18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0595
EXPERIMENTAL ANALYSIS OF 1ST AND 2ND LAWS OF THERMODYNAMICS APPLIED TO A PHOTOVOLTAIC SYSTEM IN THE CITY OF SÃO LUÍS - MA

Carlos Vital Pinto Costa Junior
Instituto Federal de Educação, Ciência e Tecnologia do Maranhão
e-mail: vital-j@hotmail.com

Lourival Matos de Sousa Filho
e-mail: lourivalsousa.cct@gmail.com
João Victor Silva Carvalho
e-mail: jvictorscarvalho97@hotmail.com
Universidade Estadual do Maranhão
Manuelle da Silva Serejo
Instituto Federal de Educação, Ciência e Tecnologia do Maranhão
e-mail: manuelle_serejo@hotmail.com

Abstract. *The increasing climate change awareness and the impacts of human activities on the environment placed solar photovoltaic energy in prominence. Solar energy is considered a clean energy source with low impacts on the environment. Nevertheless, the process of converting sunlight into electricity presents energy losses which have a negative influence on the efficiency of photovoltaic systems. Therefore, this experimental study investigated the energy and exergy performance of an off-grid photovoltaic system located at the State University of Maranhão in São Luís - MA. The results showed the operation temperature of the photovoltaic module reached higher values in the midday hours; the same pattern was obtained in all the days of experiments. The energy and exergy efficiency achieved higher values in the first hours in the morning and decreased reaching the lowest values at 13h00. The decrease in energy and exergy efficiencies in the midday hours is a result of thermal irreversibilities growth related to high operating temperatures.*

Keywords: *Energy efficiency, exergy efficiency, photovoltaic system, solar energy*

1. INTRODUCTION

Energy is essential for sustain human life and the most energy source consumed is the fossil fuels. However, the energy of fossil sources is responsible for the majority of pollution, and researches indicate the fossil fuels are the main reason for the greenhouse effect. The increasing in global energy demand in the last five decades rose significantly, and studies show this demand will increasing more in the next 50 years. Hence, the search for new energy sources to cope with this demand, received more attention motivated by an increased environment awareness, (GOSWAMI, 2015; SIMIONI, 2017).

Many other alternative energy sources can be applied to attend to human demand instead of fossil fuels. To choose which one should be utilized in each case is imperative to be aware of economic and environmental issues. Thus, it is widely believed that solar energy is sustainable energy source and does not harm the environment (KALOGIROU, 2014). The use of solar energy occurs in two ways: indirect and direct. The direct use of solar energy consists of the direct transformation of solar energy into final energy, such as solar photovoltaic or solar thermal systems. Indirect form occurs through the use of sunlight by another primary source of energy, for example, plant biomass and wind (MIT, 2015).

The photovoltaic (PV) systems transforms solar energy into electric energy directly with efficiency about 20% in controlled environments (GOSWAMI, 2015). However, during the conversion process exists losses of energy. These losses are thermal, optical and electrical types (SARHADDI et al., 2009). A thermodynamics analysis of a photovoltaic systems provides a better understanding about these losses and irreversibilities (FUDHOLI et al., 2018; JOSHI; DINCER; REDDY, 2009; PANDEY et al., 2015).

The energetic analysis, in accordance with the first law of thermodynamic, is based on the law of energy conservation, which states that in a thermodynamic process the energy cannot be created or destroyed, the energy is just transformed into another energy. Thus, the first law understands the energy in a quantitative way (ÇENGEL; BOLES, 2013). The exergetic analysis is based on the second law of thermodynamics, which states that energy has a quality and in thermodynamics processes occur energy losses. Thus, exergy is defined as the maximum work available provided by a source. Applying the concept of exergy in photovoltaic systems enables the identification of energy losses that happens during the conversion process (CALISE; FIGAJ; VANOLI, 2018; FUDHOLI et al., 2018; PANDEY et al., 2015).

The efficiency of photovoltaic systems can be calculated as the ratio between the electric energy generated to the amount of solar irradiation that reaches the PV module surface. Although, parameters such as ambient temperature, operating temperature, the position of the module should be taken into account (JOSHI; DINCER; REDDY, 2009). In practical situations, the operating temperature of the module is an important parameter and has a strong influence on the efficiency of the system. The increase of photovoltaic panel operation temperature reduces the efficiency of the system resulting in lower power output. The average reduction of efficiency is about 0,45% for each degree over 25°C (AMR et al., 2019; POPOVICI et al., 2016).

