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ENERGY ANALYSIS OF HYBRID PV-T SOLAR ASSITED HEAT PUMP VERSUS TRADITIONAL PV PANEL AND VACUUM SOLAR HEATER.

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Abstract. *This article explores the significance of the energy transition in the global context, emphasizing the importance of renewable energy sources in meeting environmental and resource challenges. Brazil's role as a leader in clean energy, particularly solar energy, is highlighted. The article discusses the need for energy policies that priorities low-carbon transitions and introduces the concept of cogeneration, specifically the photovoltaic thermal panel with heat pump system (PV-T BC), as a promising technology. The methodology section describes the mathematical description and calculations involved in the PV-T BC system, covering key components such as the evaporator, compressor and condenser. The flow diagram of the system's operation is presented and equations are provided to determine efficiency and energy balances. A scenario analysis is carried out to compare three energy scenarios to electricity and domestic hot water production: PV-T BC, and PV panel with an electric heater, and PV panel with solar collector heater. The results indicate that the PV-T BC system is highly efficient, satisfying both hot water and electricity needs, while the other scenarios have limitations. The study shows that the PV-T BC configuration increases the efficiency of the PV panel by around 79.85 per cent. This results in a 56.38 per cent increase in the production of electricity capable of supplying the energy consumed by the compressor. The final temperature of the tank in the PV-T BC system is higher than the temperature of the vacuum solar heater, with an average difference of 10.5°C. In conclusion, the PV-T system with a heat pump is an efficient and environmentally friendly option for the simultaneous production of hot water and electricity. It outperforms the other scenarios in terms of efficiency and sustainability, despite the higher initial costs. The article emphasizes the importance of considering both energy efficiency and environmental impact in energy transition strategies.*

Keywords: *Thermal - Photovoltaic, Heat pump, Water heating, Hybrid system.*

1. INTRODUCTION

Energy transition has emerged as a matter of utmost importance in the current global scenario. The threat to natural resources and the rising carbon dioxide emissions in the atmosphere, as pointed out by the United Nations, have been escalating into a problem of global proportions. Against this backdrop, it is critical not only to study energy generation but also to explore more efficient ways of utilizing it. Brazil, with its vast potential for harnessing renewable energy sources, particularly solar energy, stands out in this scenario (Hinrichs; Kleinbach, 2019).

Wills and Westin (2018) regard Brazil's energy matrix as one of the cleanest globally. The country is recognized for its commitment to renewable energy sources, which account for approximately 42% of the total primary energy supply and 85% of the electric sector's production. The nation exhibits extensive potential in sources like hydroelectric, wind, biomass, and solar energy.

Losekann and Tavares (2019) consider that most of today's energy systems are grounded on fossil sources, significant carbon emitters. The restructuring of these systems entails challenges that require suitable energy policies to support this transformation. Traditionally, energy policies have pivoted towards ensuring supply security, affordable energy access, and environmentally suitable production and use. However, in a context striving to meet climate objectives, energy policies need to converge towards a low-carbon energy transition, prioritizing four energy development strategies: energy expansion, energy reproduction, energy substitution, and energy efficiency.

The current energy crisis faced by the hydroelectric sector and global warming has spurred interest in cogeneration, especially for industrial installations, commercial buildings, and rural applications. Cogeneration is a technological process that combines the production of electric and/or mechanical power with the generation of useful thermal energy. This combination results in significant energy savings compared to conventional technologies for separate electric and thermal power generation (Raj; Iniyan; Goic, 2011).

Among promising technologies in this context, the photovoltaic/thermal (PV-T) hybrid technology stands out. This system has the capability to simultaneously harvest electricity and thermal energy, making it an attractive option. Photovoltaic (PV) energy is considered one of the most environmentally friendly methods to generate electricity. However, the challenge of relatively low conversion efficiency persists. Among various factors negatively impacting photovoltaic systems' performance, the operating temperature plays a significant role. The ideal temperature for photovoltaic cells to operate efficiently is about 25 °C. Unfortunately, in subtropical regions, particularly during peak sun hours, the operational temperature of photovoltaic panels can reach 60 to 80 °C. Consequently, researchers have been working on developing passive and active thermal management techniques to address this problem (VAISHAK; BHALE, 2021).

