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NIGHT COOLING POTENTIAL OF PV-T COLLECTORS FOR BRAZILIAN CITIES

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Abstract.*Renewable energy is a major issue in modern society. High energy consumption for ambient cooling is among the challenges of renewable energy generation. In this scenario, a model of a PV-T solar collector was simulated in Trnsys to evaluate the night radiative cooling potential for different Brazilian cities during spring and summer seasons. This technology achieves the higher potential operating as a trigeneration system, so, during the day the PV-T panels operate to generate electricity and hot water. During the night, the panels operate to generate cold water by exchanging heat with the sky by radiation. The studied system is made of three panels with a total area of 3.9 m^2, with a nominal electric power of 585 W. This paper studies the influence of the PV-T parameters, like tilt angle of the panels, flow rate and temperature of the supply water, and climate characteristics in the radiative cooling potential. The system was simulated for the following cities: Florianópolis, Recife, São Paulo, Porto Alegre, Belo Horizonte, Manaus, Salvador and Brasília. In this way it was possible to compare the equatorial, littoral, tropical and subtropical regions. Simulation results show a better potential for radiative cooling in tropical region ranging from 19 W/m^2 to 98 W/m^2. Depending on the flow rate and other parameters, the water temperature obtained was up to 5.3°C below ambient temperature. The sky temperature and its difference with the ambient temperature were identified as an important parameter in the cooling potential. Another determining factor is the amount of time of clear sky, since the atmosphere is almost transparent to the infrared radiation emitted and not being transparent in the presence of clouds. The results show that this cooling technology has a good potential to be used in trigeneration systems. Preliminary experimental data from other studies was used to validate the results of the simulated model.*
Keywords: *PV-T solar collectors, radiative cooling, annual simulations.*

1. INTRODUCTION

Nowadays, the pursuit for better energy efficiency in buildings, minimizing the consumption of residential like water, electricity and gas is essential. In residential electricity consumption, the electrical energy spent on air conditioning correspond to about 40% of electricity consumption (Ürge-Vorsatz et al., 2015). In this scenario the nighttime radiative cooling of PV modules, the focus of this paper, can be used as a complementary alternative in air conditioning systems.

Many literature reviews on this topic was developed based on North American and European countries, where meteorological conditions differ considerably from the hot climates as the Brazilian climate. Thus, this depicts the need to evaluate this phenomenon in other climate conditions beyond researched until now. Nighttime radiative cooling parameters applied in modellings are not well defined, with a big difference between knowledge about solar heating and night cooling (Hollick, 2012).

Since buildings around the world demand around 30% of the energy produced globally and generate 28% of greenhouse gases, the concept of integrating buildings with renewable energy sources is a field of study of growing interest (Che et al., 2019). Among the proposed models, generate both electricity and thermal comfort in a single system in buildings, building integrated photovoltaic-thermal (BIPV-T), stands out for being more efficient compared to systems that only integrate photovoltaic (PV) energy, whose cooling is achieved by radiative cooling (Zhao et al., 2017).

Unlike conventional cooling systems that transfer excess heat to the surroundings, such as: towards the atmosphere, bodies of water, radiative night cooling transfers heat to outer space and naturally, i.e., without energy consumption (Dong et al., 2019).

During the daylight hours, a solar thermal collector utilizes the absorbed solar energy as heat, as well as a PV module directly converts sunlight into electricity (Pinho & Galdino, 2014). PV-T collectors combine a solar thermal collector and PV module in one device, being capable of generating electricity and producing heat. The working fluid of PV-T can be recirculated at night to be refrigerated and be used later in thermal comfort systems (Allan et al., 2015; Eicker & Dalibard, 2011; Erell & Etzion, 2000).

