Exergy analysis of a Naturally Ventilated Building Integrated Photovoltaic (BIPV) System

***Rafaela A. Agathokleous*[a], *Soteris A. Kalogirou*[b] *and Sotirios Karellas*[c]**

[a] *Cyprus University of Technology, Limassol, Cyprus, rafaela.agathokleous@cut.ac.cy*
[b] *Cyprus University of Technology, Limassol, Cyprus, soteris.kalogirou@cut.ac.cy*
[c] *National Technical University of Athens, Athens, Greece, sotokar@mail.ntua.gr*

Abstract:

The integration of PV panels in a second skin creates heat behind the PVs, which if not removed it lowers the efficiency of the PV panels because of the high temperature. Consequently, it is important to find the configuration of the system that will increase the efficiency of the PVs and do not increase the cooling loads of the building in summer. For this study, various experiments were carried out to test the temperature distribution of a naturally ventilated system in terms of the inclination angle, solar radiation and the air gap width. The results concern temperature of the PVs and air flow rate. However, in order to examine the performance of the Building Integrated Photovoltaic (BIPV) systems, energy and exergy analyses should be done simultaneously since energy describes the quantity of energy while exergy represents the quality of energy. In this study an exergy analysis is used in order to find the configuration at which the system performs better.

Keywords:

BIPV, exergy, photovoltaics, thermal behaviour, natural ventilation.

1. Introduction

During the last few years photovoltaic (PV) panels are increasingly incorporated (or integrated) into the construction of buildings for generating electrical power. These are called Building Integrated Photovoltaic (BIPV) systems (see Fig.1). The integration of PV panels in a second skin creates heat behind the PVs, which can either be thrown to the environment or be used to heat the interior of the building. When the heated air is used to heat the building, then the system is called Building Integrated Photovoltaic/Thermal (BIPV/T), shown in Fig. 2.

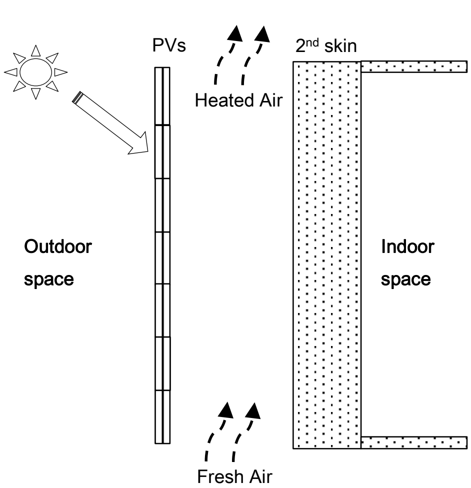

Fig. 1 A naturally ventilated Building Integrated Photovoltaic (BIPV) system driving the hot air to the environment.

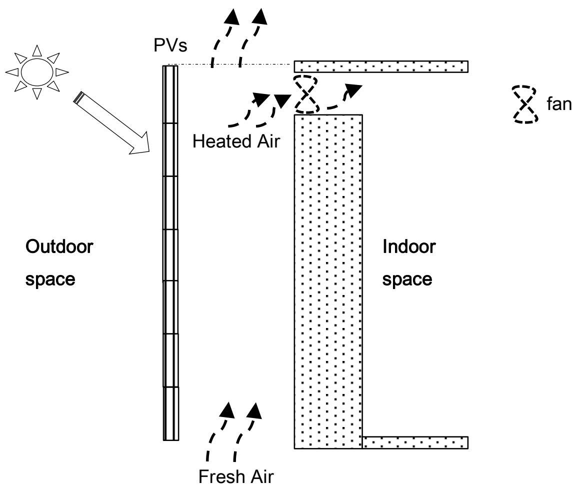

Fig. 2 A Building Integrated Photovoltaic/Thermal (BIPV/T) system driving the hot air into the building with the use of fan.

Both BIPV and BIPV/T systems are formed by PV panels integrated on a second skin part of the building, thus creating an air gap between the two skins. In BIPV systems the air gap is responsible to cool the PVs and remove excess heat to avoid building overheating and for the BIPV/T systems the air gap is responsible to circulate the heated air and drive it into the building to provide space heating.

The ventilation of the air gap can be natural or mechanical. The one investigated in this study is a naturally ventilated BIPV system. This has a number of advantages, the most important of which is the avoidance of energy to power the fans, the operation with no noise and the avoidance of overheating which can happen when the fan stops in an active system.

However, in both systems in summertime, if the heated air is not removed from the duct, it lowers the efficiency of the PV panels because of the developed high temperature. Additionally, the excess heat increases the cooling loads of the building. Consequently, it is important to find the configuration of the system that will increase the efficiency of the PVs and do not increase the cooling loads of the building in summer. For the BIPV/T Systems it is important to keep both electrical and thermal efficiencies high throughout the year.

As mentioned earlier, this study investigated a naturally ventilated BIPV system. It is considered that the air enters the air duct from the bottom and exits from the top. For this purpose, various experiments have been carried out to test the temperature distribution of a naturally ventilated system in terms of the inclination angle, solar radiation and the air gap width. The results concern the temperature of the PVs and air flow rate. Energy and Exergy analysis were carried out in order to find the configuration at which the system performs better. The aim is to optimise the construction so as to obtain the maximum energy and exergy efficiency of the BIPV system.

BIPV/T system utilize solar energy very effectively since they use both sunlight and solar heat simultaneously. One can say that PV/T systems can do this more effectively since they have PV cells and solar thermal collector on the same system. There are various studies about the performance of Photovoltaic/Thermal (PV/T) systems and BIPV/T systems. There are many researchers who agree that to examine the performance of those systems, energy and exergy analyses should be done simultaneously since energy describes the quantity of energy while exergy represents the quality of energy. According to Dincer and Rosen [1], exergy analysis identifies the causes, locations and magnitude of the system inefficiencies and provides the true measure how a system approaches to the idea.

A review on exergy analysis of various solar energy systems, is carried out by Saidur et al. [2] summarizing that comparing the thermal efficiency and exergetic efficiency of the systems, it can be concluded that the thermal efficiency is not sufficient to choose the desired system. The systems discussed in this study are solar photovoltaic, solar heating devices, solar water desalination system, solar air conditioning and refrigerators, solar drying process and solar power generation.

