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ENERGY STUDY OF PHOTOVOLTAIC-THERMAL SOLAR-ASSISTED HEAT PUMP SYSTEMS FOR HOT WATER PRODUCTION IN BRAZIL

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Abstract. Determine using a mathematical model the energy efficiency of a heat pump that takes advantage of solar thermal energy from a photovoltaic panel under the climatic conditions of Itajubá city in Minas Gerais State - Brazil. The heat water and electricity produced simultaneously have the advantage of optimizing the use of physical space and obtaining better energy efficiency when compared to the performance of the equipment separately (photovoltaic panel and solar collector). For the development of the work, the system will be simulated in Matlab software. The mathematical model of the photovoltaic-thermal system (PV/T) includes a set of 4 unknown variables that must be solved simultaneously: temperature of the PV panel, evaporator, condenser, and water in the tank. The results showed that for a PV panel of 2.4m² it is possible to heat on a winter day 300L of water from a temperature of 16°C to 45°C and at the same time generate 2kWh of liquid electricity. For comparison terms, a conventional solar collector would need more than twice the area to achieve the same level of water production.

Keywords: Heat pump, PV/T system, Solar Energy, Water heating

1. INTRODUCTION

In Brazil, the use of solar collectors has reduced this consumption of electricity since 2005, but the number of users who still use electrical resistance in their homes to heat water is high. For example, in the Southeast, which is the most populous region in the country, the consumption of electricity applied to residential water heating, changed from 42% in 2005 to 35% in 2019 (Abrahão & Souza, 2021). On the other hand, the use of photovoltaic solar energy is growing.

Photovoltaic cells (PV), one of the most used solar energy technologies, convert a certain percentage of solar radiation into electricity while a large percentage of this radiation are changed into thermal energy that can be used to heat water, reducing electric energy consumption applied to residential water heating.

The ideal operating temperature for the PV cells was identified to be 25 °C. However, in subtropical regions, during peak sunshine hours, the operating temperature of the PV panel varies between 60 and 80 °C (Vaishak & Bhale, 2021). For the above reason, over the past few decades, researchers developed several passive and active thermal management techniques. Some examples of Passive cooling techniques are fins, heat pipe, PCM, etc. Regarding active cooling techniques it is possible mention the force air and water or refrigerant fluid over the PV module for its thermal

management (Hasanuzzaman et al. 2016). The gain in electrical efficiency with passive cooling is comparatively less when compared to that of active cooling. When is desirable to use the heat extracted from the panels to apply for others practical applications, the additional power requirement of an active cooling technique is a good option. This resulted in the development of a photovoltaic/thermal (PV/T) system. Depending on working fluid employed, PV/T systems are classified as air-, water- and refrigerant-based system. The PV/T system allows to obtain a better space utilization because it is possible produce both heat and electricity together, simultaneously. And, to achieve a higher conversion efficiency over individual solar thermal a PV system.

Refrigerant-based PV/T system involves the integration of evaporator coils of the heat pump and PV module to form a cogeneration type system known as photovoltaic/thermal–solar assisted heat pump (PV/T-SAHP). The conversion efficiency of a PV cell reduces with an increase in operating temperature and the high evaporator temperature is advantageous for heat pump operation. For this reason, a heat pump evaporator and a PV module can be favorably integrated as a single module to form a hybrid system.

Many studies and researchers were executed in refrigerant-based PV/T system. One of them that can be mentioned, reported an average electrical efficiency of 13.4% and COP of 5.4 by Ji et al. (2008a, b). Furthermore, a COP of 7.09 and an overall efficiency of 86% were reported by Tsai (2014, 2015) for a PV/T collector in the form of a roof profile. Mohanraj et al. (2016) reported a COP in the range of 2.80–4.10 for a refrigerant-based PV/T system under the climatic condition of Coimbatore, India, and it was further concluded that triangular tube PV/T collector had enhanced energy performance parameters when compared to the circular tube PV/T collector.

