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Performance and Techno-Economic Analysis of a Hybrid Photovoltaic/Thermal System for Building Application in Turkey

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Abstract: Residential buildings need demand of energy for both heat and electricity. However, it's not always possible to meet this need by using individual panels due to the limited roof area. In addition, performing electrical and thermal energy production by using separate panels causes loss of performance and efficiency. The hybrid photovoltaic thermal (PV/T) collectors could be used in order to meet this necessity into the same collector. This paper investigates the performance and economic analysis of a PV/T collector for a building application in Turkey climatic conditions. For this purpose, the Matlab/Simulink model of the PV/T collector was prepared. The electrical and thermal performance of the PV/T collector has been investigated by changing various parameters on this model. In addition, market survey was conducted for economic analysis. 11 different input variables such as average daily irradiation, electrical and thermal efficiency, price of electricity and heating, operation and management cost, capital cost, debt to equity ratio, interest rate, discount rate and inflation rate are used to calculate the economic evaluation parameters such as net present value (NPV), levelized cost of energy (LCOE) and payback period (PBP). The results show that, the mean value of LCOE, NPV and PBP are 0.0467 €/kWh, 7905.3 € and 6 years respectively for the project size at 8.96 m² which is consist of 7 panels in the 25 years life cycle. Also, the average electrical and thermal efficiencies are defined as 13.4% and 69.3% respectively during.

Keywords: Solar energy; performance analysis; PV/T collector; economic analysis; LCOE; NPV

1. Introduction

The sun is the largest energy source for the world. There are basically two ways to make available the energy provided by the sun. The first is to convert the solar energy into thermal energy and the other is to convert it into electrical energy. Because of their unique advantages, both technologies are increasingly used in residential and industry applications. Because of the heat and electrical energy obtained from the sun often complement each other and in order to eliminate the disadvantages arising from the use of these two technologies separately, it is thought that it is more convenient to produce heat and electrical energy from the same panels. A PV/T collector is a module which combines the photovoltaic and thermal technologies into the same panel.

36 The technical and economic suitability of a water based PV/T collectors was first stated by Martin Wolf in 1976. Then in 1978
 37 the first liquid based PV/T was tested in a house by Böer and Tamm (2003). After these two experimental studies, many
 38 researchers started to work in this field. In 1978, TRNSYST model was developed by using mathematical equations of active
 39 cooled PV/T collectors at Arizona State University (Florschuetz 1979). In the study conducted in 1978 at the Massachusetts
 40 Institute of Technology laboratories, the electrical and thermal efficiency of the PV/T collector was measured as 6.5% and 40%
 41 respectively. After that, many studies have been done to increase the electrical and thermal efficiency of the PV/T collectors in
 42 USA, Japan, Netherlands, Denmark and Germany (Cox and Raghuraman 1985; Suzuki and Kitamura 1979; Karl 1979; Komp
 43 1985). Although studies on the PV/T collectors have been reduced due to low oil prices between 1980 and 1990, some studies
 44 have been carried out in some European countries such as Switzerland and Yugoslavia (Schwartz et al. 1983; Lalovic et al.
 45 1986; Lalovic et al. 1988). In 1992, with the political recognition of global warming and climate change, efforts in the PV/T
 46 collectors have accelerated again. Especially in Germany, Denmark and the Netherlands, many projects were realized between
 47 1990-2000 (Zondag et al. 2003; Leenders et al. 2000; Bakker et al. 2002; Bakker et al. 2004; Rockendorf et al. 1999; Hausler
 48 and Rogass 2000; Soerensen 2001). In the following years, many countries such as Japan, India, Israel, Brazil, Taiwan, Cyprus
 49 and the USA have been working in the field of PV/T (Tripanagnostopoulos et al. 2002; Tselepis and Tripanagnostopoulos
 50 2002; Kalogirou 2001; Bergene and Løvvik 1995; Meir et al. 2002; Sandnes and Rekstad 2002; Hayakashi et al. 1989;
 51 Fujisawa and Tani 1997; Ito et al. 1999; Huang et al. 1999; Huang et al. 2001; Garg and Agarwal 1995; Boer and Tamm 2003;
 52 Thomas et al. 2000; Krauter et al. 1999; Krauter et al. 2001).

53 The water-based PV/T collectors, which are the subject of this study, are widely used since they have higher efficiency than
 54 air-based collectors. Moreover, water-based collectors provide more uniform cooling of the PV cell than air-based collectors
 55 (Jai 1994). Water based PV/T collectors can be manufactured in two ways such as glazed and unglazed. Due to the increase in
 56 heat, the electrical efficiency of the glazed PV/T collector is low while the thermal efficiency of the unglazed PV/T collector is
 57 low (Jin-Hee 2012). The electrical and thermal efficiency of the PV/T collectors depends on the flow distribution of the water
 58 in the collector. Therefore, the design of water-carrying channels is of great importance. The channels should be optimized to
 59 provide maximum heat transfer area and higher retention period for effective heat transfer from the collector to fluid. Aste et al.
 60 (2015) were developed a PV/T collector that combines a top layer having amorphous silicon solar cells and microcrystalline
 61 silicon, where the top cells absorb visible solar spectrum and convert it to electrical energy, while the bottom layer is sensitive
 62 to near infrared region of solar radiation spectrum and converts it to thermal energy. Ji et al. (2006) were investigated effects of
 63 the packing factor and flow rate on the overall efficiency of the PV/T. The results of that study showed that the increase of
 64 packing factor drops the system thermal efficiency.

