Exergoeconomic analysis of photovoltaic thermal systems based on phase change materials and natural zeolites for thermal management

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Abstract

Conventional photovoltaic thermal (PVT) systems provide unstable thermal energy, which changes throughout the day. In PVT systems, phase change materials (PCMs) and heat storage materials could be used to make thermal energy more stable and provide longer-term thermal energy. In the present study, exergoeconomic analysis of PVT systems integrated with natural zeolites has been firstly carried out, and the results were compared with the results of PVT systems integrated with PCM and conventional one. PVT systems integrated with paraffin and stearic acid, common PCMs and conventional PVT systems were analyzed by specific exergy costing method, systems were compared exergoeconomically and suggestions were made to improve the economic performance of PVT systems. As a result of the analyzes conducted with 297 data obtained experimentally, the average energy efficiencies were calculated as 33%, 40%, 37% and 32% for paraffin, natural zeolite, stearic acid and conventional PVT system, respectively. Besides, average exergy efficiencies were 24%, 24%, 22% and 22% for paraffin, zeolite, stearic acid and conventional PVT system, respectively. The average entropy generation of the PVT based paraffin; natural zeolite, stearic acid and conventional one were found as 2.11, 2.29, 2.18 and 2.07 W K⁻¹, respectively. According to the exergoeconomic analysis, specific exergy flow cost values were found as 0.206, 0.176, 0.204 and 0.206 € kWh⁻¹ for the PVTs based on paraffin, natural zeolite, stearic acid and the conventional PVT. It was concluded that the natural zeolite-based PVT system was found as the best system exergoeconomically.

Keywords Photovoltaic thermal systems · Phase change materials · Natural zeolite · Exergoeconomic analysis · SPECO method

List of symbols

$\dot{C}$	Cost stream (€ s ⁻¹)
$\dot{Z}$	Capital cost stream (€ s ⁻¹)
φ	Maintenance factor
c	Average cost of per unit of exergy (€ kWh ⁻¹)
$\dot{E}_x$	Exergy rate (W)
i	Interest rate
n	Total working time
N	Annual working hours
T	Temperature (K)
$\dot{S}$	Entropy rate (W K ⁻¹)

in	Inlet
out	Outlet
dest	Destructed
0	Dead state

Abbreviations

PV	Photovoltaic
PCM	Phase change materials
PVT	Photovoltaic thermal
SPECO	Specific exergy costing
CRF	Capital recovery factor

Subscripts

P	Product
F	Fuel

Introduction

The interest for renewable energy sources is gradually increasing in our century when raw material prices are rising and energy sources such as fossil fuels are rapidly depleted and global warming has become particularly severe with the effect of greenhouse gases. As one of the

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most widely used renewable energy sources, solar energy systems include applications with many different application areas, environmentally friendly and low operating costs. Today, it is being worked on the development and dissemination of photovoltaic (PV) systems as the most feasible way to eliminate waste to increase the functionality of renewable energy sources and enrich systematic designs that will reduce the consumption of natural resources per capita and prevent environmental damage. PV systems can also be used as a hybrid with many different renewable energy sources and can solve many different problems [1]. Regarding PV technology, solar cells can convert only a limited part of the spectrum of solar radiation into electrical energy. Solar radiation, which cannot be converted into electrical energy, turns into the excessive heat load on the material. This excessive heat load increases the solar cell's electrical resistance us lowering the instantaneous electrical efficiency. It is inevitable to encounter this heat load, since there is no single material that converts the entire spectrum of the solar radiation into electricity. Moreover, due to this excessive heat load, material degradation could occur in long-term. Photovoltaic thermal (PVT) systems have been employed to remove this heat load, reducing efficiency, being used as thermal energy. However, conventional PVT systems provide unstable thermal energy, which changes throughout the day. In PVT systems, PCMs and heat storage materials could be used to make thermal energy more stable and provide longer-term thermal energy. Studies on PCMs that can be used in many different sectors are also increasing day by day [2]. Tyagi et al. [3] evaluated economic evaluation methods, including payback period, net present value (NPV), exergoeconomic and environmental impacts and useful technologies available in PVT systems using different fluids in their compilation studies. Fang et al. [4] evaluated the use of PVT systems in different designs and different fluids in different environmental conditions in their reviews. It is emphasized that in order to develop more efficient PVT systems, they should be integrated with new designs, new materials, and higher precision modeling and energy storage systems. In their theoretical and experimental studies, Agrawal and Tiwari [5] compared the hybrid photovoltaic thermal (PVT) module air collector with the PV module in terms of energy savings and showed that the hybrid PVT module reached a greater potential. They achieved annual total thermal energy and exergy gain as 1252.0 kWh and 289.5 kWh, respectively. In their study, Tiwari and Tiwari [6] calculated thermal product modeling for hybrid photovoltaic–thermal (PVT) greenhouse type solar dryer by evaluating product and greenhouse temperature, outlet air temperature and cell temperatures in different climate conditions. Fudholi et al. [7] studied experimentally and theoretically a V-slotted PVT air collector. In their theoretical and experimental studies, they found the V-corrugated PVT exergy efficiency