Indirect expansion systems are also of research interest in the past few years. Wang et al. (2015a, b, c) developed one such system with a composite collector that can absorb heat from water and air. In another study, Cai et al. (2017) integrated a PV/T collector and an air source evaporator to gain heat energy from multiple sources. More recently, Bellos and Tzivanidis (2019) carried out an optimization study for a water-based PV/T collector integrated with the heat pump system. From the study, R32 turned out to be the optimum working fluid, followed by R1234yf. Bellos et al. (2019) also investigated the performance of a heat pump integrated with a nano-fluid-based PV/T collector. Two nano-fluids, namely water/Cu and water/Al$_2$O$_3$ were tested in the system. It was concluded that with the use of nano-fluids, the heating production of the system increased by 5.75% and 5.30% for water/Cu and water/Al$_2$O$_3$, respectively. Previously, based on another study, Bellos et al. (2016) concluded that the integration of water-based PV/T collectors with a heat pump reduces the grid dependence which makes the system more environmentally friendly.

In view of the studies mentioned above, it is possible to see the great potential of this technology easily. PV/T assisted system have higher performance than the conventional system. In addition, these systems are more effective, and the payback time decreases down to 10 years in mild climates. Since the performance of PV/T is highly dependent on climate conditions, it is important investigate the performance under different climatic conditions. Therefore, it is expected that the work proposed in this article, simulating a mathematical model for the climatic conditions of the city of Itajubá in the state of Minas Gerais, can contribute in some way to the understanding and development of Photovoltaic Solar Thermal technology.

2. METHODOLOGY

The figure 1 shows the diagram of PV/T assisted by Heat Pump have chosen for study and be simulated by mathematical model. The schematic model works as following: There is an evaporator that removes excess heat from the photovoltaic panel. After, the refrigerant fluid is compressed by the compressor and pass through the condenser. The condenser shown is a coil of copper tube that is immersed in the tank. After the heat exchange that takes place in the condenser, the fluid leaves at a lower temperature, but still at a high pressure. Then the refrigerant fluid passes through the expansion valve where its pressure is reduced and returns to the photovoltaic panel, evaporator and insulation set, thus closing the cycle of the studied model. The mathematical model has the following considerations:

-The pressure drop by refrigerant flow is neglected
-The isentropic efficiency of compressor is constant
-The heat transfer by conduction of copper or aluminum is negligible
-The thermostatic expansion valve guarantees a constant superheated degree in the evaporator
-The water in tank is unstratified effect of temperature
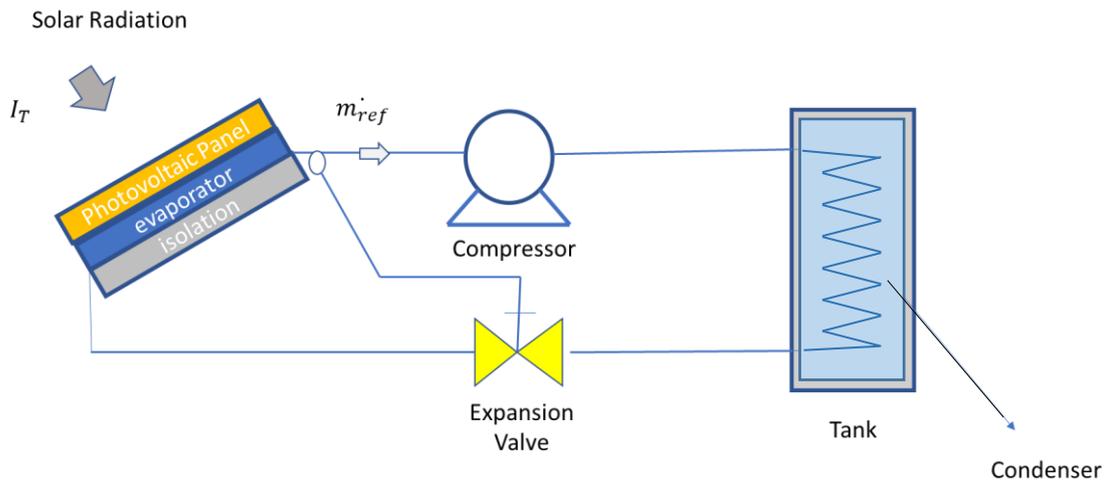-The steady state is achieved in the first minutes of each hour.

