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Original Research Article

EXERGETIC ANALYSIS OF HYBRID PHOTOVOLTAIC - THERMAL SOLAR COLLECTORS COUPLED TO ORGANIC RANKINE CYCLES

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Abstract

In this work, the application of hybrid solar modules that combine photovoltaic panels and solar thermal collectors coupled with a low-temperature thermal cycle such as the Organic Rankine Cycle is discussed, their main purpose being an increase in the total electric power production per available area. This work will study the thermal and electrical power production efficiency of the hybrid system, the increase in the PV module electric conversion efficiency due to their cooling through heat transfer to the thermal cycle and the total exergetic efficiency of the system. A simplified simulation of the system in steady state conditions based on a thermal efficiency model will be performed with the aid of the EES (Engineering Equation Solver) software using climate data from Campinas, São Paulo, Brazil. The study shows that while the PV/T+ORC system does fulfill the purpose of increasing the electrical power generation both from the generator coupled to the thermal cycle and from the increase in the PV module efficiency due to its cooling. Thus, there is an increase the overall exergy efficiency of the system compared to uncoupled PV/T collectors.

Keywords: exergy analysis, organic rankine cycle, photovoltaic, PV/thermal collector, solar thermal

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1. INTRODUCTION

Hybrid solar modules, still rarely found in the solar solutions market, combine solar thermal collectors and photovoltaic panels in the same area of construction where they're installed. This system, called PV/T (Photovoltaic / Thermal) presents advantages to the use of only PV modules, such as hot water cogeneration and saving in installation space and cooling of the PV panels, improving their efficiency. However, flat-plate PV/T collectors absorb radiation less efficiently than conventional flat-plate collectors, may require additional glass coverings to reduce heat loss to the surroundings, have much lower thermal efficiency compared to concentrating collectors, and have higher cost [1]. It is known that Organic Rankine Cycles (ORC) can be used in applications with heat source temperatures lower than 100°C. While their Carnot efficiency is low, they may still be viable as simple thermal cycles using solar energy as the heat source. In addition, working at low pressures it's possible to use water as the heat transfer fluid instead of thermal oil, achieving working temperatures as low as 65°C in the evaporator in some cases [2]. This characteristic will be used in this study to couple a PV/T collector to an ORC cycle and analyze its viability using climate data from the city of Campinas at peak solar irradiance.

2. MODELLING AND SIMULATION

2.1. Solar irradiance

In order to predict the average maximum solar irradiance on an inclined surface with its angle adjusted for the local latitude and for each month of the year, it is possible to approximate the daily irradiation curve to a sinusoidal function such as Eq. **Błąd! Nie można odnaleźć źródła odwołania.** with a minimum irradiance of 0 kW/m^2 and maximum of I_{max} at solar noon and a half-period equal to the number of sunshine hours. These functions were obtained by equating the mean total daily irradiation on an inclined surface, obtained with the aid of the SunData program from CRESESB [3], with the integral of the functions over the average sunshine hours of every month. With that, it was possible to calculate the maximum solar irradiance I_{max} for each month of the year. The effects of atmospheric refraction and apparent sunrise and sunset times were not considered, and neither were any other weather effects that could hinder the solar irradiance.

$$I(t) = I_{max}\, sin \frac{\pi}{h_d}(t - t_0) \tag{2.1}$$

$I(t)$ stands for solar irradiance, in kW/m^2,

I_{max} maximum solar irradiance,
h_d number of sunshine hours,
t_0 time of sunrise, in hours.

When taking into account the thermal inertia of the atmosphere and the earth's surface and the daily temperature cycle, since the average daily temperature value is reached shortly before the solar irradiance peak around noon, the environmental temperature was defined as the average daily value for local temperature in each month [4], with values measured at UNICAMP's School of Agricultural Engineering [5] for the city of Campinas in the São Paulo State.