Photovoltaic systems can generate electric and thermal energy (FUDHOLI et al., 2018; JOSHI; DINCER; REDDY, 2009; RAWAT, 2017; SARHADDI et al., 2009). However, in only photovoltaic systems, thermal energy is lost to the environment. This loss of energy can be identified by the exergy analysis, and the exergy efficiency takes into account the process irreversibilities (FUDHOLI et al., 2018; PANDEY et al., 2015).

The present experimental study investigated the energy and exergy performance of an off-grid photovoltaic system situated in the Campus of State University of Maranhão, in the city of São Luís.

2. METHODOLOGY

2.1 Experimental Setup

The photovoltaic system studied is located in CCT – UEMA, at the city of São Luís – MA (2.5835021 S, 44.209868 W), placed in a clean area without shading, which can affect the data collection. The system consists of a 140W photovoltaic module from Yingli, model YL140P-17B, with electrical and construction characteristics showed in Tab. 1 and Tab. 2, respectively. A PWM charge controller, a 12V battery, a frequency inverter of 1500W.

Table 1. Electrical characteristics of YL140P-17B. Available from: (YINGLI GREEN ENERGY, [s.d.])

Power output ($\boldsymbol{P_{max}}$)	140 W
Module efficiency ($\boldsymbol{\eta}$)	14,0 %
Voltage at $\boldsymbol{P_{max}}$ ($\boldsymbol{V_{máx}}$)	18,01 V
Current at $\boldsymbol{P_{max}}$ ($\boldsymbol{I_{máx}}$)	7,77 A
Open-circuit voltage ($\boldsymbol{V_{oc}}$)	22,28 V
Short-circuit current ($\boldsymbol{I_{sc}}$)	8,30 A

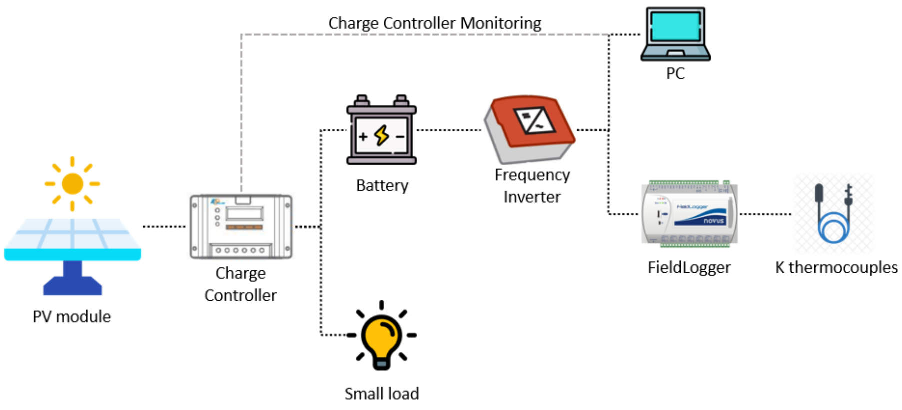
Table 2. Construction characteristics of YL140P-17B. Available from: (YINGLI GREEN ENERGY, [s.d.])

Dimensions	1470 mm x 680 mm x 25 mm
Weight	10,81 kg
Cell (quantity / material)	36 / multicrystalline silicon
Cell dimensions	156 mm x 156 mm
Operating temperature range	-40 to 85°C

2.2 Measurements

To perform the energetic and exergetic analysis, according to the first and second laws of thermodynamics, parameters such as input and output power, ambient temperature, operating temperature, wind velocity, and average irradiance at the local should be acquired. Therefore, the analysis used parameters collected by the system composed of the fieldlogger and type K thermocouples to collect the operating temperature of the module, a computer to save the data from the charge controller and fieldlogger demonstrated by Fig. 1. The average solar irradiance, wind velocity, and ambient temperature were acquired from the INMET (Meteorological National Institute) and Global Solar Atlas databases for the city of São Luís-MA. The data were registered during November and December of 2019 from 07h30 to 17h30.

Figure 1. Photovoltaic system diagram.
Author (2020)



The data collected were analyzed and utilized to calculate the energy and exergy efficiency of the system during the days of experiments throughout the energy and exergy analysis described in 2.3 and 2.4.

2.3 Energy analysis

The energy analysis calculates the efficiency according to the first law of thermodynamics, which understands energy as a quantity and takes into account only the input and output of energy, in other words, the energy analysis does not concern about the energy loss (ÇENGEL; BOLES, 2013; FUDHOLI et al., 2018; PANDEY et al., 2015).