of the PVT air collector, 13.36% and 12.89%, respectively. Habibollahzade [8] has made parametric studies by suggesting combining photovoltaic thermal (PVT), solar chimney plants with PVT to increase energy production and exergy efficiency. Exergy efficiency and cost ratio for the proposed system achieved 3.304% and $\$241.6 \text{ h}^{-1}$, respectively. Sardarabadi et al. [9] in their experimental studies, they examined conventional PV system, photovoltaic (PV/PCM) system integrated with phase change material and photovoltaic thermal (PV/PCM) systems integrated with phase change material using different fluids. As a result, they revealed that the (PV/PCM) system's electrical energy increased by 4.22% compared to the PV system. Ahmedi et al. [10] investigated the effect of using PCM in building materials for energy saving with a case study. Hossain et al. [11] examined the energy, exergy and economic performances of the system using PCM, which they developed using different designs, on a photovoltaic thermal (PVT) system at different flow rates. Passandideh-Fard et al. [12] in their numerical study, investigated the effects of usage of pure water and SiO_2 /water nanofluid and PCM on the efficiencies of PVT system. They concluded that for PCM/PVT system, the average PV cell temperature is decreased by 16°C compared to the conventional PVT system. In the other study, Sardarabadi et al. [13] evaluated the performances of nanofluid-based PVTs with and without transparent glass cover experimentally. They resulted that the maximum overall energy efficiency increase was 22.5% with GNP nano fluid and glazed PVT. Shiravi et al. [14] performed a thermodynamic analysis of PV/PCM systems with and without fins in maximum operating temperature of PV modules (85°C). They achieved a 4.2% increase in exergy efficiency and a 5% decrease in entropy generation. Ma et al. [15] investigated the daily and monthly performance of a photovoltaic thermal system integrated with phase change material based on energy and exergy analysis. Ahmed et al. [16] studied the concentrated PV (CPV)-Nanoparticle-PCM system to enhance PCM thermal conductivity and reduce the temperature rise of the CPV. They used Al_2O_3 , CuO and SiO_2 nanoparticles to increase the thermal conductivity of PCMs. Kasaeian et al. [17] investigated the effectiveness of simultaneous usage of the Co_3O_4 /water nanofluid and examined phase change material (paraffin wax/Alumina powder) as a cooling method. Kasaeian et al. [18], in another study, investigated the thermal performance of a photovoltaic/thermal system, integrated with phase change materials in a porous medium. They employed a metal foam as a porous medium and the performance of five different PCMs, as organic and inorganic, were examined. Hassan et al. [19] carried out energy, exergy, exergoeconomic and environmental (4E) evaluation for the combination of PV and distillation system. The use of PV as a reflector in conjunction with the solar-powered fixed system was found as the most effective

system from the exgoeconomic and external environmental point of view, considering current PV prices and production technologies. Afrand et al. [20] analyzed two passive/active solar still water desalination system by 6E method. Their results showed that altitude has a direct effect on the exergy of solar stills where the summit-located solar stills (passive and active) have higher exergy efficiency. Exergoeconomic analysis has been a strong method frequently used in many different areas of thermodynamics to reveal the state of components within the whole system in recent years. In this area, Ravinder Kumar [21] presented a critical review on energy, exergy, exergoeconomic and economic (4-E) analysis of thermal power plants. Ghasempour et al. [18] carried out the thermodynamic and economic analysis of a transcritical carbon dioxide power cycle coupled with solar thermal subsystem and LNG subsystem. Similarly, Ahmedi et al. [22] used the exergetic analysis as a strong tool to evaluate the performance of a vacuum evaporator for solar thermal power plant zero liquid discharge systems. Exergoeconomic analysis emerges as a correct method not only for renewable energy sources but also for the use of conventional energy sources [23]. In their other studies, Ahmedi et al. performed techno-economic and environmental analysis of a parabolic trough concentrating photovoltaic/thermal system [24].

