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PV/T System Application for Renewable Heat and Electric Energy in Buildings: Performance and Techno-Economic Analysis

Kıvanç BAŞARAN [1, *], İlayda KOÇ [2]

[1] *Manisa Celal Bayar Üniversity, Faculty of Technology, Department of Electrical Engineering, Turgutlu, 45400, Manisa, Türkiye*
[2] *Eldor Electronics and Plastic Materials Manufacturing and Trading Co. Ltd., Department of Automation Planning, Gaziemir, 35410, Izmir, Turkey*

A R T I C L E I N F O

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* *Corresponding Author*
e-mail: kivanc.basaran@cbu..edu.tr

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ORCID Numbers in author order:
0000-0001-9613-6620
0000-0002-9575-4088

A B S T R A C T

Electricity and thermal energy are used extensively in residential buildings. Meeting these needs with different systems cause loss of efficiency, and an increase initial investment cost which are critical when making investment decisions. Therefore, photovoltaic thermal (PV/T) systems are used to reduce the economic burden of home users. In this article, it is aimed to determine the performance of the PV/T system and to make an economic analysis by considering the instantaneous electrical and thermal efficiency. Net present value (NPV), payback period (PBP) and levelized cost of energy (LCOE) values were used to evaluate the system economically. The novelty of this study is 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. Also, the losses and the annual degradation of the entire system are included in the calculation. As a result of the analyses, the LCOE, NPV, PBP, average electrical and thermal efficiencies were found as 0.091 €/kWh, 2718.5 €, 6 years, 14.7% and 62.3%, respectively, for a project size of 8.96 m² in a 25-year life cycle.

Binalarda Yenilenebilir Isı ve Elektrik Enerjisi için PV/T Sistem Uygulaması: Performans ve Tekno-Ekonomik Analiz

M A K A L E B İ L G İ S İ

***Anahtar Kelimeler**:*
Fotovoltaik/termal sistemler
Tekno-ekonomik analiz
Yenilenebilir ısıtma ve elektrik
Performans analizi
Bozulma oranı

Ö Z E T

Konutlarda elektrik ve termal enerji yoğun olarak kullanılmaktadır. Bu ihtiyaçların farklı sistemlerle karşılanması verim kaybına ve yatırım kararları alırken kritik öneme sahip olan ilk yatırım maliyetinin artmasına neden olmaktadır. Bu nedenle, ev kullanıcılarının ekonomik yükünü azaltmak için fotovoltaik termal (PV/T) sistemler kullanılmaktadır. Bu makalede, PV/T sisteminin performansını belirlemek ve anlık elektriksel ve termal verimliliği dikkate alarak ekonomik bir analiz yapmak amaçlanmıştır. Sistemin ekonomik olarak değerlendirilmesinde net bugünkü değer (NPV), geri ödeme süresi (PBP) ve seviyelendirilmiş enerji maliyeti (LCOE) değerleri kullanılmıştır. Bu çalışmanın özgünlüğü, PV/T kollektörlerinin veriminin, ortam sıcaklığının yanı sıra şebeke suyu sıcaklığı da dikkate alınarak belirlenmiş olması ve saatlik bazda hesaplanan verim değerleri esas alınarak üretilecek ısı ve elektrik enerjisinin hesaplanmış olmasıdır. Ayrıca, tüm sistemin kayıpları ve yıllık bozulma oranı da hesaplamaya dahil edilmiştir. Yapılan analizler sonucunda, 25 yıllık yaşam döngüsünde 8,96 m² proje büyüklüğü için LCOE, NPV, PBP, ortalama elektriksel ve termal verimlilikler sırasıyla 0,091 €/kWh, 2718.5 €, 6 yıl, %14,7 ve %62,3 olarak bulunmuştur.

NOMENCLATURE

PV/T	photovoltaic/thermal
PV	photovoltaic
TMY	typical meteorological year
NPV	net present volue
PBP	pay back pariod
LCOE	levelized cost of energy
NOCT	nominal operating cell temperature
Q	suful heat gain
Tpm	Mean collector plate temperature
O&M	operating and maintanance
A	collector area
η	efficiency
Ta	ambient temperature
$G_{I,h}$	hourly total in-plane irradiance

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 industrial applications. Because of the heat and electrical energy obtained from the sun often complement each other and 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.

The technical and economic suitability of a water-based PV/T collector was first stated by Martin Wolf (Wolf, 1976) in 1976. Then in 1978 the first liquid-based PV/T was tested in a house by Böer and Tamm (Boer and Tamm, 2003) in 2003. After these two experimental studies, many researchers started to work in this field. In 1978, TRNSYST model was developed by using mathematical equations of active cooled PV/T collectors at Arizona State University (Florschuetz, 1979). In a study conducted at MIT's laboratories in 1978, the electrical and thermal efficiency of the PV/T collector were measured as 6.5% and 40%, respectively (Hendrie, 1982). After that, many studies have been done to increase the efficiency of the PV/T collectors in USA, Japan, Netherlands, Denmark, and Germany (Cox, 1985; Suzuki and Kitamura, 1979, Karl, 1979, Komp, 1985). Although studies on the PV/T collectors have been reduced due to low oil prices between 1980 and 1990, some studies done in Switzerland and Yugoslavia (Schwartz et al., 1983; Lalovic et al., 1986; Lalovic et al., 1988). In 1992, with the political recognition of global warming and climate change, efforts in the PV/T collectors have accelerated again. Especially in Germany, Denmark and the Netherlands, many projects were realized between 1990-2000 (Zondag et. al, 2003; Leenders et al., 2000; Bakker et al., 2002; Bakker et al., 2004; Rockendorf et al. 1999; Hausler and Rogass, 2000; Soerensen, 2001). In the following years, many countries such as Japan, India, Israel, Brazil, Taiwan, Cyprus, and the USA worked about the PV/T (Tripanagnostopoulos et al., 2002; Tselepis and Tripanagnostopoulos, 2002; Kalogirou, 2001; Bergene and Løvvik, 1995; Meir et al., 2002; Sandnes and Rekstad, 2002; Hayakashi, 1989; Fujisawa and Tani, 1997; Ito et al., 1999; Huang et al., 1999; Huang et al., 2001; Garg and Agarwal, 1995; Thomas et al., 2000; Krauter et al., 1999; Krauter et al., 2001)

