ANALYSIS AND APPLICATION OF COMBINED PHOTOVOLTAIC/THERMAL (PV/T) FLAT-PLATE COLLECTORS FOR LOW-INCOME RESIDENCES IN BRAZIL

L. Tachon – dr.loic.tachon@gmail.com
H. L. Hipolito – henriqueluishipolito@gmail.com
J. C. Passos – julio.passos@ufsc.com.br
Universidade Federal de Santa Catarina, Brazil, Departamento de Engenharia Mecânica

Abstract. *In recent years there has been growing interest in Hybrid Photovoltaic/Thermal (PV/T) systems for different applications that require hot water and electricity. The hybrid system integrates the features of photovoltaic and solar thermal systems in one combined and more efficient component, reducing material, installation and maintenance costs and also the installation space. Moreover, the electricity production of a hybrid PV system can be significantly higher than that of a standard PV module, because the cell temperatures change according to the amount of heat removed by the heat exchanger installed below the panel and this directly influences the panel efficiency. The water used in the heat exchanger will be heated to the desired temperature for consumption, which will be controlled according to the water flow. Based on these considerations, the aim of this paper is to calculate and analyze the optimal installation of a PV/T system for a low-income residence, according to the demand for electricity and hot water in different Brazilian cities. Simulations of water-based PV/T systems for domestic application were performed with TRNSYS software followed by a detailed energetic analysis. The parameters used in the software were developed from theoretical equations.*

Keywords: *PV-T collector; Photovoltaic panel; Thermal collector; TRNSYS; Brazil*

1. INTRODUCTION

With the prospect of the increased use of renewable energy and more efficient buildings in the near future, photovoltaic/thermal (PV/T) panels will play a key role in energy production. Currently, solar energy (thermal or electrical) is generated through solar thermal collectors or photovoltaic panels separately. A PV/T panel is a device which produces not only electrical but also thermal energy. With this approach a greater amount of solar energy can be converted into useful energy per unit surface area. The benefits of PV/T technology can also be observed in potential savings in material, maintenance and installation costs. Moreover, it has been observed that the electrical energy production in a PV/T system is higher in comparison with conventional photovoltaic panels, because the water circulation reduces the cell temperature. Tests show that in crystalline silicon cells every 1°C rise in the working temperature reduces the photovoltaic efficiency by 0.45 (Evans, 1977).

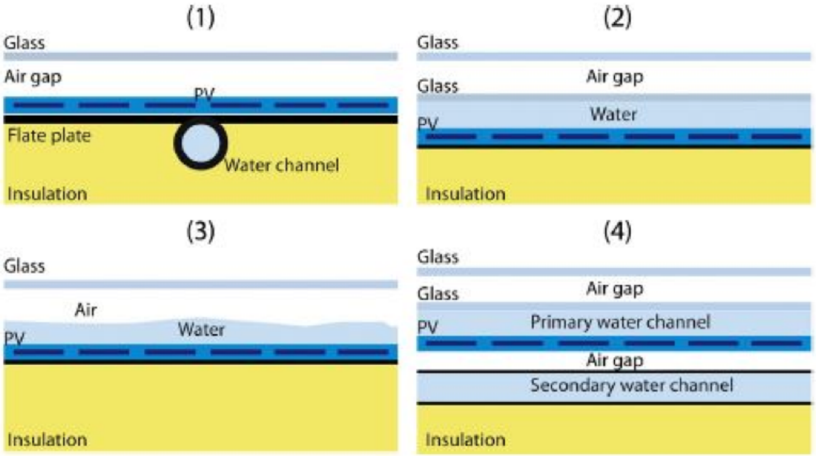

Figure 1- Various design configurations: (1) sheet-and-tube, (2) channel box, (3) free flow, (4) two-absorber (Niccolò Aste, 2014).

Initially, studies were carried out using air as the working fluid because of the simplicity and low cost aspects of the system. Furthermore, it has been noted that a water system can achieved higher overall heat exchange efficiencies than an air system due to the greater density and thermal capacity of water. In addition, hot water can be stored much more easily than air. In this context, more recently investigated PV/T technologies are based on water thermal fluid systems (IBRAHIM, et al., 2009).

In this context, (H.A. Zondag, 2003) classified the PV/T collector designs into four main categories as shown in Figure 1: (1) sheet-and-tube PV/T, (2) channel PV/T, (3) free flow PV/T, (4) two-absorber PV/T.