The input of energy is the energy received by the photovoltaic module, calculated by Eq. (1) (FUDHOLI et al., 2018; PANDEY et al., 2015; RAWAT, 2017):

$$\dot{E}_{in} = I_{solar} \times A_m \tag{1}$$

where I_{solar} is the solar irradiance in *W/m²* and A_m is the absorption area of the PV module in *m²*. Eq. (1) represents the available solar energy that can be transformed into electric energy.

The output energy is the energy produced by the photovoltaic module, given by Eq. (2) (FUDHOLI et al., 2018; PANDEY et al., 2015; RAWAT, 2017):

$$\dot{W}_{elétrica} = V_{pro} \times I_{pro} \tag{2}$$

where $\dot{W}_{elétrica}$ is the electrical power in *W*, V_{pro} is the voltage produced in *V*, and I_{pro} is the current produced in *A*.

The energy efficiency is calculated by the Eq. (3) (FUDHOLI et al., 2018; PANDEY et al., 2015; RAWAT, 2017):

$$\eta = \frac{\dot{W}_{elétrica}}{\dot{E}_{solar}} \tag{3}$$

where η is the energy efficiency.

2.4 Exergy analysis

The exergy analysis takes into account not only the input and output of energy, but also the process irreversibilities, which causes the destruction of exergy. The system studied is only photovoltaic, thus, the thermal energy generated by the irradiation of solar energy and the photoelectric conversion is lost to the environment (FUDHOLI et al., 2018; JOSHI; DINCER; REDDY, 2009; PANDEY et al., 2015; RAWAT, 2017).

The input of exergy is the solar exergy available to be transformed by the photovoltaic module calculated by Eq. (4) (FUDHOLI et al., 2018; PANDEY et al., 2015; PETELA, 1964):

$$\dot{X}_{solar} = I_{solar} \times A_m \left[1 + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4 - \frac{4}{3}\frac{T_a}{T_{sun}}\right] \quad (4)$$

where $\dot{X}_{solar}$ is the solar exergy in *W*, T_a is the ambient temperature in *K*, and T_{sun} is the sun temperature, which is 5777K.

The output exergy comprehends the electrical exergy ($\dot{X}_{elec}$) and thermal exergy ($\dot{X}_{th}$) and they can be calculated by the Eq. (5) and Eq. (6) (FUDHOLI et al., 2018; PANDEY et al., 2015; RAWAT, 2017):

$$\dot{X}_{elec} = V_{pro} \times I_{pro} \quad (5)$$

$$\dot{X}_{th} = \left(1 - \frac{T_a}{T_{panel}}\right) Q_{convec} \quad (6)$$

where T_{panel} is the operating temperature in *K*, and Q_{convec} is the convective heat transfer between the module and environment in *W*, calculated by Eq. (7) (FUDHOLI et al., 2018; PANDEY et al., 2015; RAWAT, 2017):

$$Q_{convec} = hA_m\left(T_{panel} - T_a\right) \quad (7)$$

where h is the convective coefficient in *W/m²K*, given by Eq. (8) (PANDEY et al., 2015):

$$h = 5{,}7 + 3{,}8v_w \quad (8)$$

where v_w is the wind velocity in *m/s*.

The exergy efficiency (Ψ) is calculated by the ratio of output exergy and input exergy. However, the output exergy, which includes the electrical and thermal exergies, is given by the subtraction of the electrical exergy by thermal exergy since the thermal exergy is lost to the environment. Therefore, the exergy efficiency can be expressed by Eq. (9) (JOSHI; DINCER; REDDY, 2009; PANDEY et al., 2015; RAWAT, 2017):

$$\Psi = \frac{\dot{X}_{elec} - \dot{X}_{th}}{\dot{X}_{solar}} \quad (9)$$

3. RESULTS AND DISCUSSION

The temperature is an important parameter which affects the efficiency of the system. When the panel temperature reaches higher than 25°C in the STC (Standard Test Condition) the conversion efficiency decreases, hence, the output energy and total efficiency also decrease. Furthermore, the energy and exergy efficiency decrease because a considerable part of solar energy is converted in heat, which is not a sort of energy utilized in only photovoltaic systems (PANDEY et al., 2015; POPOVICI et al., 2016; RAWAT, 2017).

3.1 Operational panel temperature

The Figures 2 - 5 show the temperature measured during the experimental days. It is noticed that the temperature increases as time reaches the midday hours, reaching its peak around 12h00. This result is related with the intensity of solar irradiation, which achieves its peak in midday hours. The same pattern is observed by Pandey *et al.* (2015) and Rawat (2017).

