Energy Equip. Sys./ Vol. 8/No. 2/June 2020/ 143-152

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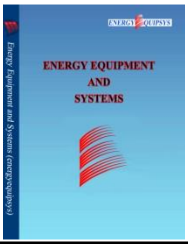

Comparative performance assessment of flat plate and evacuated tube collectors for domestic water heating systems in Kerman, Iran

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Article history:

Received : 14 June 2018
Accepted : 22 September 2019

ABSTRACT

This study represents a year-round energy performance of two solar water heating (SWH) systems with a 4m² flat plate collector (FPC) and an evacuated tube collector (ETC) operating under the same weather conditions. The energy performance of the two considered systems was compared on a monthly and yearly basis. The obtained results showed that for an annual total solar insolation of 2056kW.h.m^{-2}, a total of 3577kW.h.y^{-1} and 4201kW.h.y^{-1} of heat energy were collected by 4m^2 FPC and, ETC systems, respectively. The annual average energy efficiency by the FPC system was 43%, while its annual solar fraction was 50%. The ETC system had 51% energy efficiency with 58% solar fraction. The economic analysis showed that both solar water heating systems are not economically viable under prevailing costs in Iran. Furthermore, according to the obtained results, the FPCs are more favorable than the ETCs due to its economic analysis and energy performance. These results provide useful information for households and policymakers.

Keywords: Plat Plate Collector, Evacuated Tube Collector, Energy Performance Analysis, Economic Analysis, Solar Water Heater.

1. Introduction

All nations of the world depend on fossil fuels for their energy. However, the obligation to reduce CO_2 and other gaseous emissions in order to conform to the Kyoto agreement is the reason behind which countries turn to non-polluting renewable energy sources [1]. Over the past decades, lots of attention have been paid to renewable energy resources such as solar energy, wind energy, biomass energy, and geothermal energy [2-6]. These types of energy resources can be used to produce energy consistently with zero environmental pollution [7-11]. Solar water heating collectors are special kinds of heat exchangers that transform solar energy into the internal energy of a transport medium. The solar collectors absorb incoming solar radiation, convert it to heat, and then transfer the heat to a working fluid, usually made up of a mixture of the water and glycol that flows through the collector. The solar fluid usually is circulated within a closed circuit by using a pump. The collected energy is transformed into the water in a storage tank via a solar coil installed at the bottom of the tank. There are three common types of stationery collectors used in the SWH systems. These are flat plate collectors, evacuated tube collectors, and compound parabolic collectors (CPCs). FPCs and ETCs are the most widely deployed collectors for

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small-scaled water heating applications. Both collectors convert beam and diffuse solar radiation into heat. Typical installations for families of 4-6 persons consist of 4-6m^2 flat plate collectors and 3-4m^2 evacuated tube collectors connected to a 200-300 liters hot water tank [12]. Although, the evacuated tube collectors are increasingly in use because of their suitable thermal efficiency and high-water temperature achievable as compared to the flat plate solar water heaters.

Different authors have investigated the performance of SWH systems with numerous configurations, while the benefits of domestic solar energy systems were evaluated to illustrate the significant protection to the environment [13-16]. Zambolin and Del Col [17] tested two different types of solar collectors, a standard glazed flat plate collector, and an evacuated tube collector. They performed a steady-state and quasi-dynamic efficiency test following the EN 12975-2 standard. Furthermore, they compared the daily energy performance of these two types of collectors. An integrated appraisal of solar hot water in the UK residential sector was carried out to assess its overall energetic, environmental, and economic performance [18]. Chow et al. [19] worked on evaluating the performance of the two types of evacuated tube solar collector water heaters for domestic hot water applications. These are the single-phase open thermosyphon system and the two-phase closed thermosyphon system. The water heating systems include flat plate and evacuated tube solar collectors for the U.S typical residential buildings were evaluated from the energetic, economic, and environmental perspectives [20]. Shirinbakhsh et al. [21] used the phase change material (PCM) to improve the overall efficiency of solar-driven thermal systems. This study illustrates that integrating the PCM in the storage tank leads to an increase of 5.3% in the annular solar fraction (ASF) for a reservoir tank. In another study, the flat plate collector was optimized by using the particle swarm optimization after thermo-economic modeling [22]. Harmim et al. [23] studied the design, construction, and experimentation of an innovative integrated water heating solar collector equipped with a linear parabolic reflector. The Device was designed for integration into a building façade in Algerian Sahara.

