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Energy, exergy and economic (3E) evaluation of the photovoltaic/thermal collector-assisted heat pump domestic water heating system for different climatic regions in Turkey

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Abstract

In this study, the energy, exergy and economic (3E) analyses were performed for the photovoltaic/thermal collector-assisted heat pump domestic water heating system under two different climatic regions (Hakkari and Trabzon) in Turkey. Designed photovoltaic/thermal collector-assisted heat pump domestic water heating system with a storage tank having larger volume and cross-flow heat exchanger in Turkey can be considered as novelty of this study. The system modelled with the help of TRNSYS simulation code by using real weather data and energy analysis was performed based on year-round simulation results. And then, exergy and economic analyses were obtained based on monthly average temperatures. The system considered in this study was also compared economically with conventional natural gas and electricity water heating systems. According to the results, the maximum energy and annual average exergy efficiencies of the considered system were 68% and 22.3%, respectively, for Hakkari, and 67% and 21.4%, respectively, for Trabzon. Although Hakkari has cold climate conditions, the investigated system had lower energy consumption costs than conventional systems. The annual energy consumption costs of the system for Hakkari and Trabzon were calculated as 67.14$ and 135.75$, respectively. The results bring out that although the investment of the system is feasible for Hakkari, it is not feasible for Trabzon.

Keywords Solar water heating · Heat pumps · PV/T · Energy · Exergy · Economic analysis

Introduction

The role of energy is of great importance in the modern world in many areas. Today, how the energy is produced and the systems using it are of great importance in terms of the environment and cost. The energy for the supply of hot water used for various activities in industry, hospitals, hotels and homes is derived from fossil fuel systems. The rate of renewable energy use increases day by day because of the damage caused by fossil fuels to the nature and with limited reserves. Renewable energy sources like solar and wind are deemed necessary to ensure energy security and protect the world [1, 2]. Solar power plants have gained more popularity since they have lower emissions than conventional plants [3]. Solar-energy application is an alternative to the use of primary energy sources in large-scale energy-consuming systems, and their use with heat pumps is now a highly effective technology in reducing fossil fuel consumption [4]. Hybrid systems such as solar-assisted cogeneration systems of heat and water for residential buildings [5] or thermal solar-assisted heat pump systems for industrial applications [6] are effective and important solution to reduce global warming. According to a review study [7] on solar energy applications for electricity production, PV systems are more appropriate than the concentrated solar power plant systems for small-scale energy production. The results of the studies performed by Ahmedi et al. [8], Sadeghzadeh et al. [9], Mehrpooya et al. [10], Hossain et al. [11] and Aberoumand [12] show that the efficiency of the solar energy systems can be increased by using the nanofluids or phase-change material in the system. Nowadays, PV/T and heat pump systems are used to meet the need for electricity and thermal energy, and the systems in which both are used in an integrated manner are more noticeable than other traditional systems. Many

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researchers have been focused on the PV/T systems since they are more efficient than conventional PV systems, and they can easily be integrated with the conventional heating/cooling technologies. The energy performance of a system consists of a PV/T-assisted heat pump space heating system, which was investigated for Rome, Milan and Cracow by Vallati et al. [13] and for Venice and Crotone by Noro and Lazzarin [14]. Panagiotidou et al. [15] compared the solar-driven water heating system with conventional ones under Greece climate conditions. Aguilar-Jiménez et al. [16] made a techno-economic analysis with TRNSYS for a hybrid PV/T system located in Mexicali, Soria, Bigene, Fresno and Madison having different climate conditions. All of the obtained results in these studies show that the PV/T-assisted systems have higher performance than the conventional systems. In addition, these systems are more effective and pay-back time decreases down to 10 years in mild climates.

The increasing popularity of PV/T collectors in recent years has led researchers to conduct energy, exergy and economy analyses by using PV/T collectors with systems like heat pumps because of the combined production of electricity and thermal energy in solar-powered applications. Exergy analysis is more important in evaluating the quality of the energy produced when energy analysis is made to evaluate the performance of an energy system. Increasing the energy and exergy efficiencies of PV/T and heat pump systems was examined by many researchers. According to the results of the comparative studies performed by Li et al. [17], the photovoltaic thermal and solar thermal series performs the better performance than the conventional ones in view of energy and exergy. In addition, the performance of PV/T is highly dependent on the climate conditions. Therefore, it is important to investigate the performance under different climatic conditions. The solar irradiation and ambient temperature affect the thermal and exergy efficiencies [18]. The energy and exergy efficiencies of a hybrid solar heating, cooling and power generation system based on helical screw expander and silica gel–water adsorption chiller are higher than those of solar thermal power system with the Rankine cycle [19]. Yazdanifard et al. [20] examined the studies conducted on PV/T systems in detail and reported that the exergy of water, air and nanofluid-PV/T systems were more effective than conventional and thermoelectric-based PV/T systems. Sudhakar and Srivastava [21] found that the energy and exergy efficiencies of PV panels installed at NIT Bhopal Energy Center in India were 6.4% and 8.5%, respectively. They also reported that increasing the PV panel temperature would increase exergy loss, and therefore, lowering the temperature would increase the energy and exergy efficiencies at significant levels. Jahromi et al. [22] made the exergy and economic analysis of the PV/T system by using the MATLAB and TRNSYS programmes for three cities that had different climate conditions in Iran. The exergy efficiencies of Tabriz, Shiraz and Esfahan were reported as 9.7%, 9.6% and 9.6%, respectively. According to the results of economic analysis obtained with the net present value (NPV) method, the system was also applicable in economic terms. PV/T collectors perform better cooling with the increase in the mass flow of the fluid used in PV/T systems, and the electrical efficiency and electrical exergy are increased [23]. Sterling and Collins [24] compared the indirect solar-assisted heat pump (i-SAHP) system with the traditional solar domestic hot water (SDHW) system and an electric domestic hot water (EDHW) system. Among these systems, the lowest electricity consumption, the most utilization of the sun, and the best cost of working were realized in the i-SAHP System. According to the results of the study performed by Khatri and Singh [25], energy and exergy efficiencies of the solar tri-generation system were 50.53% and 35.87%, respectively. Bellos [26] evaluated four different heat pump systems with the help of TRNSYS in view of energetic and financial terms and reported that using PV and airborne heat pump together would be the best choice in economic terms, and the use of PV/T in conjunction with the waterborne heat pump would be the best choice.