During the nights, photovoltaic-thermal (PV-T) collectors can be used to produce cold water by means of the so-called night sky radiative cooling. This phenomenon explores the radiative exchange between a PV-T module surface at temperature T_{PV} and the sky at temperature T_{sky}. When T_{PV} is higher than T_{sky}, there is a heat transfer by radiation from the surface to the sky. Studies have been carried out to develop technologies that allow the use of this phenomenon in the cooling of buildings. This method is preferable in drier climates, with low relative humidity, because the moisture absorbs part of the radiation released to the sky and partially reflects it back (Šikula et al., 2015). As T_{sky} can reach temperatures lower than 0°C, exposed objects can attain temperatures below room temperature up to freezing temperatures (Eicker & Dalibard, 2011).

The night sky radiative cooling principle has been a promising emerging technology, as it addresses the important growing need for cooling and air-conditioning (Dong et al., 2019) in a passive way, not consuming energy. However, this technology encounters challenges, mainly as the low cooling power. Nevertheless, considering the global energy crisis and environmental issues, it is expected that the combination of PV-T with radiative cooling capacities will be applied in buildings (Ahmed et al., 2021).

The currently increasing interest in studying the potential of this technology as a source of renewable energy in cooling systems, different investigations have been carried out in various regions with different methodologies, finding on average a cooling potential in the range of 40 to 80 W/m^2 (Zhao et al., 2019).

Hu et al. (2018) performed experimental tests with a PV-T and obtained an electrical efficiency of 10.3% during periods with incidence of irradiation. At night, on clear nights, the same PV-T reached a net radiative cooling power of 72.0 W/m^2. Furthermore, the authors obtained a global cooling energy also on clear nights of 2.90 MJ.

Because the experimental models and mathematical modelling about night sky radiative cooling have been carried out mainly in non-tropical climate regions, which differ considerably from the climate found in most of Brazilian territory, a further study investigating the nighttime radiative cooling of PV panels in Brazil and its use in thermal comfort systems might be promising.

The present study aims to determine the potential for nighttime cooling in Brazil through the use of a PV-T system. A computational model is made using the TRNSYS-18 software, which has been validated with the results presented by Bogatu et al. (2019) and then adapted for different locations. The analysis will focus on the cooling potential by analyzing the heat transfer phenomena aiming to obtain the average cooling capacity (W/m²). This paper will not analyze the integration of the system proposed with a cooling demand.

2. METHODOLOGY

2.1 Trnsys Model description

A model was developed based on the study carried out by Bogatu et al. (2019). The model implemented in TRNSYS involves a tilted PV-T panel. The simulations were executed for different cities in Brazil considering the typical meteorological year (TMY) data (*EnergyPlus*, 2021). The objective is to obtain the average cooling capacity for PV-T during the nighttime. The model is represented in Figure 1.

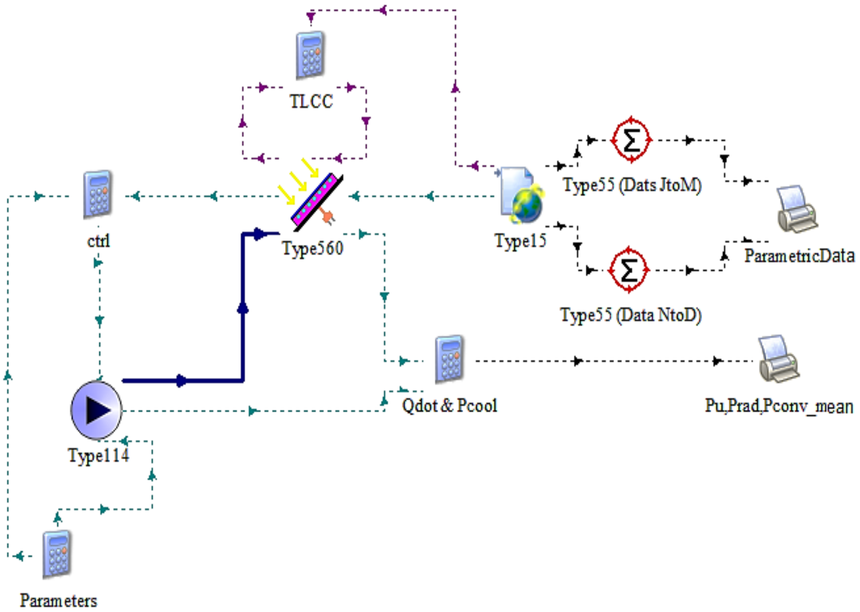

Figure 1. Trnsys PV-T model.