The use of renewable distributed power plants is important to prevent environmental pollution caused by energy supply, to eliminate geopolitical risks and to prevent losses in the transmission of energy. In particular, the issue of producing energy where it is consumed has been frequently studied recently. It will be advantageous in many ways to produce the energy needed with a single system instead of installing separate systems for the supply of electrical energy and thermal energy in houses. The importance of this study is that it has been shown that electricity and thermal energy supply in residences can be met economically with PV/T collectors. The performance rate and efficiency of PV/T panels vary depending on the current meteorological and system conditions. Therefore, using a single value in calculating the amount of energy does not give accurate results. In addition, the amount of electricity produced in PV panels is lower every year than the previous year, even if all conditions are the same. The originality of this study is to calculate the performance and efficiency values under current conditions and to know the amount of energy to be produced according to these values. In addition, the amount of thermal and electrical energy to be produced by the system during its 25-year operating life is calculated by considering the annual degradation rate.

The structure of article 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. We have organised the rest of this paper in the following way. The location, data set, PV/T collector, measurement sensors and reference house are described in the Section 2. In section 3, the market price of the system equipment's, 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.

Literature Review

The water-based PV/T collectors, which are the subject of this study, are widely used since they have higher efficiency than air-based collectors. Moreover, water-based collectors provide more uniform cooling of the PV cell than air-based collectors (Jai, 1994). Water based PV/T collectors can be manufactured in two ways such as glazed and unglazed. Due to the increase in heat, the electrical efficiency of the glazed PV/T collector is low while the thermal efficiency of the unglazed PV/T collector is low (Kim, 2012). The electrical and thermal efficiency of the PV/T collectors depend on the flow distribution of the water in the collector. Therefore, the design of water-carrying channels is of great importance. The water-carrying channels are optimized in such a way that they can effectively transfer heat from the collector to the fluid in the channel. Aste et al. (Aste et al., 2015) covered the upper surface of the PV/T collector with amorphous silicon and microcrystalline silicon solar cells. While the upper surface of the collector converts solar radiation to electrical energy, the lower surface of the collector converts solar radiation into thermal energy as it is sensitive to the infrared region. JieJia et al. (JieJia et al., 2006) investigated the effects of packing factor and flow rate on PV / T efficiency and determined that the increase in packing factor decreased the thermal efficiency of the system.

The ambient and the collector temperature affect both the electrical and thermal efficiency of the PV/T. Temperature increase in PV/T collectors adversely affects the electrical efficiency. Since the panel temperature absorbed by the liquid fluid in PV/T collector, higher efficiency is obtained than similar PV panels. Saitoh et al. (Saitoh et al., 2003) analysed the electrical and thermal efficiency of water-based PV/T system experimentally. The results showed that the electrical efficiency varied from 10% to 13%, and the thermal efficiency ranged from 40% to 50%. Minglu et al. (Minglu, 2016) examined a PV/T system for Shanghai climate condition which has heat pump. They found that when the top temperature was 69.2 °C, the electrical conversion efficiency was 12.18% and when the operating temperature decrease to 45 °C the electrical efficiency increases to 13.4%. Another experimental study was carried out at Politecnico di Milano University. The experimental study was performed in outdoor conditions on a commercial PV/T at the three different locations. In that study, the electrical efficiency of water-based PV/T was found 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 (Niccolò, 2016). Fudholi et al (Fudholi, 2014) used the spiral flow absorber to increase the efficiency. Their results showed that the total a PV/T efficiency, PV efficiency and thermal efficiency as 68.4%, 13.8%, and 54.6%, respectively. The other study has indicated that the building integrated PV/T collector's thermal energy efficiency of about 55–62% and the maximum achieved electrical efficiency was 11.4% (Ibrahim, 2014). Kiran and Devadiga (Kiran and Devadiga,2014) reported that the electrical efficiency of PV/T was 7.58% without cooling and 8.16% with cooling and the overall efficiency was 58.97%. The other experimental study was conducted during the spring season in United Arab Emirates. The results showed that electrical efficiency increased from 15% to 20% and the thermal efficiency was found as %60 (Alzaabi, 2014). Rosa-Clot et al. (Rosa-Clot, 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% and 13.19%, respectively. Also, they found thermal efficiency of PV/T as 62%. In addition to experimental studies, simulation studies were conducted in the literature for PV/T. The results obtained in these studies differ according to the results of experimental studies. Because many factors which affect the efficiency can be easily changed as desired. For example, in the simulation study by Yazdanifard et al. (Yazdanifard, 2016), several parameters changed such as solar irradiation, the number of pipes, Reynolds number, packing factor, pipes diameter, and collector length to investigate the glass covered flat plate PV/T system's electrical and thermal efficiency. They found maximum electrical and thermal efficiency as 17% and 70% respectively. Daghigh et al. (Daghigh et al., 2011) conducted the simulation study for amorphous silicon and crystalline silicon water-based PV/T systems in Malaysia. The results showed that the electrical and thermal efficiency of amorphous silicon and crystalline silicon PV/T were 4.9% and 72% and 11.6% and 51%, respectively. As summarized above, the results obtained in the studies in the literature are different from each other. Conducting the studies in different regions, different ambient temperatures and different cooling water flows and overestimating the input parameters in some simulation studies caused the results to differ from each other. Madalina Barbu et al. (Madalina et al., 2023) analyzed their PV/T system in four different weather conditions. The analysis results have shown that the performance of PV/T panels is closely linked to the distribution of thermal energy stored in the thermal storage tank. Additionally, when PV/T collectors are used in appropriately sized facilities, they exhibit superior performance compared to PV panels based on the end-user's thermal energy requirements. Different studies are being carried out to increase the efficiency of PV/T systems. In another of these studies, efficient PV/T design was demonstrated by decoupling the operating temperature of photovoltaic and thermal processes. The results showed that the temperature of the solar cells was 7.7 °C lower than the leaving water temperature in the new PV/T system, revealing the temperature-decomposition effect. Compared with the traditional PV/T system, the leaving water temperature is 3.9 °C higher and the solar cell temperature is 9.4 °C lower in the proposed system, resulting in a comprehensive efficiency increase of 17.9% (Kegui et al., 2023). In order to increase the performance of PV/T collectors, the use of different fluids other than water and air is being investigated. Dongxing Song et al. proposed a two-fold spectrum split configuration with both Therminol VP-1/Ag nanofluid and pure water. The results showed that the nanofluid absorbs shorter inappropriate radiation and water captures it longer, the total exergy efficiency increases with solar concentration, and the total energy efficiency is 0.829 in this system (Dongxing et al., 2024). Siyan Chan et al developed a new concept by replacing the backplate with the traditional PV/T collector, which can adapt to different heat demands in different seasons by opening or closing the backplate and achieve better electrical performance in summer without affecting heating in winter. They conducted comparative experiments between switchable and conventional PV/T collectors to observe the performance advantage. The results showed that the maximum stagnation temperature of the switchable PV/T collector was 18.1 °C lower than the conventional one, which relatively increased the electrical efficiency by 8.6% (Siyan et al., 2024).