PV/T systems ensure that this technology is a greener system in terms of low network electricity consumption compared to other systems. The energy and exergy analyses of the solar-assisted heat pump system used for industrial heating were discussed comprehensively by Suleman et al. [27]. While the exergetic efficiency of the heat pump and system was found to be 42.5% and 35.7%, respectively, the energetic COP values of them were calculated to be 3.54 and 2.97. Zhang et al. [28] designed and produced a new photovoltaic/loop-pipe (PV/LHP)-supported heat pump system to meet the need for electricity and hot water. As a result of their study, the basic heat performance coefficient of the system was calculated to be $\mathrm{COP_{th}}$ 5.51, and advanced system performance coefficient of $\mathrm{COP_{PV/T}}$ was 8.71. The general energy and exergy efficiencies of the system were approximately 48% and 15%, respectively. The efficiency of the designed system was calculated to be 3–5% higher than the efficiency of traditional systems and 7% higher than the efficiency of the standard PV-panel system. The COP was calculated to be 1.5–4% higher than solar/air–water heating systems. The PV/T solar-assisted heat pump/heat pipe system was analysed by Fu et al. [29] in three different modes under Hong Kong climatic conditions. When the system was operated under heat pipe mode, energy and exergy efficiencies were in the range of 36.5–38.4% and 7.4–7.8%, respectively, and when the solar-powered heat pump mode was operated, the energy and exergy efficiencies increased to 61.1–82.1% and 8.3–9.1%, respectively.

According to the literature survey, it can be concluded that there are almost no studies on the considered issue for Turkey. The novelty of this paper lies in the following: (i) a comprehensive research was performed to investigate the performance of PV/T-assisted heat pump domestic hot water system for Turkey in terms of energetic, exergetic and economical aspects, (ii) the effect of climate conditions on 3E analyses was examined by selecting two different cities (Trabzon and Hakkari) having different climatic conditions, (iii) it is aimed to increase the performance of the system by using a storage tank having larger volume and a cross-flow exchanger as different from other studies in the literature. Exergetic and economic calculations were done by using the monthly and annual energy results obtained from TRNSYS simulations. The economic usability of the system for each city discussed was examined with net present value (NPV) and internal rate of return (IRR) methods.

The description of the system and its modelling

In the presented paper, it is aimed to make energy, exergy and economic analyses (3E) in order to evaluate the performance of PV/T collector-assisted heat pump domestic water heating (PV/T-HPDHW) systems in Turkey with the help of TRNSYS Simulation Program [30]. The studies performed with TRNSYS simulation program have a good agreement within acceptable error value [31].

The schematic view of the considered PV/T-HPDHW system is given in Fig. 1. As seen in the figure, the system includes PV/T collector, battery, inverter, heat exchanger, circulation pump, heat pump, solar tank and buffer tanks.

Since the geographical conditions of Turkey, its climate varies noticeably from region to region. Although the coastal areas of West and South have generally a mild climate, the eastern region has a quite dry climate with cold winter and hot summer. In this study, two cities (Hakkari and Trabzon) with quite different climates were considered to determine the effect of climate on the performance. Although summers are warm and humid, and winters are cold and cloudy in Trabzon, summers are hot and dry, and winters are quite cold and snowy in Hakkari.

First of all, selected cities were evaluated in view of solar potential. While the ambient temperatures (T_{amb}) for the selected cities were obtained from the temperature analysis results of the Turkish State Meteorological Service [32], sunshine duration ($t_{sunshine}$) and the monthly average daily global solar radiation on a horizontal surface (I) were obtained from the Atlas of Solar Energy Potential (GEPA) prepared by General Directorate of Renewable Energy [33]. Equation 1 is used to determine the clearness index of the two cities included in the study.

$$K_T = \frac{I}{I_0} \tag{1}$$

where I_0 is daily extraterrestrial radiation and its value can be calculated by using the following equation:

$$I_0 = \frac{24}{\pi} I_{gs} \cdot f\left(\cos\delta \cdot \cos\phi \cdot \sin\omega_s + \frac{\pi}{180} \cdot \omega_s \cdot \sin\delta \cdot \sin\phi\right) \tag{2}$$

where I_{gs} is solar constant ($I_{gs} = 1.367\ \mathrm{k\,W\,m^{-2}}$), ϕ is the latitude for the selected city (37.58° for Hakkari and 40.59° for Trabzon), f is solar constant variation with time over the year (Eq. 3), δ is solar declination angle (Eq. 4) and ω_s is sunset hour angle (Eq. 5).

$$f = 1 + 0.0333 \cdot \left(\cos\frac{360 \cdot n}{365}\right) \tag{3}$$

where n is number of days of the year starting from first January (from 1 to 365).

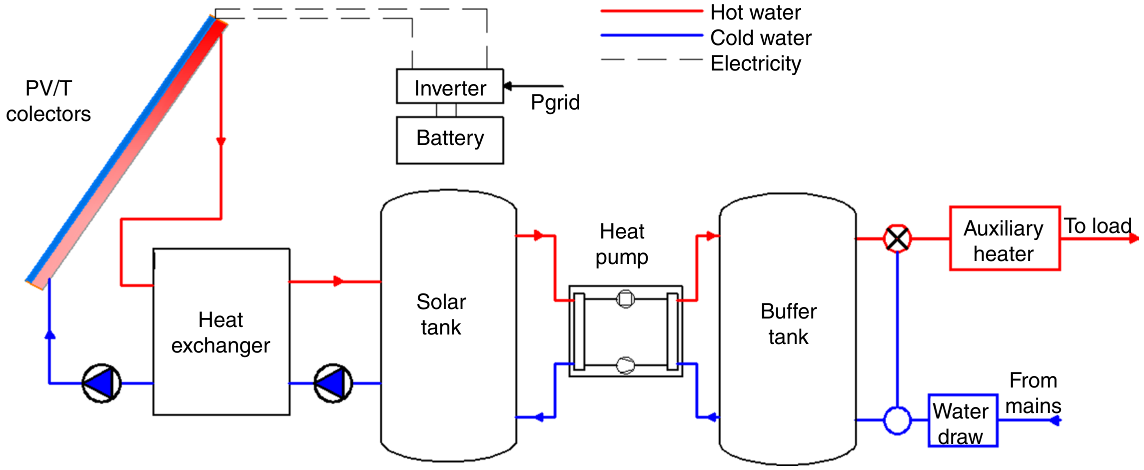


Fig. 1 The schematic view and of the considered PV/T-assisted heat pump domestic water heating system (PV/T-HPDHW)

$$\delta = (23.45 \cdot \left[\sin\left(\frac{360 \cdot (n + 284)}{365}\right)\right] \tag{4}$$

$$\omega_s = \arccos\left(-\tan\phi \cdot \tan\delta\right) \tag{5}$$

The changes of the ambient temperature and clearness index (K_T) with month for Hakkari and Trabzon are given in Fig. 2, and the variation of radiation and sunshine depending on months is also given in Fig. 3. It is seen in Fig. 1 that ambient temperatures are lower for Hakkari than for Trabzon in summer months. The clearness index were higher in Hakkari than in Trabzon all year round. However, as seen in Fig. 3, Hakkari was better than Trabzon in terms of sunshine intensity and duration in all months.