The present study aims to compare the energy and economic performance of FPC, and ETC systems installed in similar operating conditions and weather conditions in Kerman province, Iran. Energy performance analysis includes reduction in CO_2 emission, solar contribution to domestic hot water (DHW), required auxiliary heating, the energy efficiency of the system, and energy-saving. To evaluate the thermo-economic performance of the two types of solar water heating collectors under study, a numerical software (TSOL) is utilized. According to the previous literature, a few numbers of studies dedicated to technically and economically study of the different types of SWH systems and compare them in Iran's climate zones. A review of available studies illustrates that these studies mainly focused on the improvement of the thermal efficiency of existing technologies even though the comparison of available technologies to find the optimum techno-economic performance was ignored [15, 22, 24-26]. The main novelty of the present investigation is to evaluate the two most commonly used and inexpensive SWH systems in different technical and economic aspects.

2. Solar Water Heating System

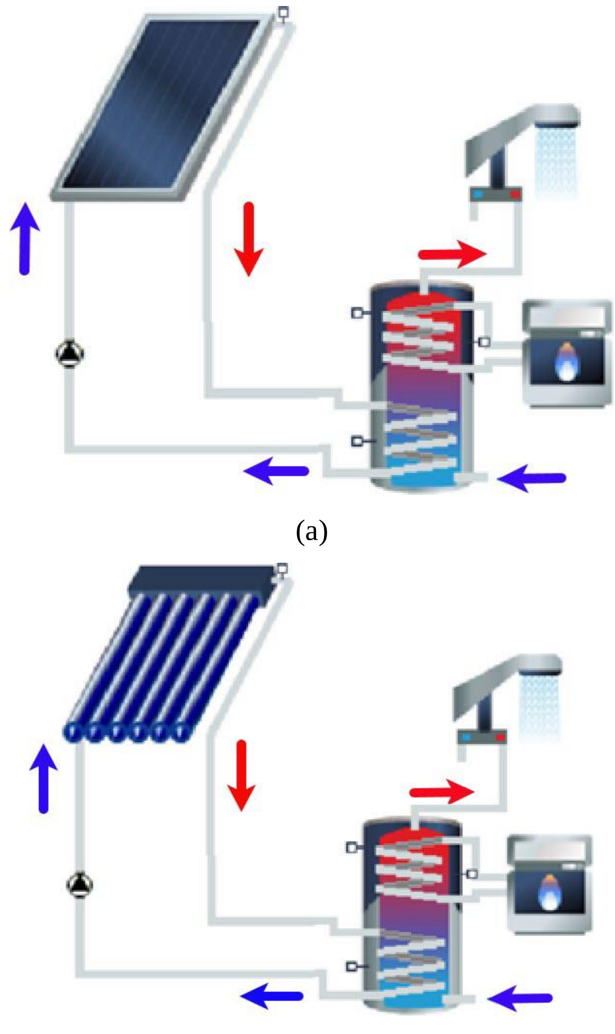
SWH systems provide a simple and cheap technology to produce hot water for domestic applications. This technology draws lots of attention due to its ease of access and use. To study SWH systems in detail, this section explains these systems both in technical and economic terms.

2.1. Design of Solar System

Small systems in detached private buildings are typically such that they mostly reach a full supply outside the heating periods so that the boiler can be shut down in the summer. Around 60% of annual hot water requirements can be covered in this way [20]. Larger solar fractions, if a large proportion of water must be heated by solar energy in spring, autumn, or in winter, give rise to a surplus in the summer, which cannot be used. The solar system is then no longer operating as effectively as possible. In other words, an increase in solar fraction reduces the efficiency of SWH systems. There are no simple methods to calculate the efficiency of solar systems precisely. The number of parameters that determine the performance of a system is too large and includes not only the changeable, nonlinear characteristics of the weather but also the dynamic processes in the systems itself. Although there are rules of thumb, such as around 1-2m^2 of collector area per person and 50 lit storage content per m^2 of collector area, these apply at best for small systems in detached or semi-detached houses [23]. Figure 1 depicts the schematic of two considered solar water heating systems, FPC, and ETC.