Among active systems, there is one known as a refrigerant-based PV-T system, involving the integration of a heat pump's evaporator coils and a PV module to create a cogeneration system called a photovoltaic/thermal-solar assisted heat pump (PV-T-SAP). Having a high evaporator temperature is beneficial for the heat pump's operation, but the conversion efficiency of a photovoltaic cell decreases as the operational temperature increases. In this context, a heat pump evaporator and a photovoltaic module can be combined as a single module to create a hybrid system. During operation, the excess thermal energy in the photovoltaic module acts as a heat source for the refrigerant's evaporation. This evaporation process reduces the operational temperature of the photovoltaic module, leading to better performance, while the extracted heat can be used for low-temperature heating applications.

A PV-T (Photovoltaic-Thermal) system with a heat pump is a combined technology aiming to improve a photovoltaic panel's overall efficiency. Based on studies by Dubey et al. (2009) and Chow (2010), these systems operate by utilizing the residual heat generated by the photovoltaic panel for heating or cooling an environment. The heat pump, in turn, further enhances the system's efficiency, as it increases the amount of thermal energy that can be extracted. This not only results in better utilization of incident solar energy but also can improve the photovoltaic panel's electrical efficiency. This is because photovoltaic cells operate with higher efficiency at lower temperatures, so any heat removed from the panel can enhance its performance evaporation, which reduces the operational temperature of the module and increases the photovoltaic cell's efficiency. Moreover, this extracted thermal energy can be used for low-temperature heating applications (Obalanlege *et al.*, 2020).

2. METHODOLOGY

2.1 PV-T assisted heat pump

This is an advanced mathematical description of the components of a PV-T panel heat pump. In the case of a hybrid heat pump utilizing PV-T panel, the electrical energy generated by photovoltaic modules is consumed by the heat pump. Concurrently, the heat absorbed by the thermal collector is employed to boost the heat pump's efficiency, as depicted in Figure 1. Therefore, in a hybrid PV-T and heat pump system, solar energy is utilized for both electricity generation and heat collection, which is then used to power and enhance the efficiency of the heat pump. This system presents several advantages, including heightened efficiency, sustainability, and the potential to decrease reliance on non-renewable energy sources.

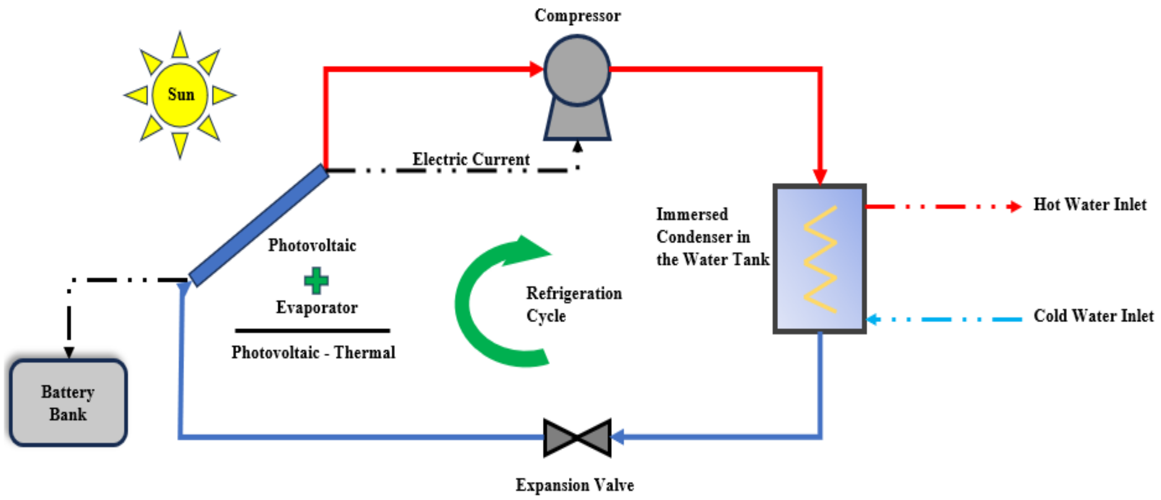

Figure 1 – Thermal – Photovoltaic assisted heat pump model.