On 01/11/2019, demonstrated by Figure 1, it observed that the temperature starts at lower values (approximately 41°C) in the early hours of the morning, increasing until 10:00, presenting a small decrease after that, which could be related to a cloudy time of the morning, allowing the operating temperature to reduce. Then, it reaches its peak around 12:30 (approximately 55°C), when it is widely believed that the irradiance also rises to its maximum values. Hence, it can be assumed that when the irradiance increases, the operating temperature will also reach higher values, impacting the system efficiency.

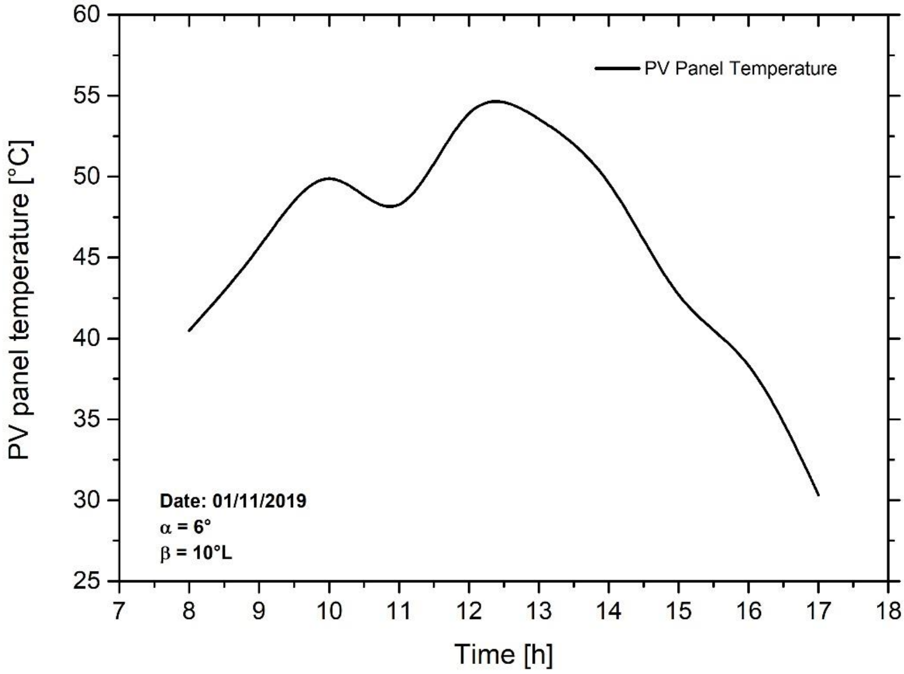


Figure 2. Temperature versus time in 01/11/2019.
Autor (2020)

Figure 3 shows the operating panel temperature on 12/11/2019. In the early hours, the temperature is lower than the midday hours, the same pattern observed in Figure 2. However, it is noticed that the temperature stayed almost constant until 10:00, and then rose until 11:30, reaching its peaks. This behavior could be explained because of the presence of clouds. The temperature peak is not at 12:30, as in Figure 2, which can also be explained by a decrease in operating temperature related to the unpredicted behavior of clouds on that day.

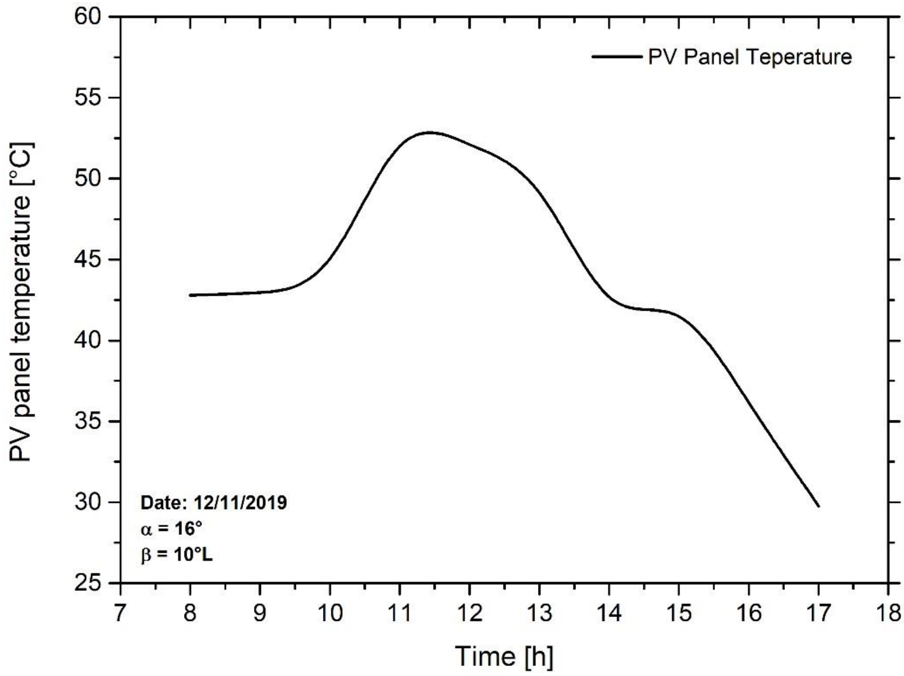


Figure 3. Temperature versus time in 12/11/2019.
Autor (2020)