65 The ambient and the collector temperature affect the electrical and the thermal efficiency of the PV/T. The temperature
 66 increase in PV panels has a negative effect on the efficiency. Since the panel temperature absorbed by the liquid fluid in PV/T
 67 collector, higher efficiency is obtained than similar PV panels. In (Saitoh et al. 2003), the authors analyzed the electrical and
 68 thermal efficiency of water-based PV/T system experimentally. The results showed that the electrical efficiency varied from 10%
 69 to 13%, and the thermal efficiency ranged from 40% to 50%. Minglu et al. (2016) was proposed a PV/T integrated dual-source
 70 heat pump water heating system for Shanghai climate condition. They found that when the top temperature was 69.2 °C, the
 71 electrical conversion efficiency was 12.18% and when the operating temperature decrease to 45 °C the electrical efficiency
 72 increases to 13.4%. Another experimental study was carried out at Politecnico di Milano University. The experimental
 73 calibration and validation of the model was performed in outdoor conditions on a commercial PV/T product and the model was
 74 run supposing the application in three different locations. In that study, the electrical efficiency of water-based PV/T was found
 75 as 13%, 13.6%, 13.4% and the overall efficiency was found as 32.7%, 36.1 and 40.6 for Paris, Milan, Athens respectively (J
 76 Niccolò et al. 2016). Fudholi et al (2014) used the spiral flow absorber in order to increase the efficiency. Their results were
 77 showed that the absorber produced a PVT efficiency of 68.4%, a PV efficiency of 13.8%, and a thermal efficiency of 54.6%.
 78 The other study has indicated that the building integrated PV/T collector's thermal energy efficiency of about 55–62% and the
 79 maximum achieved electrical efficiency was 11.4% (Ibrahim et al. 2014). Kiran and Devadiga (2014) reported that the
 80 electrical efficiency of PV/T was 7.58% without cooling and 8.16% with cooling and the overall efficiency was 58.97%. The
 81 other experimental study was conducted during the spring season in United Arab Emirates. The results showed that electrical
 82 efficiency increased from 15% to 20% and the thermal efficiency was found as %60 (Alzaabi et al. 2014). Rosa-Clot et al.
 83 (2016) performed the efficiency analysis of PV and PV/T in Italy. They found the electrical efficiency of PV and PV/T as 8.77%
 84 and 13.19%, respectively. Also, they found thermal efficiency of PV/T as 62%. In addition to experimental studies, simulation
 85 studies were conducted in the literature for PV/T. The results obtained in these studies differ according to the results of
 86 experimental studies. Because, many factors which are affect the efficiency can be easily changed as desired. For example, in
 87 the simulation study by Yazdanifard et al (2016), several parameters changed such as solar radiation, the number of pipes,
 88 Reynolds number, packing factor, pipes diameter, and collector length to investigate the glass covered flat plate PV/T system's
 89 electrical and thermal efficiency. They found maximum electrical and thermal efficiency as 17% and 70% respectively.
 90 Daghigh et al. (2011) conducted the simulation study for amorphous silicon and crystalline silicon water based PV/T systems
 91 in Malaysia. The results showed that the electrical and thermal efficiency of amorphous silicon PV/T was 4.9% and 72%,
 92 respectively and the electrical and thermal efficiency of crystalline silicon PV/T was 11.6% and 51% respectively. In the
 93 literature, there are many studies examining the performance of PV/T collectors. As summarized above, the results obtained in
 94 these studies are quite different from each other. The reasons for this are that the studies were carried out at different ambient

temperatures in different regions, different cooling water flow rates and it is due to overestimation of the input parameters in some simulation studies.

It has been seen in the detailed literature review that although there are many studies about PV/T collector performance analysis which are evaluated electrical and thermal efficiency using different design parameters, there are also some economic analysis studies. Different metrics can be used for the economic analysis such as payback period (PBP) (Herrando et al. 2014), net present value (NPV) (Buker et al. 2014), levelized cost of energy (LCOE) (Riggs et al. 2017), energy payback time (EPBT) (Wilson and Young 1996), Return on investment (ROI) (Zhang et al. 2015), internal rate of return (IRR) (Zhang et al. 2015), benefit to cost ratio (BCR) and unit cost of energy (UCE) (Michael and Selvarasan 2017). TRNSYS model created for analysis LCOE of domestic PV/T system which is based on amorphous silicon cells and crystalline silicon cells. In the study, monthly meteorological data which are in TRNSYS program is used and annual performance degradation of PV panels was not taken into consideration. The LCOE was found as 0.42 USD/kWh in ref (Coventry and Lovegrove 2003). The performance and economic analysis of water cooled PV/T system and standard PV system were studied by Tripanagnostopoulos et al (2005). They did not consider tax rebate or other cost reduction in order to find out the maximum time to overcome the initial cost and maintenance cost in their economic analysis. They found estimated cost payback period for electricity saving and electricity and gas saving between 10.3-28.2 year and 17.2-30.8 year according to the different temperature and tilt angel. In ref (Kalogirou and Tripanagnostopoulos 2007), 300 m² of hybrid PV/T collectors with polycrystalline and amorphous types PV cell and a 10 m³ water storage tank was evaluated for Cyprus, Greece and Wisconsin. In the study, Typical Meteorological Year (TMY) data is used in TRNSYS program. TMY was defined as a year, which was including all the meteorological data a period the mean life of the system. The results show that the electrical production of polycrystalline PV/T is more than the amorphous PV/T but the solar thermal fraction is slightly lower. Also, payback period was calculated for Cyprus, Greece and Wisconsin as 26, 26, 28 years respectively. The water cooled PV/T collector which has different PV cell such as c-Si, p-Si, a-Si (thin film), CdTe and CIGS evaluated and compared under New Delhi, India conditions. It was observer that the c-Si PV cell produced maximum electricity energy, maximum annual overall thermal energy and exergy. Also, the results showed that the maximum and minimum EPBT of 1.01 and 0.66 years on energy basis is obtained for c-Si and CIGS respectively, whereas on exergy basis maximum EPBT of 5.72 years is obtained for a-Si and minimum of 3.44 in obtained for CIGS PV module (Mishra and Tiwari 2013). Another economic analysis of water-cooled PV/T was carried out in UK. The authors introduced that the annual energy savings was 10.3 MW and the NPV was calculated as 19456.14 Dollar for the 25-year life span of and the cost of power generation was 0.0778 per kWh (Mahmut et al. 2014). Another water-cooled PV/T economic analysis study conducted in a real office scale building to support its electricity and hot water demand via computer program simulations in Hong Kong. The discounted payback period was estimated to be 14.7 years in that study (Ka-Kui et al. 2016). Herrando and Markides (2016) studied on water cooled PV/T systems for distributed electricity and hot-water provision in a typical house in

London, UK. According to the results of the study, a higher coverage of total household energy demands, and higher CO₂ emission savings can be achieved if the system is installed under low solar irradiance levels and low ambient temperatures. Also, they introduced that an annual electricity generation of 2.3 MWh, or a 51% coverage of the household's electrical demand (compared to an equivalent PV-only value of 49%), plus a significant annual water heating potential of to 1.0MWh, or a 36% coverage of the hot-water demand. The techno-economic challenges of PV/T systems in the housing sector for different Europe locations, with local weather profiles and energy demand data relating to homes with a total floor area of 100 m² were studied by Alba et al (2017). In the study, TRNSYS simulation models were prepared for 4 different systems based on meeting electricity and thermal energy demand and the economic viability of the solutions is then assessed based on their LCOE. The results showed that the overall levelized cost of energy of these systems is found to be in the range of 0.06–0.12 €/kW h, which is 30–40% lower than that of equivalent PV-only systems. Augusto et al (2017) studied thermal and electric yearly energy production of the PV/T, separate PV and solar thermal collector plants based on one-year measured data set in Italy. They reported that PV/T is economical solution compared to the PV and solar thermal collectors in order to produce electricity and thermal energy. This experimental study has shown that the PV/T solar system can produce about 1362 kWh/year of electricity for kWp installed, while yearly heat generation may vary between 443 and 267 kWh/m² depending on the mean inlet temperature of the cooling fluid. The LCOE of the separate PV and solar thermal collector was computed at different cooling water inlet temperatures, resulting in 0.082 Euro/kWh and 0.087 Euro/kWh and 0.092 Euro/kWh at, respectively, 35 °C, 40 °C and 45 °C of cooling water inlet temperatures. In this study, measured meteorological data were used. But no information was provided for annual produced energy degradation of PV/T collectors.