To design and optimize the solar systems by TSOL, the following factors should be considered:

Irradiation calculation, collector thermal losses, primary energy consumption, and Energy efficiency computation, and the solar fraction. TSOL provides design recommendations and standard values for the collector area and storage tank volume. In the current study, these recommendations were used to find the optimum system size.



(a)

(b)

Fig.1: The schematic of solar water heating systems (a) flat plate collector system and (b) evacuated tube collector system

Calculating Irradiation: TSOL acquires climate data from the MeteoSyn climate database that contains thousands of global climate datasets. In the supplied climate files, irradiation to the horizontal plane is given in watts per square meter of the active solar surface. TSOL converts this to the tilted surface during the simulation and multiplies it by the total active solar surface.

Calculating Collector Thermal Losses: The energy absorbed by the collector and output to the collector loop. Less heating losses are calculated in the TSOL user manual, as presented in Eq. (1) as follows:

$$P = G_{dir}\eta_0 f_{IAM} + f_{IAM,diff} G_{diff}\eta_0 - k_0(T_{Cm} - T_A) - k_0(T_{Cm} - T_A)^2 \quad (1)$$

where G_{dir} is a part of solar irradiation striking a titled surface, G_{diff} is diffuse solar irradiation striking a titled surface. T_{Cm} depicts the average temperature in the collector, while T_A and f_{IAM} are the air temperature and incident angle modifier, respectively. After the deduction of optical losses (conversion factor and incident angle modifier), a part of the absorbed radiation is lost through heat transfer and radiation to the environment. Furthermore, the storage tank losses are calculated based on the storage geometry. During the calculation of the energy supplied by the solar loop, additional tank losses are set off, which are primarily those created in summer generated through operational availability and the solar buffer.

Calculation of Primary Energy Consumption: Consumption values, efficiencies, solar fractions, and other parameters can be calculated from the temperature and the energy flows of the system.

Calculation of CO_2 Emission: To calculate the CO_2 emission saved by the solar system, it is necessary to know which type of primary energy is saved by the solar system. Emission factors by fuel type are used to calculate the CO_2 emissions of a heating system. The following emission factors are used in the TSOL user manual as Table 1.

Calculating Energy Efficiency and Solar Fraction: The collector energy efficiency is defined in Eq. (2) as follows [27]:

$$\text{Collector Efficiency} = \frac{\text{Energy output from the collector}}{\text{Energy irradiated onto the collector area}} \quad (2)$$

The solar fraction is defined as in Eq. (3) follows:

$$\text{Collector Fraction} = \frac{\text{Energy Supplied from the Solar System}}{\text{Total Supplied Energy}} \quad (3)$$

The total supplied energy includes the energy supplied by the solar system in conjunction with the auxiliary heating.

Calculation of Economic Values: The economic calculation in the current study is based on the Net Present Value method (NPV). The NPV is defined as the present value of the future net cash flows from an investment project and is one of the main ways to evaluate an investment. The net present value method is one of the most used techniques; therefore, it is a common term in the mind of any experienced business person. The total-life cycle cost of the SHW systems (C) is the sum of the capital cost (C_0) and the operation and maintenance cost ($C_{O\&M}$) given in Eqs. (4a)-(4b) as [12]:

$$C = C_O + C_{O\&M} \quad (4a)$$

$$C_{O\&M} = \sum_{n=1}^{n=N} \frac{C_{O\&M}(1+e)^n}{(1+d)^n} \quad (4b)$$

where $C_{O\&M}$ is the annual operation and maintenance cost, e is the service life, and d is the discount rate.