Of great importance to this study is the PV conversion efficiency, which decreases linearly with the panel operation temperature. In tropical climates such as that of Campinas, with the right weather conditions the surface temperature of the modules can reach upwards of their maximum operation temperature. The maximum surface temperature of the collectors is defined by Eq. 2.2 [6], in which:

$$T_s = T_a + \frac{I_{max}}{I_{NOCT}}\left(T_{NOCT} - T_{a,NOCT}\right) \tag{2.2}$$

I_{NOCT} stands for solar irradiance at NOCT (800 W/m^2)
NOCT stands for Nominal Operating Cell Temperature, reached by the solar cells in open circuit under irradiance of 800 W/m^2, air temperature of 20^{o}C and wind velocity of 1 m/s.
T_{NOCT} nominal operating cell temperature,
T_a ambient air temperature,
$T_{a,NOCT}$ reference temperature at NOCT (20^{o}C),
T_s surface temperature at peak irradiance.

While it's known that the PV cell temperature can be very sensitive to wind speed [7], Eq. 2.2 assumes that their thermal loss coefficient is constant.

2.2. PV/T Collector

Several hybrid PV/T collector prototypes have been proposed and had their analytical models validated through experimental work [1, 8, 9], but their commercial application is still limited. This paper uses the thermal efficiency model based on experimental work by Ghoneim et al. [8] and Sandnes and Rekstad [1] on PV/T collectors, as well as the dimensions and PV conversion characteristics of the commercially available PV/T collector TESP Twin Energy Solar Panel type XP60-265I+TESP from Sunerg, which can be sold in 12-collector kits including all accessories required for installation and storage of water at high temperatures. This middle-range panel of 265 W_p has a surface area of 1.628 m^2, the twelve units totalling 19.54 m^2. The mounting of the collectors is to be flat on a sloped roof facing north with angle equal to the latitude of Campinas's meteorological station (22.801° S).

The thermal model that follows was based on Zhou et al.'s method and validation of an experimental work of a solar PV/T cogeneration system [10] and adjusted to performance data from the PV/T collector's manufacturer. The thermal efficiency of the hybrid PV/T collector can be expressed by the Hottel-Whillier equation, Eq. (2.3) [10, 11], in which the thermal efficiency parameters of $F_R(\tau\alpha)$ = 0.58 and $F_R U_L$ = 6 were conservatively chosen based on experimental data on PV/T collectors by Ghoneim et al. [8], nevertheless without considering the change in these parameters due to the collectors' mounting configuration (six collectors connected in series and two groups of six connected in parallel). Then, this equation was used to calculate the energy transferred in the form of heat from the collectors to the heat transfer fluid.

$$\eta_T = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{I} \tag{2.3}$$

η_T	stands for thermal efficiency,
F_R	heat removal factor,
U_L	thermal loss coefficient,
$\tau\alpha$	transmittance-absorbance product,
T_i	collector inlet water temperature.

Meanwhile, the thermal efficiency of the PV/T collector as a function of the useful heat transferred from the collector to its circulating fluid is given by Eq. (2.4), in which:

$$\eta_T = \frac{\dot{Q}_u}{IA} \tag{2.4}$$

A	stands for total collector area,
$\dot{Q}_u$	useful heat output from the collectors at peak irradiance.

2.3. PV panel

The change in the PV panel efficiency due to cooling from the water circulating through the PV/T collector must be accounted for by means of the following Equation relating the conversion efficiency and cell temperature with its reference values at standard test conditions [8]:

$$\eta_{PV} = \eta_{ref}\left[1 - \mu\left(T_{PV} - T_{ref}\right)\right] \tag{2.5}$$

η_{PV} stands for the PV panel conversion efficiency,
η_{ref} stands for PV efficiency at reference condition,
μ stands for PV panel temperature coefficient,
T_{PV} stands for PV cell temperature,
T_{ref} is the PV cell temperature at reference conditions.

The Sunerg model has a module efficiency of 16.27% and a thermal coefficient of -0.42%/°C. Together with the peak irradiance and collector area values, the peak PV power output $\dot{W}_{PV}$ can be estimated. Furthermore, in order to estimate the power output when there is no fluid circulating in the collectors and the ORC cycle is not being powered, performance data from the manufacturer was used to predict the lower peak PV power output and the collector stagnation temperature.