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. (Tripanagnostopoulos et al., 2005). However, they did not consider tax rebate or other cost reductions in the 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. 300 m^2 of hybrid PV/T collectors with polycrystalline and amorphous types of PV cell and a 10 m3 water storage tank was evaluated for Cyprus, Greece, and Wisconsin (Kalogirou and Tripanagnostopoulos, 2007). In this 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 authors found 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 electrical energy, maximum annual overall thermal energy, and exergy. Also, the results showed that the minimum and maximum values of EPBT for energy and exergy for c-Si and CIGS were 1.01-0.66 and 3.44-5.72 years, respectively (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 were 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 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 (Herrando et al., 2014) studied on water cooled PV/T systems for distributed electricity and hot-water provision in a typical house in London, UK. The authors stated that higher coverage of total household energy demands, and higher CO_2 emission savings can be achieved if the system is installed under low irradiance and low ambient temperatures. In addition, they stated that they have 2.3 MWh of electricity production, which corresponds to approximately 51% of the electricity need of the household, and 1 MWh of water heating potential, which corresponds to approximately 36% of the hot water need. 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 were studied by Alba et al. (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 as the range of 0.06–0.12 €/kWh. Augusto et al. (Augusto et al., 2017) studied yearly heat and electricity 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 to produce electricity and thermal energy. This experimental study has shown that the PV/T solar energy system can produce approximately 1362 kWh/year of electrical energy per kWp, and the annual heat production can vary between 443 and 267 kWh/m^2 depending on the average inlet temperature of the water. The LCOE value of the PV and thermal collector were determined as 0.082 Euro/kWh and 0.087 Euro/kWh and 0.092 Euro/kWh at different inlet water temperatures (35 °C, 40 °C and 45 °C), respectively. In this study, measured meteorological data were used. But no information was provided for annual produced the thermal and electrical energy degradation of PV/T collectors. Gaurav Patel and Dr. Lalit Kumar Khurana established a 20.5 kWp PV-T system and made an economic analysis of the system. The results show that, considering the thermal energy and electricity exchange obtained, the internal rate of return (IRR) of the investment project is 21% and the modified internal rate of return is 12%. The discounted payback period of the investment is calculated as 5 years and 3 months (Gaurav and Lalit, 2024). To evaluate the production potential, economic profitability and ecological balance of the photovoltaic/thermal (PV/T) system in Cameroon, different HTF configurations based on water, vegetable and synthetic oils combined with different forms of titanium dioxide (TiO_2) were used. The results show that the net present value, emission rate, annual cost, payback period and energy cost of the PV/T-Palm/TiO2 system are 568.45 $, 7.78 kg, 7.07 $, 5.97, 0.03 $, respectively (Armel et al., 2024). Another study examined the techno-economic performance of a hybrid photovoltaic-thermal (PV/T) solar-assisted heat pump system to meet the electricity, and hot water demands of a three-bedroom terraced house occupied by four people in Belfast, United Kingdom. In the study, analyses were made for PV/T collectors of different sizes, including 12-panel, 20-panel and 24-panel systems. The results show that, thanks to the lower initial investment cost, the most economically viable system configuration for the household considered in this study is based on a 12-panel PVT array covering a total area of 16.3 m^2. This system has the potential to produce 2.4 MWh of electricity and 2.0 MWh of hot water per year; this is equivalent to just over 30% of that household's electricity needs and 80% of its hot water demand. The discounted repayment period of the system in question is determined as 14 years (Mustapha et al., 2024).

Santhan Reddy Penaka et al present a techno-economic evaluation of a water-based PV/T system for a single-family home to generate electricity and domestic hot water applications in 85 locations around the world. Simulation studies were performed using a validated tool with a one-hour time step. The results showed that the PV/T system has better energy and exergy performance for places where the annual ambient temperature is low. Also load profile, hot water storage volume etc. It has been observed that system boundaries can have a significant impact on the annual heat and electricity production of the system. Two different economic models were used in the study and show that the average net present values per unit collector area among 85 cities are 1800 and 2200 Euros respectively. The study showed that the payback periods of PV/T systems are competitive with other systems (Penaka et al., 2020). Saeed Abdul-Ganiyu et al established a PV and PV/T system in Ghana to investigate the technical and economic feasibility of the PV/T system. The technical and economic performances of both installed systems were analysed over a 25-year period. The results showed that the estimated average annual total exergy of PV and PV/T systems was 159.42 kWh/m^2 and 330.15 kWh/m^2, respectively. (Abdul, 2021). Three different systems using PV, PV/PCM (Phase Change Material) and PV/T-PCM (Thermal Phase Change Material) were investigated in Jiangxi, China. The study was conducted on two scenarios: fixed installation capacity and fixed state investment. Three alternative scenarios have been developed to determine the heat and electricity production potential and investment requirement in both scenarios. The results showed that under "fixed installation capacity" scenarios, conventional PV can produce 313 GWh/year of energy and PV/T-PCM can produce more than 340 GWh/year of energy (Rafiq et al., 2022). A PV/T system was designed for a detached house in London, considering hourly weather data and thermal and electrical energy demand profiles. The annual performance of the system was compared with a reference system using a gas boiler and mains electricity. The results show that the PV/T system can achieve an annual electricity self-sufficiency of 87% and an annual thermal energy demand coverage rate of 99%, as well as an annual primary energy saving and a relative carbon emission reduction rate of 35% and 37%. to the reference system (Jurčević et al., 2023). An economic analysis of the PV-T system with an installed power of 20.5 kWp was made in Gujarat, India. It has been determined that this system in Gujarat produces approximately 5% more electrical energy compared to a PV power plant of the same capacity and saves approximately 2900 Kg of LPG for heating needs. The results showed that the investment could provide a discounted payback period of 5 years and 3 months with a project IRR of 21%. It has been reported that the payback period may vary depending on the heat energy change and the available fuel source (coal, biomass, biogas, LPG, PNG, FO, SKO, etc.) (Patel and Khurana, 2023).