Figure 1. Diagram of PV/ T System

Figure 2 shows a refrigeration system works through a Pxh graphic for the vapor compression cycle. The thermodynamic equations help in the analysis of the mass and energy balance from the internal point of view - refrigerant fluid.

$$\dot{Q}_{evap} = \dot{m}_{ref}(h_{suc} - h_{valv}) \quad (W) \tag{1}$$

where $\dot{Q}_{evap}$ is evaporator heat, $\dot{m}_{ref}$ is refrigerant mass, h_{suc} is suction enthalpy in the compressor and h_{valv} is suction at valve enthalpy.

$$\dot{Q}_{cond} = m_{ref}(h_{des} - h_{valv}) \quad (W) \tag{2}$$

where Q_{cond}, h_{des} are condenser heat and compressor discharge enthalpy, respectively.

$$\dot{W}_{comp} = m_{ref}(h_{des} - h_{suc}) \quad (W) \tag{3}$$

where $\dot{W}_{comp}$ is compressor work.

$$h_{des} = \frac{(h_{isen} - h_{suc})}{\eta_{isen}} + h_{suc} \quad (kJ/kg) \tag{4}$$

where h_{isen}, η_{isen} are isentropic enthalpy outlet and isentropic efficiency of compressor, respectively.
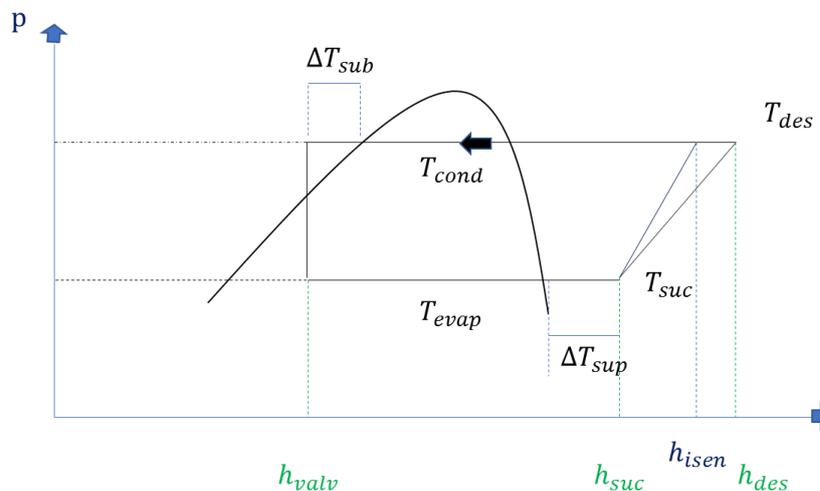

Figure 2. Vapor Compressor Cycle Model

2.1 COMPRESSOR MODEL

The mass flow of compressor depends on evaporation and condensation temperatures:

$$\dot{m}_{ref} = \eta_{vd} \cdot \rho_{suc} \cdot V_d \qquad (kg/s) \tag{5}$$

$$\eta_{vd} = 1 - r_{m,ef}\left(\left(\frac{p_{cond}}{p_{evap}}\right)^{\frac{1}{k}} - 1\right) \quad (-) \tag{6}$$

where V_d, $r_{m,ef}$ are displacement volume, and effective clearance ratio of compressor, respectively. and k is a isentropic coefficient of fluid.

2.2 EVAPORATOR MODEL

The figure 3 shows the internal configuration inside the evaporator. The evaporator is made for square mini channels of aluminum, assembled in top with a poli-crystalline silicon PV panel of length of 2m and width of 1.2m. The panel photovoltaic heat ($\dot{Q}_{PV}$) is the solar energy that can't be converted to electricity. The PV panel can be transfer heat with air and evaporator. Additionally, the evaporator exchange heat on the bottom of isolation.
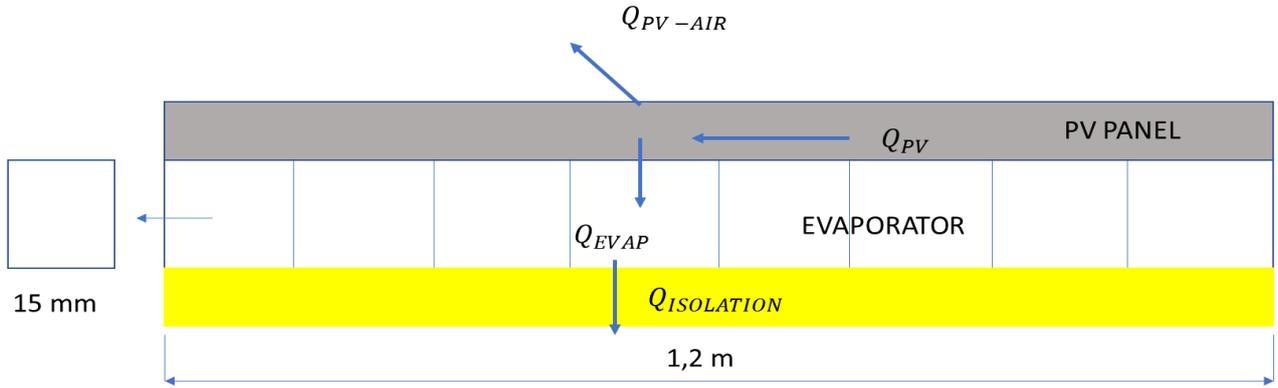