1.1. Limitations of previous studies

It has been seen from detailed literature review that there are still limitation or gap on the economic analysis of the PV/T systems. These can be summarized as follows.

- The amount of energy to be produced from the PV/T collector is calculated using monthly meteorological data. Moreover, these data are often obtained from various simulation programs rather than being measured. However, performance and economic analysis studies using monthly average data do not give clear technical and economic results.
- Many studies ignore the annual performance degradation for electricity and thermal production of the PV/T. Hence, the annual generated energy amount doesn't change over the lifecycle of the system.
- The required electricity energy to circulate the water and the resulting loss of earnings wasn't considered in the economic analysis.
- In many studies, an economic analysis was performed based on only the panel. There are no economic analysis studies for the entire PV/T system.

- In many studies, the economic analysis was performed on the simple PBP by ignoring the economic parameters such as interest rate, inflation rate and discounted rate. Also, the NPV value required to make an investment decision is often not calculated. PV/T systems are becoming feasible due to changing investment and financial costs. However, especially in recent years only a few economic studies have been listed for the PV/T systems
- In some countries there is no heating price. That is, as the heat energy is not purchased from the grid, such as electrical energy, the price is not specified. Therefore, heating prices should be determined correctly for the study region for the economic analysis of the PV/T systems. None of the articles has stated how the heat price is determined.
- In almost all studies, the electrical and thermal efficiency of the PV/T collector was taken constant while conducting economic analysis. Whereas electrical and thermal efficiency varies depending on many factors.
- Also including comprehensive energy and economic comparisons among optimized solutions as a function the design and operating parameters, weather conditions, and national energy prices.

1.2. Aim and Novelty of This Work

The main goal of this paper is to analyze the thermal-electrical performance of a PV/T collector and to assess the economic feasibility of water-based PV/T systems under real measured meteorological data. For this purpose, the meteorological data such as irradiation and temperature were collected every 5 minutes for one year. The thermal and the electrical performance analysis were performed using this real data for everyone hour. The economic analysis was performed by considering all financial and technical parameters such as annual degradation rate, inflation rate, dept to equity ratio, interest rate based on the yearly energy output. Therefore, this study will provide a critical view on design and the associated parameters that affect the PV/T system performance and economic results.

The novelty of this study is that the entire gap in the literature listed above has been examined separately. These are summarized as follows.

- Hourly performance and energy production were performed for one year using real meteorological data. Then the annual performance degradation rate implemented for life cycle of the PV/T collector.
- While calculating the efficiency of the PV/T collectors, the ambient temperature as well as the main water temperature was taken into consideration and the heat and electrical energy to be produced were calculated by taking the efficiency values calculated on an hourly basis.
- The economic analysis was carried out using NPV, LCOE and PBP techniques which are most commonly used in the literature taken in to account all the technical and economical parameters. We present these techniques which examines the technical, financial, and geographic factors which affect the cost of heat and electrical production for the PV/T system.
- The losses and the annual degradation of the entire system are included in the calculation.

- Hot water supply cost has been determined using the average unit price of some of the central hot water plants in Turkey and it has been determined by considering the costs that will occur in case of using natural gas for heating.

The paper is organized as follows: Firstly, a detailed literature review was conducted, and related papers were presented in the introduction in accordance with the subject compliance and the date of presentation. The remaining parts of the paper are organized in the following order. Section 2 gives a detailed description of the PV/T system such as location, data set, PV/T collector, measurement sensors and reference house. In section 3, the market price of the system equipments, electricity and thermal energy prices, financial parameters and assumptions were explained. The electrical and thermal model, the economic analysis model and the developed MATLAB/Simulink model of the PV/T collector were explained in section 4. The rest of the manuscript includes the results and conclusion sections.

2. Description Of The PV/T System, Location, Data Set, Components And Reference House

The PV/T systems are systems that produce electrical and low-grade thermal energy from solar irradiation simultaneously. Therefore, PV/T systems require less space than PV and solar thermal systems. In addition to the advantage of these systems producing electricity and thermal energy at the same time, the cooling of the PV cell while the thermal energy is obtained has a positive effect on the PV efficiency. The water is the most widely used fluid in PV/T systems due to its low price, availability and cooling properties. The water-carrying pipes under the PV/T collector are intended to draw heat from the PV panel, thereby improving the output voltage and current of the PV panel. At the same time, this heat is used for heating domestic water. In this study, the PV/T system consists of the 7 panels, converter, inverter, solar absorbing tube, storage tank and circulating pump. Figure 1 shows the block diagram of the analyzed system.

Fig. 1. Block Diagram of the PV/T System

2.1 Location of the PV/T System

Aksaray was selected for the evaluation of the proposed PV/T system. Aksaray is located at a longitude of between 33-35° E, latitude of between 37-38° N and at an altitude of 980 m. The yearly average solar irradiation is 1.603 kWh/m², with a yearly total irradiation period of over 2880 h and the average yearly annual temperature is 10 °C in Aksaray.

The data were collected every 5 minutes from May 2016 to June 2018. This study was carried out using data which were collected in the year 2017. The access rate to the data is greater than 99% during the year 2017. The lost data occurs either due to electrical maintenance outage or inverter communication module failure. The data was stored in a data logger. The data logger records all data such as irradiation and temperature every 5 minute. The specifications of the data logger are given in Table 1.

Table 1. Specification of Data Logger

Parameter	Value
Power supply	20-60 V DC
Power consumption	Typically, 5 W
ESD protection	Tested in accordance with DIN EN 61000-4-2
Operating temperature	-20 °C to 70 °C
Storage and transport temperature	-20 °C to 85 °C
Protection class	IP 20
Elevation	max. 2000 m
Rel. air humidity	max. 80%
Precision (Voltage input)	0-10 V DC, 2 mV DC 0-1 V DC, 0,5 mV DC 0-100 mV DC, 50 µV DC
Precision (Current input)	0-20 mA, 4 µA

The global horizontal irradiance (GHI) and Plane-of-array (POA) irradiance, was measured by a Kipp&Zonen SMP11 pyranometer. Typical measurement uncertainties of this device are shown in Table 2.

Table 2. Typical measurement uncertainties of irradiance sensors

Parameter	Kipp&Zonen SMP 11
Response Time	<2 s
Offset	< 2 W/m ²
Temperature Dependency	<1%
Non-stability	<0.5%
Non-linearity	<0.2%

PT1000 temperature sensor with integrated converter was used to measure the ambient air temperature. With this sensor, the temperature between -50 and 70°C is converted into voltage values between 0 V and 10 V. PT1000 temperature sensor (resistance) was used to measure module temperature connected directly to the back-sheet panel.