The *sheet-and-tube type* (1) represents the simplest way to construct a PV/T collector. It consists of a channeled plate, made of metal or, more recently, of a polymeric material, overlaid by a laminated photovoltaic cell. The thermal insulation of this design can be improved by increasing the number of top covers. Nevertheless, the electrical efficiency will be reduced. The sheet and tube configuration can also be used without a glass cover, resulting in a reduction in the thermal efficiency and an increase in the electrical efficiency.

In the *channel PV/T type* (2), the fluid channel is located on top of the PV panel. This configuration can reduce the electrical performance due to interference in the absorption spectrum of the PV panel caused by the fluid. Another disadvantage of this design is the need to use very thick glass in order to support the fluid pressure, especially when water is used, resulting in a heavy and less efficient construction.

In the *free flow PV/T type* (3) the fluid flows unrestrained over the PV panel. In comparison to the *channel PV/T type*, this design eliminates one glass layer, reducing the reflection, weight and material costs. However, due to the difficulty associated with building a free surface, which could lead to the formation of condensation on the cover, this configuration remains purely theoretical.

The *two-absorber PV/T type* (4) consists of a transparent PV laminate as a primary absorber and a black metal plate as a secondary absorber. The heat transfer fluid flows both above the PV panel and below it, spaced by a layer of air, where the second channel is located. This design provides better heat exchange from the PV panel, but has a much more complex construction than the other types, increasing the weight and final cost.

In studies by (H.A. Zondag, 2003) the authors concluded that the electrical performance of the *sheet-and-tube type* is higher than those of the other designs and also this PV/T collector is easier to build. (G. Fraisse, 2007) analyzed configurations of the covered and uncovered PV/T designs and concluded that, from a thermal point of view, the covered collectors have higher performance than the uncovered collectors, due to lower convection and radiation losses. Depending on the type of collector, the thermal performance gain can vary between 10% and 30%.

On the other hand, the electrical performance can decrease significantly (1-10%) due to the thermal dependence of the cell efficiency. Consequently, for almost all kinds of applications, the uncovered PV/T construction seems more appropriate even though the thermal efficiency is lower.

In a hot country like Brazil, the thermal dependency of the solar cell efficiency decreases the electrical production of photovoltaic panel considerably. The temperature can easily reach 60 °C and thus the PV/T solution is of great interest for producing electricity and hot water for direct domestic use with a higher efficiency. A study by (R.M. da Silva, 2010) shows that the PV/T technology produces more electrical energy than the PV collectors and it was almost able to satisfy the thermal and electrical energy needs of a family house in Cape Verde. In other studies, (Huang, 2013) and (Swapnil Dubey, 2013), it was shown that the tropical climates of Taiwan and Singapore are ideal for PV/T technology. However, no global studies for Brazil could be found in the literature.

Given the current energy scenario in Brazil, where the energy tariffs are rising and the risk of blackouts is becoming higher, a new technology like this could offer an excellent solution for the modification of the energy grid. Furthermore, the Brazilian government is seeking solutions for building low-income residences that are energy self-sufficient, providing the basis for the main objective of this paper.

In this context, the aim of this study was to develop a simulation method, with the TRNSYS software, based on a theoretical approach to PV/T. This theoretical approach demonstrates how some TRNSYS parameters can be defined, depending on the PV/T design, based on a physical model. After characterizing the TRNSYS model it was applied to simulations for low-income residences in different cities in Brazil. The results of the applications were then analyzed and compared with those obtained for a PV system.

2. MATERIALS AND METHODS

The software used was TRNSYS, developed at the University of Wisconsin, which is an extremely flexible tool used to simulate the performance of transient systems, where several dynamic models can be coupled.

To facilitate the identification of the components an information flow diagram was built for the system. In this flow diagram each component is represented as a box which requires a number of constant PARAMETERS and time-dependent INPUTS and produces time-dependent OUTPUTS. An information flow diagram can highlight the manner in which all system components are interconnected. The information flow diagram built for the mathematical model proposed herein can be seen in Figure 2.

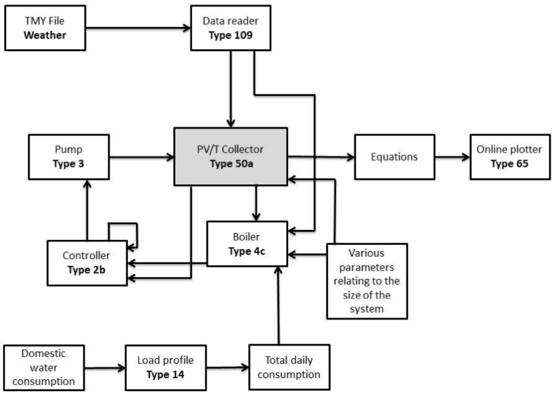

Figure 2- TRNSYS information flow diagram for the hybrid PVT solar system.