The simulation model of the PV/T-HPDHW system was developed using the TRNSYS Simulation Program [30]. Monthly and annual energy results were obtained from this program for the cities of Trabzon and Hakkari separately. The TRNSYS Model of the considered PV/T-HPDHW system is given in Fig. 4. The components selected in TRNSYS for the elements used in the system are given in Table 1. The weather data of Trabzon and Hakkari can be read from a Meteonorm file with the data set reader of Type 15–6 in TRNSYS. The simulation time step was kept short to have a more precise result in the modelling, and it was taken as 60 s. The water draw element used in PV/T-HPDHW system performed 20 min of water draw at six different times (at 7 a.m., 10 a.m., 13 p.m., 16 p.m., 19 p.m., 22 p.m.) in a day at flow rate of 250 kg h^{-1}. The temperature value of the hot water going to the user is determined as 50 °C. Main water of 15 °C will be drawn to complete the water reduced from the system. Mains water will be added to replace the water going to the user from the top at the desired temperature in accordance with the thermal stratification. In case the water from the solar PV/T system exceeds 50 °C, it will be reduced to the desired temperature by pulling cold water from the water supply. Type50b flat-plate PV/T collector area was selected as 5 m^2. Collector was positioned at tilt angle of 45°, and the azimuth angle of 0° positioned facing south. Under nominal working conditions of the PV/T collector, the cell radiation was determined to be 1000 Wm^{-2}, cell temperature was 25 °C, cell efficiency temperature was 0.0032 K^{-1} and cell efficiency was 15%. In order to prevent the water freezing because of the cold climatic conditions of the cities where the system was examined, 50% glycol–water mixture is used in the solar cycle, and the specific temperature of the fluid mixed at certain proportions is determined as 3.29 kJ kg^{-1} K^{-1} [34].

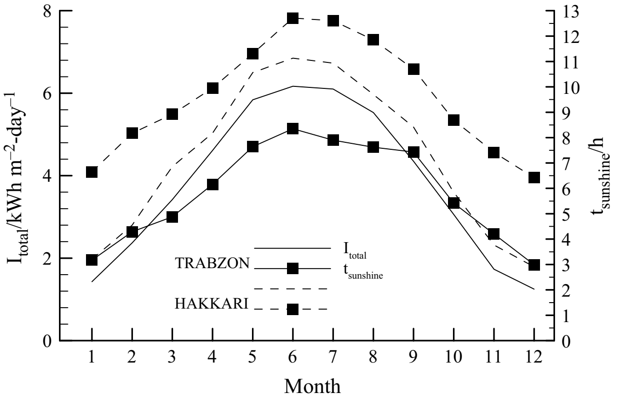
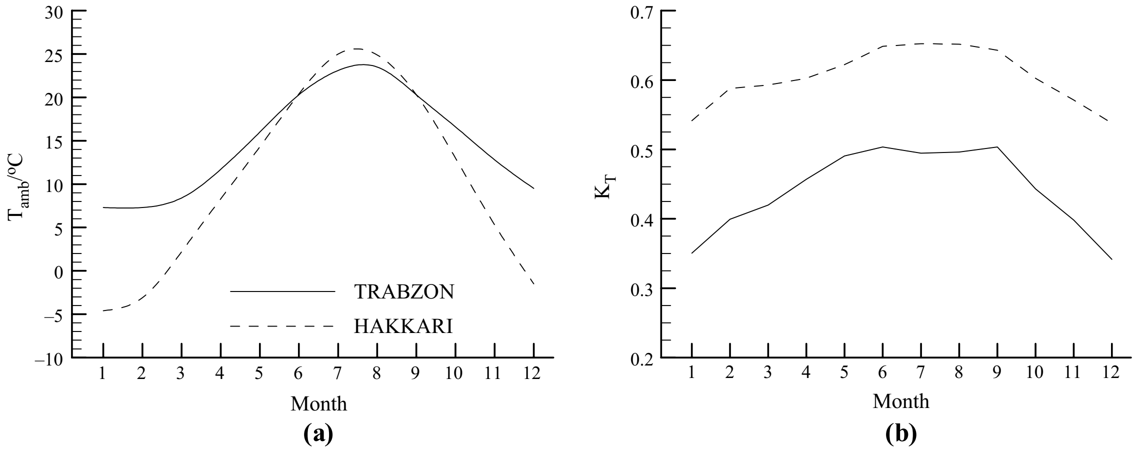


Fig. 3 Change of radiation and sunshine times of Trabzon and Hakkari by months [33]

A solar tank is added to system in order to store the heat obtained from the PV/T to supply continuous electricity and thermal energy due to the fact that solar energy is not continuous and is affected by weather conditions. A large tank, which has volume of 1000 L, is selected to make greater use of solar energy. And this solar tank generates the source



(a) **(b)**

Fig. 2 **a** Change of ambient air temperature [32] and **b** clearness index by months for Trabzon and Hakkari

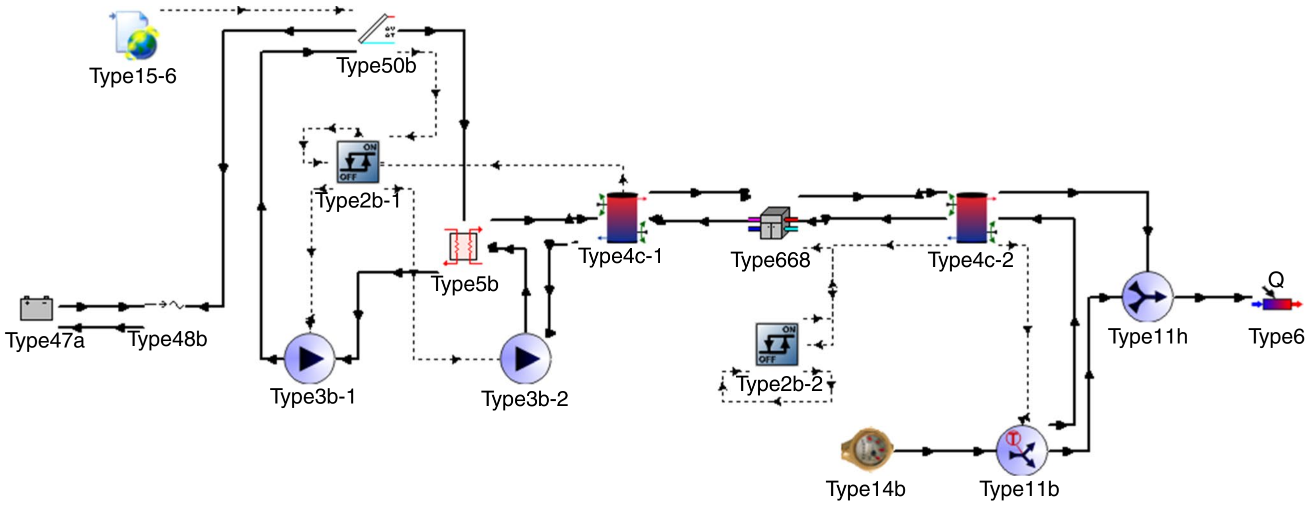


Fig. 4 The TRNSYS model of the considered PV/T-assisted heat pump domestic water heating system (PV/T-HPDHW)