Technical and economic analysis studies of PV/T systems in the literature have shown that PV/T systems have reached an economically feasible level. Providing electricity and thermal energy from a single source is advantageous, especially due to the lack of space on residential roofs. The use of PV/T systems in residences is very important to create energy self-sufficient residences. In addition, PV/T systems should not be evaluated economically but also in terms of their contribution to the environment. Providing electricity and thermal energy from a single source significantly reduces the use of fossil-based resources.

Limitation of Previous Studies

A detailed literature review has shown that there are still limitations or gaps in the economic analysis of PV/T systems. These gaps in the literature are listed below.

- The amount of the thermal and electrical energy that the PV/T collector can generate is calculated using generally 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 accurate technical and economic results because panel performance and efficiency values are not calculated exactly. Some studies consider TMY datasets as hourly values. The disadvantage is that the method may be applied only to one parameter (e.g.DNI), and although the selected months in TMY are close to the long-term average, the distribution of (sub) hourly values (histogram) in the chosen months may not well represent the distribution of values in the original data.
- Many studies ignore the annual performance degradation for electricity and thermal production of the PV/T. Hence, the annual generated thermal and electrical energy amount doesn't change over the lifecycle of the system.
- The required electrical 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 thermal 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 prices are determined.
- In almost all studies, the electrical and thermal efficiencies of the PV/T collector were taken constant while conducting economic analysis. Whereas electrical and thermal efficiency varies depending on many factors.

Aim and Novelty of This Work

The chief aim of this article is to analyse the thermal-electrical performance of a PV/T collector and to conduct 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 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.

In previous studies on PV/T systems, a single average performance value is taken for PV/T collectors. Taking a single average value for 8760 hours of working time per year causes a large erroneous calculation of the amount of energy to be produced. In this study, the efficiency of the PV/T collector on an hourly basis was determined and the electricity and thermal energy to be produced were calculated. In addition, there is a decrease of 0.07% in the amount of electrical energy to be produced each year in photovoltaic systems. In previous studies, the decrease in the amount of energy to be produced was not considered when making the 25-year economic analysis. Therefore, the results of the NPV and LCOE values of the system could be inaccurate. In this study, the amount of energy to be produced from the system is calculated on an hourly basis, considering all uncertainties and losses. Therefore, this study has the potential to make a significant contribution to original research, current practices and teaching involving capital investment issues. The novelty and contribution of this study is that the gaps listed above in the literature have been studied separately. These are summarized as follows.

Hourly performance and heat and electricity 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 conducted using the most commonly used NPV, LCOE, and PBP techniques in the literature, considering all parameters. We present these techniques by considering the technical, financial, and geographical factors that influence the cost of heat and electricity production for PV/T systems.

- 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 Türkiye and it has been determined by considering the costs that will occur in case of using natural gas for heating.

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. Water is the most widely used fluid in PV/T systems due to its low price, availability, and cooling properties. 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 7 panels, converter, inverter, solar absorbing tube, storage tank and circulating pump.

Location of the PV/T System

Aksaray was selected for the evaluation of the proposed PV/T system. The reason for this is that we were able to obtain the needed meteorological data from a solar power plant in Aksaray. The data was taken through the solar power plant's remote reading system, with the permission of the plant owner. The solar power plant from which the data is obtained is located close to the center of Aksaray. Due to the personal data protection law, the name and exact location of the solar power plant was not shared upon the request of the plant owner. 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/m^2, with a yearly total irradiation period of over 2880 h and the average yearly annual temperature is 10 °C in Aksaray.

The data such as irradiation and temperature were collected every 5 minutes from May 2016 to June 2018. Among the data measured between these years, it was found appropriate to use the data belonging to 2017. Because the rate of missing data in 2017 is quite low compared to other years. The data set for the year 2017 used in this study is the actual data measured that year. In PV power plants, data loss can occur due to various reasons such as power outages, interruptions during solar panel maintenance/cleaning, inverter failures, or communication module faults. In this study, it was observed that there was less than 1% data loss during 2017. To eliminate the disadvantages of the TMY dataset, it was preferred to use real measured data. Some critical features of the Data logger are presented in Table 1.

Table 1. Technical Features of Data Logger

Parameter	Value
Power supply	20-60 V DC
Consumption	5 W
Protection	DIN EN 61000-4-2
Operating temperature	-20-70 °C
Storage temperature	-20-85 °C
Protection class	IP 20
Raising	2000 m
Humidity	80%
Precision (Voltage input)	0-10 V, 2 mV
	0-1 V, 0,5 mV
	0-100 mV, 50 µV
Precision (Current input)	0-20 mA, 4 µA

Kipp&Zonen SMP11 pyranometer was used for irradiation (GHI, POA) measurement. Table 2 shows the typical measurement uncertainties of this device. PT1000 (with integrated converter) and PT1000 (resistance) temperature sensors were used to measure the ambient temperature and the panel cell temperature, respectively.