Sahin et al. [3] studied the thermodynamic characteristics of solar PV cells based on exergy. They developed a new efficiency which is useful in studying PV performance and possible improvements. The energy efficiency was found to vary between 7-12 % during the day while the exergy efficiency between 2-8%. On the same aspect, Joshi et al. [4] attempted to investigate the performance characteristics of a PV and PV/T systems based on energy and exergy efficiencies. They found that the energy efficiency vary from 33 % - 45 %. The exergy efficiency of a PV/T and PV systems varies from 11.3 % - 16 % and 7.8 % - 13.8 % respectively. Saloux et al. [5] carried out analysis of PV and PV/T systems using the exergy method. The modelling approach presented in this paper is more complete than those given by [3] and [4].

Nayak and Tiwari [6] carried out an energy and exergy analysis of a PV/T integrated system with a solar greenhouse. The exergy analysis calculations of the PV/T integrated greenhouse system show an exergy efficiency of 4% approximately. The exergy efficiency is defined as:

$$\varepsilon = \left(\frac{\dot{E}x_{out}}{\dot{E}x_{in}}\right) \times 100 \qquad (1)$$

Where $\dot{E}x_{out}$ is the exergy output of greenhouse (kWh)

$\dot{E}x_{in}$ is the exergy input for PV modules (kWh)

Fujisawa and Tani [7] studied the annual exergy on PV/T hybrid collector. From the experimental evaluation, they concluded that the PV/T collector can produce higher output density than a unit PV module or liquid heating flat plate solar collector. Assuming that the initial temperature of the fluid medium is equal to the ambient temperature, the overall exergetic efficiency (ε) of a PV/T system is defined by:

$$\varepsilon_{pvt} = \varepsilon_{pv} + \varepsilon_t = \eta_{pv} + \left(1 - \frac{T_{amb}}{T_2}\right)\eta_t \quad (2)$$

Where ε_{pv} is the exergetic efficiency of the PV equivalent to the η_{pv} which is the energetic efficiency of the PV.

ε_t is the exergetic efficiency of the thermal collector, related to the η_t by the Carnot efficiency

T_{amb} is the ambient temperature (K)

T_2 is the final temperature of the fluid (K)

Chow et al. [8] made an energy and exergy analysis of a PV/T collector with and without glass cover. The energetic efficiency of the glazed collector was found to be always better than the unglazed collector. The exergetic efficiency of the unglazed collector has been found to be better than the glazed one in the specific range of the tested parameters. So if the target is to have either more electrical energy or overall energy output, the second law is more appropriate to assess the system.

Hepbasli [9] presented a key review on exergetic analysis and performance evaluation of a wide range of renewable energy resources. Among them, the analysis of PV/T system and solar collector applications are also presented. According to [9] the exergetic efficiency for a PV/T system is the ratio of the total exergy output to total exergy input given by:

$$\varepsilon_{pvt} = \frac{\int_{t1}^{t2}\left(A_c\,\dot{E}x_{\mathrm{th}} + A_{PV}\dot{E}x_{\mathrm{pv}}\right)dt}{A_c\int_{t1}^{t2}\dot{E}x_{\mathrm{sun}}\;dt} = \varepsilon_t + \beta\,\varepsilon_{pv} \quad (3)$$

Where $\dot{E}x_{\mathrm{pv}}$ is the photovoltaic exergy output per unit PV cell area (W/m^2)

$\dot{E}x_{\mathrm{th}}$ is the thermal exergy output per unit collector area (W/m^2)

$\dot{E}x_{\mathrm{sun}}$ is the exergy input of solar radiation (W/m^2)

A_c is the collector area (m^2)

A_{PV} is the PV cells area (m^2)

β is the cell packing factor

The exergy outputs are related to the energy outputs as shown in (4) and (5):

$$\dot{E}x_{\mathrm{pv}} = \dot{E}_{\mathrm{pv}} \quad (4)$$

$$\dot{E}x_{\mathrm{th}} = \dot{E}_{\mathrm{t}}\left(1 - \frac{T_a}{T_2}\right) \quad (5)$$

Where T_2 is the final temperature of the fluid (K)

$\dot{E}_{\mathrm{pv}}$ is the photovoltaic energy output (W)

$\dot{E}_{\mathrm{th}}$ is the thermal energy output of the collector (W)

The exergy input of solar radiation is determined by different methods. According to Chow et al. [8], the three most commonly used calculation methods are those suggested by [10]–[12] shown by (6),

(7) and (8) respectively. According to Shahsavar et al. [13], the differences in the results comparing the three equations are less than 2%.

$$\dot{E}x_{\text{sun}} = \left[1 + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3}\frac{T_{amb}}{T_{sun}}\right] G \tag{6}$$

$$\dot{E}x_{\text{sun}} = \left[1 - \frac{4}{3}\frac{T_{amb}}{T_{sun}}\right] G \tag{7}$$

$$\dot{E}x_{\text{sun}} = \left[1 - \frac{T_{amb}}{T_{sun}}\right] G \tag{8}$$

Where T_{amb} is the ambient environment temperature (K)

T_{sun} is the solar radiation temperature (K)

G is the solar radiation per unit area (W/m^2)

Shahsavar et al. [13] analysed the energy and exergy performance of a naturally ventilated PV/T air collector designed, manufactured and tested in Iran. The total exergy efficiency of the studied PV/T system is calculated by:

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{th} \tag{9}$$

Where ε_{el} is the electrical exergy efficiency calculated from (10)

ε_{th} is the thermal exergy efficiency calculated from (11)

$$\varepsilon_{el} = \frac{\dot{X}_{el}}{\dot{X}_{in}} \tag{10}$$

$$\varepsilon_{th} = \frac{\dot{X}_{th}}{\dot{X}_{in}} \tag{11}$$

Where $\dot{X}_{in}$ is the $\dot{E}x_{\text{sun}}$ presented in (5) by Petela [10], $\dot{X}_{el}$ is equal to the electrical energy (E_{el}=I V) and $\dot{X}_{th}$.is the thermal exergy as defined by Dubey et al. [14]:

$$\dot{X}_{th} = \dot{Q}_U \left[1 - \frac{T_{amb} + 273}{T_{f,o} + 273}\right] \tag{12}$$

Where $\dot{Q}_U$ is the rate of useful energy transfer (kW)

$T_{f,o}$ is the outlet fluid temperature (K)

The analysis by Shahsavar et al. [13] showed that the total energy efficiency of the system increases with increasing solar radiation intensity but the total exergy efficiency decreases. There is also an optimum channel depth at which total energy and exergy efficiencies of the system is maximum. Finally, it is observed that the total energy and exergy efficiencies of the system increase with the increase of the PV cell efficiency.