Since all data measured from the plant are recorded at intervals of 5 minutes for 24 hours, the data must be passed through quality control and filtered. The night measurements for irradiation were filtered due to the negative irradiance value. In addition, the results of irradiation measurements at sunrise or sunset may contain abnormal values. Also, the values of irradiation at sunrise and sunset are quite small and not effective for energy production. Apart from these, same measured

values exceed their physical limits. So, a quality control procedure was applied, and some improper values were removed from row data set. It has been lost values in some time periods during the year. Instead of these missing data, new values were written according to the previous and next measured values. When measurements were taken at 5-minute intervals, new data were close to the actual values. The number of raw data before the filtering process was 105120. After the filter process, the data set contains 43800 values (Jacovides et al. 2016; Scharmer and Greif 2000; Reindl et al. 1990).

2.2 Specification of PV/T Collector

PV/T collector is provided electricity and usable thermal hot water at the same time from one collector. In this study, water-based PV/T collector has been selected. In this collector there are 72 PV cell with glass covered and 66 tubes. The gross area of this collector is 1.28 m². The maximum temperature and maximum operating pressure are 101°C and 6 bar respectively. The specifications of the PV/T collector are given in Table 3.

Table 3. Specification of Proposed PV/T Collector

Parameter	Symbol	Value	Unit
Number of covers	N_g	1	
Ambient Temperature	T_a	293	K
Emittance of plate	ε_p	0.95	
Emittance of cover	ε_e	0.88	
Number of tubes	n_t	66	
Number of cells	n_c	72	
System flow rate	m	2	Lps
Collector area	A	1.28	m ²
Wind speed	v	2	m/s
PV Trans/Abs	$\tau\alpha_{pv}$	0.8	
Thermal Trans/Abs	$\tau\alpha_T$	0.925	
Absorber thickness	t	0.5	mm
PV thickness	L_{pv}	0.4	mm
PV conductivity	k_{pv}	130	W/mK
Tube Hydraulic Diameters	d_h	9.7	mm
Tube spacing	w	0.1	mm
Ratio of tube width to spacing	d/w	1.5	
Heat transfer coefficient	h_{pvA}	45	W/m ² K
Insulation conductivity	k	0.095	W/mK
Edge insulation thickness	L_{edge}	0.025	m
Absorber conductivity	k_{abs}	50	W/mK
Heat removal efficiency factor	F_R	0.85	
Packing Factor	s	0.4	
Collector heat losses coefficient	U_{loss}	6	W/mK
Tilt Angle	β	30	degree
Nominal Electrical Power	P	200	W
Current at maximum power	Im	5.28	A
Short circuit current	Isc	5.66	A
Voltage at Maximum power	Vm	37.89	V
Open Circuit voltage	Voc	45.26	V
Electrical efficiency	η_e	13.5	%
Thermal efficiency	$\eta_{thermal}$	64.5	%
Temp. coeff. of P_{mpp}	P_{mpp}	-0.45	%/°C
Temp. coeff. of Voc	Voc	-0.34	%/°C
Temp. coeff. of Isc	Isc	+0.06	%/°C

2.3 Reference House

In this study, Simple House SFH15, which is used by IEA in Task44 project, was chosen as the reference for the analysis of the PV/T system (Heimrath and Haller 2007). The floor area of this house is 140 m². The roof area on the south and north side is 59.7 m², 28.9 m² respectively. The roof pitch of the southern facade is 20° and the roof pitch of the north facade is 45°. It was assumed that 4 people lived in this house. The average collector area of considered collector is 1.37 m² for one panel. Therefore, it was thought that the panels would be placed only on the southern façade. The average daily water consumption is 111 litres per capita in Turkey according to 2014 data of State Planning Organization. 40% of clean domestic water is consumed as hot water. According to this statistic, hot water consumption of a standard 4-person house was accepted as 50 L per month.

The electricity demand of an individual house is dependent on the number of person and their activities, as well as on the electrical appliances available and their associated use. In this study, electricity consumption of a standard 4-person house was accepted as 200 kWh per month.

3. Market Analysis and Assumptions

Turkey is one of the world's fastest growing energy markets in the world. Installed photovoltaic capacity has increased from 1,500 MW in 2017 to 5,238 MW in 2019. The cost of solar power has come down in recent years, majorly due to initiatives taken on an international level by governments and private organizations to promote research and development in this field. This cost reduction has made solar technology, especially solar PV technology, more accessible. Furthermore, favorable government regulations and private partnerships, downstream innovation and expansion, and various incentive schemes for the use of renewable energy for power generation, are also driving the solar power market at an exponential rate. The solar thermal system market was initiated during the 1970s in response to the growth of the tourism industry and the need for plentiful hot water. Turkey is one of the countries with the largest installed power in the world in this field. It is estimated that over 10 million m² of flat plate collectors have been installed. Turkey offers opportunities in PV/T area because of the high potential of solar energy and experience in solar technology. The fact that PV/T systems have less installation costs than installing both individual PV and solar thermal collectors is considered an opportunity for the development of the PV/T market. In addition, because the PV market is directed to grid-connected distributed systems and national policies are developed for low-energy buildings, it is expected that the PV/T market will expand mostly in building sector in Turkey.

The unit electricity prices in Turkey are determined by Energy Market Regulatory Authority (EPDK). The unit price of electricity was determined as 0.5727 TL/kWh (0.096\$/kWh) for Single Term Residential Subscribers in December 2019. When calculating the net energy price to be billed, distribution price (It has been determined by EPDK as 0.1171147 TL/kWh (0.0196\$/kWh) in July 2019), energy fund price (1% of energy price), TRT share price (2% of energy price), energy

consumption tax (5% of energy price) are added to unit electricity price. When all taxes and rates are added to the unit price, the price of electricity for household users is calculated as 0,101 E/kWh.

The cost of heat energy in an example geothermal power plant in Turkey is calculated as follows. The amount of heat energy is determined by the calorimeter. This amount of energy is multiplied by the unit price of heat. Then, the apartment share fee, system improvement maintenance and repair fee and VAT are charged to the heat energy price. However, if there is no possibility of using the central heating system water can be heated by electricity. In this case, the cost of heating water with electricity can be calculated by utilizing basic heat formulas. However, this method would be more expensive than obtaining heat from central heating plants. Furthermore, installing a separate heating system will have an additional investment cost. Heating cost is determined as 0.08 Euro/kWh when using natural gas.

Although the installation costs are decreasing day by day, the economic results will vary from country to country or from year to year due to the policies of countries, feed-in tariff, interest rate and inflation. Therefore, it should be considered in financial parameters and policies as well as installation costs.

The key input variables required for economic analysis can be classified as geographical, technical and financial. The geographical variables include irradiation, altitude and ambient temperature. These variables were measured with high precision instruments as described in the previous section and used in the calculations.