Table 2. Measurement uncertainties of Kipp&Zonen SMP11

Parameter	Value
Response Time	<2 s
Offset	< 2 W/m^2
Temperature Dependency	<1%
Non-stability	**<0.5%**
Non-linearity	<0.2%

During 2017, 105120 data were recorded from the PV/T system. For the results to be accurate, the data must be quality controlled and filtered. For example, since there is no radiation at night, the data measured during these hours must be filtered. Apart from that, the irradiation values at sunrise and sunset are quite small and are not effective for electricity production and may contain abnormal values. Therefore, the data in the mentioned time periods were filtered. In addition, there were missing data for various reasons in some time periods during the year. Since the data were recorded at 5-minute intervals, new values were written according to the previous and next measured values instead of the few missing data. After the filter process, the data set contains 43800 values (Scharmer and Greif, 2023; Reindl et al., 1990).

Specification of PV/T Collector

PV/T collector is provided electricity and usable thermal hot water at the same time from one collector. As far as we know, there is only one PV/T panel manufacturer in Turkey (Solimpex). At the time we conducted this study, there were 72 glass-covered PV cells and 66 tubes in the PV/T panel we could obtain from this manufacturer. The gross area of this collector is 1.28 m^2. Maximum temperature and maximum working pressure are 101°C and 6 bar respectively.

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 m^2. The roof area on the south and north side is 59.7 m^2, 28.9 m^2 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 total residential usage area of 14.962.998 house for which Building Permits were obtained in Turkey between 2002 and 2024 is 1.767.099.964 m^2 (data.tuik.gov.tr, 2024). So, an average house is 118 m^2. All these houses have from 1 to 5 rooms. Therefore, a 4-room apartment for a standard family of 4 people is expected to be around 140 m^2 on average. The heating energy demand of the reference house with a floor area of 140 m^2 is given as 15 kWh/m^2a in Strasbourg climate conditions. The annual lowest temperature values and the number of rainy days in Strasbourg and Aksaray are similar (mgm.gov.tr, 2024; tr.weatherspark.com, 2024). Therefore, the selected reference flat is suitable for the conditions of Aksaray. The average collector area of considered collector is 1.37 m^2 for one panel. Therefore, it was thought that the panels would be placed only on the southern facade. The average daily water consumption is 111 litres per capita in Türkiye 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. In this study, electricity consumption of a standard 4-person house was accepted as 200 kWh per month.

Market Analysis and Assumptions

The energy market in Türkiye is growing day by day. Photovoltaic energy is increasing its importance in the energy mix day by day. At the end of 2020, the world installed PV capacity has exceeded 760 GW. Photovoltaic panel costs are decreasing day by day due to technological developments and rapid increase in installed power (IEA PVPS, 2021). Photovoltaic energy applications are expected to increase rapidly in the coming years due to cost reduction and environmental sensitivities. The solar thermal system market was initiate during the 1970s to meet the hot water demand in parallel with the growth of the tourism industry. Türkiye has 10 million m^2 of flat plate collectors installed. Türkiye offers opportunities in PV/T area because of the high potential of solar energy and experience in solar technology (IEA, 2021). The fact that PV / T systems have less installation costs than the installation of both individual PV and solar thermal collectors is one of the important advantages for the expansion 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 Türkiye.

The unit electricity prices in Türkiye are determined by Energy Market Regulatory Authority (EPDK). The unit price of electricity was determined as 1.92 TL/kWh (0.0597$/kWh) for Single Term Residential Subscribers in February 2024. When calculating the net energy price to be billed, distribution price (It has been determined by EPDK as 0.1171147 TL/kWh (0.0196$/kWh) in July 2019), energy fund price (1% of energy price), TRT share price (2% of energy price) and 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 0,07 E/kWh (EPDK, 2024).

The cost of thermal energy in an example geothermal power plant in Türkiye is calculated as follows. The amount of thermal 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 thermal 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 0.02 Euro/kWh when using natural gas (İzmir Jeotermal, 2024).

Although the installation costs are decreasing day by day, the results of economic analysis will differ between countries due to variables such as policies, 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 and used in the economic analysis.

According to the market investigation results, the average cost of whole reference PV/T system was determined to be between 250 and 350 dollars per square meter. This price includes project cost, installation cost and all necessary equipment costs. In this study, pro forma invoices were received from two companies for the turnkey price of the system mentioned. The price of the system was determined by taking the average of the price quotes provided by the two companies. Accordingly, the total price of the system is determined to be 2355 Euros.

The project can be financed with equity, using an amount of bank loan, or using bank loan entirely. To make the economic analysis results realistic, it is stipulated to use bank loans. 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 Türkiye 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 from country to country and depends on the economic and political conditions of the countries. For this reason, it is more suitable 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 Türkiye varies between 4% and 8%.

According to the Türkiye Statistical Institute data, considering the annual percentage change in the price index between 2005 and 2024, the average interest rate was 15.85% annually (Tcmb, 2024).

The O&M cost of the PV/T system may vary depending on the agreements and from country to country. It is determined from the literature that the O&M cost of these systems is around 1% of the total cost of the project (Kalogirou and Tripanagnostopoulos, 2006; Rasoul et al., 2017; Gu et al., 2018). When calculating the electrical energy and thermal energy produced by PV/T collectors, the annual loss of efficiency should be included in the calculation. 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' catalogues.

TECHNO-ECONOMİC MODELLİNG METHODS

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. To perform thermal analysis, the useful heat gain should first be calculated. The useful heat gain represented with Eq.1 (Farghally et al., 2015).

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

where, Q is the useful heat gain (W), A is the collector area (m^2), F_R is the heat removal efficiency factor, $\tau\alpha$ is the transmittance absorptance product of the PV cells, G is the irradiation (W/m^2), U_{loss} is the heat loss coefficient (W/m^2°C), T_i is the inlet temperature (°C) and the Ta is the ambient temperature (°C). The heat removal efficiency factor is calculated using Eq.2 (Calise et al., 2012).

$$F_R \frac{mC_p}{AU_{loss}}[1\exp(-\frac{AU_{loss}F'}{mC_p}] \qquad (2)$$

where, m is the mass flow rate in the collector (lps), Cp is the collector cooling medium and F' is the corrected fin efficiency. The corrected fin efficiency and the fin efficiency (F) are calculated with Eq.3 and Eq.4, respectively (Calise et al., 2012).