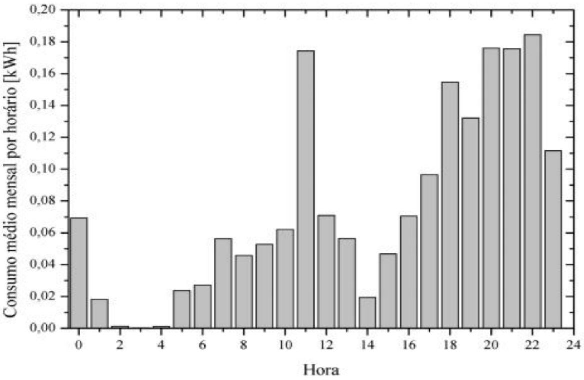

Figure 3- Load profile produced by (Salazar, 2004). (Average monthly water consumption per hour over a period of 24 h)

Each TYPE number shown in Figure 2 represents a component of the system modelled by a Fortran subroutine. Most of the TYPES components also have a UNIT number which specifies different configurations of the TYPE.

2.1 Description of the components

Data Reader Type 109:

The Data Reader component (TYPE 109) serves the main purpose of reading the weather data at regular time intervals from a data file. The meteorological data used in this study was obtained from "The Solar and Wind Energy Resource Assessment (SWERA)" for several cities.

The meteorological data files correspond to a typical year that best represents the analysis period. Thus, the typical year is formed by months originated from different years. With this data it is possible to simulate the system in different cities for different periods of time.

Load Profile – Type 14:

(Salazar, 2004), in his master's thesis for the Federal University of Santa Catarina, provided a large number of hot water consumption profiles and produced the profile that best represents the real impact caused by the hot water consumption in the solar collector and associated with the energy demand. The load profile used as a reference in this paper can be seen in Figure 3. The load profile shown in Figure 3 is applied in the Load Profile - TYPE 14 of the TRNSYS simulation in such a way that the sum of the daily hot water consumption becomes 1. Therefore, to simulate different daily consumptions, a multiplier was connected to the load profile.

The Brazilian Standard for hot water installations in buildings (NBR 7198/82 - *Instalações Prediais de Água Quente*) establishes that the minimum requirement for hot water installations in residences with modest hot water consumption is 36 liters per person per day.

Therefore, in a modest/low-income house, which will be the focus of this paper, with four inhabitants, the daily consumption of hot water will be on average around 150 liters per day. The above-mentioned Brazilian Standard also considers that the hot water temperature should be between 35 and 50°C to provide acceptable comfort for personal use and for bathing. Thus, for calculation purposes, the hot water temperature will be considered to be 45°C.

Boiler – Type 4a

The storage tank (boiler) stores the heated water provided by the solar collector. The tank considered herein does not have an internal auxiliary heating system, since this would result in a lower overall efficiency. The temperature gradient inside the tank can be modelled with N nodes. If N is equal to 1, the tank is considered as a fully-mixed tank and no stratification effects need to be considered.

According to (Oberndorfer, 1999), the stratified model is a good approximation of the real model and these authors concluded that, based on ten volume segments, there is no difference in the annual results and usually three to five segments are sufficient. Therefore, a storage tank with five different volume segments will be adopted.

PV/T Collector – Type 50a

Type 50a is a component used in TRNSYS to simulate a hybrid photovoltaic/thermal collector. Of the four PV/T types available in the TRNSYS library, type 50a was chosen mainly because this component has provided more realistic results in many studies in comparison with other types.

The mathematical model of the hybrid thermal/electric flat-plate collector used in TRNSYS originates from the thermal analysis of a conventional flat-plate collector developed by (Hottel H.C, 1942). This conventional model is reviewed in a book by (Duffie, 2013).

2.2 Description of the PVT model

In 1978 (Florschuetz, 1979) developed the first mathematical formulations for photovoltaic/thermal collectors by extending and adapting the Hottel-Whillier model. This model is thoroughly reviewed in the book by (Duffie 2013). The method presented herein is strongly based on this model. As shown on Figure 4-5, the solar radiation, S, which has been absorbed by the cell after crossing the transparent glass laminated on the cell is partially considered as useful energy, Q_u, and partially considered as thermal and optical loss, Q_{loss}.

