), Polytechnic University of Tirana, Albania. The author research area focuses on solar applications. Since October 2001, he is employed as lecturer in the Department of Energy, FME, PUT, Tirana- Albania. The covered courses are three: Alternative Energy, Thermal Power Plants, and Technical Thermodynamics. His doctorate thesis was part of the project “Section: Water and Energy 2010-2012”. Dr. Maraj has published many papers in different journals and conference proceedings. Also, has participated in several national and international projects.