2.2 Evaporator

The first step in sizing the evaporator is the calculation of the energy balance given in Watts, on the photovoltaic panel side, according to Eq. 1:

$$Q_{evap} = Q_{pv} - Q_{isolação} - Q_{ar} \quad \text{(W)} \tag{1}$$

Where Q_{air} is the heat between the photovoltaic panel and the air, expressed in Eq. 2, and U_{air} is the air heat transfer coefficient, T_{pv} is temperature Photovoltaic-Thermal. Finally, the efficiency of the photovoltaic panel depends on the reference conditions provided by the manufacturer.

$$Q_{air} = U_{air} * A_{PV} * (T_{pv} - T_{air}) \quad \text{(W)} \tag{2}$$

To calculate the heat from the photovoltaic panel (Q_{pv}), Eq. 3 is used:

$$Q_{pv} = I_t * \left(1 - \eta_{pv}\right) * A_{pv} \quad \text{(W)} \tag{3}$$

Where I_t is the total irradiation, η_{pv} is the photovoltaic panel efficiency, and A_{pv} is the panel area. To calculate the heat loss due to insulation, Eq. 4 can be considered.

$$Q_{isolação} = U_{isol} * A_{evap} * \left(T_{air} - T_{evap}\right) \quad \text{(W)} \tag{4}$$

The calculation of the average heat transfer is expressed by Eq. 5:

$$U_{evap} = \frac{1}{\left(\frac{1}{HT_{ref}}\right) + \left(\frac{1}{C_b}\right)} \quad (\text{W/m}^2\text{K}) \tag{5}$$

Where T_{air} are the temperatures of the enveriment, provided by the IRN – Institute of Natural Resources. U_{evap} is the average heat transfer coefficient. HT_{ref} for evaporator refrigerant and considering the contact resistance factor C_b. For two-phase flow, the Shah correlation (2017) is used, which is valid for micro, mini and macro channels. For single-phase flow, the Prabhanjan, Rennie, and Raghavan (2004) correlation is used. The area of evaporator is function of his length and diameter serpentine tube, according to Eq.6:

$$A_{evap} = L_{evap} * D_{evapo} * \pi \quad (\text{m}^2) \tag{6}$$

To calculate the heat in the evaporator on the side of the refrigerant fluid, which for this dissertation was used the fluid R134a. according to Eq. 7.

$$Q_{evap} = m_{ref} * (h_{sai,evap} - h_{ent,evap}) \quad \text{(W)} \tag{7}$$

2.3 Compressor

Mass flow also plays an important role in proper distribution of refrigerant within the system. Inadequate refrigerant flow can result in imbalanced heat transfer and decreased system efficiency. By calculating the correct mass flow rate, it is possible to ensure that the refrigerant is distributed evenly and efficiently, guaranteeing adequate system performance, and avoiding problems such as overheating or sub-cooling at different points in the system, according to Eq. 8.

$$m_{ref} = \eta_{vd} * \rho_{suc} * V_d \quad \text{(kg/s)} \tag{8}$$

Using Eq. 9, the volumetric efficiency can be obtained.

$$\eta_V = a_1 + b_1 * (RC) \quad (-) \tag{9}$$

Where ρ *and* V_d are, respectively, the density values and displacement volume, RC is the compression ratio, and a_1, b_1 are constants provided by the manufacturer.

Determining the isentropic efficiency of the compressor is important to evaluate the effective performance of the equipment and compare it with the ideal efficiency. Isentropic efficiency is a measure of how efficiently the compressor does work, considering energy losses during the process. Using Eq. 10, the isentropic efficiency can be obtained.

$$\eta_{isen} = a_2 * (RC)^2 + b_2 * (RC) + c_2 \tag{10}$$

The isentropic work of a compressor $W_{c_{isen}}$ is the amount of work required to compress a gas adiabatically and reversibly, that is, without heat loss to the external environment. Through Eq. 11 it is possible to obtain the isentropic work of the compressor.

$$W_{c_{isen}} = m_{ref} * (h_{isen,sai,comp} - h_{ent,comp}) \quad \text{(W)} \tag{11}$$

Eq. 12 calculates the actual compressor work.

$$W_{c_{real}} = \frac{W_{c_{isen}}}{\eta_{vol}} \quad \text{(W)} \tag{12}$$

2.4 Condenser

For sizing the capacitor, it is necessary to calculate the energy balance according to Eq. 13:

$$Q_{water} = Q_{cond} - Q_{isol_{tank}} \quad \text{(W)} \tag{13}$$

To calculate the heat of the tank insulation ($Q_{iso_{tank}}$), Eq. 14 is used:

$$Q_{isol_{tank}} = U_{isol_{tank}} * A_{tank} * (T_{water} - T_{air}) \quad \text{(W)} \tag{14}$$

Where $U_{isol_{tank}}$ and A_{tank} are the heat loss from the tank walls by conduction and the surface area of the tank, respectively. The heat of water is calculated using Eq. 15.

$$Q_{water} = V_{tank} * \rho_{water} * cp_{water} * \left(\frac{T_{final_{water}} - T_{first_{water}}}{\Delta t}\right) \quad \text{(W)} \tag{15}$$

Where $Q_{\text{water}}, \text{V}_{\text{tank}}, cp_{\text{water}}, T_{final_{\text{water}}}, T_{first_{\text{water}}}$ and Δt, are the heat of the water, the mass of water in the tank, the specific heat of the water, the temperature of the water, the initial temperature of the water and the change in time, respectively.