Joshi and Tiwary [15] made an attempt to evaluate exergy analysis of a hybrid PV/T parallel plate air collector for cold climatic conditions in India. The energy and exergy efficiencies of a PV/T air collector were estimated. It is observed that an instantaneous energy efficiency of a PV/T air heater varies between 55-65% and exergy efficiency 12-15%. The results obtained are in agreement to the results predicted by Bosanac et al. [16] who studied the potential of PV/T solar collectors in Denmark. The exergy efficiency of the PV/T air collector is determined by:

$$\varepsilon = \eta_o[1 - \beta\Delta T] + \eta_{th}\left[1 - \frac{(T_{amb} + 273)}{293 + \Delta T}\right] \tag{13}$$

Where β is the packing factor of solar cell

η_o is the electrical efficiency under standard test conditions

η_{th} is the thermal efficiency

ΔT is the difference between the ambient temperature and collector outlet temperature

Park et al. [17] presented a comprehensive literature review on energy and exergy analyses of renewable energy conversion systems including solar air heater, solar water heater, solar photovoltaic and cooking devices. The authors recommended to use PV/T collectors than PVs alone for better performance and economic benefits of these systems. Regarding the PVs, the exergy efficiency was determined as shown by:

$$\varepsilon = \frac{V_{mp}I_{mp} - \left(1 - (T_{amb}/T_c)\right)h_c A_{PV}(T_c - T_{amb})}{\left(1 - (T_{amb}/T_s)\right)G\, A_{PV}} \tag{14}$$

Where V_{mp} is the voltage at the maximum power point (V)

I_{mp} is the current at the maximum power point (Amps)

T_c is the temperature of the cell (K)

T_{amb} is the ambient temperature (K)

h_c is the convective heat transfer coefficient; h_c =5.7+3.8v where v is the wind speed

T_{sun} is the temperature of the sun taken as 5777K

A_{PV} is the area of the module (m^2)

Sarhaddi et al. [18] carried out a study to evaluate the exergetic performance of a PV/T air collector. It is concluded that the thermal efficiency of the PV/T air collector is about 17.18%, the electrical efficiency is 10.01%, the overall energy efficiency is 45% and the exergy efficiency is 10.75% for sample climatic operating and design parameters.

2. Experimental Analysis

The exergy analysis in this study is supported by the experimental results. The experimental analysis is carried out to record the temperature of the system under various configurations. Three inclination angles were tested 30º, 45º and 90º and two air gap width sizes 0.10 m and 0.15 m. All tests were performed under high incident radiation of 800 W/m^2 and low radiation 400 W/m^2 and the ventilation of the system was natural since no fan was implemented to drive the air through the duct.

The experiments are carried out in a laboratory with the use of a large scale solar simulator and a BIPV custom made experimental apparatus. Various thermocouples and data acquisition devices were used to monitor the thermal response of the system under different conditions. The custom made experimental apparatus comprises a 180 W polycrystalline PV panel, 1.60 m long and 0.80 m wide. The back and the sides of the apparatus are made from wood forming an air duct representing the air gap formed when a PV is integrated to the wall or roof of the building. The experimental set up is shown in Fig. 3.

The BIPV apparatus was exposed to the radiation of 800 W/m^2 and 400 W/m^2 from the solar simulator, while a number of thermocouples were already placed in various places of the apparatus. The thermocouples were connected with DaqPro devices to record the temperature of every point and store the data in a computer. Table 1 shows the instruments used and some their characteristics.

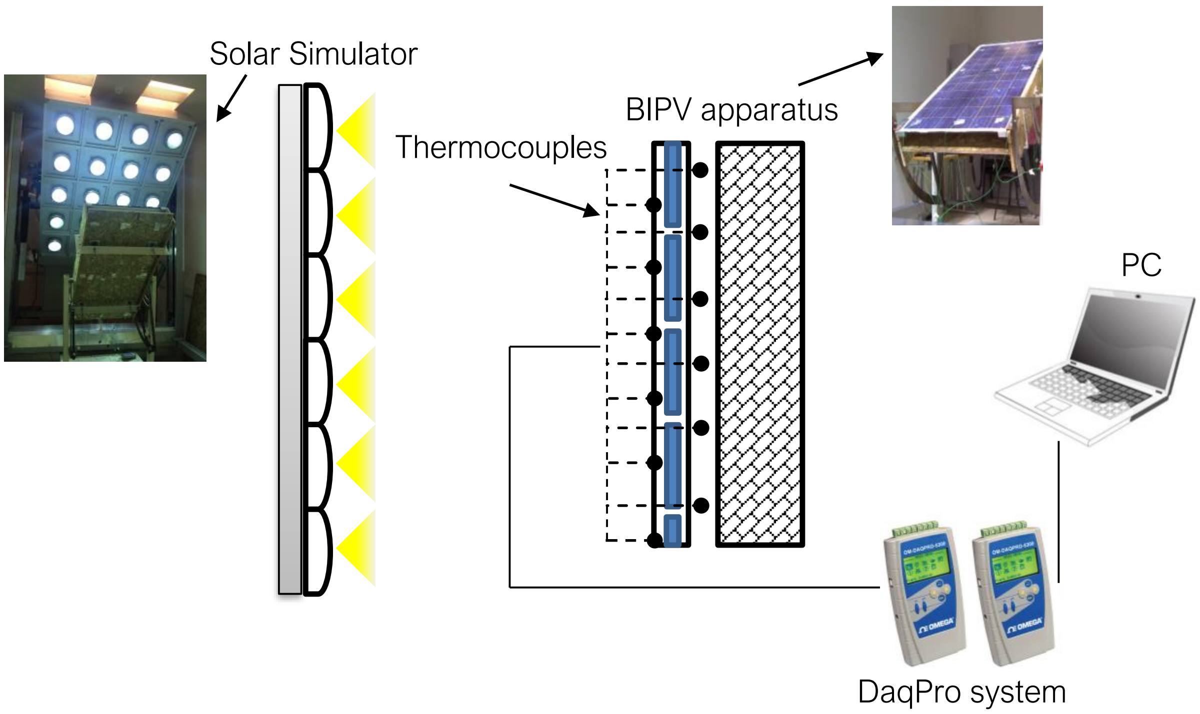

Fig. 3 The experimental set up.