Table 1 The system components of the TRNSYS model

No.	Component name	Type	No.	Component name	Type
1	PV / T	50b	9	Inverter	48b
2	Heat pump	668	10	Battery	47a
3	Storage tank	4c	11	Heat exchanger	5b
4	Pump	3b	12	Integrator	24
5	Weather data	Type15-6	13	Tee-piece	11 h
6	Printer	25c	14	Diverter	11b
7	Online plotter	65d	15	Auxiliary heater	6
8	Controller	2b	16	Water meter	14b

temperature of the heat pump. There is also buffer tank which stores the thermal energy coming from the heat pump, and the domestic hot water is drawn from this tank which has a volume of 500 L. Buffer tank consists of 10 equal layers since providing the thermal stratification. These layers are at different water temperatures, and the hot water obtained from the PV/T will enter in suitable layer depending on its temperature. This case ensures the maximum efficiency in heat storage and hot water generation. In the simulations, Type4c storage tank was selected from the TRNSYS component library to define the solar and buffer tanks. The average annual ambient temperatures for Hakkari and Trabzon were assumed as 11 °C and 16 °C, respectively, in this system, and these temperatures will be used to determine tank losses.

Type5b reverse-flow heat exchanger was used to transfer heat between the fluid exited from the PV/T collector and the fluid entering the solar tank.

In case of insufficient solar heat, two heaters having a power of 2 kW are located on the 2nd and 8th layers of the buffer tank. In addition, an auxiliary heater is located after buffer tank to heat the water when the temperature of water exiting from the buffer tank is lower than desired temperature when water is drawn. It is assumed that there is no heat loss from the auxiliary heater.

Two Type3b circulation pumps were used to ensure the circulation of glycol–water mixture at a constant flow rate of 250 kg h^{-1} between PV/T and heat exchanger (first pump) and between heat exchanger and solar tank (second pump). These pumps are operated with 100% power to provide a constant flow rate, and they consumes 60 kJ h^{-1} electrical energy during operation.

Two Type2b differential controllers were used to control the solar cycle and heat pump of the system. These controllers ensure the increasing of the solar utilization rate and the operation of the system more safely. The first controller used in the solar cycle will activate the first pump until the temperature difference is equal to 3 °C when the output temperature of fluid exited from PV/T collector is 5 °C higher than the output temperature of fluid exited from solar tank. The first controller also prevents the temperature in the solar tank from exceeding the boiling temperature (80 °C). The second controller controls the temperature of the water in buffer tank, and the desired temperature in this tank is 50 °C. If the temperature of water drops below 3 °C below the desired temperature, controller runs the heat pump to warm the water. The controller also stops the heat pump if the temperature of water in buffer tank is higher than the desired temperature. Therefore, water draw element will not be operated and so the more energy will not be wasted to cool the water.

Furthermore, in the case of the boiling temperature in solar tank, (80 °C) is higher than the desired temperature in the buffer tank (50 °C), and more heat will be collected in the solar tank. And in this case, heat pump will act as a circulation pump consuming lower energy instead of the compression process that consumes more energy because the compressor will not be operated. Water will be stored at more higher temperatures in the solar tank with this adjustment, and it is aimed to increase the solar utilization by using the hot water from the solar tank instead of using electricity for hot water.

Energy and exergy analysis

Energy and exergy analyses are important to evaluate the performance of any energy systems. As is known, while the energy analysis gives information about the quantity of energy, exergy analysis gives information about the quality of energy for a system. Exergy analysis can give optimum performance of the system in the case of evaluating systems by combining conservation of energy law with non-conservation of entropy law. The electricity production depending on the heat collected from the PV/T collector is important in order to determine the performance of it. Therefore, each energy and exergy analysis was investigated separately, in this study.

In the presented paper, the investigation procedure is given in Fig. 5. The first step in this study is the simulation of PV/T-HPDHW system for year-round with the TRNSYS program. The monthly energy performances of the PV/T-HPDHW system were evaluated through TRNSYS simulation results. And secondly, conventional exergy analysis was performed by using TRNSYS simulation results, and monthly average amounts of exergy gain and exergy efficiency were determined. Finally, economic analysis of the considered system was determined and compared to conventional water heating systems which are electric and natural gas heating.

Energy analysis

In this paper, the thermal efficiency of the PV/T-HPDHW system and the performance coefficient of the heat pump are determined by using the following equations to reveal the performance of the system.

The radiation value coming to PV/T collector (Q_i) is calculated with Eq. 6 [25]:

$$Q_i = A \cdot I \tag{6}$$

where A and I refer to PV/T collector area (m^2) and solar radiation value (Wm^{-2}), respectively. Equation (7) gives the useful heat output (Q_{th}) obtained from PV/T collector.

$$Q_{th} = \dot{m} \cdot Cp \cdot (T_{out} - T_{in}) \tag{7}$$

where $\dot{m}$ is the mass flow rate (kg s^{-1}) of the fluid cooling PV/T collector, C_p is the specific heat (J kg^{-1} K^{-1}), T_{in} and $T_{out,}$ are the input and output water temperatures of the collector.

The thermal (η_{th}) and electric (η_e) efficiencies of the PV/T collector are calculated by using Eqs. (8a) and (8b), respectively [28].

$$\eta_{th} = \frac{Q_{th}}{A \cdot I} \text{ and } \eta_e = \frac{Q_{el}}{A \cdot I} \tag{8}$$

where Q_{el} refers to the electricity amount produced by the PV/T collector. The total efficiency of PV/T collector is obtained with Eq. (9).

$$\eta_t = \eta_{el} + \eta_{th} \tag{9}$$

The performance coefficient of the heat pump (COP) is calculated by using Eq. (10) [28].

$$COP = \frac{Q_{heat}}{P_{hp}} \tag{10}$$

where Q_{heat} refers to the amount of the heat energy produced by the heat pump, P_{hp} refers to the amount of the electric energy consumed by the heat pump [23].

3.2. Exergy analysis.

Exergy efficiency of a PV/T collector is defined as the ratio of net output exergy rate to the net input exergy rate (see Eq. 11).

$$\eta_{ex} = \frac{E_{X_{out}}}{E_{X_{in}}} \tag{11}$$

where $E_{X_{in}}$ refers to the radiation exergy coming to the collector, and $E_{X_{out}}$ refers to the output exergy of the system elements [23].

Inlet solar exergy (Ex_{in}) coming from solar irradiation for PV/T collector is calculated with Eq. (12) [23].

$$E_{X_{in}} = A\,I\left[1 + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right) - \frac{4}{3}\frac{T_a}{T_{sun}}\right] \tag{12}$$

where T_a refers to the ambient air temperature and T_{sun} refers to the surface temperature of the Sun (6000 K).