Figure 3. Evaporator Model

The energy balance in the evaporator is:

$$\dot{Q}_{evap} = \dot{Q}_{pv} - \dot{Q}_{isol} - \dot{Q}_{pv-air} \qquad (W) \tag{7}$$

$$\dot{P}_{ele} = I_T \cdot \eta_{PV} \cdot A_{PV} \qquad (W) \tag{8}$$

$$\dot{Q}_{pv} = I_T \cdot (1 - \eta_{PV}) \cdot A_{pv} \qquad (W) \tag{9}$$

where I_T, η_{PV}, A_{PV} are irradiation, efficiency, and area of PV panel, respectively.

$$\dot{Q}_{isol} = U_{isol} \cdot A_{evap}(T_{air} - T_{evap}) \qquad (W) \tag{10}$$

where $\dot{Q}_{isol}, U_{isol}, A_{evap}, T_{air}, T_{evap}$ are isolation loss heat, heat transfer coefficient of isolation, evaporator area, air temperature and evaporation refrigerant temperature.

$$\dot{Q}_{evap} = \bar{U}_{evap} \cdot A_{evap} \cdot (T_{pv} - T_{evap}) \qquad (W) \tag{11}$$

where T_{pv} are PV panel temperature. $\bar{U}_{evap}$ is the average coefficient of heat transfer for refrigerant fluid from evaporator. For vapor flow, the Gnielinski (1976) correlation is used, which is valid for flow with $2300 < Re < 10000$. While for the two-phase flow, it is calculated using Shah (2017) correlation which is valid for micro, mini and macro-channels

$$\dot{Q}_{pv-air} = U_{air}.A_{pv}.(T_{pv} - T_{air}) \quad (W) \tag{12}$$

where $\dot{Q}_{pv-air}$, is heat between photovoltaic panel and the air, and U_{air} is heat transfer coefficient of air.
Finally, the efficiency of PV panel depends on the reference conditions given by manufacturer

$$\eta_{vp} = 0.2(1 - 0.0035(T_{pv} - 45)) \quad (-) \tag{13}$$

In the model of evaporator, the input is the air temperature, solar radiation and the mass flow refrigerant of compressor, the Eq. 1 and 7 should be resolved simultaneously to find T_{pv} e T_{evap} unknown.

2.3 CONDENSER MODEL

The condenser is a round helical coiled tube submerse in the water tank, where the fluid refrigerant flows inside of it. The tank has heat losses $Q_{isol,tank}$ to environment. The energy balance in the tank is:

$$\dot{Q}_{water} = \dot{Q}_{cond} - Q_{isol,tank} \quad (W) \tag{14}$$

$$\dot{Q}_{isol} = U_{iso,tank}.A_{s,tank}.(T_w - T_{air}) \quad (W) \tag{15}$$

where $U_{iso,tank}$, $A_{s,tank}$ are heat loss of the tank walls by conduction and superficial area of tank, respectively.

$$\dot{Q}_{water} = m_w cp_w. \frac{(T_W - T_{w,i})}{\Delta t} \quad (W) \tag{16}$$

where $\dot{Q}_{water}$, m_w, cp_w, T_W, $T_{w,i}$ and Δt are water heat, water mass in the tank, specific heat of water, water temperature, initial water temperature and time variation.