Table 1. Characteristics of the devices used in the experimental procedure.

Solar Simulator			
Radiation Range: 0-1200 W/m^2	No of lamps: 20 (575 W each)	Frame Area: 2.15 m x 1.65 m	Test area: 2 m x 1.5 m
Daq Pro			
Thermocouples: K- type	Accuracy: ±0.5ºC	No of plugs: 8	Temperature: -250ºC to 1200ºC
Photovoltaic			
Area: 1.6 m x 0.8 m	Power: 180 W	Type: Polycrystalline	Efficiency: 14%

3. Energy and Exergy Analysis

Generally, the exergy is the amount of energy available to be used. After the system reach equilibrium with the environment, the exergy is zero. This section presents the energy and exergy analysis of a naturally ventilated BIPV system in terms of the system performance. The most appropriate way to discuss the performance of a BIPV system and a PV/T system is to estimate the energy and exergy efficiency of the system.

The energy efficiency is defined as the total energy yield and can be calculated from the first law of thermodynamics. The exergy efficiency is defined as the total exergy yield which is the part of energy that could theoretically be converted to work in an initial Carnot process. The exergy efficiency is related to the second law of thermodynamics known as the exergy efficiency law.

The system considered for the analyses is a naturally ventilated BIPV system with air inlet and outlet through an open ended channel. The system is tested experimentally in a laboratory with the use of a large scale solar simulator and a BIPV custom made experimental apparatus. The conditions under consideration to the system are shown in Fig. 4.

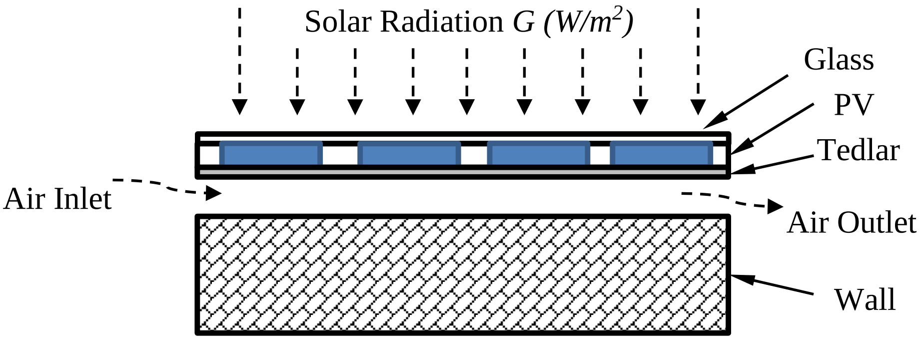

Fig. 4 The cross-sectional view of a naturally ventilated BIPV system.

3.1. Energy Analysis

The actual power output of a PV module is given by:

$$P = V_{OC}\, I_{SC}\, FF \tag{15}$$

Where V_{oc} is the open circuit voltage (V) (see Fig. 5)

I_{sc} is the short circuit current (Amps) (see Fig. 5)

FF is the fill factor

Fill factor describes the quality of solar cells:

$$FF = \frac{P_{max}}{I_{SC}\, V_{OC}} = \frac{I_{mp}\, V_{mp}}{I_{SC}\, V_{OC}} \tag{16}$$

Where I_{mp} is the current at maximum power point (Amps) (see Fig. 5)

V_{mp} is the voltage at maximum power point (V) (see Fig. 5)

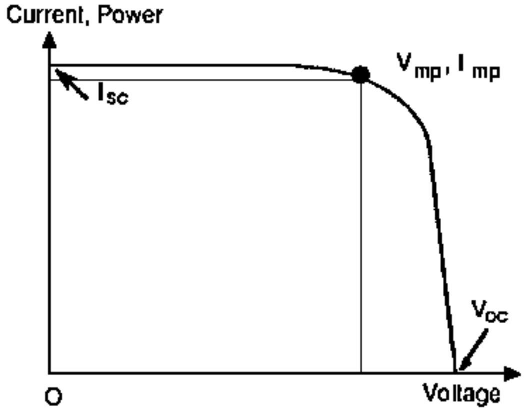

Fig. 5 Current – Voltage (I-V) curve.

The nominal energy efficiency of solar cells and PV module can be defined by:

$$\eta_{ref} = \frac{P_{max}}{A_{PV}\, G} = \frac{FF\, I_{SC}\, V_{OC}}{A_{PV}\, G} \tag{17}$$

Where G is the incident solar radiation (W/m^2)

A_{PV} is the area of the PV module (m^2)

The efficiency is always specified under the Standard Test Conditions (STC) 25°C, 1000 W/m^2. The electrical efficiency 'η_{el}' at particular irradiance or temperature is the result of the nominal efficiency (η_{ref}) minus the change in efficiency:

$$\eta_{el} = \eta_{ref} - \Delta\eta \tag{18}$$

Accordingly, the cell electrical conversion efficiency can be defined by:

$$\eta_{el} = \eta_{ref} \left[1 - \beta_c \left(T_C - T_{ref}\right)\right] \tag{19}$$

Where T_{ref} is the reference temperature at STC 25°C

T_c is the cell temperature (K)

β_c is the cells temperature coefficient

The cell temperature can be defined by:

$$T_C = T_{amb} + \left(\frac{NOCT - 20°C}{800\, W/m^2}\right) G \tag{20}$$

Where T_{amb} is the temperature at the ambient environment (K)

$NOCT$ is the Nominal Operating Cell Temperature reached by open circuit cells in a module under standard operating conditions (K).