Afrand et al. [25], in the section of the conclusion of their review article on phase change materials, suggested further studies for overcoming the challenges of PCMs such as corrosion, causing damage, affecting the life and stability of heat storage units, leakage, high price. They emphasized that thermal conductivities, densities, specific heat capacities, and volume expansions of liquids and solids are not fully consistent across studies, although the melting points of most PCMs and nano-PCMs are known. Although PCMs are one of the most considered materials for PVTs in recent years due to their high phase change enthalpy, their low thermal conductivity is one of the most important disadvantages.

In the literature, PCMs are generally used or nanofluids are employed to improve the efficiency of PVT systems. However, when considered as a commercial product, there are serious problems in terms of mass production and practical use of PVT systems integrated with PCMs. The main problems could be explained as below:

- a. PCMs, as chemical materials, pose significant health risks. There is a risk of serious health problems in case of leakage and mixing with water in systems that transfer the excessive heat load that occurs in PV directly to utility water.
- b. Since there are conditions such as expansion during the melting-freezing process, it also causes mechanical problems such as leakage and cracking.
- c. Many different PCMs are available, each with different thermophysical properties. Depending on where a PVT

with PCM is to be used, it must be integrated with the PCM at different melting temperatures. This means that PVTs with PCM will also create a problem during the production phase. Developing different PVTs suitable for different climatic characteristics is far from practical both during the production phase and the marketing phase of the product.

- d. PCMs are expensive materials when market conditions are considered. Having PCM at the desired melting temperature and melting enthalpy values, material supply is difficult and costly.
- e. Lower thermal conductivity is the main disadvantage of PCMs.

On the other hand, "Zeolite" means "Boiling Stone" as a word from ancient Greek. Zeolites, one of the most important raw materials of recent years, are chemically known as "aqueous alumina silicates". Zeolites were discovered by Swedish mineralogist Frederick Cronstet in 1756, the first zeolite samples found were volcanic (igneous zeolite) origin, and later, "sedimentary zeolite" formations were obtained by hydrothermal and collapse. Turkey, with 75% of the world reserves are zeolites, more than half of Turkey also holds reserves of Gordes district of Manisa. In addition, Ankara, Kutahya, Manisa, Izmir, is located in Balikesir and Cappadocia have significant amount of the natural zeolite sources in Turkey. The main physical and chemical properties of zeolites are; the ability to make ion exchanges, adsorption and molecular sieve structure, silica content, as well as being light colored in sedimentary zeolites, lightness, and pore structure of small crystals caused zeolites to be used in a wide variety of industrial areas. The usage areas of natural zeolites are pollution control, mining, metallurgy, paper, construction, health and chemistry sectors [26]. Kandilli [27] first introduced the PVT systems integrated with natural zeolite and compared to the performance to conventional PVT and the PVT based on PCMs. As a result of this study, higher overall energy efficiency and better economic performance have been obtained by the PVT integrated with natural zeolites. In the other study, Kandilli and Uzel [28] also presented the annual performance of the PVT integrated with natural zeolites. Natural zeolites have important advantages in overcoming the difficulties for PCMs mentioned above:

- a. Natural zeolites are the materials compatible with human health, which is also used in areas such as water treatment. In this respect, its use is suitable for health, especially for systems where domestic water is heated.
- b. Since there are no physical phenomena such as expansion, it is easier to design a stable and mechanically durable PVT system with natural zeolite plates.