The total revenue (R_t) accrued over the service life of the SWH system is given in Eq. (5) as [12]:

$$R_t = \frac{Q_u}{\eta_h} \sum_{n=1}^{n=N} \frac{(1+e)^n}{(1+d)^n} \quad (5)$$

where η_h is the auxiliary heater efficiency and Q_u is the useful energy collected by the solar

Table 1. Emission Factor of Different Fuels

Fuel	Heating Value	Emission Factor
Oil	36722 *kJ/L*	7.32748 *g* CO2/*kJ*
Gas	41100 *kJ/m*^{3}	5.14355 *g* CO2/*kJ*

collector. The NPV for the SWH systems is given in Eq. (6) as [12]:

$$NPV = R_t - C \quad (6)$$

In other words, NPV is obtained by subtraction of total revenue, Rt, from the cost of the SWH system, C.

2.2. System Description

Typical SWH systems used in temperate climates consist of a hot water storage tank, a control unit, a pump station, and either FPCs or ETSs. The collectors were south facing and inclined 30o equal to the local latitude of the location. The FPC and ETC used in this study are standard commercially available collectors. The simulated solar system includes two complete forced circulation SWH systems with a 4m2 flat plate collector and 4m2 heat pipe evacuated tube collector that are subjected to similar weather and operating conditions in Kerman, Iran. The two water heating systems each had a 300 Lit hot water tank equipped with an auxiliary heater, which is used to top up the tank temperature to 50°C in the morning and evening whenever the solar system falls short of doing so. The average daily consumption is considered 600 Lit, while the simulation was done over a year.