The useful heat gain induced to the system by the air flow is defined by:

$$\dot{Q}_U = \dot{m}\, C_p \left(T_{f,o} - T_{f,i}\right) = \eta_{th}\, G\, A_{PV} \tag{21}$$

Thus, the thermal PV efficiency can be defined by:

$$\eta_{th} = \frac{\dot{m}\, C_p \left(T_{f,o} - T_{f,i}\right)}{G\, A_{PV}} \tag{22}$$

Where $\dot{m}$ is the fluid mass flow rate (kg/s)

$T_{f,o}$ is the temperature of the fluid at the outlet (K)

$T_{f,i}$ is the temperature of the fluid at the inlet (K)

C_p is the specific heat of the fluid (kJ/kg K)

The total efficiency can be defined by:

$$\eta_{total} = \eta_{th} + \eta_{el} \tag{23}$$

The air mass flow rate for the BIPV system can be defined by (24) given by Tonui and Tripanagnostopoulos [19] for PV/T collector.

$$\dot{m} = \left(\frac{2\, g\, \beta\, (A_{ch}\, \rho)^2\, A_{ch}\, \eta_{th}\, G\, L\, \sin\theta}{C_p\, \left(f \frac{L}{D_H} + 2\, \beta\, T_{f,o}\right)}\right)^{\frac{1}{3}} \tag{24}$$

Where g is the acceleration due to gravity (m/s^2)

β is the thermal expansion of air

A_{ch} is the cross section area of the channel (m^2)

ρ is the fluid density (kg/m^3)

η_{th} is the thermal efficiency of the PV

L is the length of the panel (m)

θ is the inclination angle of the system

f is the friction factor

D_H is the hydraulic diameter of the channel (m)

The friction factor *(f)* and the hydraulic diameter *(D_H)* are given by (25) and (26) respectively.

$$f = 1.906 \left(\frac{Gr}{Pr}\right)^{\frac{1}{12}} \quad (25)$$

Where Gr is the Grashof number

Pr is the Prandtl number

$$D_H = 4 \frac{A_{ch}}{p} \quad (26)$$

Where p is the perimeter of the channel (m)

3.2. Exergy Analysis

The quantity of energy is not valuable when is considered alone. The exergy is the quality of available energy which is equal to the gain work at the state point. After the system and surroundings reach equilibrium, the exergy is zero.

The amount of energy flowing in and out of a system is the same under thermally steady-state conditions according to the law of energy conservation; whereas, the amount of exergy flowing out is smaller than flowing in, since exergy is consumed within the system to produce entropy.

The exergy analysis is based on the second law of thermodynamics which includes an account of the total exergy inflow, exergy outflow and exergy destructed from the system. The general exergy balance of a BIPV/T system can be written as:

$$\sum \dot{E}x_i - \sum \dot{E}x_o = \sum \dot{E}x_{sys} \quad (27)$$

Where $\sum \dot{E}x_i$ is the rate of overall exergy inlet, given by (28)

$\sum \dot{E}x_o$ is the rate of overall exergy outlet, given by (35)

$\sum \dot{E}x_{sys}$ is the exergy loss rate of the system

$$\dot{E}x_i = \dot{E}x_{i,th} + \dot{E}x_{i,el} \quad (28)$$

Where $\dot{E}x_{i,th}$ is the rate of thermal exergy inlet of PV module, given by (29)

$\dot{E}x_{i,el}$ is the rate of electrical exergy inlet of PV module, given by (34) as defined by [10]

The flow rate of the exergy transferred from the sun to the fluid that is heated while crossing the duct may be defined by:

$$\dot{E}x_{i,th} = \dot{m}\, e_f = \dot{m} \left[\left(h_{f,i} - h_{amb}\right) - T_{amb}\left(s_{f,i} - s_{amb}\right)\right] \quad (29)$$

Where the variation of specific enthalpy is given by:

$$h_{f,i} - h_{amb} = C_p\left(T_{av,i} - T_{amb}\right) \quad (30)$$

And the variation of specific entropy from:

$$s_{f,i} - s_{amb} = C_p \ln\left(\frac{T_{av,i}}{T_{amb}}\right) \quad (31)$$

Thus, (29) becomes:

$$\dot{Ex}_{i,th} = \dot{m}\, C_p \left[\left(T_{av,i} - T_{amb}\right) - T_{amb}\ \ln\left(\frac{T_{av,i}}{T_{amb}}\right) \right] \tag{32}$$

Where $T_{av,i} = \frac{T_{f,i}+T_{amb}}{2}$ (33)

$$\dot{Ex}_{i,el} = A_{PV}\, G \left[1 - \frac{4}{3}\frac{T_{amb}}{T_{sun}} + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 \right] \tag{34}$$

Where T_{sun} is the temperature of the sun taken as 5777K

$$\dot{Ex}_{out} = \dot{Ex}_{o,th} + \dot{Ex}_{o,el} \tag{35}$$

Where $\dot{Ex}_{o,th}$ is the rate of thermal exergy outlet of PV module, given by (36)

$\dot{Ex}_{o,el}$ is the rate of electrical exergy outlet of PV module, given by (37)

With the same way as shown in (30) and (31), $\dot{Ex}_{out,th}$ may be defined by:

$$\dot{Ex}_{o,th} = \dot{m}\, C_p \left[\left(T_{f,o} - T_{amb}\right) - T_{amb}\ \ln\left(\frac{T_{f,o}}{T_{amb}}\right) \right] \tag{36}$$

$$\dot{Ex}_{o,el} = \eta_{el}\, A_{PV}\, G \left[1 - \frac{4}{3}\frac{T_{amb}}{T_{sun}} + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 \right] \tag{37}$$

Where η_{el} is defined earlier by (19).

Accordingly, (27) can be written:

$$\dot{Ex}_{sys} = \left(\dot{Ex}_{i,th} + \dot{Ex}_{i,el}\right) - \left(\dot{Ex}_{o,th} + \dot{Ex}_{o,el}\right) \tag{38}$$

The exergy efficiency of the system can be defined by:

$$\varepsilon = 1 - \frac{\dot{Ex}_{sys}}{\dot{Ex}_{i}} \tag{39}$$

All the equations for energy and exergy efficiency calculations were solved using Matlab software. The results obtained are discussed in the following section.

4. Results Discussion

The experimental results showed that the air movement in the air duct between the integrated PV panel and the second skin, plays an important role in the thermal behavior of the building. The recording of the temperature in various points on the system gives the temperature gradient of the system under the tested conditions.

As expected, the higher the incident radiation on the PV, the higher is the temperature of the PV surface and thus the temperature of the system. From the three inclination angles tested of 30°, 45° and 90° it is shown that the 90° provides more ventilation in the air gap and as a result, the temperature of the PV panel was lower than the other two angles tested. The highest temperatures are observed in the inclination angle of 30° because the air particles could not move directly upwards to exit the duct and recirculate the air, so the heated air remains in the duct for longer time and caused the higher PV temperature. The temperature distribution of the system in the three angles are shown in Fig. 6.