The heat in the condenser on the refrigerant side. Use Eq. 16.

$$Q_{cond} = m_{ref} * (h_{ent_{cond}} - h_{sai_{cond}}) \quad \text{(W)} \tag{16}$$

Thus, the enthalpy at the exit can be calculated effectively by employing Eq. 17.

$$h_{sai_{cond}} = h_{ent_{cond}} - \left(\frac{Q_{cond}}{m_{ref}}\right) \quad \text{(W)} \tag{17}$$

The amount of heat in the condenser is expressed by Eq. 18.

$$Q_{cond} = U_{cond} * A_{cond} * (T_{cond} - T_{water}) \quad \text{(W)} \tag{18}$$

Where $Q_{cond}, U_{cond}, A_{cond}, T_{cond}$ are the condenser heat, condenser heat transfer coefficient, coil surface area, and condenser temperature, respectively, Eq. 19.

$$A_{cond} = L_{cond} * D_{cond} * \pi \quad (\text{m}^2) \tag{19}$$

HT_{ref} for two-phase flow, the used correlation of Shah (2016) is used, expressed in Eq. 20, which is valid for micro, mini and macro-channels. For single-phase flow, Prabhanjan, Rennie, and Raghavan (2004) is used. To help in the development of the system, some values were calculated using coolprop.

$$U_{cond} = \frac{1}{\left(\frac{1}{HT_{ref}}\right) + \left(\frac{1}{H_{water}}\right)} \quad (\text{W/m}^2\text{K}) \tag{20}$$

2.5 Flow chart of PV-T system with heat pump

Figure 2 illustrates the operation of the hybrid system model. The simulation will be carried out in one-hour intervals, and in addition to the geometric parameters of all components, it also inputs three variables: solar irradiation incident on the panel(I_T), ambient temperature(T_{amb}), and initial tank temperature ($T_{tank,i}$) that change every hour. To find the energy parameters of the system and solve the equations of each component, it is necessary to calculate the temperatures of the photovoltaic panel, the evaporator, the compressor, and the end of the tank, simultaneously, thus creating a system of non-linear equations with 4 unknowns. The solution of this equation system 1-6 was done using the "SOLVE" tool in Matlab.

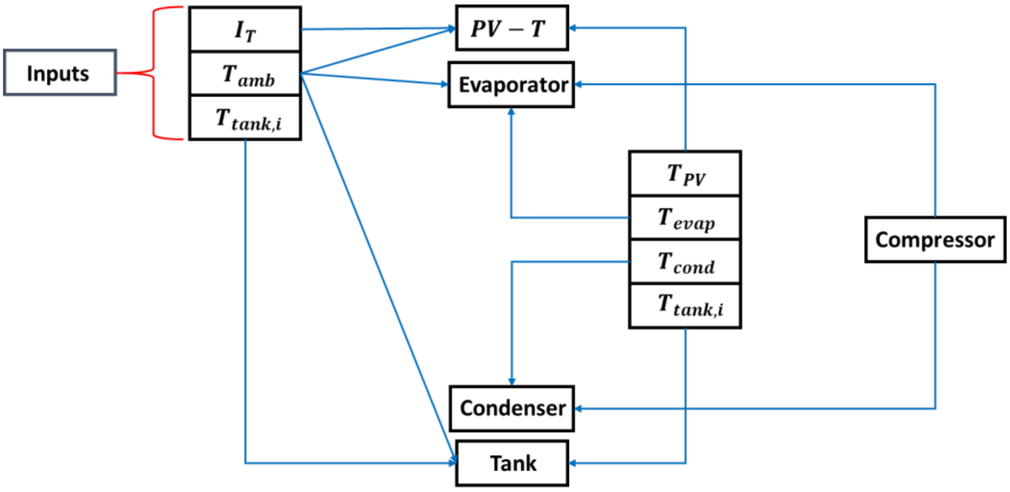

Figure 2. Flow chart of PV-T system with heat pump.