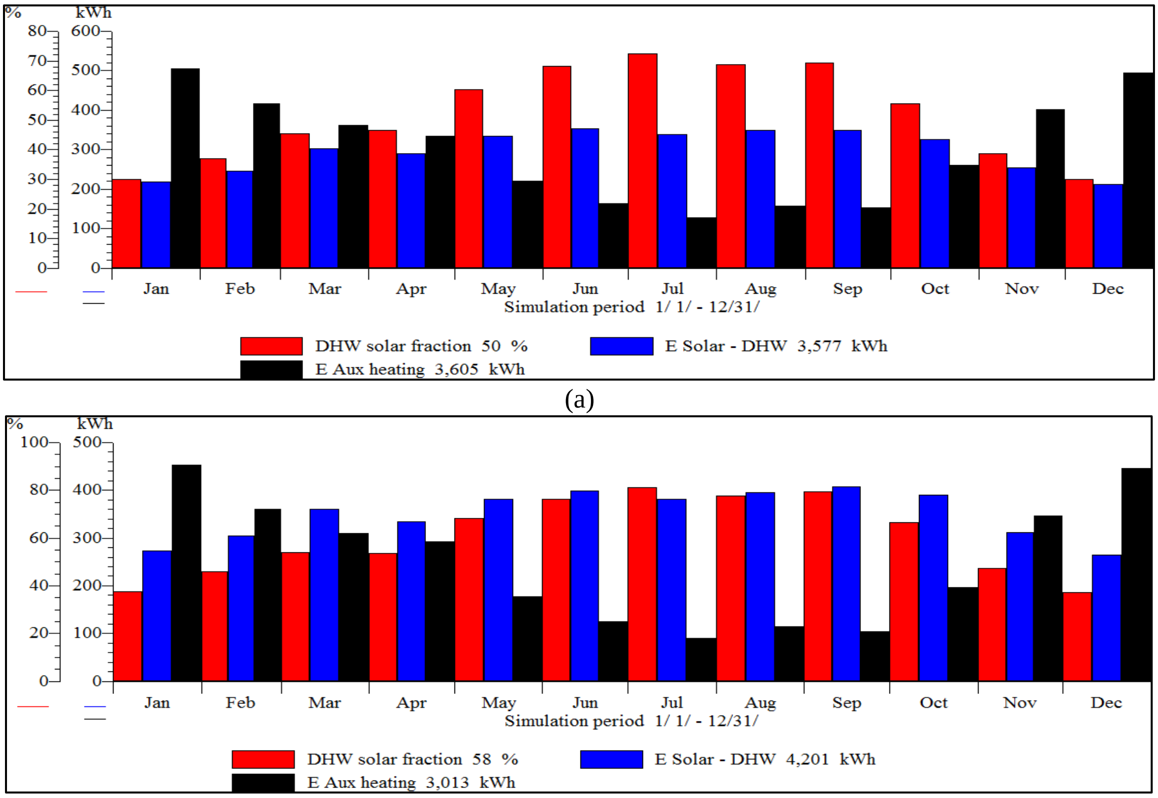
3. Results and Discussions

3.1. Geological Data

The hourly dry bulb temperature and the solar insolation data during a year period, which were collected in the Kerman weather station, have been used in the current study.

3.2. Energy Collected

Figures 2a-b depict average daily solar insolation and energy collected by the FPC and ETC systems. The annual total solar insolation received by the collectors' area is 8224kW.h.y-1. The results also show that over the year, the considered FPC, and ETC generated 3577kW.h.y-1 and 4201kW.h.y-1 of heat energy, respectively.



(b)

Fig.2: The solar water heating system performance (a) flat plate collector system and (b) evacuated tube collector system

3.3. Auxiliary Energy and Solar Fraction

Figures 2a-b show monthly average daily auxiliary energy supplied to the FPC and ETC systems. During the monitoring period, a total of 3605kW.h and 3013kW.h of auxiliary heat energy were added to the FPC and ETC systems. The solar fraction of the ETC systems ranged between 30% and 73% in December and July, respectively, while the solar fraction of the ETC systems ranged between 37% and 81% in December and July, respectively.

3.4. System Energy Efficiency

Table 2 depicts the results of system efficiency for the FPC, and ETC systems. The respective minimum and maximum system energy efficiency for the FPC was 39.8% in January and 45.7% in June, while that of the ETC was 49.7% in January and 52.3% in October.

3.5. Avoided CO_2 Emission and Saved Natural Gas

The amounts of CO_2 emission that were avoided by using the FPC and ETC are shown in Table 3. The saved CO2 emission by using SWH systems is the equivalent of the CO_2 that is saved to produce the same amount of heat by burning primary fuels such as natural gas. The total amounts of 1179kg and 1377kg of CO_2 were reduced by PFC and ETC systems, respectively. The minimum and maximum saved natural gas for the FPC were 24m^3 in December and 61.8m^3 in June, while the ETC saved 29.8m^3 in December and 71.1m^3 in September. The FPC and ETC saved the total amounts of 558m^3 and 651m^3 over a year, respectively.

Table 2: Solar system energy efficiency

Month	System Energy Efficiency (%)	
	FPC	ETC
Jan	39.8	49.7
Feb	42.3	52.1
Mar	43.5	51.7
Apr	44.4	51.2
May	45.2	51.5
Jun	45.7	51.5
Jul	44.5	50.1
Aug	44.8	50.7
Sep	43.6	50.7
Oct	43.5	52.3
Nov	41.9	51.1
Dec	40.4	50
Annual Average	43	51

Table 3: The amount of equivalent CO_2 emission avoided and saved natural gas

Month	equivalent CO2 emission avoided (kg)		Saving Natural Gas (m^3)	
	FPC	ETC	FPC	ETC
Jan	52	65	24.6	30.8
Feb	62	76	29.1	35.9
Mar	90	107	42.6	50.4
Apr	103	119	48.4	56.1
May	123	141	58.4	66.5
Jun	131	147	61.8	69.7
Jul	125	141	59.2	66.6
Aug	129	146	60.8	69.0
Sep	129	150	61.1	71.1
Oct	117	140	55.3	66.3
Nov	68	82	32	39.0
Dec	51	63	24	29.8
Annual Average	1179	1377	558	651

3.6. Economic Evaluation

The NPV of a project is defined as the sum of discounted annual cash flows during the *n* years under analysis. For a given year, the cash flow is the difference between incomes and expenses. To do a financial analysis by the NPV method, the required economic parameters are presented in Table 4.