Regarding the two air gap widths tested, a comparison is shown in the graph of Fig. 7. As shown in the graph, the system has lower temperature at the air gap of 0.15 m. This happens because of the bigger amount of air that enters the duct of 0.15 m than in the air duct of 0.10 m. Thus, the more the air in the duct is, the lower is the temperature of the PV and the other system's parts.

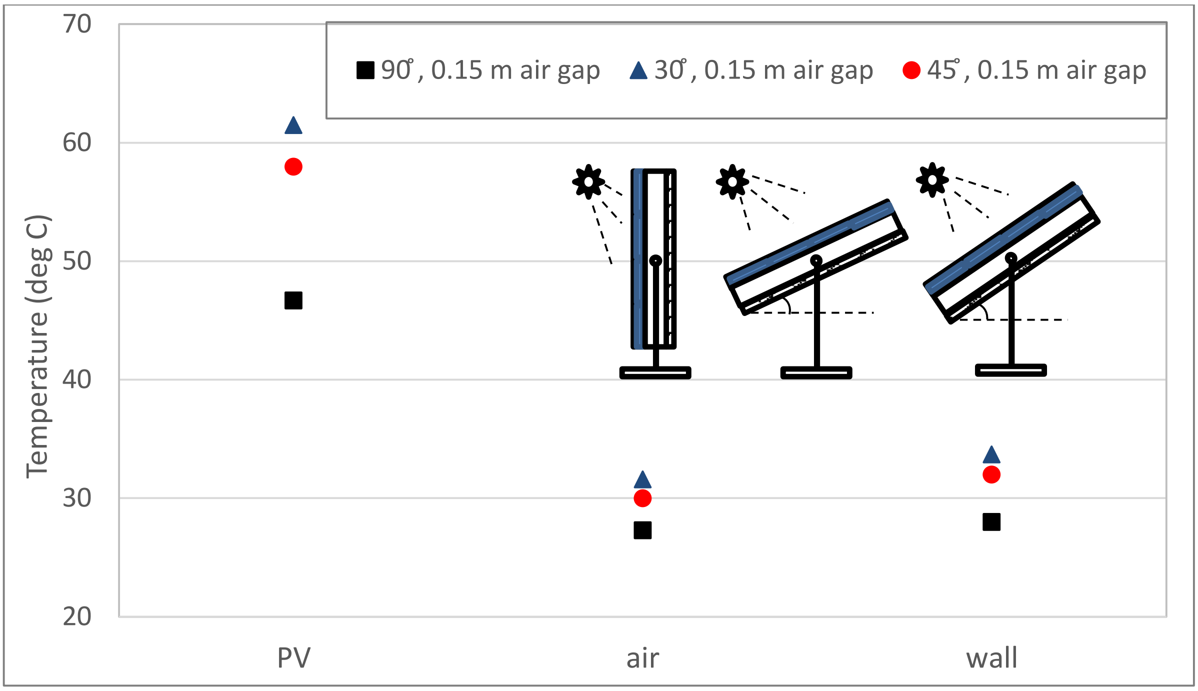

Fig. 6 The temperature distribution of the PV, air and second skin (called wall) for three inclination angles 90°, 4°5 and 30°.

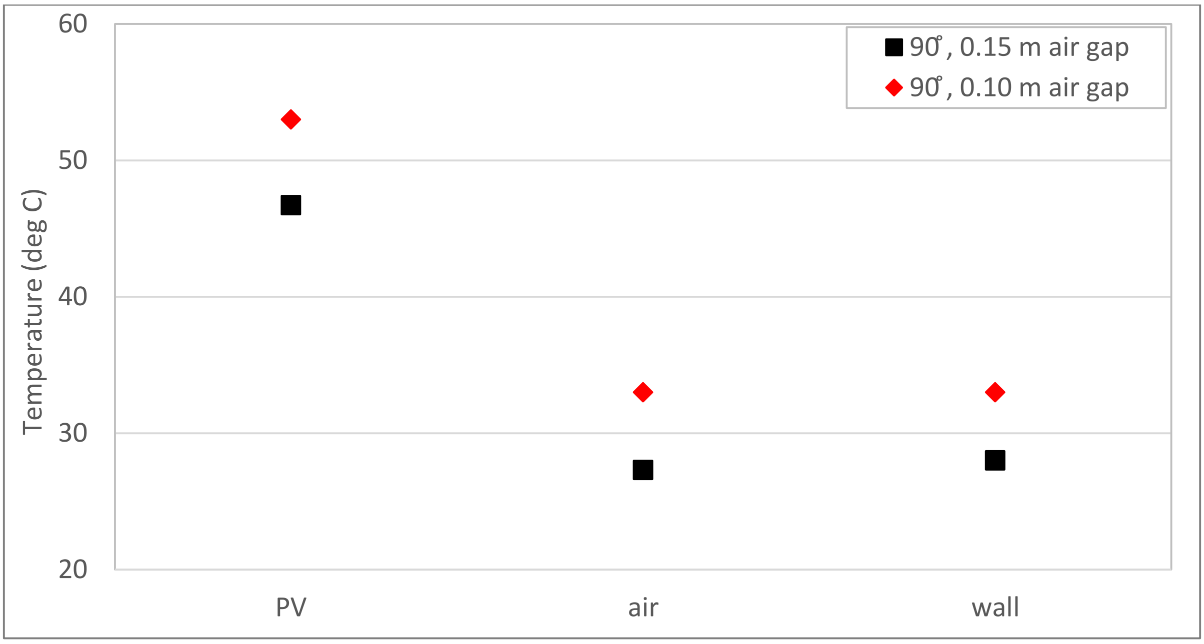

Fig. 7 The temperature distribution of the PV, air and second skin (called wall) for air gap widths 0.10 and 0.15 m.

The energy and exergy analysis is made based on some assumptions in order to simplify the analysis:

- The mass flow rate of the air across the duct is considered to be constant
- The air velocity across the duct is considered to be constant
- The temperature of the PV is considered to be the same in all its area

For all the cases tested, the energy efficiency of the system is estimated to be up to 35% while the exergy efficiency estimated between 11-13.5%. The role of the temperature of the PV module plays an important role in both energy and exergy efficiency of the system. Fig. 8 shows the exergy efficiency for the measured PV temperature. As can be observed, the higher is the PV temperature, the lower is the exergy efficiency. The trend of the graph shown in Fig. 8 is the same for all the parameters tested. This means that, since there is an increase in the PV temperature, there is a decrease in the exergy efficiency.