As a result of the market research, the average cost of whole reference PV/T system was determined to be between 750 and 850 dollars per square meter. This price includes project cost, installation cost and all necessary equipment costs. In this study, the total cost of the PV/T system was taken as 7287 Euros (813.28 Euro per square meter).

The project can be financed with equity, using an amount of bank loan or using bank loan entirely. In this study, it is assumed that bank loans will be used. Therefore, credit interest rates should be determined. The regulations in the energy law allow small and medium-sized enterprises to generate electricity up to 1 MW without licensing and establishing a company. Many banks in Turkey provide loan to small and medium-sized enterprises to produce their own renewable energy. Within this framework, financial support prepared with appropriate maturity and interest rates can be utilized for all turn-key costs such as purchase of equipment, installation and construction. The loan interest rate varies according to the economic conditions of the country. Therefore, it is more appropriate to determine the loan interest rates by taking the average of long years rather than based on the interest rates in the year of installation. Renewable energy loan interest rate in Turkey varies between 4% and 8%. According to the Turkey Statistical Institute data, considering the annual percentage change in the price index between 2005 and 2019, the average interest rate was 9% annually (tcmb 2020).

The O&M cost of the PV/T system may vary depending on the agreements and from country to country. When the literature is examined, it is seen that the O&M cost of these systems is around 1% of the total cost of the project (Kalogirou and Tripanagnostopoulos 2006; Rasoul 2017; Gu et al. 2018). When calculating the electrical energy and heat energy produced by

PV/T collectors, it is necessary to consider the annual efficiency loss. Due to the aging of the materials, PV panels lose their efficiency each year compared to the previous year. This value is stated as 0.07% annually in the manufacturers' catalogs. In this study, the assumed key input parameters are given in Table 4.

Table 4. Input Parameters and Their Ranges for the financial Model

Description	Symbol	Average	Unit
Electricity Price		0.101	€/kWh
Heating Price		0.08	€/kWh
Effective PV/T Area		8.96	m ²
Project Life Cycle		25	Years
Electrical Efficiency (STC)		13.4	%
Thermal Efficiency		69.3	%
Degradation Rate		0.7	%/year
Capital Cost		7287	€/m ²
Debt to Equity		0.2	%
Interest Rate		6	%/year
Loan Term		25	Years
Effective Tax		18	%/year
Nominal Discount Rate		4	%/year
O&M Cost		1	%/year
Inflation Rate		9	%/year

4 TECHNO-ECONOMIC MODELING METHODS

4.1 Thermal Model of PV/T

The performance analysis of the PV/T collector can be performed by evaluating the electrical and thermal efficiency together. Electrical and thermal efficiency affect environmental factors such as irradiation and temperature. For thermal analysis it is necessary to determine the useful heat gain. The useful heat gain represented with equation 1 (Farghally et al. 2015).

$$Q = AF_R[(\tau\alpha)_{PV} * G - U_{loss}(T_i - T_a)] \quad (1)$$

Where, Q is the useful heat gain (W/m²), A is the collector area (m²), F_R is the heat removal efficiency factor, $\tau\alpha$ is the transmittance absorptance product of the PV cells, G is the irradiation (W/m²), U_{loss} is the heat loss coefficient (W/m²°C), T_i is the inlet temperature (°C) and the T_a is the ambient temperature (°C). The heat removal efficiency factor is calculated using equation 2.

$$F_R = \frac{mC_p}{AU_{loss}} \left[1 - \exp\left(-\frac{AU_{loss}F'}{mC_p}\right) \right] \quad (2)$$

Where, m is the mass flow rate in the collector (lps), C_p is the collector cooling medium and F' is the corrected fin efficiency.

The corrected fin efficiency and the fin efficiency (F) are calculated with equation 3 and 4 respectively.

$$F' = \left[\frac{\frac{1}{U_{loss}}}{\frac{1}{U_{loss}(d+(w-d)F)}} \right] + \frac{1}{wh_{pVA}} + \frac{1}{\pi dh_{fluid}} \quad (3)$$

$$F = \frac{\tanh\left(M\frac{w-d}{2}\right)}{M\frac{w-d}{2}} \quad (4)$$

Where, M is the coefficient term which accounts for the thermal conductivity of the absorber and PV cell, w is the tube spacing (m), d is the diameter of the tube (m), h_{fluid} is the heat transfer coefficient of fluid (W/m²°C) and h_{PVA} is the heat transfer coefficient (W/m²°C). The M is determined using equation 5.

$$M = \sqrt{\frac{U_{loss}}{k_{abs}l_{abs} + k_{PV}l_{PV}}} \quad (5)$$

The loss coefficient (U_{loss}) can be divided to three parts. These are the top loss coefficient (U_t), bottom loss coefficient (U_b) and the edge loss coefficient (U_e). These loss coefficients can be calculated using equations 6, 7, 8 and 9.

$$U_{loss} = U_t + U_b + U_e \quad (6)$$

$$U_t = \left\{ \frac{\frac{N_g}{c}}{\frac{T_{pm} - T_a}{N_g + f}e} + \frac{\sigma(T_{pm} + T_a)(T_{pm}^2 + T_a^2)}{(\varepsilon_p + 0,0059N_g h_w)^{-1} + \frac{2N_g + f^{-1} + 0,33C_p}{\varepsilon_g} - N_g} \right\} \quad (7)$$

$$U_b = \frac{K_b}{L_b} \quad (8)$$

$$U_e = \frac{(UA)_{edge}}{A_c} \quad (9)$$

In order to calculate the loss coefficient, it is necessary to determine the value of c , e , f , h_w , UA and T_{pm} . These parameters are calculated with following equations.

$$c = 520(1 - 0,000051\beta^2) \quad (10)$$

$$e = 0,43(1 - \frac{100}{T_{pm}}) \quad (11)$$

$$f = 0(1 + 0,089)^{h_w} - 0,1166h_w\varepsilon_p(1 + 0,07866N) \quad (12)$$

$$h_w = 5,7 + 3,8v \quad (13)$$

$$T_{pm} = T_i + \frac{\frac{Q_u}{A_e}}{F_R U_L}(1 - F_R) \quad (14)$$

Where, N_g is the number of covered glass, ε_p is the plate emittance, ε_g is the glass emittance, T_{pm} is the mean plate temperature, h_w is the wind transfer coefficient, v is the wind speed, β is the tilt angel of collector, p is the collector perimeter and L is the absorber thickness.