- c. It is foreseen that the marketing of PVT with zeolite will be easy in the production and marketing stages. There is no need to use different materials for different climate zones and to design various systems. Once the optimum design is determined, the use case for different climate zones will be like using other flat plate solar energy systems and photovoltaic solar panels.
- d. One of the most important advantages of natural zeolites is their low cost.
- e. Thermophysical properties of natural zeolites are very close to or even superior to paraffin which is the most commonly used as PCM.
- f. As with PCMs, it is possible to improve the thermophysical properties in natural zeolites in a suitable way.
- g. Another advantage of the natural zeolites is that water temperatures do not drop suddenly during intermittent solar radiation, as in conventional systems. Thanks to the heat storage feature of zeolites, the system provides a stable thermal output even in cloudy weather [25].
- h. Unlike PCMs, it does not have latent heat, but can be used in many different solar energy applications thanks to its superior heat storage properties.

To conduct first and second law analyses of energy systems is important in evaluating the performance of their systems. In addition, thermodynamic analysis of an energy system is not sufficient in evaluating it with the whole system. Economic analysis of an energy system, revealing unit exergy costs and determining the place of the system in practice are guiding. Although there are many studies in the literature within the scope of exergoeconomic analysis, there are limited number of studies on exergoeconomic analysis of PVT systems. Experimental studies in this area are invaluable and present important results on the commercial applicability of PCM-based PVT systems. At the same time, as in all energy systems, determining the economic costs is very important for the systems to be commercialized and to find a real-life response. Otherwise, it is far from applicable. In the literature, there are no studies regarding exergoeconomic analysis of PVT systems integrated with natural zeolites. It is the motivation behind the present study. Exergoeconomic analysis of PVT systems integrated with natural zeolites have been firstly investigated by the present study. This study is an original one with this aspect. Furthermore, in no study on exergoeconomic analysis of PVTs, the specific exergy cost of the system has not been given and has not been compared with existing systems. The main purpose of this study is to perform the exergoeconomic analysis of PVT systems integrated with natural zeolites, for the first time in the literature. Besides, the objectives of the present study could be listed: (1) To demonstrate the exergoeconomic analysis model of PVT systems with the SPECO method [29], (2) to apply this model to natural zeolite PVT systems, (3) to compare the PVT systems integrated with paraffin and stearic

acid from the commonly used PCMs, natural zeolites and conventional PVT system by exergoeconomically, (4) to evaluate exergy efficiency and entropy generation of the PVT systems and (5) to offer suggestions for improving the economic performance of PVT systems.

This study may encourage the use of natural zeolites for a wide range of the application of solar energy systems.

System description

In the second part, information about the layers where the PVT system is formed, the test scheme and system, and the devices used in the measurements and their features are mentioned. The system has been tested using a kind of paraffin, stearic acid as an acid, natural zeolite and finally conventional PVT. A thin copper plate is placed on the back surface of the PV module for better transfer of heat into the fluid pipes. The pipes through which the fluid passes are selected from copper due to high heat conduction, and are joined to the copper plate by welding. The experiments were carried out in the experimental area on the terrace floor of MA1 Block, Usak University, Faculty of Engineering, and Mechanical Engineering Department. In Fig. 1, the experimental setup of the PVT system and measuring devices have been shown. The schema of the experimental set up of the PVT system is presented in Fig. 2.

A boiler was used to complete the water circulation in the system. Measuring devices are connected to the data logger, and data are received hourly. Layers of the PVT system have been drawn in Fig. 3. In the experiments, whichever material is to be tested, the relevant material is placed under copper plate welded the working fluid pipes. No material was used for conventional PVT. Paraffin with a melting temperature of 56 °C is placed in a 4-cm thick structure to enter and cover the fluid pipes. However, it is very complicated to insert paraffin and it is necessary to melt both when inserting and removing. For the 1.6 m² PV module, 40 kg paraffin was used in the 4 cm chamber. Natural zeolite with 3–4 mm particle sizes from Gordes region was employed. The melting temperature of stearic acid is 69 °C. Although it is easy to place, it is not easy to find a market. In chemical use of stearic acid, shelf life is important. This material to be used is actually quite expensive as a PCM. Devices employed for the measurements and their properties have been given in Table 1.