Output exergy of a PV/T collector is the total of electrical exergy and thermal exergy (see Eq. 13) [23].

$$E_{X_{out}} = E_{X_{el}} + E_{X_{th}} \tag{13}$$

Since the electrical energy is converted as work with a rate of 100%, electrical exergy is equal to the electricity generated from PV/T as given in Eq. (14) [28].

$$E_{X_{el}} = \eta_{el} \cdot A \cdot I \tag{14}$$

The thermal exergy of the PV/T collector ($(E_{X_{th}})$ is calculated with Eq. (15) [28].

$$E_{X_{th}} = Q_{th}\left(1 - \frac{T_a + 273}{T_{fo} + 273}\right) \tag{15}$$

where T_{fo} refers to the fluid output temperature of the collector.

The exergy value of the heat pump is obtained by using Eq. (16) [28].

$$E_{X_{hp}} = \left(\frac{COP}{COP_r}\right) x Q_{gen} \tag{16}$$

Q_{gen} refers to the amount of the electrical energy given to the heat pump and COP_r refers to the possible maximum performance coefficient of the heat pump [25].

Economic analysis

Economic analysis is important to be performed to comprehensively analyse the performance of a system by evaluating the financial investments which are based on parameters such as the discount rate, inflation rate and risk. There are different techniques to make economic analysis based on statistical or dynamic models. In the statistical methods, the evaluation that is based on costs and revenues is limited to only one-period accounting records. However, in dynamic models, all expenditures including time value of money, expected proceeds and expenses associated with the investment project through the project life are considered. Therefore, the accuracy and precision are higher in dynamic methods for assessing the profitability of projects than the statistical methods.

There are different ways to measure the economic value of a project in dynamic methods. In this study, the net present value (NPV) and internal rate of return (IRR) methods were selected for economic analysis because of being the most popular and most used economic evaluation techniques. These methods are based on all future cash flows over the project period. While the NPV measures the increase in value of the investment, IRR measures the return of the project measured in percentage. NPV is the difference between discounted present value of cash inflows and initial investment, and it can be calculated by using Eq. (17). If the NPV has positive value, the project is feasible, and it can be accepted. If it has negative value, it should not be implemented since the required minimum return will not be provided. If NPV is equal to zero, it means that the annual revenue amount only covers the operating costs and annual investment costs.

$$NPV = \sum_{t=0}^{n} \frac{Bt}{(1+r)^t} - \sum_{t=0}^{n} \frac{Ct}{(1+r)^t} \tag{17}$$

where Bt and Ct are the cash inflow and outflow at the year of t, r is discount rate, n is life span. Discount rate states the expected efficiency rate from the investment, and it significantly affects the analysis result.

IRR which is the discount rate that makes the net present value zero represents the true interest yield over project life span. IRR value can be calculated by using Eq. (18). If this value is equal to or greater than the required rate of return, the project can be financially accepted.

$$IRR = \sum_{t=0}^{n} \frac{Bt}{(1+r)^t} = \sum_{t=0}^{n} \frac{Ct}{(1+r)^t} \tag{18}$$

Results and discussion

Energy analysis

The thermal and electrical energy production values of PV/T-HPDHW system are given in this part. The electrical and thermal energy efficiencies of the PV/T-HPDHW system for Trabzon and Hakkari depending on the months are plotted in Fig. 6. Electricity efficiencies for both cities change between at high values of 10–15% throughout the year. The reason of this is that the electrical efficiency varies depending on operating temperature of PV and cooling increases the efficiency. Namely, PV can be cooled down near to reference temperature of it (25 °C) with heat extraction by water circulation from heat pump and thereby efficiency increases. In some cases, the efficiency of PV was achieved more than the reference state. This was because of the decrease in the collector output temperature below 25 °C during winter.

Thermal efficiency increased to August in Hakkari, and then decreased. But in Trabzon, it varies with ups and downs. The thermal efficiency value was higher in Hakkari than the efficiency in Trabzon between April and October. Lower ambient temperature in the winter months in Hakkari increased heat to the environment and caused the efficiency to decrease. Although difference between minimum and maximum values of thermal efficiency throughout the year in Hakkari is distinct, the thermal efficiency varied in a more balanced manner because the ambient temperature in Trabzon did not vary excessively in summer and winter like Hakkari. The thermal efficiency was maximum (68%) for Hakkari in August and minimum (39%) in January. With the advantage of the high radiation in August, the difference between inlet and outlet water temperatures of PV/T was increased, and therefore, more heat was extracted by heat pump. Unlike Hakkari, Trabzon had higher thermal efficiency values in winter. The maximum thermal efficiency (65%) was in December for Trabzon, and the minimum efficiency (48%) was in March.

Figure 7 shows the monthly electricity and thermal energy production of Hakkari. As seen, electricity and thermal energy productions increased in Hakkari in summer months. The maximum and minimum values of both electricity and thermal energy production were in July and December, respectively. Maximum and minimum electrical energy values were 142 and 38 kWh, respectively, and maximum and minimum thermal energy values were 638 and 116 kWh. For Trabzon, monthly electricity and thermal energy production values are given in Fig. 8. A distribution like the distribution in Hakkari province was observed in Trabzon. Maximum electricity and thermal energy production were produced in July in Trabzon, and the values were found as 117 kWh and 516 kWh, respectively. Minimum electricity production (28 kWh) was in December, and minimum thermal energy production (125 kWh) was in January.

According to Figs. 7 and 8, the total annual electricity and thermal energy production were 1083 and 4512 kWh, respectively, for Hakkari, and 851 and 3737 kWh, respectively, for Trabzon. As shown in these figures, more high values in thermal and electricity energy production were obtained in Hakkari. It is well known that conditions such as high solar radiation value, high daily sunshine time and clearness increase electricity and thermal energy production. Since these parameters were more advantageous for Hakkari, higher production rates were obtained. Due to the fact that the T_{amb} values of Trabzon are higher than that of Hakkari and the Kt values of Trabzon are lower than that of Hakkari (see Fig. 2a and b), the electricity and thermal energy production were negatively affected.

Exergy analysis

Exergy analysis were carried out and detailed out to evaluate the system performance as a result of thermal and the electrical conversion processes. Exergy gains and exergy efficiencies of PV/T and heat pump, overall exergy gain and overall exergy efficiency were determined for each city considered in this paper throughout the year.