From using above equation, it is possible to calculate the thermal and electrical efficiency of PV/T collector. The thermal efficiency can be expressed as a function of the inlet temperature, ambient temperature and irradiation, while the electrical efficiency can be expressed as a function of the nominal operating cell temperature ($NOCT$) and T_{pm} . Equation 14 and 15 expressed thermal and electrical efficiency respectively.

$$\eta_{thermal} = F_R(S * \tau\alpha_{PV}) + (1 - S * \tau\alpha_T) - F_R U_{loss} \frac{T_i - T_a}{G} \quad (15)$$

$$\eta_e = 0,15(1 - 0,005(T_{pm} - NOCT)) \quad (16)$$

4.2 Electrical Energy Model of the PV/T

The PV panels convert solar irradiation into the direct current. However, most devices used in the daily life run with the alternating current. Therefore, the voltage produced in PV panels must be converted to alternating voltage. In addition, maximum power point tracker (MPPT) is required in order to operate the PV panel at maximum power point under all conditions. Otherwise, if the system is off-grid, a storage device is needed. Although the electrical energy produced in PV panels depends on a large amount of radiation, panel area and panel efficiency also affect the amount of energy to be produced. The hourly energy generated by the PV panel is calculated using equation 17.

$$E_{A,h} = G_{I,h} \cdot A_a \cdot \eta_{PV} \quad (17)$$

Where the $G_{I,h}$ is the hourly total in-plane irradiance (kWh/m²), A_a is the PV/T available area (m²) and η_{PV} is the overall PV system efficiency (%). The overall PV system efficiency varies depending on many factors such as the PV panel efficiency (η_{module}), inverter efficiency (η_{inv}), the PV panel temperature efficiency (η_{temp}), power conditioning efficiency (η_{pc}) and the annual PV module degradation (η_d). The overall PV panel efficiency is calculated with equation 18.

$$\eta_{PV} = \eta_{module} \cdot \eta_{pc} \cdot \eta_{temp} \cdot \eta_{inv} \cdot (1 - (t - 1) \cdot \eta_d) \quad (18)$$

where t is the index for years. The output DC energy of the PV panel, hence the panel efficiency decreases linearly with increasing temperature. This efficiency depends on the temperature power coefficient (β) of the panel and the cell temperature ($T_{c,h}$).

$$\eta_{temp} = [1 - \beta(T_{c,h} - T_{c,ref})] \quad (19)$$

The cell temperature also varies depending on the ambient temperature ($T_{a,h}$), irradiation and ($NOCT$).

$$T_{c,h} = T_{a,h} + \left[\frac{(NOCT - 20)}{800} \right] \cdot H_{I,h} \quad (20)$$

β and $NOCT$ vary according to panel technology and are determined from PV panel catalogs.

4.3 Economic Analysis Model

In this study, it is aimed to determine the LCOE, NPV and PBP values by economic analysis of the PV/T system. LCOE is a widely accepted index which indicates the total unit energy cost of installing and operating an energy system over its lifetime. Since LCOE represents the unit cost of generated electricity, it enables economic comparison of different energy generation technologies and the installation of similar systems in different regions. LCOE should contain many factors such as investment costs, financial costs, fuel costs, revenues and energy production amount during its lifetime. The formula of LCOE is given in equation 21.

$$LCOE = \frac{\sum_{j=0}^{n-1} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{n-1} \frac{E_t}{(1+r)^t}} \quad (21)$$

where C_t is the total cost in the year of t (€), n is the lifetime of the PV/T (year) and r is the discount rate (%).

The total cost of PV/T system contains investment expenditures in the initial year, financing loan cost (L_t), operating and management cost (OM_t) and tax paid for energy generation ($T_{a,t}$).

$$C_t = I_0 + L_t + OM_t + T_{a,t} \quad (22)$$

Investment expenditure is the capital investment provided by the proprietor. It depends on the debt to equity ratio in accordance with the agreement with the bank. The investment expenditure for the first year is calculated by equation 23.

$$I_0 = C_0 x (1 - DE) \quad (23)$$

Where C_0 is the capital cost (€) and DE is the dept to equity ratio (%).

The loan cost is equal to the sum of the annual invested capital with the interest rate on the invested capital.

$$L_t = C_0 \cdot DE / n + C_0 \cdot DE (1 - t/n) \cdot Itr_t \quad (24)$$

Where Itr_t is the interest rate in the year t (%).

Another method used to evaluate a project, measure economic efficiency and make decisions is NPV. Probably the most popular method among the all methods is the NPV and it is considered the most theoretically reliable. The NPV involves discounting all future cash flows (both in- and out-flow) at a discount rate and then combining them. The NPV can be defined in one formulation. The required historical data to calculate the NPV can be obtained from public sources, engineering documents, and past projects. By using historical data, the approximate probability density of costs, benefits, and discount factors can be formulated for the expected life of the project. Thereby, uncertainty in the project economy is taken into consideration. The NPV can be defined by equation 25 (Žižlavský 2014; Marchioni and Magni 2018; Heyd 2018).

$$NPV = -C_0 + \sum_{t=0}^{n-1} \frac{CF_t}{(1+r)^t} \quad (25)$$

Where CF_t is the cash flow of the year t (€). The CF_t can be calculating by equation 26.

$$CF_t = S_{et} + S_{tht} - C_t \quad (26)$$

S_{et} and S_{tht} describe the electrical and thermal energy savings respectively. S_{et} and S_{tht} can be calculated by using equations 27 and 28.

$$S_{et} = EP_t \cdot E_{et} \cdot (1 + Ifr_t) \quad (27)$$

$$S_{tht} = HP_t \cdot E_{tht} \cdot (1 + Ifr_t) \quad (28)$$

Where EP_t is the electricity price in the year t (€/kWh), HP_t is the heating price in the year t (€/kWh), Ifr_t is the inflation rate in the year t.

The payback period (PBP) is the simplest investment appraisal method. The PBP refers to the required time to offset the initial cash outflow by cash inflows generated by a project. In most cases, a longer PBP means a less lucrative investment, while a shorter PBP means that the capital cost can get back earlier. There are two ways to calculate the PBP, the averaging method and subtraction method. The averaging method is used when cash flows are expected to be steady in subsequent years and the subtraction method is used when cash flows are expected to vary in subsequent years. Due to various factors such as variable

inflation and loan interest rates, the long PBP makes the investment risky (Imteaz and Ahsan 2018; Lawrence et al. 2019). The equation 29 can be used to define the PBP.

$$PBP = T_{CF_t} \geq 0 \quad (29)$$

4.4 MATLAB/Simulink Model of the PV/T Collector

The model of the PV/T collector was created using MATLAB/Simulink program by considering all above-mentioned parameters in order to analysis the performance of the PV/T. All these parameters such as ambient temperature, emittance of plate, number of tubes, number of cells, collector area, absorber thickness, heat transfer coefficient etc. affect the PV/T collector performance. The simulink program allows us to analysis how these parameters changes affect the thermal and electrical efficiency. Figure 2 shows the simulink model of the PV/T collector.