2.6 Electric Shower

Using Eq. 21, the energy consumption ($E_{consumed}$) value can be calculated over the course of a month.

$$E_{consumed} = \frac{P_{shower} * t_{uso} * daymonth}{1000} \quad \text{(kWh/month)} \tag{21}$$

Where $P_{chuveiro}$ represents the power of the shower in the residence in watts, which was 5500 W, t_{uso} is the shower usage time in hours, equating to 10 minutes per person, and $daymonth$ is the number of days within a month.

2.7 Vacuum solar heater

Is a type of solar water heating system that utilizes vacuum glass tubes to capture and retain the sun's heat. These systems provide a highly efficient and sustainable way to supply hot water for residential or commercial use, harnessing the sun's renewable energy. The vacuum glass tubes are the main part of the heating system. They consist of two concentric glass tubes, between which a vacuum is created. These vacuum spaces serve as an excellent thermal insulator, helping to prevent heat loss to the environment. The inner tube is coated with a special material that absorbs solar energy and converts it into heat.

To determine the useful power provided by the solar collectors, the thermal efficiency of the collectors, the area of the collectors, and the incident solar irradiation are considered, as per Eq. 22.

$$P_{collector} = A_{collector} * \eta_{stc} * I_T \quad \text{(W)} \tag{22}$$

Where $P_{collector}$ represents the thermal power in watts, $A_{collector}$ denotes the collector area in square meters, η_c stands for the collector efficiency, and I_T represents the total irradiation in watt-hours per square meter. By subtracting the P collector from the heat absorbed by the tank insulation, the heat absorbed by the water can be calculated as shown in Eq. 23.

$$Q_{water} = P_{collector} - Q_{iso,tank} \quad \text{(W)} \tag{23}$$

2.8 Photovoltaic system

Photovoltaic panels convert the sun's energy into electricity for use in homes, businesses, and other facilities. An important aspect of these systems is the potential to supply the grid with energy generated beyond what is locally consumed. This energy surplus, when fed back into the grid, can result in credits or payments for the owners in certain regions, a practice known as "net metering" or a compensation system.

The selected panel has a total area of A_{PV} equal to 2.83 m². Using this data, one can obtain the efficiency of the photovoltaic panel (η_{PV}) and the power it will generate daily or monthly, expressed by Eq. 24.

$$P_{ele} = I_T * \eta_{STC} * A_{PV} \quad \text{(W)} \tag{24}$$

As panel manufacturers provide the values of irradiance, ambient temperature, and the panel's nominal operating temperature, one can obtain the heat transfer ratio. The operating temperature of the panel is $NOCT$ equals 43±2ºC, $(I_{T,NOTC})$ with an irradiance of 800 W/m², and an ambient temperature of 20ºC, expressed by Eq. 25.

$$\frac{\alpha\tau}{UL} = \left(\frac{NOCT - T_{amb,NOCT}}{I_T}\right) \quad \text{(W)} \tag{25}$$

By determining the global coefficient, it is possible to obtain the operating temperature of the panel (T_{pv}), expressed by Eq. 26, that is, the temperature that is incident on the panel when there is no active cooling system.

$$\bar{T}_{PV} = T_{amb} + \left(\frac{\alpha\tau}{UL} * I_T\right) \quad \text{(°C)} \tag{26}$$

The variation in the efficiency of the photovoltaic panel as a function of the panel's operating temperature(T_{pv}), using the STC conditions, is as per Eq. 27:

$$\eta_{PV} = \eta_{STC} - 0{,}0035 * \left(\bar{T}_{PV} - \bar{T}_{PV,STC}\right) \quad \text{(-)} \tag{27}$$

2.9 Constants used

In the table 1 are presented the values of parameters used in the mathematical model.

Table 1 - Constants used.

CONSTANTS	VALOR	UNIT	CONSTANTS	VALOR	UNIT
A_{evap}	$7{,}8540\ e^{-5}$	m²	η_{stc}	21	%
A_{cond}	$7{,}8540\ e^{-5}$	m²	$\bar{T}_{PV,STC}$	20	ºC
$A_{collector}$	2,4	m²	V_{tank}	300	Liters
A_{pv}	2,83	m²	U_{air}	3.5	W/m²K
A_{tank}	2,64	m²	U_{isol}	0,4	W/m²K
L_{evap}	20	m	$U_{isol,tank}$	2	W/m²K
L_{cond}	20	m	C_b	828	W/m²K
D_{evap}	11	mm	V_d	$3{,}56\ e^{-4}$	m³/s
D_{cond}	11	mm	a_2	-0,0015	-
a_1	0,9121	-	b_2	0,0301	-
b_1	-0,0155	-	c_2	0,4388	-