Theoretical analysis

The present PVT systems integrated with PCMs, natural zeolites and conventional PVT systems were established, tested and evaluated. The performance of the system was evaluated by testing different materials. The measured

Fig. 1 PVT test system and measuring devices **Fig. 2** Schema of experimental set up of the PVT system

parameters are listed as solar irradiance on PVT surface (W m^{-2}); global solar irradiance (W m^{-2}); wind speed (m s^{-1}); ambient temperature ($^{\circ}\text{C}$); mass flow rate of the water as a working fluid (kg s^{-1}); inlet and outlet temperatures of PVT ($^{\circ}\text{C}$); PV electrical measures are covering voltage (V) and current (A). In the experiments, monocrystalline PV modules (250 W) were used. The characteristic features of these PVs have been presented before [25]. When we consider the experimental system, besides the devices mentioned in Table 1, auxiliary equipment such as solar regulator, battery and data logger for recording temperature and electrical measurements were used. It is essential to carry out the thermodynamic analysis of PVT systems as well as to reveal the heat transfer mechanism. For this purpose, the assumptions listed below are taken into consideration during the thermodynamic analysis:

1. The system is assumed as a continuous flow open system.
2. The inner surface of the fluid channel is smooth.
3. Thermal resistance and external radiation losses of the fluid channel are neglected.
4. Atmospheric pressure is considered as $P_0 = 1 \text{ atm}$.
5. Thermal losses on the side and bottom surfaces of PVT are neglected due to the insulation layer.

Energy and exergy analysis for the PVT system integrated with PCM and natural zeolite that is the subject of this study are given in detail in previous studies [27]. Thermodynamic analysis of an energy system may be inadequate in terms of evaluating the relevant system alone, revealing its commercialization potential and comparing it with similar systems. At this stage, the demonstration of thermoeconomic analysis of thermal systems is both a tool for evaluating the economic performance of the system and helps to improve the system components. Thermoeconomic analysis combines exergy analysis with economic constants for the optimization of the thermal system. It is useful to calculate the specific unit

Fig. 3 Layers of the PVT system **Table 1** Devices employed for the experiments

Device	Properties	Sensitivity
Meteorological station (Davis Vantage Pro 2)	Operating temperature $-40\text{ }^{\circ}\text{C}$ to $+65\text{ }^{\circ}\text{C}$ It can measure wind speed in the range of $1\text{--}80\text{ m s}^{-1}$ It can measure radiation in the range of $0\text{--}1800\text{ W m}^{-2}$	$\pm 5\%$
Flowmeter	It can measure mass flow in the range of $0.5\text{--}10\text{ m s}^{-1}$	$\pm 0.2\%$
Irradiance meter (Delta Ohm Lp471)	It operates between 400 and 1050 nm spectral response range	$\pm 2\%$
Thermal camera (Fluke Ti27)	It can measure between 253 and 873 K	$\pm 2\text{ K}$
Thermo-couple (Ordell KR6R6 K Type)	It can measure temperature between 273 and 913 K	$\pm 2\text{ K}$

external cost of the system in the process and for each component. In the analysis, which equipment, which component is effective to improve the system and the most suitable economic investment to improve the system are presented. Specific exergy costing (SPECO) method evaluates based on fuels and products. SPECO It is important to use the SPECO method, which is the definition of "Fuel" and "Product" in each component [29]. The product is defined as equal to the sum of all exergy values, taking into account the starting point. Fuel is defined equally to all exergy values to be considered at the entrance. Decisions need to be taken to implement the definitions.

Basic thermoeconomic equations and other exergoeconomic parameters for the SPECO method are given below [29]:

$$\dot{C}_P = \dot{C}_F + \dot{Z} \quad (1)$$

$\dot{C}_P$ and $\dot{C}_F$ are cost streams associated with the corresponding exergy streams, while subscripts F and P expresses "Fuel" and "Product", respectively.

$\dot{Z}$, capital cost stream, covers all expenses covering operating and maintenance costs. Capital cost stream ($\dot{Z}_i$) could be calculated for any component of a system by Eq. 2:

$$\dot{Z}_i = Z_i \cdot \text{CRF} \cdot \varphi (\text{€s}^{-1}) \quad (2)$$

In the present study, the maintenance factor (φ) was assumed as 1.06. The unit cost of electricity is assumed as 0.142 € kWh^{-1} . Capital recovery factor (CRF) is an economic parameter that depends on the interest rate and estimated equipment life and is calculated by Eq. 3:

$$\text{CRF} = i \cdot \left[\frac{(1+i)^n}{(1+i)^n - 1} \right] \cdot \frac{1}{N \cdot 3600} \quad (3)$$

where " i " is the interest rate, " n " is the total working time of the equipment over the years, " N " annual working hours.