The PV-T panel loses heat from its top surface. This heat loss occurs mainly by radiation and convection. For determination of convection losses, it is important to define the convective heat transfer coefficient. According to the equations from Duffie & Beckman (2006), the top loss convective coefficient (TLCC) is a combination of forced and natural convections. A constant convective coefficient for the bottom panel surface was considered as 0.64 W/m^2K.

$$h_{TLCC}{}^3 = h_{c,forced}{}^3 + h_{c,nat}{}^3 \tag{1}$$

$$h_{c,forced} = 2.8 + 3u_w \tag{2}$$

$$h_{c,nat} = 1.78\,(T_{PV} - T_{amb})^{1/3} \tag{3}$$

Where $h_{c,forced}$ is the forced convection heat transfer coefficient that is a linear function of the wind speed u_w, $h_{c,nat}$ is the natural convection heat transfer coefficient, T_{PV} and T_{amb} are the average PV panel surface and ambient air temperatures, respectively.

"Ctrl" at Fig. 1 is a control signal created as a function of the inlet and outlet temperatures to determine the periods in which the outlet temperature of the collector is lower than its inlet temperature, i.e., when the water is being cooled. Some parameters, constants and variables are present in different components; thus, it is more practical to define them as variables in an equation component, in this case "Parameters" is defined for it.

In the component named "Qdot & Pcool", the mathematical models are entered to determine the rates of radiative energy transfer in the top surface ($Q_{loss,top,rad}$) and convective energy transfer in the top and bottom surfaces ($Q_{loss,top,cover}$,$Q_{loss,back}$). Using these energy transfers, the average cooling power, P_{cool}, is obtained for the simulation period. Equation (4) result of the energy balance on the entire collector when energy is not absorbed, i.e., during the night.

$$P_{cool} = Q_{loss,top,conv} + Q_{loss,top,rad} + Q_{loss,back} \tag{4}$$

$$Q_{loss,top,conv} = h_{c,wind}\, A_c\, (T_{PV} - T_{amb}) \tag{5}$$

$$Q_{loss,top,rad} = \varepsilon\, A_c\, \sigma\, (T_{PV}{}^4 - T_{sky}{}^4) \tag{6}$$

Where ε is the top PV surface emissivity, A_c is the panel area and σ is the Stefan-Boltzmann constant ($5.67X10^{-8}$ $W/(m^2.K^4)$). Finally, the useful energy power, Q_u, is related to P_{cool} because the energy losses in PV-T surface amount to Q_u delivered for PV-T collectors. i.e., $-Q_u = P_{cool}$, expressed by Eq. 7, where $\dot{m}$ is the mass flow rate and C_p is the specific heat of the fluid.

$$Q_u = \dot{m} C_p (T_{outlet} - T_{inlet}) \tag{7}$$

2.2 Validation

In order to validate the model developed in TRNSYS, the results obtained by Bogatu et al. (2019) were replicated in simulations realized by modelling represented in Figure 1. Figure 2 compares the results obtained by Bogatu et al. (2019) and by TRNSYS model from Figure 1. On average, the data differ by about 8%, as long as the temperatures are above 15 °C.