2.4. Organic Rankine Cycle

The nature of the Organic Rankine Cycle, which allows the use of working fluids with lower boiling point than water, makes it more adapted than steam power to convert renewable energy resources with lower heat source temperature, such as from a solar collector [13]. The system has been modelled according to the first and second Law equations of a simple ORC cycle with no internal heat exchangers, as illustrated in Fig. 1. Assuming no heat losses from the PV/T collectors to the ORC evaporator, the mean peak heat input at maximum irradiance is used to predict the upper performance limits of the ORC cycle in steady state conditions. The choice work fluid used in this ORC cycle is Toluene based on optimization studies for a similar ORC cycle in which Toluene delivered the highest exergy efficiency out of several work fluids [14], and the chosen heat rejection temperature at the condenser was 45°C with a water cooling flow. For simplification purposes, it was assumed that the evaporation temperature is the maximum surface temperature of the collectors, calculated from Eq. 2.6. This temperature ranges up to 65°C in this work, and temperatures as low as that were shown to power other PV/T+ORC systems such as the one from Kosmadakis at al. [2]. Coupled with low pressures, this enabled water to be used as the heat transfer fluid between the PV/T collectors and the ORC evaporator. Pumping power consumed in the evaporator heating and condenser cooling flows was not considered.

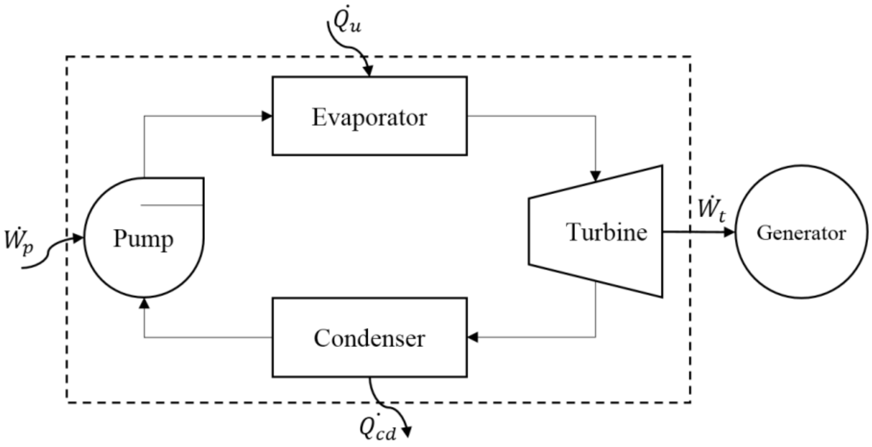

Fig. 1. Layout and control volume of the simplified ORC cycle

The Second Law efficiency of the ORC cycle is in Eq. (2.6), in which:

$$\eta_{ex,ORC} = \frac{\dot{W}_t - \dot{W}_p}{\dot{Q}_u\left(1 - \frac{T_0}{T_{ml}}\right)} \tag{2.6}$$

$\eta_{ex,ORC}$	is the exergetic efficiency of the cycle,
$\dot{W}_t$	is the power generated in the turbine,
$\dot{W}_p$	is the power input to the pump,
T_0	is the environment temperature (298 K),
T_{ml}	is the mean logarithmic temperature of the heat transfer fluid between the collector inlet and outlet.

2.5. Overall PV/T + ORC system

Lastly, the overall exergy efficiency of the studied PV/T system coupled to a ORC cycle is defined by the following equation, where the denominator is the exergy input of the solar radiation to the collectors defined by Joshi *et al.* [15] for a PV/T system as a function of the total solar radiation it receives:

$$\eta_{ex} = \frac{\dot{W}_{PV} + \dot{W}_{ORC}}{IA\left(1 - \frac{T_0}{T_{sun}}\right)} \tag{2.7}$$

$\dot{W}_{PV}$	is the net power output from the PV cells,
$\dot{W}_{ORC}$	is net power output from the ORC cycle,
T_{sun}	is the surface temperature of the sun, 5777 K.