As mentioned earlier for Fig. 7, the air gap affects the temperature distribution of the system. Fig. 9 shows the values of exergy efficiency estimated for the air gap of 0.10 and 0.15 m for the measured PV temperature. As can be observed, the air gap of 0.15 m, due to the lower temperature of the system, has higher exergy efficiency than the system with air gap 0.10 m. For the air gap width of 0.15 m the exergy efficiency varies from 13.1-11.7% but for the system with 0.10 m air gap the exergy efficiency varies from 12.8-11.5%.

Fig. 10 shows the exergy efficiency of the system estimated for the three inclination angles tested, also in relation with the PV temperature measured from the experimental procedure. As can be observed, the higher the inclination angle, the lower is the PV temperature and thus the higher is the exergy efficiency.

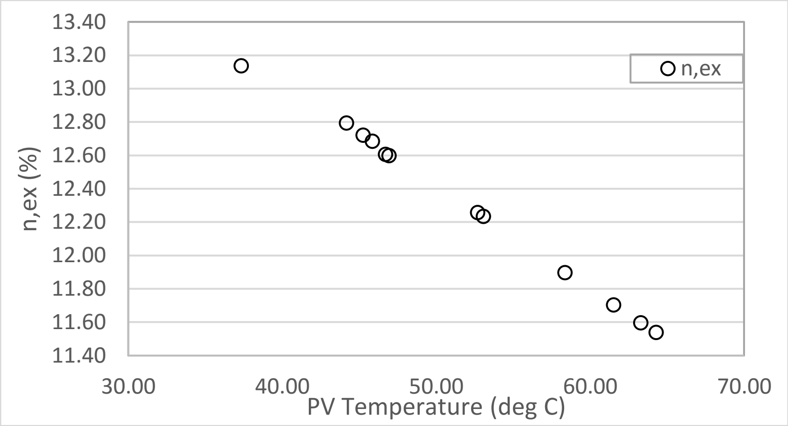

Fig. 8 The exergy efficiency estimated, plotted regarding the measured PV temperature.

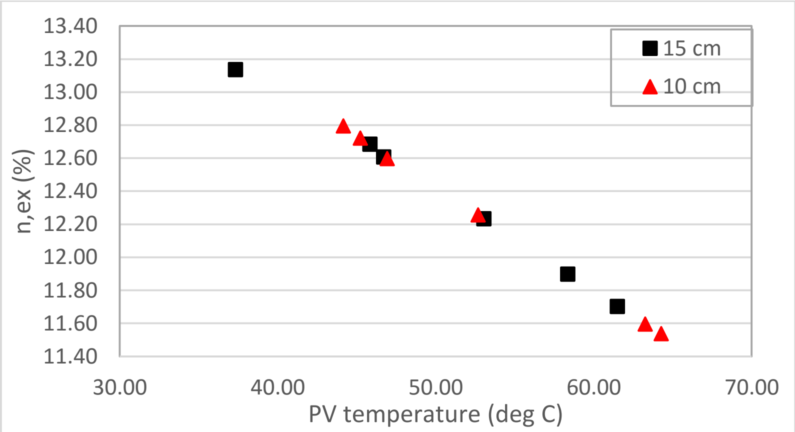

Fig. 9 The exergy efficiency of the BIPV system regarding the measured PV efficiency for the two air gap widths tested.

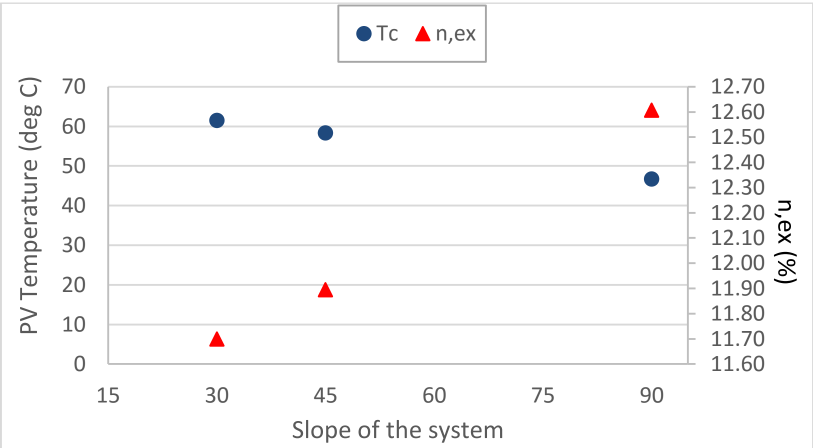

Fig. 10 The estimated exergy efficiency for the tested inclination angles, and the measured PV temperature.

5. Conclusions

This study presents the energy and exergy analysis of a naturally ventilated BIPV system. The literature review presents various studies on the exergy analysis of PV/T systems and the various correlations obtained for the estimation of the exergy efficiency of the PV/T systems.

This manuscript presents an experimental procedure carried out for a BIPV system in a laboratory with a solar simulator in order to record the temperature distribution of the system under various conditions of different air gap widths, different inclination angles and different incident solar radiation. Then, based on the energy balance of the system, energy and exergy analysis are carried out and the correlations for the energy and exergy efficiencies are presented.

The most important outcomes of this study are:

- The higher the inclination angle of the system (from the horizontal), the more it is ventilated, the lower its temperature and thus the higher is its efficiency. The system in vertical position showed that performs better than the systems inclined at 30° and 45°.
- The air gap with 0.15 m width allows more air to pass through the duct than the width of 0.10 m. Thus the system is cooled more effectively and its energy and exergy efficiency is higher.
- The energy efficiency of the system is estimated to be up to 35% for all the cases tested.
- The exergy efficiency estimated between 11-13.5% for all the cases tested. Both energy and exergy efficiencies estimated in this study are in the range estimated from Joshi et al. [4].