2.10 Scenario Analysis

Three scenarios are analyzed to enable a comparison between them. Scenario 1 consists of the combination of photovoltaic-thermal panel (PV-T) with a heat pump, which boasts high energy efficiency. PV-T panels generate electricity and heat through the capture of solar energy, while the heat pump utilizes this heat to heat either water or the indoor environment. Efficiency is a significant advantage of this scenario since it optimizes the available solar energy, resulting in considerable energy savings over time and a reduction in carbon emissions. Nevertheless, the initial costs can be higher due to the sophistication of the PV-T system. In scenario 2, electricity generation and water heating are treated as distinct tasks. Photovoltaic panels generate electricity, while a thermal solar heater is used exclusively for heating water. Both systems are highly effective, however, there is a loss of efficiency when electricity is converted into heat for the purposes of heating. Although this scenario's upfront costs are lower, higher long-term operating costs could potentially arise, especially if electricity prices are high in the region. The environmental impact depends on the source of electricity used for the power supply or thermal heater. In scenario 3, the photovoltaic panels generate electricity that powers an electric heater responsible for water heating. This scenario has the lowest energy efficiency of the three since electricity is converted into heat, resulting in significant energy losses. While the initial costs can be reduced due to the simplicity of the system, operating costs, including electricity consumption for heating, can be substantial. In addition, the environmental impact increases because of the efficiency losses in converting electricity to heat, unless the electricity is sourced from renewables.

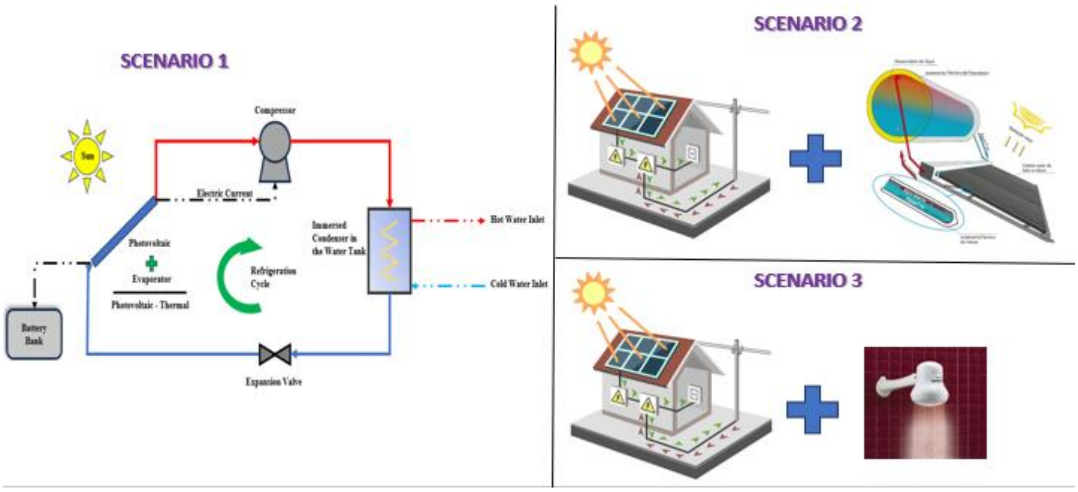

Figure 3 - Three types of scenarios.

3. RESULTS

The results are analyzed for three types of systems: the Vacuum Solar Heater, the On-grid Photovoltaic System, and the PV-T system with a heat pump under study. A one-year period was analyzed, and in this chapter, the monthly and annual tables for these systems will be presented.

3.1 Electric Shower

The energy consumption of a 5500 W electric shower in a domestic setting where three people use the shower once a day for 10 minutes is presented in Table 1. These values can be compared to the energy outputs generated by the three systems to verify if they are capable of meeting the energy needs of the shower.

Table 2. Average monthly and annual shower consumption.

Month	Electricity consumption (kWh/month)
January	85
February	77
March	85
April	83
May	85
June	83
July	85
August	85
September	83
October	85
November	83
December	85
Annual Average	**84**

3.2 Vacuum solar heater

Table 2 displays the system's overall efficiency, defined as the proportion of solar energy successfully converted into usable thermal energy, considering all system losses, such as those occurring in the solar collector, during heat transportation to the point of use, and to the environment. With this analysis, the system's actual thermal energy output can be calculated. It is observed that the generated thermal energy is sufficient to meet the shower's energy consumption. Nonetheless, this system has certain drawbacks, including the need to replace vacuum tubes periodically, which could increase maintenance costs and overall system expenses. Furthermore, in areas with high solar radiation and during periods of low demand for hot water (e.g. summer vacations), the system may overheat. This could cause pressure problems and require the installation of pressure and temperature relief systems.