The monthly variations of thermal and electrical exergy gains for Hakkari and Trabzon are given in Fig. 9. For both cities, the electrical exergy gain was higher than thermal exergy gain. The exergy gain values in both electricity generation and thermal energy production systems are higher for Hakkari than Trabzon all year-round. While the exergy gain for Hakkari increased to July and then decreased, it increased to June in Trabzon and then decreased. The maximum electrical exergy gain value was obtained in Hakkari and Trabzon 142 kWh and 116.6 kWh, respectively. The electrical exergy gain was maximum in June in both cities, and these values for Hakkari and Trabzon were 50.2 and 46 kWh, respectively. When exergy gain was examined by months for the heat pump, a different distribution was observed for Hakkari and Trabzon. The exergy gain values of the heat pump were lower for Trabzon than for Hakkari except in summer months (June, July and August). While the highest exergy gain of heat pump for Hakkari was in

Table 2 Comparison of energy consumption values by cities

City	Hakkari	Trabzon	City	Hakkari	Trabzon	City
System	PV/T-HPDHW system	Natural gas HW system	System	PV/T-HPDHW system	Natural gas HW system	System
Consumption	Electric consumption kWh	Natural gas consumption m^3	Consumption	Electric consumption kWh	Natural gas consumption m^3	Consumption
Month						
January	118.83	52.99	613.21	129.56	53.02	607.38
February	105.92	47.93	554.56	113.11	47.95	549.30
March	110.67	53.06	613.98	126.71	53.09	608.16
Aprıl	73.21	51.35	594.17	98.03	51.38	588.54
May	– 15.62	53.06	613.98	64.10	53.09	608.16
June	– 82.44	51.35	594.17	– 11.12	51.38	588.54
July	– 89.51	53.06	613.98	18.09	53.09	608.16
August	– 71.53	53.06	613.98	42.64	53.09	608.16
September	16.89	51.35	594.17	97.87	51.38	588.54
October	114.41	53.06	613.98	129.59	53.09	608.16
November	125.40	51.35	594.17	133.81	51.38	588.54
December	123.69	53.06	613.98	134.98	53.09	608.16
Annual	529.91	624.69	7228.35	1077.37	625.02	7159.81

Table 3 Comparison of energy consumption costs by cities

City	Hakkari			Trabzon		
System	PV/T-HPDHW system	Natural Gas HW system	Electrical HW system	PV/T-HPDHW system	Natural Gas HW system	Electrical HW system
Cost	Electric cost/$	Natural gas cost/$	Electric cost/$	Electric cost/$	Natural Gas cost/$	Electric cost/$
Month						
January	14.97	15.90	77.26	16.32	15.91	77.30
February	13.35	14.38	69.87	14.25	14.39	69.91
March	13.94	15.92	77.36	15.97	15.93	77.40
Aprıl	9.22	15.41	74.87	12.35	15.41	74.91
May	– 2.41	15.92	77.36	8.08	15.93	77.40
June	– 12.70	15.41	74.87	– 1.71	15.41	74.91
July	– 13.79	15.92	77.36	2.28	15.93	77.40
August	– 11.02	15.92	77.36	5.37	15.93	77.40
September	2.14	15.41	74.87	12.33	15.41	74.91
October	14.50	15.92	77.36	16.33	15.93	77.40
November	15.89	15.41	74.87	16.86	15.41	74.91
December	15.67	15.92	77.36	17.01	15.93	77.40
Annual	67.14	187.41	910.77	135.75	187.51	911.25

Table 4 The investment cost of each main component for the considered PV/T-HPDHW system

Component	Cost/$
PV/T array	900
Heat pump	3300
Storage tank with auxiliary heater	800
Circulation pump	150
Inverter	200
Battery	900
Engineering, installation and shipping	150
Pipes and fittings	150
Total	6550

September with a value of 42.2 kWh, that for Trabzon was in August with a value of 23.8 kWh.

Figure 10 presents the exergy efficiencies in electricity and thermal energy production, and the change in exergy efficiency for heat pump for Hakkari and Trabzon. Similarly to exergy gain, electrical exergy efficiency was higher than thermal energy efficiency for both cities. The average annual efficiency of electrical and thermal exergy efficiencies was around 14% and 4%, respectively, in both cities. The exergy efficiency of the heat pump was higher for all months for Hakkari than for Trabzon. The average annual exergy efficiency of the heat pump was approximately 48% for Hakkari and 31.2% for Trabzon. Exergy efficiencies for heat pump are higher than the thermal and electrical efficiencies in both cities. The most important reason for this may be explained as that when the controllers used in the system exceed the temperature values set for the solar tank, the heat pump acts as a circulation pump instead of compression, and the heat pump transports heat with lower energy.

The change in the system's total exergy gain for the two cities by months is depicted in Fig. 11. A similar distribution is observed for both cities throughout the year. It increased exponentially towards summer months and reached maximum value and then decreased exponentially towards winter months. For all months, Hakkari's total exergy values were higher than Trabzon's. Due to the factors like high radiation in Hakkari and the low average ambient air temperature, the amount of exergy was higher.

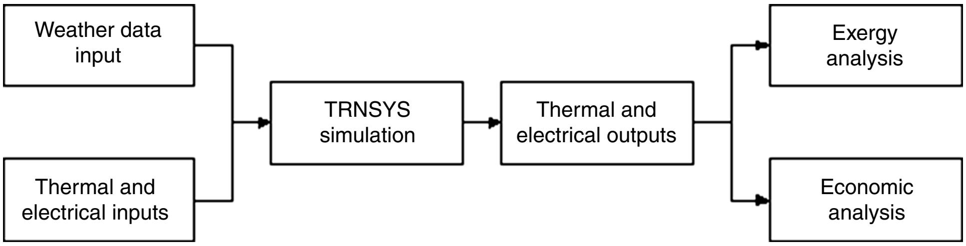


Fig. 5 The investigation procedure for analysis

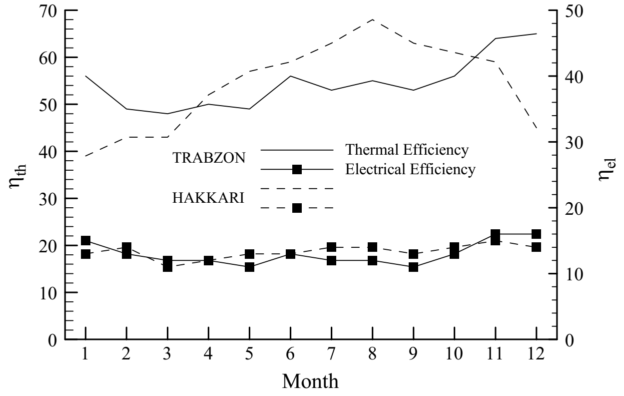


Fig. 6 Change of electric and thermal energy efficiencies of PV/T-HPDHW system by months for Hakkari and Trabzon