This work has some limitations. All values of irradiance refer to solar noon, and thus these results show only the maximum performance the PV/T+ORC system could reach under ideal weather conditions. Cloud cover and wind speed can greatly affect peak irradiance and PV cell temperature, impacting the total electrical power output.

3. RESULTS AND DISCUSSION

3.1 Collector temperature and PV panel efficiency

The graph from Fig. 2 shows the average peak solar irradiance for every month of the year and the two PV cell temperature curves illustrate the effect the cooling of PV cells due to the water circulation has on their surface temperature.

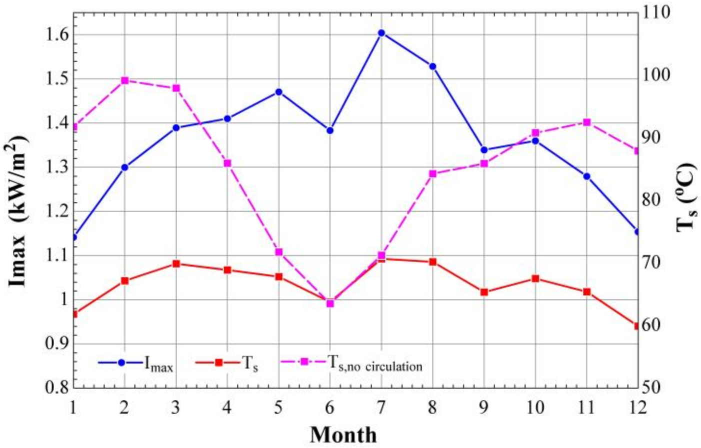

Fig. 2. Peak solar irradiance (I_{max}), solar cell temperature with cooling (T_s) and solar cell stagnation temperature (T_s, no circulation) at peak irradiance for each month of operation

The effect is visibly more pronounced from mid-summer to early autumn in Campinas, where rainfall during these months is usually expected late in the day, thus far from solar noon. While the stagnation temperature at peak irradiance can easily exceed the PV collector manufacturer's maximum temperature of stagnation (83°C), we're reminded that this simulation only applies to clear weather conditions and doesn't account for wind speed, which has a great effect on the collector's surface temperature. Following these results, Fig. 3 shows the effects of temperature on the PV panel efficiency and the subsequent increase due to the circulation of fluid in the collectors.

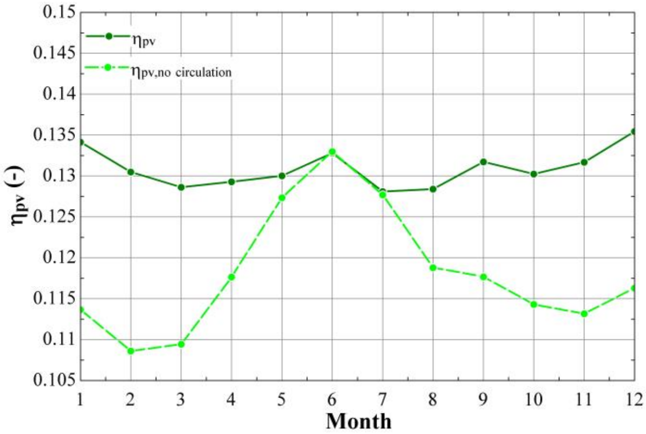

Fig. 3. PV panel efficiency with (η_{PV}) and without circulation (η_{PV}, no circulation) of fluid or cooling of the PV cells at peak irradiance for each month of operation

3.2 Organic Rankine Cycle

Fig. 4 shows the overall efficiencies of the ORC cycle. The average first law efficiency, limited by the Carnot efficiency of around 4.9%, is around 4.1% while the average second law efficiency is 37.2%, which shows the importance of exergy analysis in evaluating the usefulness of low-temperature cycles for heat recovery and renewable power applications such as the ORC in converting energy from low-quality heat into high-quality work.