Fig. 2. MATLAB/Simulink Model of the PV/T Collector

5. RESULTS

There are several factors that influence the thermal and electrical efficiency of the PV/T collector, such as mass flow rate, absorbent plate parameters (such as tube spacing, pipe diameter, and fin thickness), thermal conductivity of the fluid in the absorbent plate, packing factor inlet temperature and irradiation. Although s and $\tau_{a_{pv}}$ are effective on electrical and thermal efficiency, these are taken as a constant value since they are the coefficients of the materials used in the PV/T collector. However, the effect of s and $\tau_{a_{pv}}$ on the electrical and thermal efficiency is shown in figure 3. The increases of the s means that more collector areas are covered by PV cells. Therefore, the increase of the absorber block area has the effect of decreasing the heat increase in PV cells. This means that more areas are heated under the same irradiation. Therefore, a decrease in thermal efficiency will occur due to the s . So, increasing the s increases the electrical efficiency and decreases the thermal efficiency. Therefore, an optimal value for the

s should be determined. The wavelength of the light that a typical PV cell absorbs smaller than the wavelength of the light that the thermal collector absorbs. Therefore, large wavelength lights are reflected from the PV cell and absorbed by the thermal collector. Therefore, increasing the $\tau\alpha_{pv}$ increases the thermal efficiency. Since $\tau\alpha_{pv}$ has little effect on electrical efficiency, it is preferred that $\tau\alpha_{pv}$ is close to 1.

Fig. 3. The effect of the s and $\tau\alpha_{pv}$ on the performance of the electrical and thermal efficiency

The aim of this simulink model is to determine the thermal and electrical efficiency of the PV/T collector depending on the temperature and irradiation. In this study, in order to examine the effect of the temperature and irradiation on the electrical and thermal efficiency, $\tau\alpha_{pv}$ and s , was kept constant at 0.8 and s 0.4, respectively. Thus, only the effect of the temperature and irradiation on the efficiency was observed. As shown in Figure 3, the increase in $(Ti-Ta)/G$ decreases both the electrical and thermal efficiency.

Figure 4 shows the monthly average mains water temperature which is used as inlet water temperature of the PV/T collector.

Fig. 4. Mains Water Temperature

Mains water temperature is associated with soil temperature. As the temperature of the soil does not change as fast as the ambient temperature, mains water temperature does not change very fast. Therefore, it has been found appropriate to use monthly average mains water temperature.

In this study, the electrical and thermal efficiency of the PV/T were calculated by using the temperature and irradiation data taken at 15-minute intervals. Hourly average irradiation and the ambient temperature are shown in Figure 5. However, the data which are recorded at 15-minute intervals were used in calculation. The reason for showing hourly average values is to be able to draw plainer and more understandable graph.

Fig. 5. Hourly average irradiation and ambient temperature

The lowest ambient temperature and PV cell temperature were measured in January at -9.7°C and -8.42°C , respectively. The highest ambient temperature and PV cell temperature were measured in June at 42.78°C and 60.19°C , respectively. The

monthly average minimum ambient temperature and PV cell temperature were measured in January at 3.78 °C and 8.6 °C, respectively. The monthly maximum ambient temperature and PV cell temperature were measured at 29.61 °C and 37.55 °C, respectively, in July. Table 5 shows the minimum, maximum and average temperature values of PV cells and media.

Table 5. Minimum, Maximum and Average PV Cell and Ambient Temperature

Months	Min. Ambient Temp. (°C)	Min. PV Cell Temp. (°C)	Max Ambient Temp. (°C)	Max PV Cell Temp. (°C)	Average Monthly Ambient Temp. (°C)	Average Monthly PV Cell Temp. (°C)
January	-9.7	-8.42	13.3	14.99	3.78	8.6
February	-2.1	-2.11	18.56	45.38	10.08	18.72
March	-2.43	-2.61	27.07	49.72	13.09	21.04
April	1.61	-0.79	32.05	54.77	17.42	28.22
May	10.99	9.26	34.33	57.74	22.55	31.6
June	14.99	10.42	42.78	60.19	27.41	35.46
July	18.25	14.77	42.44	57.77	29.61	37.55
August	11.52	8.83	37.28	58.24	26.65	35.67
September	6.77	2.86	38.04	57.96	22.69	32.98
October	-0.48	-2.37	27.88	54.1	16.4	26.84
November	-5.01	-7.98	18.47	41.54	10.1	19.04
December	-5.83	-8.59	17.03	41.02	7.09	15.73

In the MATLAB/simulink model, the electrical and thermal efficiency of the PV/T collector was determined using hourly data. These data were used when calculating the electrical and thermal energy production values of PV/T collector. Thermal efficiency is significantly affected by the inlet water temperature, ambient temperature and the irradiation, while the electrical efficiency is significantly affected by the panel cell temperature. The thermal and electrical efficiency of the PV/T collector are shown in Figure 6. Annual average thermal and electrical efficiency was calculated as 69.3% and 13.4%, respectively.

Fig.6. Thermal and electrical efficiency of the PV/T collector

In order to meet the annual energy needs of the reference house, seven PV/T collectors should be used. Accordingly, the amount of electrical energy and heat energy produced by the designed PV/T system was calculated on an hourly basis. While calculating on an hourly basis, the current efficiency value of the PV/T collector was taken into consideration. It has been

calculated from the system that it will generate 2333.18 kWh of electrical energy and 10864.43 kWh of heat energy for the first year. Figure 7 shows the amount of electricity and heat energy that the system will generate on an hourly basis.

Fig.7. Monthly Electricity and Heat Generation

Table.6. shows the estimated financial results of the PV/T system over its 25-year economic life. In the economic analysis, the degradation rate of the panel and the electricity consumption of the pump were taken into consideration.

Table 6. The Estimation of Financial Results During the Life Cycle of PV/T System