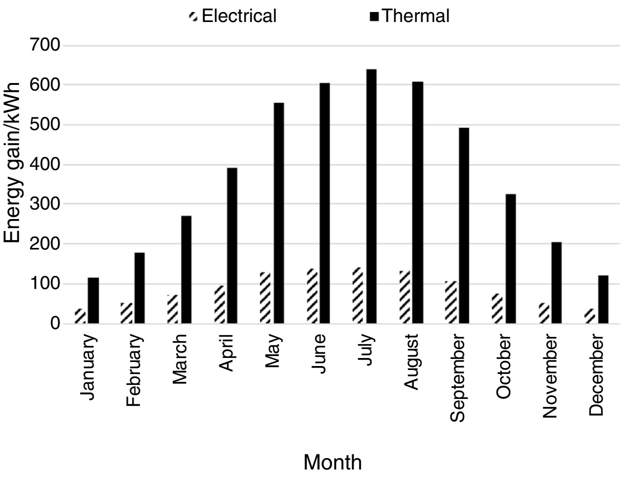


Fig. 7 Monthly electric and thermal energy production for Hakkari

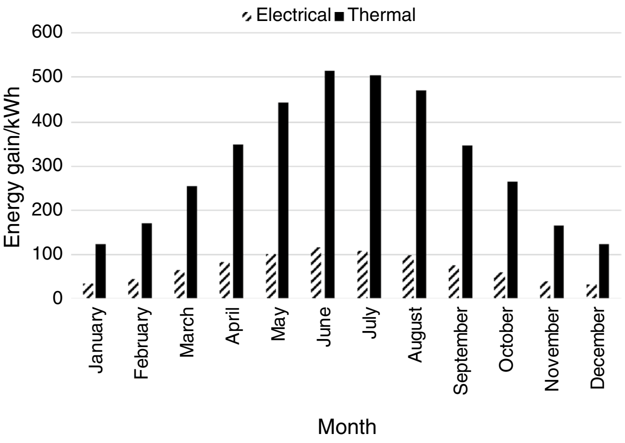


Fig. 8 Monthly electric and thermal energy production for Trabzon

Figure 12 shows the monthly variation of the overall exergy efficiency for Trabzon and Hakkari. Higher efficiencies were achieved for Hakkari in the spring and autumn seasons compared to summer. The exergy efficiency of the system was lower in Trabzon than in Hakkari except for January, November and December. The average annual exergy efficiency was calculated as 22.3% for Hakkari and 21.4% for Trabzon. Considering the annual variation in general, higher exergy efficiencies were obtained in winter months.

Economic analysis

In this study, for the considered PV/T-HPDHW system, the energy consumption values and costs were investigated. In Turkey, while domestic hot water production is substantially covered by natural gas systems which operate with 92% efficiency, it is followed by electrical systems which operate at a 99% efficiency. Therefore, energy consumption values and costs for considered system in this study were compared with conventional systems being natural gas and electrical water heating systems. In the calculations, the higher value of natural gas was taken into account and its value was 10.64 kWh (9155 k cal m^{-3}). It was accepted that the unit price of natural gas and electricity was set as 0.3 $\$m^{-3}$ and 0.126 $\$kWh^{-1}$, respectively.

The energy consumption values given in Table 2 were compared in cases of the considered PV/T-HPDHW system and conventional natural gas and electricity water heating systems. It was seen that the electric consumption has negative value for Hakkari from May to August. This means that there is no electric consumption because of high solar radiation. This case for Trabzon was occurred only on June. This negative electricity value is generated excess electricity, and it was assumed that the revenue was generated by selling the excess electricity to grid with a price of 0.154 $\$kWh^{-1}$. Since higher solar energy was collected in Hakkari, there was lower electricity consumption than Trabzon. The total annual energy consumption value of the system discussed in the present study was 529.91 and 1077.37 kWh for Hakkari and Trabzon, respectively. In case the energy of the system was supplied from natural gas, the results were 624.69 and 625.02 m^3, and in case that from electricity, 7228.35 and 7159.81 kWh for Hakkari and Trabzon, respectively.

Table 3 presents the energy consumption costs of the PV/T-HPDHW system and conventional natural gas and electric water heating systems. The annual energy consumption costs of PV/T-HPDHW, natural gas and electric systems were calculated as 67.14\$, 187.41\$, 910.77\$, respectively, for Hakkari, and 135.75\$, 187.51\$, 911.25\$, respectively, for Trabzon. According to these results, it was seen that the PV/T-HPDHW system was more advantageous than the other conventional systems. It was revealed that the PV/T-HPDHW system is more feasible for cities with high solar

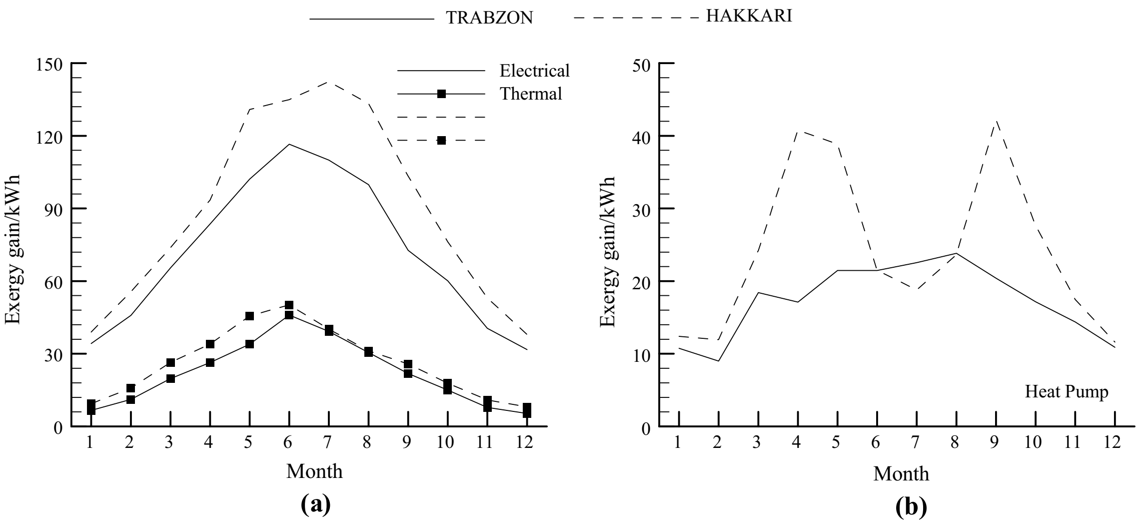


Fig. 9 Change of exergy gain for **a** electric and thermal, **b** heat pump for Hakkari and Trabzon by months

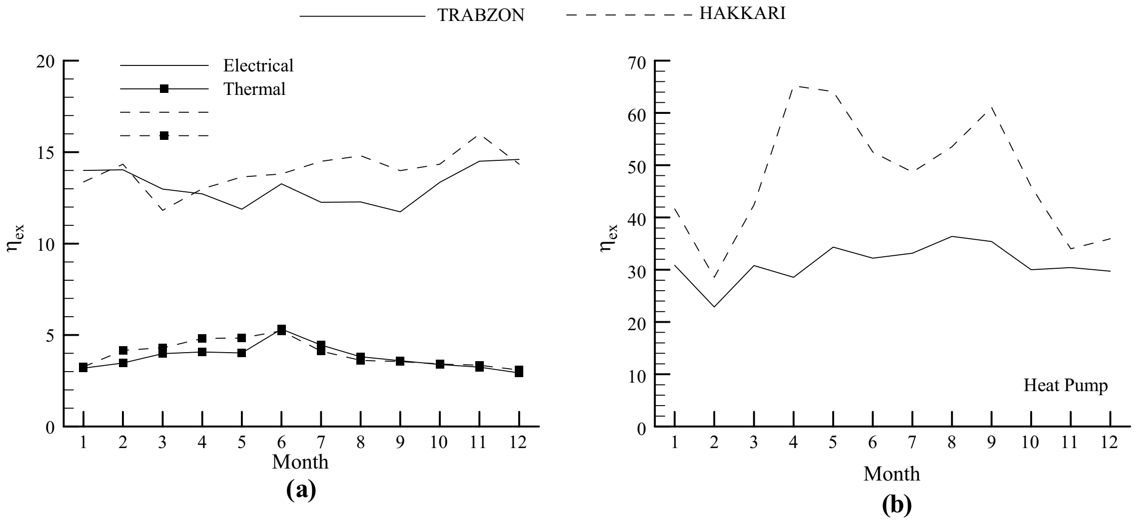


Fig. 10 Change of exergy efficiencies for **a** electric and thermal, **b** heat pump of Hakkari and Trabzon by months