$$\dot{Q}_{cond} = \bar{U}_{cond}.A_{cond}.(T_{cond} - T_w) \quad (W) \tag{17}$$

where $\dot{Q}_{cond}$, $\bar{U}_{cond}$, A_{cond}, T_{cond} are condenser heat, heat transfer coefficient condenser, superficial area of coil, and condenser temperature, respectively.

$$A_{cond} = L_{sep}.D_{cond}.\pi \quad (m^2) \tag{18}$$

where A_{cond}, L_{sep}, D_{cond} are condenser area, coil length, and diameter of coil tube, respectively.

$$\bar{U}_{cond} = \left(\frac{1}{HTC_{cond,int}} + \frac{1}{HTC_{cond,ext}}\right)^{-1} \tag{19}$$

where $\overline{HTC}_{cond,int}$ is the average coefficient heat transfer of refrigerant. It used the Shah (2016) correlation for two-phase flow and the Gnielinski (1976) correlation for liquid and vapor phase. The $\overline{HTC}_{cond,ext}$ is the average coefficient heat transfer of water side, correlation Devannahalli (2004) was chosen, because was developed to specific conditions of tank of this model.

In the model of condenser, mass flow refrigerant of compressor and initial water temperature, the Eq. 2 and 14 should be resolved simultaneously to find T_{cond} e T_w unknown.

3. RESULTS

The mathematical model was applied for a case study, using the conditions of solar radiation and air temperature of Itajubá city provided from the UNIFEI meteorological station. The chosen day belong to winter season in June 2022. The PV/T system was dimensioned considering a family residence for 4 people. Thus, according to the NBR 15569 (ABNT, 2008) standard, a tank with a volume of 300L was defined. Other values adopted for the simulation are shown in table 1. The refrigerant fluid chosen was R1234yf, a fluid that is part of the fourth generation with low global warming potential (GWP <1) that has recently started to be sold in Brazil. Regarding water consumption, it was considered that the greatest demand will be at night after 6:00 pm.

Table 1. Values of parameter of PV/T system

Parameter	Parameter
$L_{PV} = 2.0\ m$	$\Delta T_{sup} = 5\ K$
$w_{PV} = 1.2\ m$	$\Delta T_{sub} = 5\ K$
$h_{channel} = 0.015\ m$	$U_{air} = 3.5\ W/m^2 K$
$w_{channel} = 0.015\ m$	$V_d = 1.5 m^3/h$
$V_{tank} = 0.3\ m^3$	$\eta_{isen} = 0.6$
$D_{tank} = 0.55\ m$	$r_{m,ef} = 0.25$
$U_{isol,tank} = 0.4\ W/m^2 K$	$D_{cond} = 0.01\ m$
$U_{iso} = 2\ W/m^2 K$	$L_{cond} = 20\ m$