In this study, the interest rate was assumed as 9.0%. Economic lifetime and daily working hours of the PVT systems were assumed 20 years and 7.2 h day⁻¹ in calculations, respectively.

There is no fuel cost for solar radiation. The SPECO method is based on the unit exergy cost of fuel and product. The cost stream of any component is calculated by multiplying the average cost per unit of exergy (c_i) and exergy value of the component ($\dot{E}x_i$) as follows:

$$\dot{C}_i = c_i \cdot \dot{E}x_i \quad (4)$$

Exergy analysis is performed by balancing exergy input (fuel) rates and exergy output (product) rates in the control volume. The exergy balance can be written as follows:

$$\dot{E}x_p = \dot{E}x_F + \dot{E}x_D \quad (5)$$

The exergy produced ($\dot{E}x_p$) is equal to the sum of the exergy of the fuel ($\dot{E}x_F$) and the exergy destructed ($\dot{E}x_D$). Cost stream of the exergy destructed ($\dot{C}_D$) could be calculated as follows:

$$\dot{C}_D = c_F \cdot \dot{E}x_D \quad (6)$$

In the present study, c_F is assumed as zero since solar radiation has no cost. Each PVT system discussed in the study was analyzed as a whole system and the cost balance equation (Eq. 7) was used. In other words, the solar energy cost per unit of exergy can be accepted as zero and then the exergy value of the product is calculated easily:

$$c_F \cdot \dot{E}x_F + \dot{Z}_{PVT} = c_P \cdot \dot{E}x_P \quad (7)$$

As mentioned earlier, the detailed theoretical background for energy and exergy analysis has been presented in previous studies. Entropy generation rate (W K⁻¹) values discussed in this section were calculated by the equation given below:

$$\dot{E}x_D = T_0 \dot{S} \quad (8)$$

Results and discussion

The exergoeconomic analyses of the PVT systems discussed in the study are investigated. In the study, PVT systems integrated with PCMs, natural zeolites and conventional ones were tested under real ambient conditions, and experiments were performed. The measurements were obtained by the system established on the terrace of the Mechanical Engineering Department building. Usak province (38.41° N; 29.25° E) is located in the transition zone between the Mediterranean and continental climate in the Aegean Region of Turkey and has the altitude as 906 m. According to the

data of the General Directorate of Meteorology, Usak has 2789 h year⁻¹ of sunshine duration and annual solar energy amount of 1540 kWh m⁻²a⁻¹ [30]. The experiments of the system were carried out on April–June 2016, and the analysis was made on 297 experimental data. For economic analysis, energy and exergy values calculated using the results by the experiments were used. Properties of the materials used in the PVT systems, energy and exergy values of all PVT types and uncertainties of the calculated parameters were reported before [27]. Overall average energy efficiency, produced energy, annual income, average cost and cost stream values for all PVT types are presented in Table 4. Overall average energy efficiencies were calculated as 33%, 37%, 40% and 32% for paraffin, stearic acid and natural zeolite based PVT systems and conventional PVT, respectively [27]. Since it is closely related to specific exergy costing, the exergy efficiency and entropy production features of the systems investigated will be discussed.

First, it should be presented the solar energy amount and sunshine duration to show solar profile in the location where the experiments were carried out. Variations of monthly variation of average daily solar irradiance (kW m⁻²day⁻¹) and sunshine duration (h) for Usak province were plotted in Fig. 4. For each calculation, 8760 solar radiation data were used. Monthly variation of average daily solar irradiance values was found as 2.11; 3.38; 4.73; 5.22; 5.98; 7.20; 7.53; 6.44; 5.11; 3.44; 2.85; 2.13 from January to December, respectively. One of the important data in energy calculations produced from photovoltaic panels is sunshine duration. Monthly average sunshine duration values for Usak Province were also given by Fig. 4. That is listed as 3.7; 4.4; 5.4; 6.6; 8.6; 10.7; 11.5; 11.1; 9.4; 7.1; 5.1 and 3.6 h for January to December, respectively.