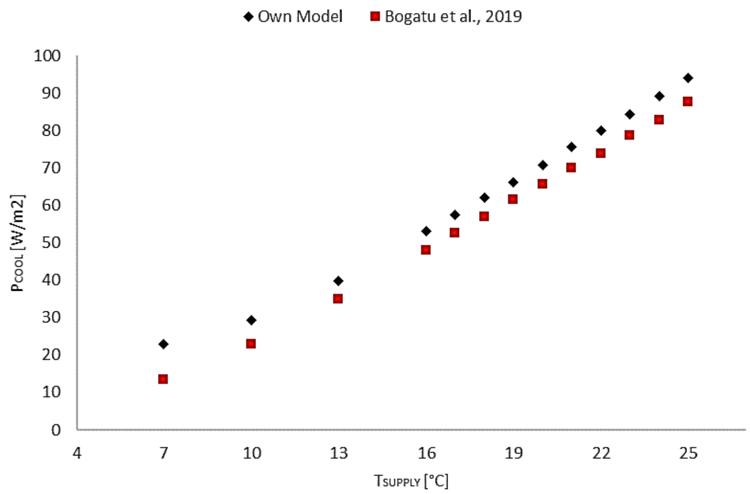

Figure 2. Comparison between Figure 6 of Bogatu et al. (2019) and results obtained with the modelling on TRNSYS.

Discrepancies can be caused mainly by four reasons. First, the exact values of the cooling power by unit area are not available, so they were indirectly determined by analyzing the graphs provided. Second, the impossibility of carrying out exactly the same data processing as the author. Third, the difference between the TRNSYS software versions and finally, TMY could have been updated. However, the error is not greater than 8%, during the months of November to March, for the temperatures above 15 °C.

2.3 Study in different locations in Brazil.

In this study three PV-T panels with an area of 1.3 m^2 each connected in series were modeled with the TRNSYS 18 software, as shown in Figure 1. Table 1 shows the parameters of the PV-T used in this study. These parameters represent the commercially available PV-T 195M of the WIOSUN company.

Table 1. Module PVT-195M properties to configure the Type 560.

Parameter	Unit	Value
Collector length	m	1.315
Collector width	m	0.996
Absorber plate thickness	m	0.001
Thermal Conductivity of the absorber	W/(m.K)	380
Number of tubes	-	15
Tube diameter	m	0.018
Bond width	m	0.01
Bond thickness	m	0.001
Bond thermal conductivity	W/(m.K)	380
Resistance of substrate material	(m^2.K)/W	0.001
Resistance of back material.	(m^2.K)/W	1.56
Fluid specific heat	kJ/(kg.K)	4.19
Reflectance	-	0.15
Emissivity	-	0.98
Collector slope	°	45

Back Heat Loss Coefficient	W/(m^2.K)	0.64
Fluid heat transfer coefficient.	W/(m^2.K)	350
PV cell reference temperature	°C	25
PV cell reference radiation	W/m^2	1000
PV efficiency at reference condition	%	18.43

A more detailed study will be carried out for Florianópolis city. The inlet temperature range goes from 16 ºC to 32 ºC, in steps of 2 ºC from 16 ºC to 22 ºC, and in steps of 1 °C from 22 °C to 32 °C.

Two values for the flow rate were chosen. The mass flow rate determined by Péan et al. (2016) of 121 kg/hr, and the flow mass shown in Jordan et al. (2015) of 194 kg/hr. In order to investigate the influence of the slope of the modules, three slopes oriented towards the north were chosen, 0º (H), 27º (E) and 90º (V). The vertical and horizontal slopes were chosen due to the ease of integration with the building architecture.

For the other cities, the potential cooling was performed for only one slope according to Table 2, which will be given according to the latitude, i.e., what is expected to be optimal electrical production, and therefore, it is the most common tilt in which PV panels are installed. More a mass flow of 121 kg/hr and equal temperature range are used.

Table 2. Latitudes of the cities studied to define the collector slope (E).

City	Acronym	Latitude (South) [°]
Manaus	MAN	2.7
Recife	RCF	8.4
Salvador	SALV	13.3
Brasilia	BRAS	15.8
Belo Horizonte	BH	19.8
São Paulo	SP	23.5
Florianópolis	FLN	27.6
Porto Alegre	PA	30

3 RESULTS AND DISCUSSIONS

3.1 Florianópolis

Figure 4, summarizes how the cooling potential is affected by varying the parameters of mass flow and slope of the panels as a function of the temperature supplied to the collector. Between 16 °C and 20 °C, there is no appreciable variation. From this point on, a slight increase in the cooling power for the flow of 194 kg/hr with respect to the flow of 121 kg/hr is observed, reaching a maximum of 3% difference when the temperature is set at 32 °C. The influence of the slope of the collector was unnoticeable.