Figure 4 shows the results of the simulation of the equilibrium temperatures of the PV panel, evaporator, condenser, and water stored in the tank. According to the manufacturer, the PV panel for an ambient temperature of 20°C and a solar radiation of 800W/m² the operating temperature of the panel is 45°C without any type of cooling system, in comparison, figure 4 shows that using the system cooling temperature for simulated conditions ($T_{air} = 26$°C, $I_T = 707\ W/m^2$) at 12:00, the panel temperature is 20°C, a reduction of 25°C. This fact improves the panel efficiency from 20% (@T_PV=45°C) to 36% (@T_PV=20°C). On the other hand, the thermal energy absorbed from solar radiation and the external environment, allowed the water to reach a temperature at the end of the day of 45°C, very close to the recommendation of the NBR 15569 standard, which is 50°C for the volume of the tank and number of people chosen.
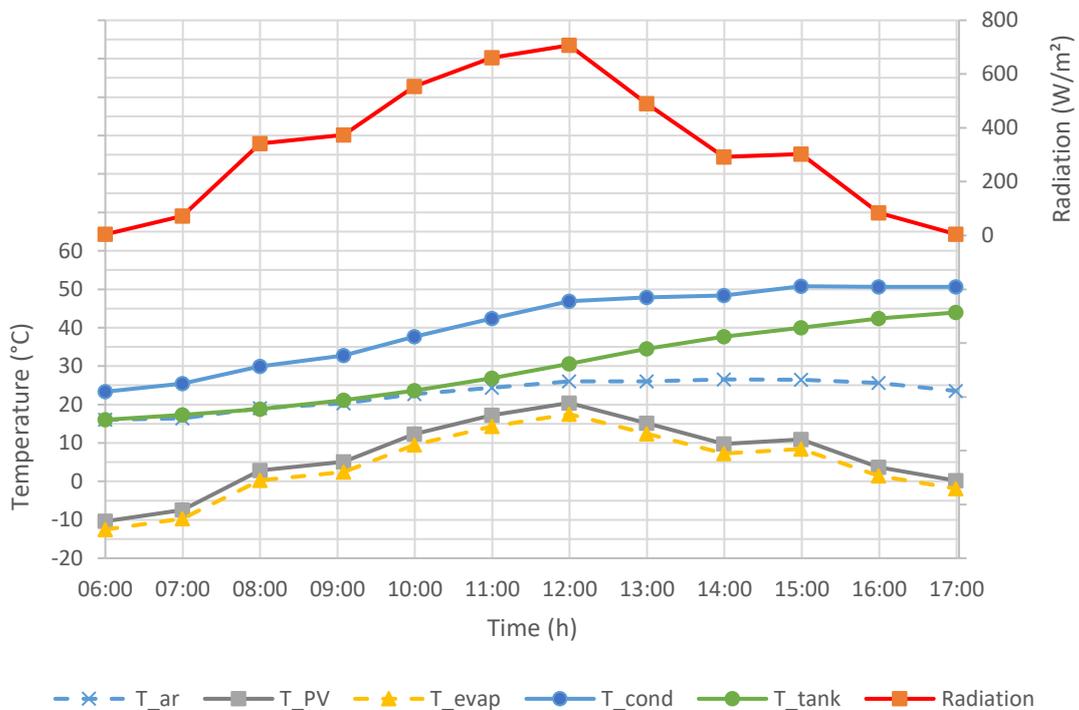

Figure 4. Temperature and radiation profile for the day 06/22/2022 in Itajubá MG, Brazil

Figure 5 shows the results of electrical power produced by the PV panel, heat stored in the water and work consumed by the heat pump compressor. The PV panel reaches a peak power of 623W at 12 pm. The compressor's work varies between 90 and 200W throughout the day. The heat stored in the tank varies between 450 and 1380W, including periods of very low solar radiation. In terms of energy, the figure 5 allows calculating that the PV/T system transforms solar energy using an area of 2.4m² into 3.7kWh of electrical energy and 10.3kWh of thermal energy, consuming 1.7kWh of electrical energy by the compressor. Therefore, calculating the net electrical energy would be 1.9kWh.
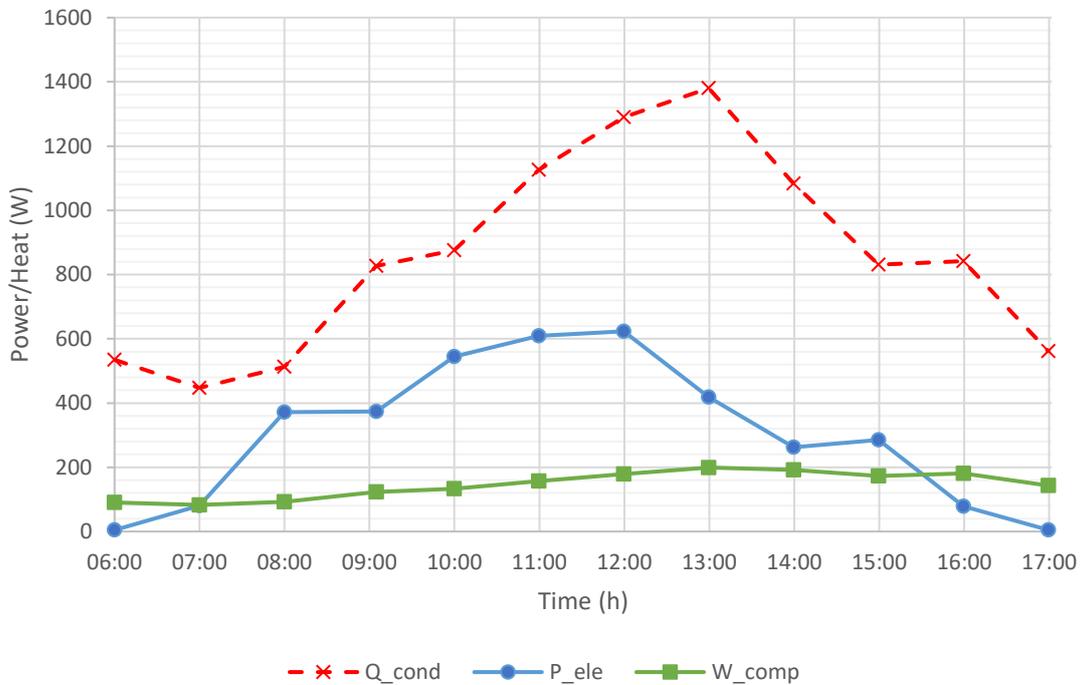