Figures 4 and 5 show the operating panel temperature on 06/12/2019 and 10/12/2019, respectively. The peak of operating temperature was at 12:30 on 06/12/2019 and 13:00 on 10/12/2019. Both curves presented higher temperatures during midday hours, as observed by Pandey et al. (2015) and Rawat (2017). In the city of São Luís, the maximum irradiance is close to noon all year, leading to high temperatures around this time of day.

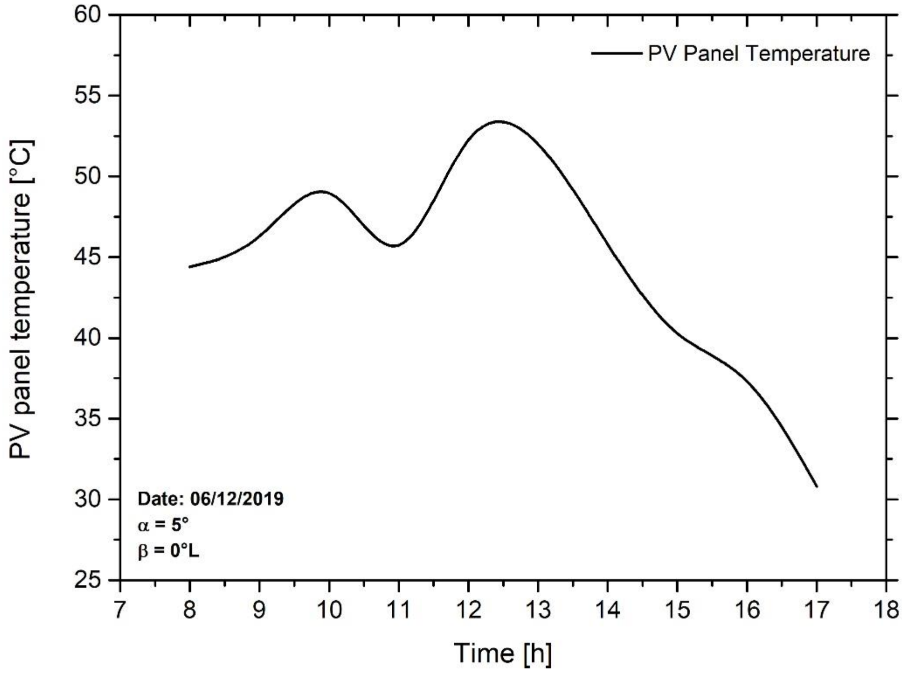


Figure 4. Temperature versus time in 06/12/2019.
Autor (2020)

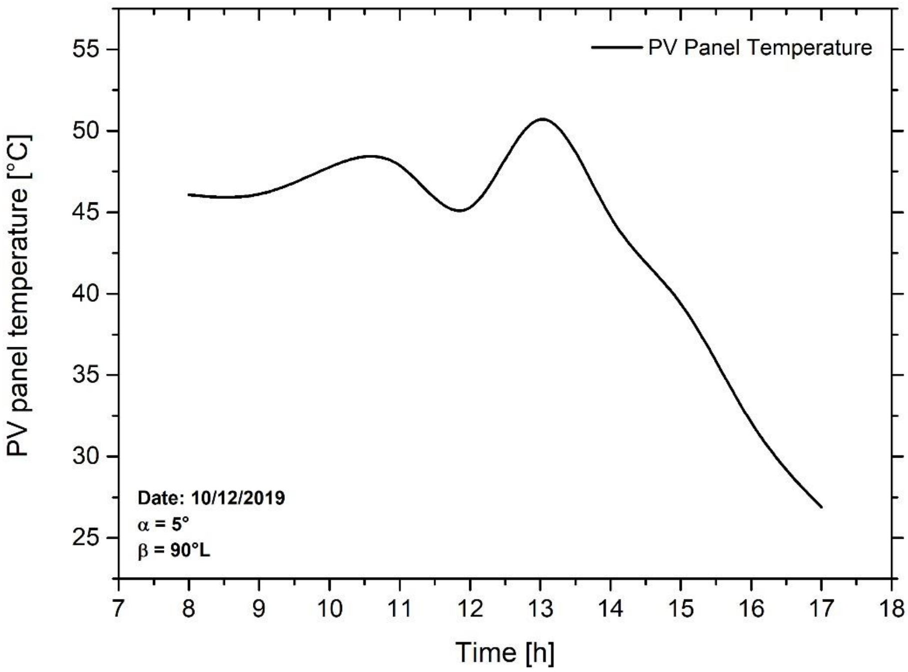


Figure 5. Temperature versus time in 10/12/2019.
Autor (2020)