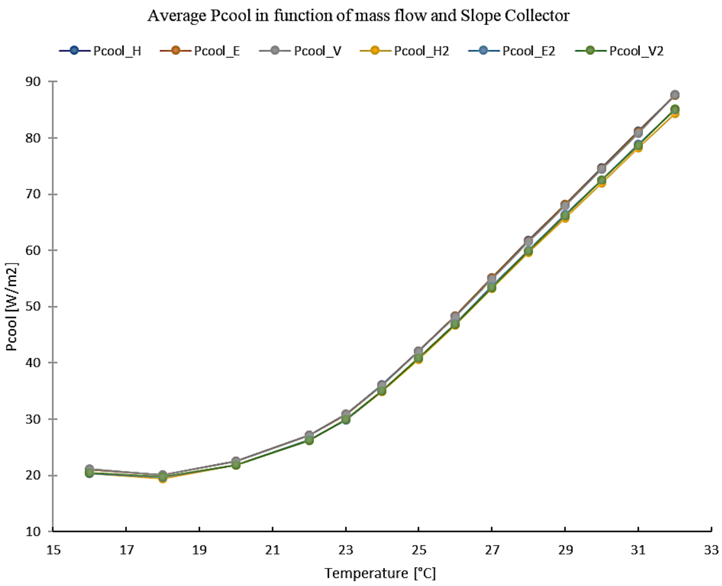

Figure 4. Cooling potential for FLN, influenced on the parameters: inlet temperature, inclination (H = 0 °, E = 26º, V = 90º) and mass flow. The index 2, refers to the mass flow 2 (121 kg/hr).

For the period of time studied, at 7565 hours, corresponding to 5 am on November 12, the lowest sky temperature is reached, with a value of -0.83 °C and an ambient temperature of 14 °C, as shown. in Figure 5. With a fixed temperature of 16 °C and a flow of 121 kg/hr, the outlet temperature is slightly lower than the ambient temperature, therefore all the cooling is given by radiative loss.

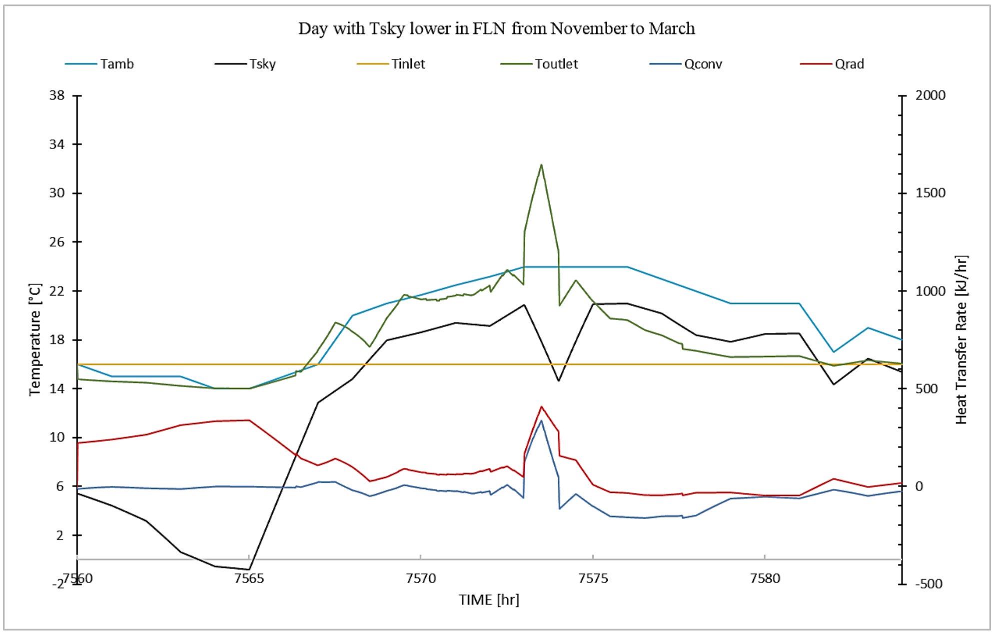

Figure 5. Ambient, sky and collector inlet and outlet temperatures, and radiative and convective components during November 12, in which a sky temperature of -0.83 °C is presented, the lowest between the months of November to March.