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

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

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/m^2°C) and h_{PVA} is the heat transfer coefficient (W/m^2°C). The M is determined using Eq.5.

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

The loss coefficient (U_{loss}) can be divided to three parts. These are the top loss coefficient (Ut), bottom loss coefficient (U_b) and the edge loss coefficient (U_e). These loss coefficients can be calculated using Eq.6, 7, 8 and 9 (Farghally et al, 2015).

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

$$U_t = \left\{\frac{N_g}{\frac{C}{Tpm(\frac{Tpm-Ta}{N_g+f})e}} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{(\varepsilon_p+0{,}0059N_g h_W)^{-1}+\frac{2N_g+f^{-1+0{,}33Cp}}{\varepsilon_g}-N_g}\right\} \qquad (7)$$

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

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

To calculate the loss coefficient, the value of c, e, f, hw (the convection heat transfers due to the wind), Ue (edge loss coefficient) and Tpm (the mean collector plate temperature) should be determined. These parameters are calculated with following equations (Anderson et al., 2009).

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

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

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

$$h_W = 5{,}7 + 3{,}8v \qquad (13)$$

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

where, N_g is the number of covered glasses, ε_p is the plate emittiance, 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.

Thermal efficiency is a function of inlet temperature, ambient temperature, packing factor (S) and irradiation, while electrical efficiency is a function of nominal operating cell temperature ($NOCT$) and T_{pm}. Eq.15 expresses thermal efficiency (Green, 1998).

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

Electrical Energy Model of the PV/T

The PV panels convert solar irradiation into the direct current. However, some of the devices we use in daily life operate on alternating current (AC), while others operate on direct current (DC). Battery charging of devices operating with direct voltage is also done from an alternative voltage source using various converter equipment. The electrical grid in homes also operates on alternating current. Therefore, the voltage produced in PV panels must be converted to alternating current. In addition, maximum power point tracker (MPPT) is required 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 irradiation, panel area and panel efficiency also affect the generated electricity. The hourly electricity generated by the PV panel is calculated using Eq.16 (Ayan et al., 2022).

$$E_{A,h} = G_{I,h} . A_a . \eta_{PV} \qquad (16)$$

where the $G_{I,h}$is the hourly total in-plane irradiance (kWh/m^2), A_a is the PV/T available area (m^2) and η_{PV} is the overall PV system efficiency (%). The overall PV system efficiency is affected by 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 Eq.17 (Amine et al., 2023).

$$\eta_{PV} = \eta_{module} . \eta_{pc} . \eta_{temp} . \eta_{inv} . [1 - \{(t - 1).(\eta_d)\}] \qquad (17)$$

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 ($T_{c,h}$).

$$\eta_{temp} = [1 - \beta(T_{c,h} - T_{c,ref})] \qquad (18)$$

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

$$T_{c,h} = T_{a,h} + \left[{}^{(NOCT-20)}/_{800}\right].H_{I,h} \quad (19)$$

β and $NOCT$ vary according to panel technology and are determined from PV panel catalogues. Eq.20 expresses electrical efficiency.

$$\eta_e = 0{,}15(1 - 0{,}005(T_{pm} - NOCT)) \quad (20)$$

Economic Analysis Model

In this article, the LCOE, NPV and PBP values are determined by economic analysis of the PV/T system. LCOE is a widely accepted index which is 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 heat and electricity production amount during its lifetime. The formula of LCOE is given in Eq.21.

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

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 Eq.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.

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

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 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 Eq.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_tcan be calculating by Eq.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 Eq.27 and Eq.28.

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

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

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. It is possible to calculate PBP using averaging or subtraction methods. 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 PBP is expressed by Eq.29.

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

In this study, the assumed key input economic parameters are given in Table 3.

Table 3. Key Parameters for the financial analysis

Description	Symbol	Average	Unit
Electricity Price		0.101	€/kWh
Heating Price		0.08	€/kWh
Effective PV/T Area		8.96	m²
Project Life Cycle		25	Years
Electrical Efficiency (STC)		14.7	%
Thermal Efficiency		62.3	%
Degradation Rate		0.7	%/year
Capital Cost		7287	€
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

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 (S) inlet temperature and irradiation. Although s and $\tau\alpha_{pv}$ 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 $\tau\alpha_{pv}$ on the electrical and thermal efficiency is shown in figure 1. 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, there will be a decrease in thermal efficiency due to the increase of S. So, increasing the S increases the electrical efficiency and decreases the thermal efficiency. Therefore, an optimal value for the S should be determined (Koç and Başaran, 2019). When the absorption properties of PV cells are examined, it is observed that they respond well to short wavelengths in the range typically from about 400 nm to approximately 1200 nm. However, the solar spectrum extends up to around 2500 nm, and these longer wavelengths tend to be reflected from PV cells while being absorbed by solar thermal collectors. Therefore, increasing $\tau\alpha_{pv}$ enhances thermal efficiency. Since ταpv has minimal impact on electrical efficiency, a $\tau\alpha_{pv}$ value close to 1 is preferred.