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Cost saving from energy generation													
Electricity generation	2333.2	2316.8	2300.6	2284.5	2268.5	2252.7	2236.9	2221.2	2205.7	2190.2	2174.9	2159.7	2144.6
Electric Pump Consumption	511	511	511	511	511	511	511	511	511	511	511	511	511
Total electricity generation	1822.2	1805.8	1789.6	1773.5	1757.5	1741.7	1725.9	1710.2	1694.7	1679.2	1663.9	1648.7	1633.6
Heat generation	10864	10788	10713	10638	10563	10489	10416	10343	10271	10199	10127	10057	9986.1
Electricity savings	184.04	198.81	197.02	195.25	193.49	191.74	190	188.28	186.57	184.87	183.18	181.5	179.84
Heating savings	869.15	940.75	934.16	927.62	921.13	914.68	908.28	901.92	895.61	889.34	883.11	876.93	870.79
TOTAL ENERGY GENERATION	13198	13105	13013	12922	12832	12742	12653	12564	12476	12389	12302	12216	12131
TOTAL ENERGY SAVING	1053.2	1139.6	1131.2	1122.9	1114.6	1106.4	1098.3	1090.2	1082.2	1074.2	1066.3	1058.4	1050.6
Cost of operation & Maintenance and Tax													
OM cost	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87
Tax for electricity	33.127	35.785	35.464	35.145	34.828	34.513	34.2	33.89	33.582	33.276	32.972	32.671	32.371
TOTAL (Omt)	106	108.66	108.33	108.01	107.7	107.38	107.07	106.76	106.45	106.15	105.84	105.54	105.24
Financial cost													
Loan payment	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296
Loan interest	87.444	83.946	80.448	76.951	73.453	69.955	66.457	62.96	59.462	55.964	52.466	48.969	45.471
TOTAL (Lt)	145.74	142.24	138.74	135.25	131.75	128.25	124.75	121.26	117.76	114.26	110.76	107.26	103.77
Discounted cash flow and energy generation													
Net Profit (CFt)	-5028	888.66	884.1	879.61	875.17	870.79	866.46	862.18	857.96	853.8	849.69	845.63	841.62
Discounted Cost (Ct)	6081.3	250.9	247.08	243.26	239.45	235.63	231.82	228.02	224.21	220.41	216.6	212.81	209.01
Discounted Energy Generation	13198	12601	12032	11488	10969	10473	9999.8	9547.9	9116.4	8704.4	8311	7935.4	7576.8
Cash Flow	-5028	-4139	-3255	-2376	-1501	-629.8	236.64	1098.8	1956.8	2810.6	3660.3	4505.9	5347.5

Year	13	14	15	16	17	18	19	20	21	22	23	24
Cost saving from energy generation												
Electricity generation	2129.6	2114.6	2099.8	2085.1	2070.5	2056.1	2041.7	2027.4	2013.2	1999.1	1985.1	1971.2
Electric Pump Consumption	511	511	511	511	511	511	511	511	511	511	511	511
Total electricity generation	1618.6	1603.6	1588.8	1574.1	1559.5	1545.1	1530.7	1516.4	1502.2	1488.1	1474.1	1460.2
Heat generation	9916.2	9846.8	9777.9	9709.5	9641.5	9574	9507	9440.4	9374.4	9308.7	9243.6	9178.9
Electricity savings	178.19	176.55	174.92	173.3	171.69	170.1	168.51	166.94	165.37	163.82	162.28	160.75
Heating savings	864.7	858.64	852.63	846.66	840.74	834.85	829.01	823.21	817.44	811.72	806.04	800.4
TOTAL ENERGY GENERATION	12046	11961	11878	11795	11712	11630	11549	11468	11388	11308	11229	11150
TOTAL ENERGY SAVING	1042.9	1035.2	1027.5	1020	1012.4	1004.9	997.52	990.14	982.82	975.54	968.32	961.15
Cost of operation & Maintenance and Tax												
OM cost	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87	72.87
Tax for electricity	32.074	31.778	31.485	31.194	30.904	30.617	30.332	30.049	29.767	29.488	29.211	28.936
TOTAL (Omt)	104.94	104.65	104.35	104.06	103.77	103.49	103.2	102.92	102.64	102.36	102.08	101.81
Financial cost												
Loan payment	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296	58.296
Loan interest	41.973	38.475	34.978	31.48	27.982	24.484	20.987	17.489	13.991	10.493	6.9955	3.4978
TOTAL (Lt)	100.27	96.771	93.274	89.776	86.278	82.78	79.283	75.785	72.287	68.789	65.292	61.794
Discounted cash flow and energy generation												
Net Profit (CFt)	837.67	833.77	829.92	826.12	822.38	818.68	815.03	811.44	807.89	804.4	800.95	797.55
Discounted Cost (Ct)	205.21	201.42	197.63	193.84	190.05	186.27	182.48	178.7	174.92	171.15	167.37	163.6
Discounted Energy Generation	7234.4	6907.5	6595.3	6297.2	6012.6	5740.9	5481.5	5233.8	4997.2	4771.4	4555.8	4349.9
Cash Flow	6185.2	7019	7848.9	8675	9497.4	10316	11131	11943	12750	13555	14356	15153
Evaluation Metrics												
NPV	7905.3											
LCOE	0.0467											
Payback Period	6 year											

It is seen that the economic performance is good and acceptable for the market, where LCOE is calculated at 0.0467 €/kWh while NPV and PP are respectively estimated at 7905.3 € and 6 years. PV/T systems are not yet widely used in daily life. Therefore, initial investment costs are still high. However, PV/T systems are still economically viable today. While performing this economic analysis, input variables are determined by taking the average of the values under current conditions. In particular, inflation and changes in the Euro exchange rate may change the economic analysis results. In order to minimize the impact of these changes, both variables have been averaged over many years and the future perspectives of various institutions according to the current conditions have been considered.

6. CONCLUSIONS

Turkey is the country with the highest potential in Europe in terms of radiation and sunshine duration. For these reasons, both electrical energy and thermal energy supply from solar energy is increasing rapidly. Since the consumption of energy at the place where it is produced reduces losses, distributed power plants have started to be preferred instead of central long-distance power plants. The easiest way to build a distributed power plant is to utilize solar energy. With the developing technology and the decrease in costs, solar energy applications are seen in many buildings. However, these systems are often installed separately either to obtain thermal energy or to obtain electrical energy. However, there is very limited space for the installation of such systems in buildings. For this reason, it may be more appropriate to install PV/T-based systems that can generate electricity and thermal energy at the same time. The available literature provides scarce information about the performance and economic analysis of PV/T based systems. In this study, for the first time in Turkey, the performance and economic analysis were performed using real meteorological data's. It is aimed to provide hot water and electrical energy of a house by using water-based PV/T collectors. The results of this study are briefly summarized below.

- The ambient temperature of the region changes from -9.7 to 42.78 °C. The PV cell temperature changes from -8.42 to 60.19 °C.
- Annual average thermal and electrical efficiency was calculated as 69.3% and 13.4%, respectively.
- The system can generate 2333.18 kWh of electrical energy and 10864.43 kWh of heat energy for the first year.
- The LCOE was calculated at 0.0467 €/kWh while NPV and PP are respectively estimated at 7905.3 € and 6 years.

It is expected that this study and its results will lead to the use of PV/T based systems in buildings. Also, it is clear that the results will contribute to the literature.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due [personal data protection law] but are available from the corresponding author on reasonable request.

Competing interest

The authors declare that they have no competing interests

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Authors' Contributions

KB realized the creation and analysis of the system model, and was a major contributor in writing the manuscript. IK realized the creation and analysis of the system model. All authors read and approved the final manuscript.

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Figures

Figure 1

Block Diagram of the PV/T System

Figure 2

MATLAB/Simulink Model of the PV/T Collector

Figure 3

The effect of the s and τ_{apv} on the performance of the electrical and thermal efficiency

Figure 4

Mains Water Temperature

Figure 5

Hourly average irradiation and ambient temperature

Figure 6

Thermal and electrical efficiency of the PV/T collector

Figure 7

Monthly Electricity and Heat Generation