In Figure 6, the outlet collector temperatures are shown for each inlet temperature. The difference between each of them ranges from 2 °C to 5.3 °C. Convective losses influence from 17 °C to 32 °C with a range of 5.4 W/m^2 to 43.5 W/m^2, while the radiative component ranges from 72.7 W/m^2 to 144.6 W/m^2, was obtained.

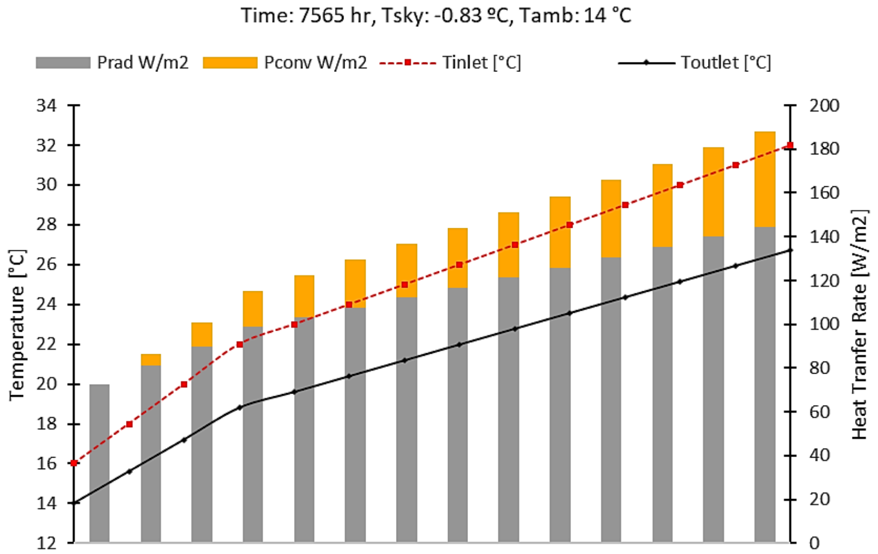

Figure 6. Average outlet collector temperatures during hour 7565 for each set inlet temperature. In bars, the convective and radioactive components.

3.2 Different cities of brazil

The cities under study are located in different regions of Brazil, as shown in Table 4. From Figure 7, in the established range of temperatures, an average of cooling potentials is obtained for the tropical region from (19.3 to 98) W/m^2. In the subtropical region, from (18.8 to 87.7) W/m^2. In the humid littoral region, from (4.8 to 66.1) W/m^2. The equatorial region presented values of (3.8 to 60.7) W/m^2.

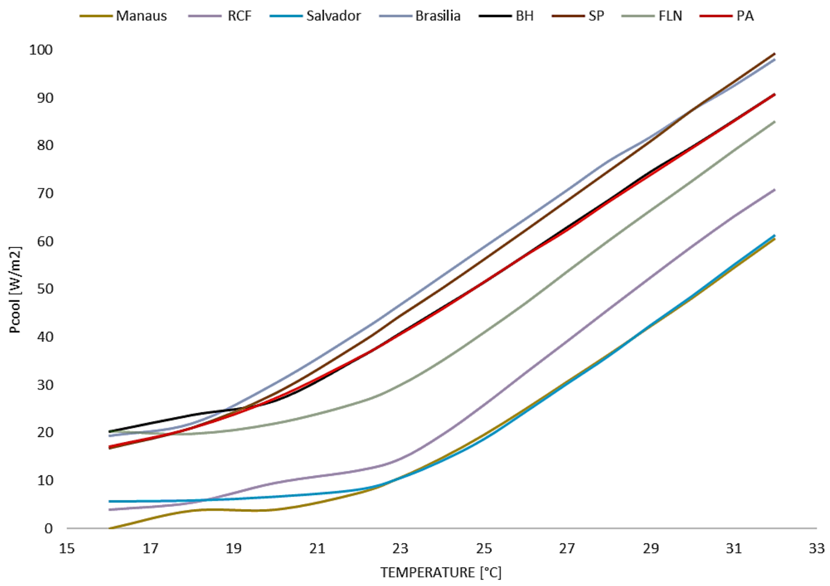

Figure 7. Average cooling potential in cities of Brazil.