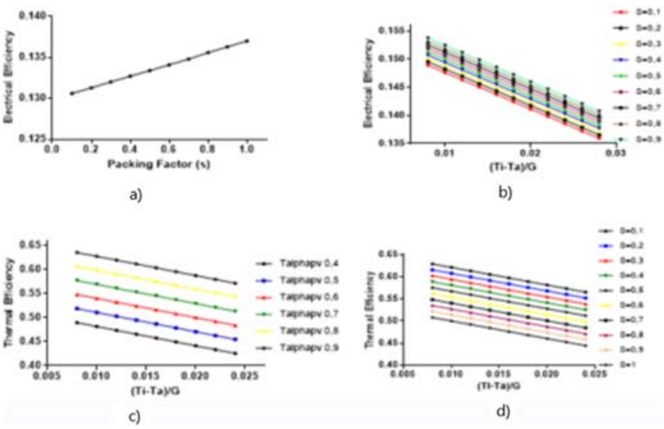

Figure 1. The effect of the s and $\tau\alpha_{pv}$ on the efficiency a) packing factor versus thermal efficiency, b) electrical efficiency at varying packing factor, c) thermal efficiency for varying transmittance/absorptance products, d) thermal efficiency at varying packing factor

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. To determine 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 0.4, respectively. Thus, only the effect of the temperature and irradiation on the efficiency was observed. Inlet water temperature (Ti), ambient temperature (Ta) and irradiation (G) affect the thermal efficiency of PV/T as shown in equation 15. Therefore, the change in (Ti-Ta)/G affects the thermal efficiency. As seen in Figure 3, the increase in (Ti-Ta)/G reduces the thermal efficiency. Although thermal efficiency theoretically depends on these three variables, the change in ambient temperature or inlet water temperature during the day is not as sudden as the change in irradiation. For this reason, thermal efficiency varies especially depending on irradiation. In addition, irradiation changes the panel internal temperature more than it changes the ambient temperature, that is, it indirectly changes the temperature for the PV/T panel. This affects PV/T efficiency. Also, PV panels are the current source. That is, the current produced by the panel change rapidly depending on the irradiation. Therefore, the decrease in irradiation reduces both the electrical efficiency and the thermal efficiency. After the optimal values of S and $\tau\alpha_{pv}$ were determined, the electrical and thermal efficiency of the PV/T collector was determined depending on the temperature values and radiation value in each 1-hour period during the year. During the year, the lowest electrical efficiency was calculated as 13.5% and the lowest thermal efficiency as 54.1%. The highest electrical efficiency was calculated as 15.1% and the highest thermal efficiency as 58.2%.

There may be serious differences between measured irradiation values and DNI values in the database of simulation programs, especially on an hourly basis. Aksaray's irradiation values were obtained from the database of the PVGis program and compared with the actual values obtained from the irradiation sensor. Figure 2 shows the DNI values of the PVGis program and measured irradiation values for the first week of January for Aksaray. As can be seen in Figure 2, there are big differences between the DNI values in the database of the simulation program and the measured irradiation values. For example, while DNI was 124.61 kWh/m^2 at midday on January 2, the measured value by the pyronometer was 586.9 kWh/m^2. The large difference between these two values causes large differences in technical and economic analyses.

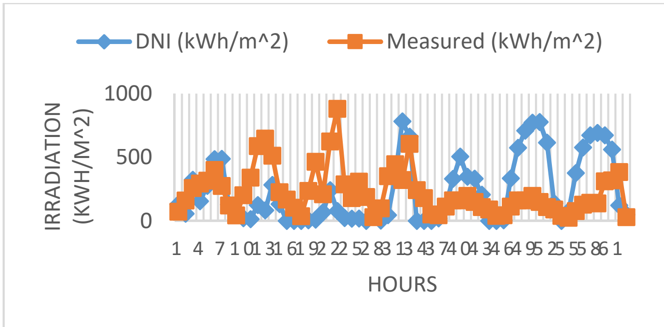

Figure 2. Sample DNI and measured irradiation

Although meteorological data were measured at 5-minute intervals in the study, hourly average values were used in the calculations to avoid complexity in the electrical and thermal efficiency of the PV/T panel. Figure 3 shows hourly average irradiation and the ambient temperature.

Figure 3. 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.

In the MATLAB/Simulink model, the electrical and thermal efficiency of the PV/T collector was determined by using hourly data. These data were used when calculating the electrical and thermal energy production values of PV/T collector. The inlet water temperature, ambient temperature and the irradiation are affecting the thermal efficiency, while the collector cell temperature is affected electrical efficiency. Figure 4 shows the thermal and electrical efficiency of the PV/T collector. Annual average thermal and electrical efficiency was calculated as 62.3% and 14.7%, respectively.

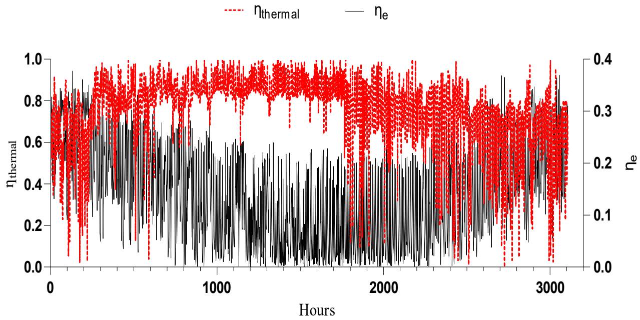

Figure 4. Efficiency of the PV/T collector

To meet the annual energy needs of the reference house, seven PV/T collectors should be used. Accordingly, the amount of electrical energy and thermal energy produced by the designed PV/T system was calculated on an hourly basis. The current efficiency value of the PV/T collector was used for hourly calculation. It has been calculated that the system will generate 2333.18 kWh electrical energy and 10864.43 kWh thermal energy in the first year. Figure 5 shows the amount of electricity and thermal energy that the system will produce hourly for a month in each season.

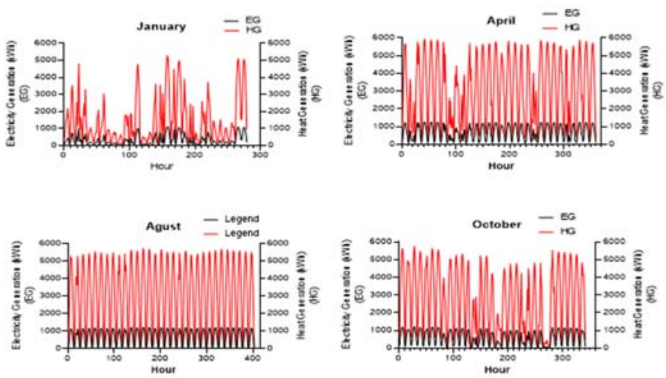

Figure 5. Monthly electricity and heat generation

Electricity and heat production occurred at minimum levels in January and peaked in August. Specifically, electricity production in January and August was 85.6 kWh and 266,639 kWh, respectively. Thermal energy production in January and August was 398.7 kWh and 1,241.6 kWh, respectively. As seen in Figure 4, electricity and heat production remain relatively constant during the summer months, while they exhibit significant variability during the winter months. On a daily basis, the lowest electricity and heat production occurred in March. These results indicate that the production of electricity and thermal energy is highly dependent on meteorological conditions.