The FPC and ETC systems had the NPVs of -1090$ and -1150$, respectively. Over the considered service life of 20 years, none of the SWH systems was economically viable. The result shows that under the prevailing cost and the assumed discount rate, the SWH systems are not yet economically viable in Kerman.

3.7. Parametric Study

To evaluate the FPC and ETC performances comprehensively, a parametric study is performed to assess the main features of the SWH systems. These evaluated features include impacts of the collector's area and the latitude of the system's location on the performance of the SWH. To study these factors, the collectors' area was increased and decreased by 25 %, respectively, while the latitude of the system's location was increased to 38° and decreased to 27°. The latitudes of 38° and 27° were selected; since Tabriz and Bandar Abbas are the largest northernmost and southernmost cities in Iran are located in the latitudes of 38° and 27°. Tables 5 and 6 briefly represents the parametric study of these two considered systems.

Table 5 shows the impact of the collector's area on the performance of the FPC and ETC systems. This table illustrates that variation of collector's area by 25% results in the variation of energy efficiency by approximately 5% to 4% for the FPC and ETC systems, respectively. While the NPV alters near 17% and 25% in the FPC and ETC systems, respectively, it can be concluded that increasing the collector's area is not a cost-effective approach to improve the performance of the FPC and ETC systems.

Table 6 evaluates the impacts of latitude coordinate and climate conditions on the performance of FPCs and ETCs. In other words, the variation of latitude coordinate and climate condition can significantly affect the performance of the solar heaters, while the NPV approximately remains constant in the considered scenarios.

Table 4: Parameters for NPV evaluation

Parameter	Value
Life span	20 years
Investment (FPC)	200 $\$/m^2$
Investment (ETC)	300 $\$/m^2$
Interest on capital	15%
Specific fuel cost	0.012 $\$/m^3$
Specific electricity cost	0.04 $/kW.h
Operation and maintenance cost	50 $

Table 5: Evaluation of the collector's area on the performance of FPC and ETC

	Collector's Area					
	FPC			ETC		
Factor under Study	3m^2	4m^2	5m^2	3m^2	4m^2	5m^2
Solar Fraction	39%	50%	58%	46%	58%	68%
Energy Efficiency	45%	43%	41%	53%	51%	48%
NPV	-901$	-1090$	-1281$	-862$	-1150$	-1443$

Table 6: Evaluation of latitude of system and climate condition on the performance of FPC and ETC

	Latitude of Installation					
	FPC with 4m^2 collector's area			ETC with 4m^2 collector's area		
Factor under Study	27° (Bandar Abbas)	30° (Kerman)	38° Tabriz	27° (Bandar Abbas)	30° (Kerman)	38° (Tabriz)
Solar Fraction	64%	50%	45%	74%	58%	54%
Energy Efficiency	41%	43%	43%	48%	51%	52%
NPV	-1088$	-1090$	-1090$	-1149$	-1150$	-1151$

4. Conclusions

SWH systems are capable of providing 50°C domestic hot water for the most climates in Kerman, Iran, with a reasonable solar collector area. The obtained results show that for a total annual solar insolation of 2056$kW.h.m^{-2}$, a total of 3577$kW.h$ and 4201$kW.h$ of heat energy were collected by 4m^2 FPC and, ETC systems, respectively. For 3605$kW.h$ and 3013$kW.h$ of auxiliary heat energy supplied to the FPC and ETC systems, their annual solar fractions are 50% and 58%. The annual average system efficiency was 43% and 51% for the FPC and ETC, respectively. The Economic analysis illustrated that both SWH systems are not economically viable with the NPV of -1090$ and -1150$ for the FPC and ETC systems, respectively. Parametric study of the two main features of solar heaters, the collector's area and latitude of installation, illustrate that the latitude of installation can significantly affect the performance of the system, while the collector's area is not a cost-effective approach to improve the performance of the systems.

The results show that the FPC systems are quite favorable than the ETC systems due to energy performance and economic analysis. These results provide helpful information to households, policymakers, and installers.

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