The relationship between exergy efficiency, entropy generation and solar radiation for PVT integrated with paraffin, natural zeolite, stearic acid and conventional PVT were plotted by Figs. 5–8. With the increase in solar radiation values, while the exergy efficiency values decrease, entropy production increases. Average exergy efficiency values were calculated as 0.24; 0.24; 0.23 and 0.22 for the PVT based paraffin, natural zeolite, stearic acid and conventional one, respectively. Concerning the entropy generation, the average entropy generation values of the PVT based paraffin, natural zeolite, stearic acid and conventional one were found as 2.11; 2.29; 2.18 and 2.07 W K⁻¹, respectively. Although there is no significant difference between these values, the reason for the average entropy value for the PVT with natural zeolite to be relatively high is to reach higher temperatures. It is thought that the reason of this result is the thermal energy storage by the natural zeolites. It is predicted that if a more effective pipe design can be made that absorbs the heat energy stored; the higher entropy in this system can be reduced.

Fig. 4 Monthly variation of average daily solar irradiance ($\text{kW m}^{-2}\text{day}^{-1}$) and sunshine duration (h)

Fig. 5 Exergy efficiency and entropy generation versus solar radiation for PVT integrated with paraffin

Fig. 6 Exergy efficiency and entropy generation versus solar radiation for PVT integrated with natural zeolite

After evaluating the exergy and entropy production of the systems under consideration, it could be started to analyze their economic implications. The amount of energy produced and the annual returns over the average efficiencies accepted are given in Table 2. The unit cost of electricity is assumed as 0.142 € kWh^{-1} . The average cost of each system changes only due to the additional material cost used in the system. PVT cost includes PV panel, copper plate and serpentine copper pipes, PCM or heat storage material,

insulation material, back sheet, plumbing materials, boiler, valves. R&D cost including measurement devices are not included in the total cost. The additional costs brought by the materials to the system were calculated as 94.87 and 47.44 € for paraffin and stearic acid, respectively, and there was no additional cost due to the cheapness of natural zeolite.

For the PVT system based on paraffin, stearic acid, natural zeolite and conventional, the experiments were carried out, and the exergy flows ($\dot{W}$) entered, exited and destroyed,

Fig. 7 Exergy efficiency and entropy generation versus solar radiation for PVT integrated with stearic acid

Fig. 8 Exergy efficiency and entropy generation versus solar radiation for conventional PVT

Table 2 Average overall energy efficiency, produced energy, annual income, average cost and cost stream values for all PVT types

PVT type	Overall energy efficiency/%	Produced energy per year/kWh a ⁻¹	Annual income/€	Average system cost/€	Cost stream $\dot{Z}_t/\text{€ s}^{-1}$
Paraffin	33	838	119.12	1043.01	0.000010818
Stearic acid	37	887	126.11	995.58	0.000010326
Zeolite	40	936	133.10	948.14	0.000009834
Conventional	32	801	113.81	948.14	0.000009834

Table 3 Average energy and exergy efficiencies and exergy values of the PVT systems tested [25]

Parameter	Paraffin	Stearic acid	Natural zeolite	Conventional
$\dot{E}x_{in}/W$	806.78	832.51	868.58	787.95
$\dot{E}x_{out}/W$	188.75	182.47	200.72	171.60
$\dot{E}x_{dest}/W$	618.02	650.05	667.86	616.35
η	0.33	0.37	0.40	0.32
ε	0.24	0.22	0.24	0.22

Table 4 Specific exergy unit costs of PVT types

PVT type	$c_p/\text{€ Ws}^{-1}$	$c_p/\text{€ kWh}^{-1}$
Paraffin	0.0000000573	0.206
Stearic acid	0.0000000566	0.204
Zeolite	0.0000000490	0.176
Conventional	0.0000000573	0.206

and the average exergy and energy efficiencies were calculated and compared for each system. Table 3 shows that the average energy and exergy efficiencies obtained are higher in the system where zeolite is used.

Average costs per unit of exergy (Specific exergy unit costs) of PVT types are given in Table 4. The average costs per unit of exergy values were calculated as 0.206, 0.204, 0.176 and 0.206 € kWh⁻¹ for the PVT types based on Paraffin, Stearic Acid, Zeolite and Conventional one, respectively. In this study, the cost of solar energy (c_F) was neglected.