From Figure 7, for the period between the months of November to March, two special cases are observed; the difference in the cooling potential between the cities of Porto Alegre (subtropical) and Belo Horizonte (tropical), and between the cities of Salvador (littoral) and Manaus (equatorial), are negligible, despite being at a difference of around of 10° in latitude, according to Table 3. São Paulo and Brasilia, are located in the same tropical region, the latter with a slightly higher potential to produce cold water, being approximately 8° more in latitude towards the equator, and São Paulo located on the border between the tropical and subtropical regions.

Generally, it is reported that the cooling potential is higher for the subtropical zone, because the sky temperature is lower than for the tropical and equatorial zones. Therefore, it is evident that although the sky temperature is a very important factor for the production of cold water due to radiative losses, it is not a determining factor. In this way, there are publications where other factors are analyzed, such as wind speed and relative humidity. Water vapor, by absorbing long wavelengths, between 8 μm, and 14 μm, an area known as the sky window, interferes with the radiative transfer and therefore reduces the cooling potential. The wind speed counteracts this effect.

To analyze these factors, averages were obtained throughout the established period of the following parameters: Ambient temperature, sky temperature, wind speed and the percentage of relative humidity, as shown in Table 4. With the average ambient temperature, the cooling potentials are determined from Figure 4. Thus, Figure 8, would result from establishing to the PV-T system, a constant fluid temperature equal to the average temperature during the night period in each city.

Figure 8, shows that despite the fact that Brasilia has a lower sky temperature than Belo Horizonte and Porto Alegre, its cooling potential is 14.5% and 10.3% lower, respectively. So, factors like wind velocity and relative humidity can make the difference. In the case of Belo Horizonte and Porto Alegre, they present a negligible difference in relative humidity, the latter being a favorable factor, 20% more wind speed, and a difference in sky temperature of 2.7%, even so, their potential for cold is less than Belo Horizonte. Therefore, it can be inferred that under this situation, the temperature of the sky is decisive.

However, a factor that seems to be more relevant is the difference in temperatures between ambient and sky temperatures, in this case, from Table 4, Belo Horizonte is a little more than 9%. In this way, this difference in temperatures can serve as an indication for determining the cooling potential, since it is greater as the temperature difference is greater.

The lower cooling potential in Manaus is due to the fact that there are the most unfavorable conditions, as shown in Table 4, with respect to the other locations, it has the highest sky temperature, the highest relative humidity, and the lowest wind speed. and the smallest difference between ambient and sky temperatures.

Table 4. Average Parameters.

City	Region	P_{cool} [W/m2]	T_{amb} [°C]	T_{sky} [°C]	Wind Velocity [m/s]	RH [%]	$(T_{amb}-T_{sky})$ [°C]
Manaus	Humid Equatorial	22.80	25.59	20.66	0.85	89.93	4.92
Recife	Humid Littoral	25.80	25.05	19.05	1.65	79.09	6.01
Salvador		27.10	26.47	21.03	1.74	80.23	5.44
Brasilia	Tropical	30.30	19.85	12.93	1.30	78.84	6.92
Belo Horizonte		34.70	21.80	13.78	1.13	79.90	8.02
São Paulo		28.20	20.13	14.13	2.52	86.52	6.01
Florianópolis	Humid Subtropical	26.20	22.18	17.18	2.71	88.74	5.00
Porto Alegre		33.42	21.44	14.16	1.41	80.00	7.28