potential such as Hakkari, which has a cold climate and high solar potential. Since Hakkari has high solar potential even if it has also a cold climate, it was revealed that the PV/T-HPDHW system is more feasible for Hakkari.

The investment cost of each main component for the considered PV/T-HPDHW system is given in Table 4.

The annual incomings from electrical and thermal energy for Hakkari and Trabzon were 735.3$ and 603.9$, respectively. It was accepted that the expected profit rate is 8%, the annual operation cost was 50 $ and the life span of the system was 20 years.

The Bt and Ct for Hakkari were 7219.28 and 7040.90. According to these values, NPV was calculated as 178.38$. Since this value is greater than zero, the investment is accepted. In case discount rate is assumed as %5, IRR is equal to 1990.35. Since it was not equal to zero, IRR was recalculated by accepting discount rate is 10%, and it was found − 715.65. When an interpolation was made between these results, IRR was found 8.7%. Because of being discount rate is bigger than 8%, investment is feasible. The Bt and Ct for Trabzon were 5929.18 and 7040.90. For Trabzon, NPV was obtained as − 1111.73$. Since this value is less than zero, the investment is not accepted. For the values of discount rates that were accepted as 5 and 10%, IRR was determined as 352.82 and − 1834.34. When IRR was equal to zero, discount rate was found as 5.8%. And this value is

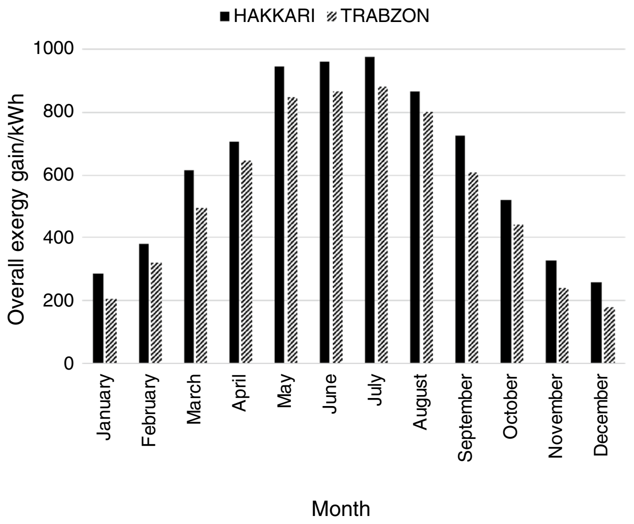


Fig. 11 Change of exergy gain of the overall system for Hakkari and Trabzon by months

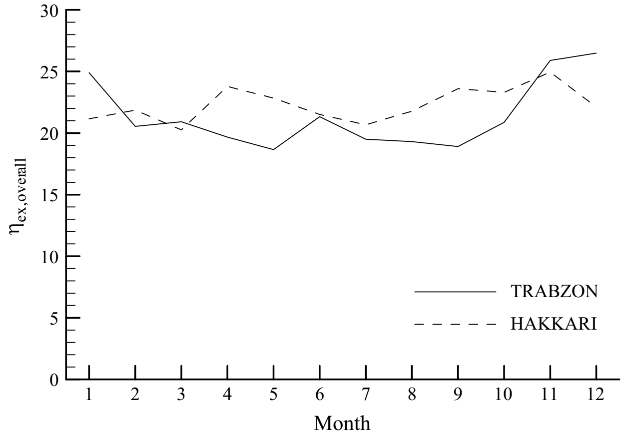


Fig. 12 Change of the exergy efficiency of the overall system for Hakkari and Trabzon

less than 8%, the investment is not acceptable for Trabzon. According to the results of both NPV and IRR methods, although the investment of the considered PV/T-HPDHW system is feasible for Hakkari, it is not feasible for Trabzon.

Conclusions

In the present study, the energy analyses of the domestic hot water preparation system for Turkey were carried out by using the TRNSYS simulation program and the exergy and economic analyses were made by using the results obtained. Two cities with different climatic conditions, Hakkari and Trabzon, were selected to determine the effect of climate conditions. The examined system was compared with natural gas and electrical systems used as energy source for domestic water heating in economic terms. The main results obtained in the study are given briefly below:

- The low clearness index and high ambient temperature negatively affected the energy production. For this reason, due to the high clearness index and low annual average ambient temperature, the PV/T-HPDHW System is more applicable to Hakkari for hot water.
- Electricity and thermal energy production of PV/T collector that has an area of 5m^2 in the examined system was 1083 kWh 4512 kWh for Hakkari and 864 kWh and 3737 kWh for Trabzon, respectively.
- The electrical, thermal and heat pump exergy production values were 1074 kWh, 315.6 kWh and 291 kWh for Hakkari, and 862.8 kWh, 263.5 kWh and 207.5 kWh for Trabzon, respectively.
- According to the results of the economic analysis of the PV/T-HPDHW system, the annual energy consumption costs were calculated as 67.14$ and 135.75$ for Hakkari and Trabzon, respectively. And these values are lower compared to natural gas and electricity-consuming systems.
- According to results of both NPV and IRR methods, although the investment of the considered PV/T-HPDHW system is feasible for Hakkari, it is not feasible for Trabzon.
- It is observed that the designed system in this paper has high thermal energy efficiency than the ones in the literature. Hazami et al. [35] modelled a similar system having 200 lt solar tank in Tunisian and calculated average thermal energy efficiency value of 50%. He et al. [36] reported the thermal efficiency values of 40% for a PV/T collector having 100 lt solar tank. In this study, the obtained overall average value of thermal efficiency is calculated 55%.

Regarding the results obtained in this paper, it can be concluded that PV/T-HPDHW systems should be employed wherever possible since they are efficient and economical. And so, environmentally positive results will be obtained as a result of using a cleaner energy source which is solar energy. In conclusion, the results support the integrated use of the heat pump and the PV/T collector, emphasizing that it will energize the increase of studies in this field. Future studies can be conducted on the optimization of the system in view of solar tank capacity, cost and efficiency.

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