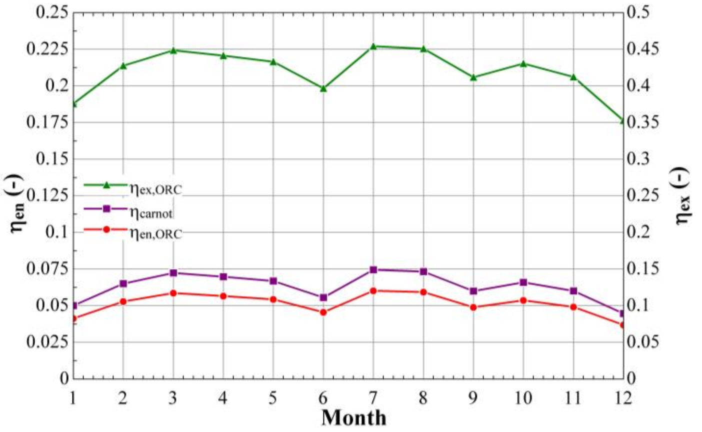

Fig. 4. First (η_{en}), Second law (η_{ex}) and Carnot (η_{carnot}) efficiencies of the ORC cycle at peak irradiance for each month of operation

After the Carnot efficiency limit, ORC performance is limited only by the thermal input to the cycle, which is high all year-round due to the relatively steady yearly solar irradiance in Campinas, which is also true for most cities in Brazil [3].

3.3 Total power generation

Fig. 5 shows the electric power generated by the PV cells at stagnation, the increment of power due to their cooling and the further increment generated by the ORC cycle. The ORC output seems to be more dependent on solar irradiance than the collector fluid temperature, because while this limits the cycle's Carnot efficiency, it is already very low due to the flat-plate PV/T collector's design.

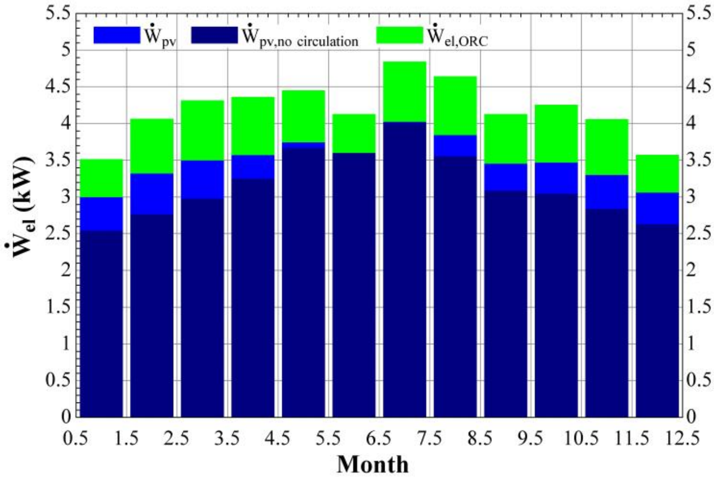

Fig. 5. Electric power generated by the PV cells with ($\dot{W}_{PV}$), without circulation of fluid ($\dot{W}_{PV}$, no circulation) and total electric power generated by the PV/T+ORC system ($\dot{W}_{el,ORC}$) at peak irradiance for each month of operation

For the sake of this energy analysis, the inverter and generator are outside the system control volume and their efficiencies weren't accounted for. Both the cooling effect on the PV cells and in consequence the ORC power generation are more effective during the beginning of autumn and the end of spring, since summer has a noticeable rainy season which impacts solar irradiance [5] The average power increase due to the ORC system output averages 16.1%.

3.4 First and Second Law efficiencies

Meanwhile, illustrates the overall efficiencies of the studied system. The average first law efficiency of the PV/T+ORC is 65,4% and the second law efficiency is around 16.4%, a significant increase from the averages of 51.9% and 12.5% from the PV/T system, respectively, which are compatible values with the efficiencies described in Ghoneim *et al.*'s work [8]. It shows how due to PV and ORC generation the energy efficiency of the PV/T+ORC system is on average 13% higher than the thermal efficiency of the PV/T collector, equivalent to its energy efficiency when it's used only as a water heater. In the other hand, ORC generation and the cooling effect of the PV cells contributes to only around 2% of first law efficiency increase, but around 4% of the second law efficiency increase.