3.2 Energy and Exergy efficiencies

The system efficiency is inversely proportional to the increase of panel temperature (FUDHOLI et al., 2018; PANDEY et al., 2015; RAWAT, 2017). Hence, as the Figures 6 – 9 shows the energy efficiency and exergy efficiency reaches its lowest values when the temperature of the panel is higher.

Figures 6 and 7 present the energy and exergy efficiency results for days of November 2019. It is noticed that energy efficiency is always higher than exergy efficiency because the exergy analysis takes into account the exergy destruction related to thermal exergy loss to the ambient. The thermal exergy is directly proportional to the panel temperature, and in the early hours of the morning, the operating temperature is lower, leading to reduced thermal exergy destruction, and consequently, to higher energy and exergy efficiency.

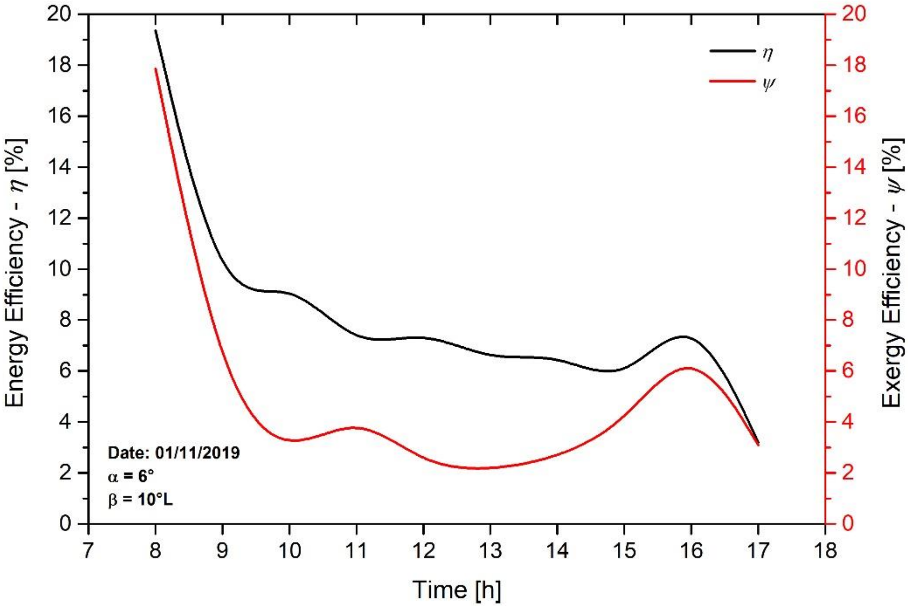


Figure 6. Energy and exergy efficiencies versus time in 01/11/2019.
Autor (2020)

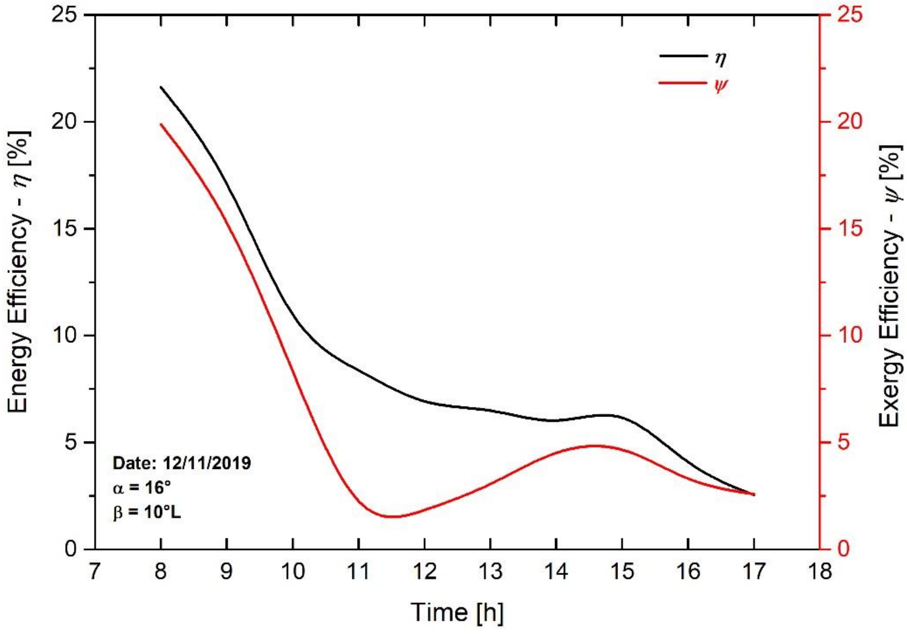


Figure 7. Energy and exergy efficiencies versus time in 12/11/2019.
Autor (2020)