Table 3 – Vacuum solar heater system averages.

Month	Ambient temperature (°C)	Irradiation (W/m²)	Thermal energy (kWh/month)	Final tank temperature (°C)
January	25	457	286	38
February	24	415	234	36
March	24	414	259	37
April	23	429	259	34
May	21	384	240	31
June	19	388	235	29
July	19	422	264	30
August	24	441	276	36
September	25	399	241	37
October	23	398	249	31
November	24	494	299	36
December	24	414	258	35
Annual Average	**23**	**421**	**258**	**34**

3.3 Photovoltaic system

Table 3 shows that the temperature difference between the room and the solar panel can reach an average of 10°C. The average energy consumption of the shower is 84 kWh/month, and a conventional photovoltaic system produces an average of 78 kWh/month, which means that the energy produced by the photovoltaic panel alone is not able to meet the electrical demand of the shower. In other words, the power supply from the power company would still be necessary.

Table 4 – Averages PV panel.

Month	Ambient temperature (°C)	Irradiation (W/m²)	PV Temperature (°C)	Electricity production (kWh/month)	Average Efficiency do PV
January	25	457	32	85	18,66%
February	24	415	30	70	19,14%
March	24	414	31	78	19,04%
April	23	429	30	79	19,15%
May	21	384	29	76	19,75%
June	19	388	28	76	20,04%
July	19	422	29	84	19,76%
August	24	441	31	82	18,92%
September	25	399	30	76	19,35%
October	23	398	30	73	19,32%
November	24	494	32	84	18,40%
December	24	413	30	77	19,14%
Annual Average	**23**	**421**	**30**	**78**	**19,22%**

3.4 PV-T assisted Heat Pump

In Table 4, the monthly and annual averages of the PV-T system with heat pumps are displayed. When comparing the tank temperatures of the vacuum SWH system, as shown in Table 5, and those of the proposed system, we observe that the tank temperature is higher than in vacuum SWH systems. Specifically, approximately 83.8% of the temperature in the condenser is retained within the tank, and the temperature of the photovoltaic panel without cooling tends to be high, thus impacting the panel's efficiency. However, when a cooling system is introduced, the efficiency tends to increase.

Table 5 - Temperature averages PV-T assisted heat pump.

Month	Irradiation (W/m²)	Condensation temperature (°C)	Evaporation temperature (°C)	PV temperature (°C)	Final tank temperature (°C)
January	457	57,73	16,56	19,78	47,73
February	415	55,89	13,56	16,61	46,43
March	414	57,28	13,73	16,76	47,81
April	429	54,45	13,43	16,51	44,84
May	384	49,88	9,99	12,85	40,83
June	388	47,81	9,27	12,12	38,73
June	422	48,87	11,02	14,03	39,33
Agosto	441	57,05	15,24	18,37	47,28
September	399	57,20	13,71	16,65	48,09
October	398	51,23	11,52	14,49	41,83
November	494	56,18	17,59	21,00	45,57
December	413	54,53	12,38	15,35	45,28
Annual Average	**421**	**54,01**	**13,17**	**16,21**	**44,48**

Table 5 - Averages of efficiencies and energies of PV-T heat pump.

Month	COP	PV Efficiency	Thermal energy (kWh/month)	Electrical energy (kWh/month)	Compressor power (kWh/month)
January	4,73	24,47%	347,39	196,19	95,92
February	4,77	23,70%	232,36	102,33	91,57
March	4,95	23,42%	243,09	120,68	127,84
April	4,11	23,17%	284,72	145,48	109,72
May	4,45	25,18%	230,66	106,39	124,51
June	4,53	22,81%	237,39	113,93	112,79
June	4,5	23,19%	323,95	161,63	109,72
Agosto	4,76	24,54%	248,08	121,61	118,20
September	4,35	24,74%	242,00	108,22	127,84
October	4,57	23,07%	284,93	151,38	127,84
November	4,5	25,47%	286,36	156,76	126,00
December	4,77	25,08%	307,36	175,63	108,69
Annual Average	**4,58**	**24,07%**	**272,36**	**138,35**	**115,05**

3.5 Scenarios energy comparison

Table 6 illustrates a significant increase in electrical energy when compared with photovoltaic systems, reaching approximately twice as much. In other words, the energy generated by the PV-T assisted heat pumps is not only sufficient to supply the energy consumed by the compressor, but also results in surplus energy.