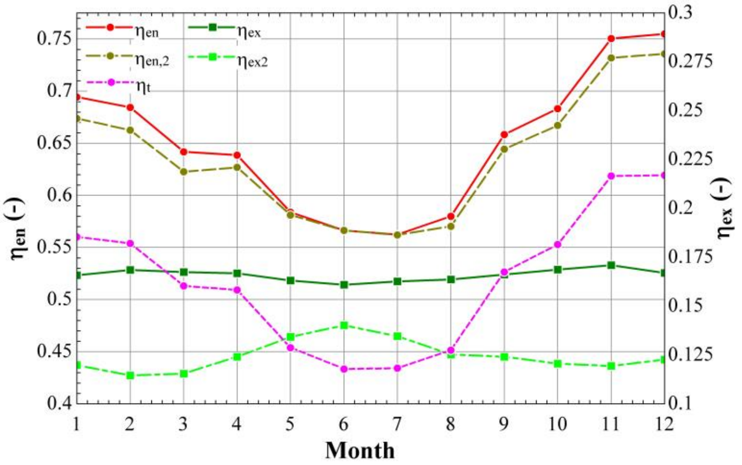

Fig. 6. Thermal efficiency of the PV/T collector (η_t), 1st (η_{en}) and 2nd (η_{ex}) efficiencies of the PV/T+ORC system and of the PV/T system with no circulation of fluid ($\eta_{en,2}$, $\eta_{ex,2}$) at peak irradiance

4. CONCLUSION

The addition of an ORC cycle to the PV/T system was able to improve the overall first and second law efficiencies by an average of 13% and 4%, respectively, even though the electric power output increased by 15.7%. While the purpose of adding the ORC system is an increase in power output, exergy analysis shows that the increase came with more irreversibilities inherent to the ORC cycle that however can be studied in a component-by-component basis, and that the achieved results, while acceptable for hot, tropical climates, might not be viable in temperature climates with lower average solar irradiance. As a possible follow-up to this study, a transient system simulation with the addition of a water storage tank to the analysis is proposed to account for the effects of thermal shift and to predict the average performance of the system under variable solar irradiance and ambient air temperature. The model then may be used to validate PV/T performance data from the collector’s manufacturer and better estimate the efficiency increase with the ORC cycle and optimize for its working fluid. Furthermore, a cost evaluation of coupling the ORC cycle to the PV/T collectors would be needed to cement its viability.

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ANALIZA EKOLOGICZNA HYBRYDOWEGO UKŁADU FOTOWOLTAIKA - KOLEKTORY SŁONECZNE ZWIĄZANYCH ORGANICZNYM CYKLEM RANKINE'A

Streszczenie

W pracy omówiono zastosowanie hybrydowych modułów słonecznych łączących panele fotowoltaiczne z kolektorami słonecznymi w połączeniu z niskotemperaturowym cyklem termicznym, takim jak cykl organiczny Rankine'a, którego głównym celem jest zwiększenie całkowitej produkcji energii elektrycznej. W pracy zbadano wydajność produkcji energii cieplnej i elektrycznej w systemie hybrydowym, wzrost sprawności konwersji energii modułu fotowoltaicznego ze względu na ich chłodzenie poprzez przeniesienie ciepła do cyklu termicznego i całkowitą efektywność energetyczną układu. Uproszczona symulacja systemu w warunkach stanu ustalonego w oparciu o model sprawności cieplnej została przeprowadzona za pomocą oprogramowania EES (Engineering Equation Solver) wykorzystującego dane klimatyczne z Campinas, São Paulo, Brazylia. Badania wykazały, że system PV/T + ORC spełnia cel zwiększenia wytwarzania energii elektrycznej zarówno z generatora połączonego z cyklem termicznym, jak i ze wzrostu sprawności modułu PV ze względu na jego chłodzenie. W ten sposób zwiększa się ogólna efektywność egzergii systemu w porównaniu z niezwiązanymi kolektorami PV/T.

Słowa kluczowe: analiza egzergii, organiczny cykl Rankine'a, fotowoltaika, kolektor PV/T, energia słoneczna

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