Nomenclature

A_C	Area of the collector (m^2)	L	Length of the PV (m)
A_{PV}	Area of the PV (m^2)	$\dot{m}$	Fluid mass flow rate (kg/s)
A_{ch}	Cross section area of the channel (m^2)	$NOCT$	Nominal Operating Cell Temperature (°C)
C_p	Specific heat of the fluid (J/kg K)	P	Power output (W)
D_H	Hydraulic diameter of the duct (m)	Pr	Prandlt number
$\dot{Ex}$ or $\dot{X}$	Exergy rate (W)	p	Perimeter (m)
$\dot{E}$	Energy rate (W)	$\dot{Q}_u$	Rate of useful energy transfer (W)
f	Friction factor	s_f	Specific Entropy (J/kg K)
FF	Fill factor	T_{amb}	Ambient temperature (°C)
Gr	Grashof number	T_2	Final fluid temperature (°C)
G	Solar radiation (W/m^2)	T_{sun}	Temperature of the sun (K)
g	Acceleration of the gravity (m/s^2)	$T_{f,o}$	Outlet fluid temperature (°C)
h_f	Specific enthalpy of the fluid (J/kg)	$T_{f,i}$	Inlet fluid temperature (°C)
h_c	Convective heat transfer coefficient (W/m^2 K)	T_c	Cell temperature (°C)
I_{SC}	Short circuit current (A)	V_{mp}	Voltage at maximum power point (V)
I_{mp}	Current at maximum power point (A)	V_{OC}	Open circuit voltage (V)

Greek symbols:

β	packing factor of solar cells	η	Energy efficiency
β_c	cells temperature coefficient	θ	inclination angle of the system (°)
ε	Exergy efficiency	ρ	Fluid density (kg/m^3)

Subscripts and superscripts:

av	average	*i*	inlet or inside	*ref*	reference conditions
en	energy	*max*	maximum	*sys*	system
ex	exergy	*o*	outlet or outside	*tot*	total
el	electrical	*pv*	photovoltaic	*t, th*	thermal
f	fluid	*pvt*	Photovoltaic thermal		

Acknowledgements

The research presented in this paper was carried out under the research program Building-integrated fibre-reinforced solar technology (BFirst), funded by the EU Seventh Framework Programme FP7/2007-2013, under grant agreement n° 296016.

References

- **Journals**

[1] I. Dincer and M. A. Rosen, *Exergy, Energy, Environment and Sustainable Development*. Elsevier, 2007.

[2] R. Saidur, G. BoroumandJazi, S. Mekhlif, and M. Jameel, “Exergy analysis of solar energy applications,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 350–356, Jan. 2012.

[3] A. Duran Sahin, I. Dincer, and M. A. Rosen, “Thermodynamic analysis of solar photovoltaic cell systems,” *Sol. Energy Mater. Sol. Cells*, vol. 91, no. 2–3, pp. 153–159, Jan. 2007.

[4] A. S. Joshi, I. Dincer, and B. V. Reddy, “Thermodynamic assessment of photovoltaic systems,” *Sol. Energy*, vol. 83, no. 8, pp. 1139–1149, Aug. 2009.

[5] E. Saloux, A. Teyssedou, and M. Sorin, “Analysis of photovoltaic (PV) and photovoltaic/thermal (PV/T) systems using the exergy method,” *Energy Build.*, vol. 67, pp. 275–285, Dec. 2013.

[6] S. Nayak and G. N. Tiwari, “Energy and exergy analysis of photovoltaic/thermal integrated with a solar greenhouse,” *Energy Build.*, vol. 40, no. 11, pp. 2015–2021, Jan. 2008.

[7] T. Fujisawa and T. Tani, “Annual exergy evaluation on photovoltaic-thermal hybrid collector,” *Sol. Energy Mater. Sol. Cells*, vol. 47, no. 1–4, pp. 135–148, Oct. 1997.

[8] T. T. Chow, G. Pei, K. F. Fong, Z. Lin, A. L. S. Chan, and J. Ji, “Energy and exergy analysis of photovoltaic–thermal collector with and without glass cover,” *Appl. Energy*, vol. 86, no. 3, pp. 310–316, Mar. 2009.

[9] A. Hepbasli, “A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future,” *Renew. Sustain. Energy Rev.*, vol. 12, no. 3, pp. 593–661, Apr. 2008.

[10] R. Petela, “Exergy of Heat Radiation,” *J. Heat Transfer*, vol. 86, no. 2, pp. 187–192, 1964.

[11] D. . Spanner, *Introduction to Thermodynamics*. London New York: Academic Press, 1964.

[12] S. M. Jeter, “Maximum conversion efficiency for the utilization of direct solar radiation,” *Sol. Energy*, vol. 26, no. 3, pp. 231–236, 1981.

[13] a. Shahsavar, M. Ameri, and M. Gholampour, “Energy and Exergy Analysis of a Photovoltaic-Thermal Collector With Natural Air Flow,” *J. Sol. Energy Eng.*, vol. 134, no. 1, p. 011014, 2012.

[14] S. Dubey, S. C. Solanki, and A. Tiwari, “Energy and exergy analysis of PV/T air collectors connected in series,” *Energy Build.*, vol. 41, no. 8, pp. 863–870, Aug. 2009.

[15] A. S. Joshi and A. Tiwari, “Energy and exergy efficiencies of a hybrid photovoltaic–thermal (PV/T) air collector,” *Renew. Energy*, vol. 32, no. 13, pp. 2223–2241, Oct. 2007.

[16] M. Bosanac, B. Sørensen, I. Katic, H. Sørensen, B. Nielsen, and J. Badran, *Final Report EFP project 1713 / 00-0014 Photovoltaic / Thermal Solar Collectors and Their Potential in Denmark*, no. May. 2003.

[17] S. R. Park, A. K. Pandey, V. V. Tyagi, and S. K. Tyagi, “Energy and exergy analysis of typical renewable energy systems,” *Renew. Sustain. Energy Rev.*, vol. 30, pp. 105–123, Feb. 2014.

[18] F. Sarhaddi, S. Farahat, H. Ajam, and A. Behzadmehr, “Exergetic performance assessment of a solar photovoltaic thermal (PV/T) air collector,” *Energy Build.*, vol. 42, no. 11, pp. 2184–2199, Nov. 2010.

[19] J. K. Tonui and Y. Tripanagnostopoulos, “Performance improvement of PV/T solar collectors with natural air flow operation,” *Sol. Energy*, vol. 82, no. 1, pp. 1–12, 2008.