Figures 8 and 9 show the results for two days in December 2019. The exergy efficiency is lower than energy efficiency during the hours of experimental study. The lowest values were reached in midday hours and at the end of the day. The efficiencies are reduced close to noon mainly because of the high operating temperature when the irradiance is its higher values. On the other hand, at the end of the experiment, the reduction of solar irradiance is the main reason the efficiencies dropped tend to zero. Therefore, from 08:30 to close to 17:00 the main parameter that reduces the efficiencies is the operating temperature and after this time the main parameter is the reduced solar irradiance incident on the photovoltaic module.

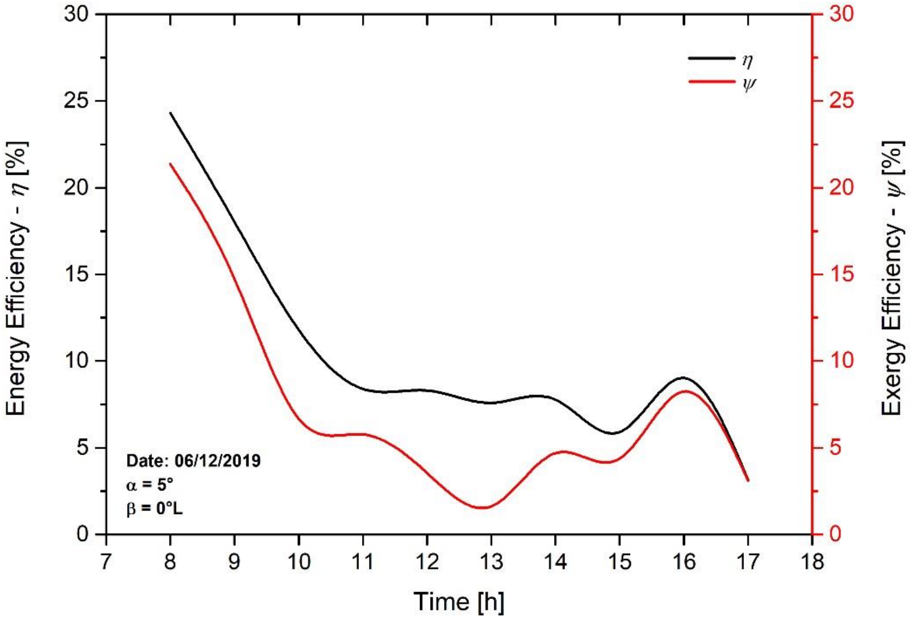


Figure 8. Energy and exergy efficiencies versus time in 06/12/2019.
Autor (2020)

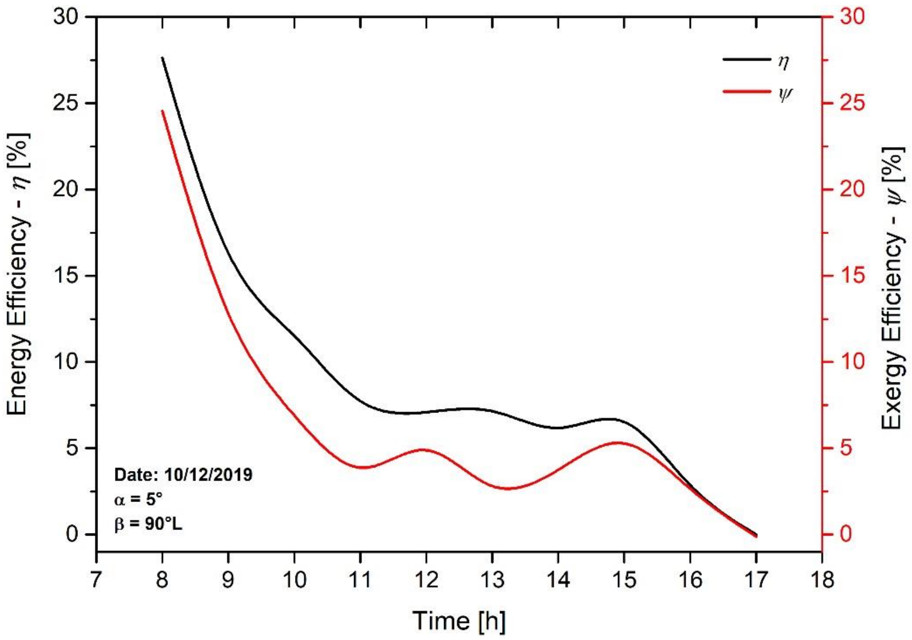


Figure 9. Energy and exergy efficiencies versus time in 10/12/2019.
Autor (2020)