Figure 6 shows the monthly average mains water temperature which is used as inlet water temperature of the PV/T collector.

Figure 6. 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.

Table 4. shows the values in the sample years for the economic parameters calculated for the 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. While the amount of electrical energy to be produced by PV/T in the first year was 2333.2 kWh, the amount of energy to be produced in the 25th year decreased by 0.07% in the following years to 1971.2 kWh. Similarly, the amount of thermal energy to be produced by PV/T in the first year is 10864 kWh, and the amount of energy to be produced in the 25th year has decreased by 0.07% in the following years to 9178.9 kWh. Considering that the electric pump consumes 511 kWh of energy annually, the net electrical energy amount to be obtained from the PV/T system is 1822.2 kWh, and the net thermal energy amount is 10864 kWh.

Table 4. The Estimation of Financial Results during the Life Cycle of PV/T System

Year	1	6	12	18	24
Cost saving from energy generation					
Electricity generation (kWh)	2316.8	2236.9	2144.6	2056.1	1971.2
Electric Pump Consumption	511	511	511	511	511
Totol electricity generation (kWh)	1805.8	1725.9	1633.6	1545.1	1460.2
Heat generation (kWh)	10788	10416	9986.1	9574	9178.9
Electricity savings (kWh)	146,45	139,96	132,47	125,30	118,41
Heating savings (kWh)	249,97	241,34	231,38	221,83	212,67
TOTAL ENERGY GENERATION (kWh)	13105	12653	12131	11630	11150
TOTAL ENERGY SAVING (kWh)	396,41	381,30	363,85	347,13	331,09
OM cost and Tax					
OM cost ($)	23,55	23,55	23,55	23,55	23,55
Tax for electricity (€)	26,36	25,19	23,85	22,55	21,31
TOTAL (Omt) (€)	49,91	48,74	47,40	46,10	44,86
Financial cost					
Loan payment (€)	19	19	19	19	19
Loan interest (€)	27	21	15	8	1
TOTAL (Lt) (€)	45,97	40,32	33,54	26,75	19,97
Discounted cash flow and energy generation					
Net Profit (CFt)	300,53	292,24	282,92	818.68	797.55
Discounted Cost (Ct)	95,88	89,06	80,93	186.27	163.6
Discounted Energy Generation (kWh)	12601	9999.8	7576.8	5740.9	4349.9
Cash Flow	-1332	145,35	1865,85	3532,7	5150,04
Evaluation Metrics					
NPV	**2718.5**				
LCOE	**0.091**				
Payback Period	**6 year**				

The LCOE, NPV and PP were calculated 0.091 €/kWh, 2718.5 € and 6 years, respectively. These results showed that the system is economically viable. 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. In the economic analysis, input variables were used by taking their averages over many years. Inflation and changes in the Euro exchange rate may change the economic analysis results. The long-term averages of both variables were taken and future perspectives of various institutions according to the current conditions were considered to minimize the impact of these changes.

CONCLUSION

Türkiye's average irradiation and sunshine duration are higher than the average of European countries. For these reasons, both electrical energy and thermal energy supply from solar energy are 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. Therefore, installing PV/T systems that can generate electricity and thermal energy at the same time provides advantages. There are limited studies on the performance and economic analysis of PV/T systems in the current literature. In this study, for the first time in Türkiye, the performance and economic analysis were performed using real meteorological data. 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 area where the system is installed varies between -9.7 and 42.78 °C, and the PV cell temperature varies between -8.42 and 60.19 °C.
- Annual average thermal and electrical efficiency were calculated as 62.3% and 14.7%, respectively.
- The system can generate 2333.18 kWh of electrical energy and 10864.43 kWh of thermal energy for the first year.
- The LCOE was calculated as 0.0911 €/kWh while NPV and PBP are respectively estimated at 2718.5 € and 6 years.

In the literature, electrical efficiencies of PV/T collectors vary between 11.4% and 13.6%, thermal efficiencies vary between 55% and 62%, LCOE vary between 0.42 USD/kWh and 0.092 kWh, and PBP vary between 10.3 and 15 years. As a result of this study, the LCOE, NPV, PBP, average electrical and thermal efficiencies were found as 0.0911 €/kWh, 2718.5 €, 6 years, 14.7% and 62.3%, respectively, for a project size of 8.96 m^2 in a 25-year life cycle. It should be noted that these results depend on meteorological conditions. It is seen that the results obtained within the scope of this study are better than the results in the literature.

With the MATLAB/Simulink model of the PV/T collector developed within the scope of this study, the S and $\tau\alpha_{pv}$, which are important design parameters, can be determined optimally for the PV/T collector to be installed in any region (according to the temperature and radiation values of the region) to operate it at optimum electrical and thermal efficiency. In addition, the annual deterioration rate of the collector and the fact that devices such as electric pumps were considered, showed that the economic model created was more successful in the analyses to be made for many years. Paying attention to these in economic analysis studies for PV/T collectors to be made in any region will provide important gains. The use of renewable energy sources will reduce fossil fuel consumption. Among the renewable energy sources, especially in cities, the use of solar energy is relatively easier and more economical. In countries such as Türkiye, whose irradiation and temperature averages are above the world average, electricity and heat needs must be met from solar energy. The results obtained in this study show that PV/T systems are an economical way to supply electricity and heat. For this reason, it is very important to prepare both incentive mechanisms and technical standards by regulators for the spread of PV/T systems. It is necessary to prepare typical projects and facilitate legal procedures, especially for small powerful systems to be used in residential. It is expected that this study and its results will lead to the use of PV/T based systems in buildings.

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