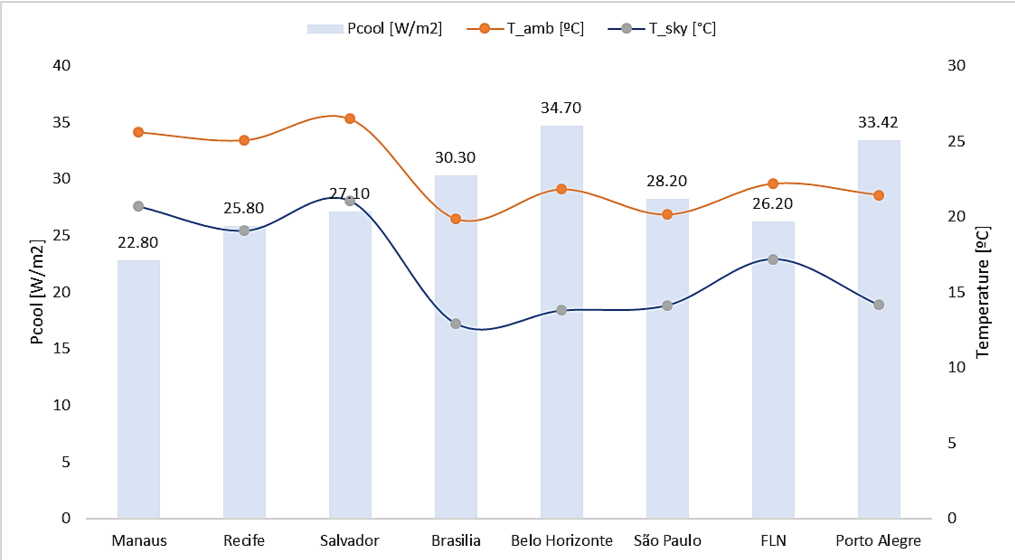

Figure 8. Variation of the average P_{cool} with respect to the average T_{amb} and T_{sky}.

4 CONCLUSIONS

The use of the PV-T panel as an alternative for replacing or optimizing the thermal comfort system at night is a possibility, depending above all the temperature difference between the PV-T panel and sky temperature. There is a gap between the knowledge of the capacity utilization of nightly thermal behavior of PV (or PV-T) panel in non-tropical and tropical regions, showing the lack of study proposes about the phenomenon of radiative cooling in hot climates even during night.

Cities located in the tropical region of Brazil have the highest potential for nighttime radiative cooling during the spring and summer seasons, reaching a maximum average of 98 W/m^2 for a collector inlet temperature of 32 °C. In addition, the tropical region does not present seasonal climate changes as marked as in the subtropical region, thus, it has the potential to be applied throughout the year.

Relative humidity negatively influences the cooling potential, therefore, cities located in the continental zone have greater potential than those located in the littoral region.

The cities with the best results in the application of the technology studied, Brasília, São Paulo, and Porto Alegre, are cities where solar energy presents the highest rates of investment and high population density. Furthermore, in the case of Brasilia, in accordance with what has been reported in the literature, it has very favorable conditions, such as: low sky temperatures and relatively dry climate.

In addition to a low sky temperature, its difference with the ambient temperature is decisive to reach higher potential nighttime cooling. Thus, in the case of setting the fluid temperature equal to the ambient temperature, the city of Belo Horizonte surpasses the city of Brasilia by approximately 14% of the cooling potential.

The cooling potential achieved by PV-T night sky radiative cooling is relatively low, but it is obtained in a passive way, without energy consumption or with minimum energy consumption by the pump. As the nighttime is usually cooler than daylight time both convective and radiative heat transfer act to decrease the fluid temperature, which could then be stored and used during the day, when the ambient temperature is higher.

For large commercial or industrial PV-T installations, such as hotels, clubs and beverage industries, this technology could play important cost saving operating as a refrigeration water pre-cooler. The storage and use of the cooled water should be analyzed in further studies as well as an economic evaluation of this technology.

Brazil presents promising results to develop the energy trigeneration potential of PV-T systems throughout the year. With future experimental research, a more precise model can be adjusted to carry out energy and economic analyzes of PV-T systems and thus contribute to increasing the market share of renewable sources in the country's energy matrix.

5 ACKNOWLEDGEMENTS

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