Table 6 – Energy comparison with annual average.

Scenarios	Thermal energy (kWh/month)	Net electricity production (kWh/month)
PV-T BC	272	23
PV+ electric heater	0	-6
PV + vacuum solar collector	258	78

4. CONCLUSION

The PV-T system with heat pumps, using just one photovoltaic panel coupled with an evaporator and utilizing R134a refrigerant under the climatic conditions of Minas Gerais, proved to be efficient enough to provide hot water throughout the day, without any heat loss from the storage tank, and to produce a substantial amount of electrical energy. This energy output is not only sufficient to meet the energy consumed by the compressor but also generates a surplus for domestic use.

The grid-connected system, however, has not been able to produce enough energy from a single panel to satisfy the shower's energy consumption. Moreover, the excess energy is inadequate to meet other household demands.

Comparatively, the vacuum solar heating system is highly unviable compared to the PV-T system with a heat pump. This is first due to the cost of the systems. Despite the DWH being more affordable than a PV-T system with heat pumps, its maintenance cost is higher. This is due to the vacuum system's sensitivity to adverse weather conditions such as frost or hail, which can damage the tubes. Moreover, the system only heats the water and does not generate electricity. Conversely, the PV-T system with heat pumps generates both hot water and electricity simultaneously.

Scenario 1 is a highly efficient option that utilizes PV-T panels to generate electricity and heat in tandem with a heat pump, effectively maximizing the use of solar energy and reducing carbon emissions over time. However, it comes with higher initial costs. Scenario 2, on the other hand, strikes a balance in energy efficiency by conducting electricity generation and water heating separately. Although the upfront costs may be lower, it is crucial to consider the higher long-term operating expenses. The environmental consequences are contingent on the electricity source utilized to power the thermal heater. In Scenario 3, energy efficiency is reduced because of the direct conversion of electricity into heat for heating purposes. Despite having lower initial costs, it can produce higher operating expenses and a greater environmental footprint due to losses in efficiency during the conversion process.

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6. REFERENCES

CHOW, T. T. A review on photovoltaic/thermal hybrid solar technology. Applied Energy, v. 87, n. 2, p. 365–379, 2010. Disponível em: <http://dx.doi.org/10.1016/j.apenergy.2009.06.037>.

DUBEY, Swapnil; SANDHU, G. S.; TIWARI, G. N. Analytical expression for electrical efficiency of PV/T hybrid air collector. Applied Energy, v. 86, n. 5, p. 697–705, 2009. Disponível em: <http://dx.doi.org/10.1016/j.apenergy.2008.09.003>.

HINRICHS, Roger A.; KLEINBACH, Merlin. Energia e Meio Ambiente. Journal of Chemical Information and Modeling, v. 53, n. 9, p. 1689–1699, 2019.

LOSEKANN, Luciano; TAVARES, Felipe Botelho. Política energética no BRICS: desafios da transição energética. Textos para discussão, p. 60, 2019.

OBALANLEGE, Mustapha A. et al. Performance assessment of a hybrid photovoltaic-thermal and heat pump system for solar heating and electricity. Renewable Energy, v. 148, p. 558–572, 2020. Disponível em: <https://doi.org/10.1016/j.renene.2019.10.061>.

PRABHANJAN, Devanahalli G.; RENNIE, Timothy J.; RAGHAVAN, G. S.Vijaya. Natural convection heat transfer from helical coiled tubes. International Journal of Thermal Sciences, v. 43, n. 4, p. 359–365, 2004.

RAJ, N. Thilak; INIYAN, S.; GOIC, Ranko. A review of renewable energy based cogeneration technologies. Renewable and Sustainable Energy Reviews, v. 15, n. 8, p. 3640–3648, 2011. Disponível em: <http://dx.doi.org/10.1016/j.rser.2011.06.003>.

SHAH, Mirza M. Une corrélation unifiée pour le transfert de chaleur durant l'ébullition dans les mini/micro canaux lisses et standards. International Journal of Refrigeration, v. 74, p. 604–624, 2017. Disponível em: <http://dx.doi.org/10.1016/j.ijrefrig.2016.11.023>.

VAISHAK, S.; BHALE, Purnanand V. Performance analysis of a heat pump-based photovoltaic/thermal (PV/T) system. Clean Technologies and Environmental Policy, v. 23, n. 4, p. 1121–1133, 1 maio 2021.

WILLS E WESTIN. Es W W Co M . D W Es. p. 6459, 2018.

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