Figure 5 – Electric Power produced by PV/T, Work consumed by Compressor, Heat stored in Tank

Compressor size is one of the parameters that most affect system performance. Larger compressors mean higher photovoltaic efficiency and higher heat for hot water, but it means higher consumption. Table 2 presents the summary of results obtained when there was a variation in volumetric displacement of the compressor.

Table 2. Results for different sizes of compressors

	$V_d = 1.5\ m^3/h$	$V_d = 2.0\ m^3/h$
Final temperature of water (°C)	45,0	47.5
$P_{ele,max}$ (W)	609.4	648.7
$E_{ele,PV,day}$ (kWh)	3.7	3.8
$E_{comp,day}$ (kWh)	1.7	2.2
$E_{ele,net,day}$ (kWh)	1.9	1.6
$E_{water,day}$ (kWh)	10.3	11.2
$E_{T,net,day}$ (kWh)	12.2	12.8
COP_{max} (kWh)	7.2	5.9

The results of Tab. 2 show that net electricity production ($E_{ele,net,day}$) decrease with upsize of compressor, however, energy to heat water ($E_{water,day}$) increase. The total energy produced ($E_{T,net,day}$) increase because the work of compressor became heat to condenser. From Fig. 4 can be calculated that the solar energy available is 31.1kWh, the global efficiency of system is increased in 2% from the 39% to 41% when the size of compressor increase. It is important highlight that the limit to increase of displacement volume of compressor will be when its consumption ($E_{comp,day}$) be the same to energy produced by PV panel ($E_{ele,PV,day}$) and the net electricity ($E_{ele,net,day}$) decrease to zero.

Other information from the Tab.2 is the coefficient of performance ($COP = Q_{cond}/W_{comp}$) of heat pump cycle. The maximum COP_{max} occurs at the maximum solar radiation when the evaporation and condensation temperature are closer between them. The COP_{max} decrease with the increasing of size compressor.

4. CONCLUSIONS

A hybrid system that harnesses solar energy using a solar panel as an electrical energy generator and thermal energy collector along with a heat pump to store this heat in a water tank was mathematically modeled. For the case analyzed, the system showed advantages such as: (1) cooling of the photovoltaic panel leading to an improvement in the efficiency of electrical energy conversion. (2) The net electrical energy is positive despite the consumption of the compressor. (3) The consumption of the compressor is justified by the increase in the capture of thermal energy. (4) Adding the electrical and thermal energy used by the PV/T panel, it is possible to check an increase in the use of area when compared to the simple use of the PV panel. (5) The system allows water heating even with low/no solar radiation.

A highlight of PV panel with heat pump is use of space, according with NBR 15569 (ABNT, 2008) in similar conditions, a family of four people need approximately 6m² of conventional solar collector to store 300L of water at 50°C. PV panel with heat pump require 2.5-2.8m² to achieve the same goal, because the heat pump also take energy from air environmental when the solar radiation is low.

These results are considered preliminary, as future work is expected to study in more detail the effects of other parameters on the system such as tank volume, level of thermal insulation in the PV panel, as well as simulating a longer time range and using profiles of different hot water consumption. The biggest disadvantage expected of the system are the economic aspects, the initial investment of the PV/T system needs to be studied and the use of a separate PV panel and a water heating system (electric, gas burner or solar collector) must be compared.

5. ACKNOWLEGEMENTS

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