It is observed from Figures 6 – 9 a small increase after 14h00 or 15h00 in the results in both efficiencies, this is related to the drop of panel operating temperature, however, it is a slight change in both efficiency because at this period of the day the intensity of solar irradiation is lower than the previous hours. Also, after this time, the energy and exergy efficiencies tend to have the same values, mainly because of the drop in temperature and solar irradiance after 17:00.

4. CONCLUSIONS

In this work, the experimental thermodynamic analysis was carried out according to the first and second laws of thermodynamics, applied on an off-grid photovoltaic system located at CCT-UEMA in São Luís-MA.

The applied methodology for energetic and exergetic analysis allows a better understanding of the system by involving a thermodynamic approach that allows the identification of the energy flow. Therefore, the analysis represents a useful tool in the evaluation of the performance and the feasibility of implementing photovoltaic systems in São Luís-MA.

The operating temperature of the PV module becomes the factor of greatest impact when the solar incidence is maximum, and there is no cloudiness. The sunlight that falls on the module at peak times also results in an increase in temperature, which negatively reflects the efficiency of the system, due to the energy lost by heat being greater compared to the morning and late afternoon periods.

The exergy efficiency presents itself as an excellent indicator of the performance of an off-grid photovoltaic system for the locality of São Luís, since it provides an understanding of the irreversibilities of the system. It is worth mentioning that when identifying such losses, it is possible to take measures and develop ways that increase the efficiency of the system.

5. REFERENCES

AMR, A. A. RAHEIM et al. Enhancement of photovoltaic system performance via passive cooling: Theory versus experiment. **Renewable Energy**, v. 140, p. 88–103, 2019.

CALISE, F.; FIGAJ, R. D.; VANOLI, L. One-dimensional exergy analysis of an unglazed low-cost PhotoVoltaic/Thermal solar collector. **International Journal of Exergy**, v. 26, n. 1–2, p. 107–130, 2018.

ÇENGEL, Y. A.; BOLES, M. A. **Termodinâmica**. 7ª ed. Porto Alegre: AMGH EDITORA LTDA, 2013.

FUDHOLI, A. et al. Energy and exergy analyses of photovoltaic thermal collector with ∇-groove. **Solar Energy**, v. 159, n. November 2016, p. 742–750, 2018.

GOSWAMI, D. Y. **Principles of Solar Engineering**. 3. ed. New York: CRC Press, 2015.

JOSHI, A. S.; DINCER, I.; REDDY, B. V. Thermodynamic assessment of photovoltaic systems. **Solar Energy**, v. 83, n. 8, p. 1139–1149, 2009.

KALOGIROU, S. A. **Solar Energy Engineering**. 2ª Edição ed. Oxford: Elsevier, 2014.

MIT, E. I. **The Future of Solar Energy**. Massachusetts: Massachusetts Institute of Technology, 2015.

PANDEY, A. K. et al. Energy and exergy performance evaluation of a typical solar photovoltaic module. **Thermal Science**, v. 19, p. S625–S636, 2015.

PETELA, R. Exergy of heat radiation. **Journal of Heat Transfer**, v. 86, n. 2, p. 187–192, 1964.

POPOVICI, C. G. et al. Efficiency Improvement of Photovoltaic Panels by Using Air Cooled Heat Sinks. **Energy Procedia**, v. 85, n. November 2015, p. 425–432, 2016.

RAWAT, P. Exergy Performance Analysis of 300 W Solar Photovoltaic. **International Journal of Engineering Scineces & Research Technology**, v. 6, n. 3, p. 381–390, 2017.

SARHADDI, F. et al. Exergetic optimization of a solar photovoltaic array. **Journal of Thermodynamics**, p. 11, 2009.

SIMIONI, T. **O impacto da temperatura para o aproveitamento do potencial solar fotovoltaico do Brasil**. [s.l.] Universidade Federal do Rio de Janeiro, 2017.

YINGLI GREEN ENERGY. **Especificações Técnicas do Painel YL140P-17b**BaodingYingli Solar, , [s.d.].

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.