Natural zeolite is very abundant and inexpensive resources in Turkey can be obtained without being dependent on the outside and reduces the system cost.

In order to make sense of the results obtained, it would be useful to compare them with similar results in the literature. Hepbasli et al. [31], in their study, presented the exergoeconomic analysis of BIPV. In the analysis including inverter costs, the unit exergy cost for the produced electrical energy was found as 0.368 € kWh⁻¹. Although only PV systems were involved in this study, it is understood that PVT systems are advantageous; however, due to the cost advantage of natural zeolite in PVT systems, unit exergy costs can be relatively low. Ameri et al. [32] studied concentrated photovoltaic systems. They report that the unit cost of electrical power production is 0.180 € kWh⁻¹ (56.21 \$ GJ⁻¹). Kerdana et al. [33] described a systematic framework that uses exergoeconomic theory integrated into 'building energy retrofit' (BER) design. An exergoeconomic module, based on the SPECO method, has been embedded into 'EXRETOpt', a recently developed retrofit-oriented exergy simulation tool based on EnergyPlus. They resulted that the enhanced value of exergy price of produced electricity is 0.31 € kWh⁻¹.

From these results, we could concluded that PVT systems integrated with natural zeolite give better results for unit exergy cost and efficiency.

Conclusions

In this section, the results obtained from four different PVT systems performed in the light of experimental data are listed, and the results of thermoeconomic analysis by the SPECO method are listed, and then, suggestions are made to run and improve the system more efficiently.

- The average overall energy efficiency values were calculated as 34%, 36%, 40% and 32% for the PVT types based on Paraffin, Stearic Acid, Zeolite and Conventional one, respectively. In this case, it is understood that the highest energy efficiency belongs to the natural zeolite system with 40%.
- Related to average exergy efficiencies, they were found as 24%, 22%, 24% and 22% for the PVT integrated with Paraffin, Stearic Acid, Zeolite and Conventional one, respectively.
- The average entropy generation values of the PVT based paraffin, natural zeolite, stearic acid and conventional one were found as 2.11; 2.29; 2.18 and 2.07 W K⁻¹, respectively.
- Total produced energy values were determined as 838, 887, 936, 801 kWh a⁻¹ per a module for the PVT types based on Paraffin, Stearic Acid, Zeolite and Conventional one, respectively.
- From the exergoeconomic analysis, average costs of unit exergy were found as 0,206, 0,176, 0,204, 0,206 € kWh⁻¹ by SPECO method for the systems with Paraffin, Stearic Acid, Zeolite and Conventional one, respectively. The lowest cost of unit exergy value is determined to belong to the PVT system integrated with natural zeolite.

In addition to these results, the conclusions from the experiments and suggestions that can guide future studies are presented below:

- As known, PCMs are the first material that comes to mind to provide more thermal energy in PVTs. However, it is a critical advantage that natural zeolite has an almost free, very affordable cost. On the other hand, PCMs significantly increases PVT costs.
- Another issue is the ease of application. Natural zeolite can be easily integrated into PVTs than PCMs. In order to use paraffin, it is necessary to melt, split or apply as microcapsules. It is also necessary to quickly remove paraffin from the PVT system when it is hot. High cost,

harmful to health and risk of leakage makes PCMs disadvantageous.

- On the other hand, natural zeolites are superior to PCMs in terms of human health both in terms of antibacterial structure and lack of harmful chemicals.

Considering the industry, transportation and housing sectors, the highest share in energy consumption belongs to the buildings. According to research by the International Energy Agency [34], it has been revealed that in many IEA member countries, energy use in buildings accounts for over 40% of primary energy consumption. Energy use in buildings has increased significantly over the past few decades due to population growth, economic growth and an increase in quality of life. However, as of 2020, the Covid-19 pandemic, quarantine processes and remote work applications, which have been on the agenda of the world, increase the energy consumed in the buildings far above these values. Increasing demand for energy supply has led to even faster development of low energy technologies for building applications, with global warming due to CO₂ emissions from the use of non-renewable energy sources.

Different systems in which natural zeolites are integrated with PVT systems can be designed and examined for future studies. Natural zeolite appears to have great potential for PVT researchers and the solar industry.

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