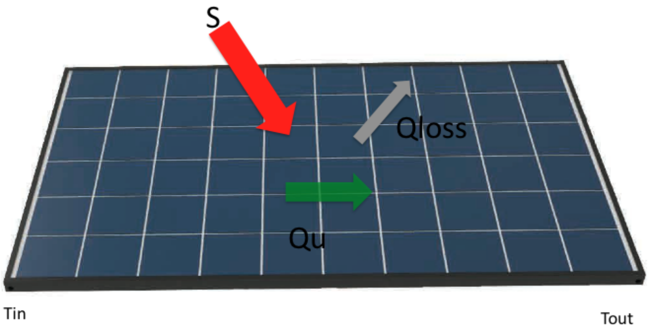

Figure 4- Energy Balance for PV/T.

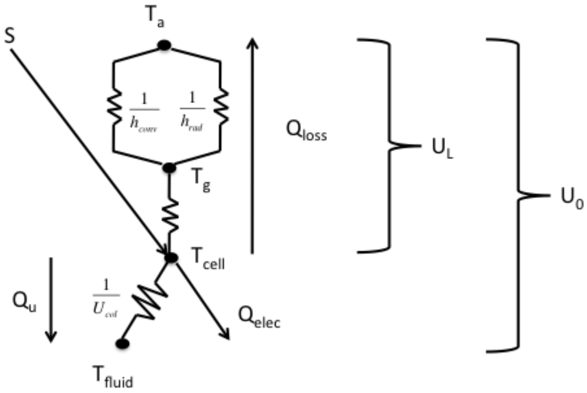

Figure 5- Equivalent thermal network for PV/T.

An energy balance allows us to write:

$$S = Q_u + Q_{loss} \tag{1}$$

where Q_{loss} is composed of radiation and convection losses which are mainly dependent on the cell temperature and the air temperature. Q_u is the useful energy absorbed by the system as thermal (Q_{th}) and electrical (Q_{elec}) energy. The part of Q_u that is not transformed into electrical energy is exchanged with a fluid after conduction and convection transfer in the lower part of the panel. The capacity of the PV/T design to transfer this thermal energy is characterized by U_{col}. The value of U_{col} is strongly dependent on the PV/T technology. An equivalent thermal network is shown in Figure 5. From Figure 5 we can deduce the following equation:

$$Q_u = Q_{th} + Q_{elec} = A_c\left[S - U_L\left(T_{cell} - T_a\right)\right] \tag{2}$$

Where U_L corresponds to an overall heat loss coefficient. The cell efficiency, η, can be defined as the ratio of the electrical output to the incident energy. Thus, the local electrical output can be written as:

$$Q_e = A_c q_e = A_c \eta \frac{S}{\alpha} \tag{3}$$

Where α is the laminated glass on the cell transparency. The temperature dependence of the cell efficiency is defined by (Evans D. L., 1981) as:

$$\eta = \eta_r\left[1 - \beta\left(T_{cell} - T_r\right)\right] \tag{4}$$

Where η is the cell efficiency, η_r is the cell efficiency under reference conditions, β is the temperature coefficient, T_{cell} is the cell temperature and T_r is the reference temperature. Studies show that the temperature coefficient for a polycrystalline panel is around 0.0045/°C.

Combining these equations and considering than T_r is close to the ambient temperature T_a, we can deduce the following equations:

$$Q_{th} = A_c\left[\tilde{S} - \tilde{U}_L\left(T_{cell} - T_a\right)\right] = \dot{m} C_p\left(T_{out} - T_{in}\right) \tag{5}$$

Where, $\tilde{S} = S\left(1 - \frac{\eta_r}{\alpha}\right)$ and $\tilde{U}_L = U_L - \eta_r \beta_r \frac{S}{\alpha}$.

It is more convenient to write this equation as a function of the fluid temperature. Therefore, (Duffie 2013) introduced a new parameter, F', which represents the relationship between the resistance to heat transfer from the cells to the ambient air and from the fluid to the ambient air.

$$F' = \frac{U_0}{U_L} \tag{6}$$

F' represents the ratio of the actual useful thermal energy gain to the useful thermal energy gain that would result if the absorbing surface of the collector had been at the local fluid temperature. The value of F' is totally dependent on the PV/T technology. Consequently, the previous equation becomes:

$$Q_{th} = A_c F' \left[\tilde{S} - \tilde{U}_L \left(T - T_a \right) \right] = \dot{m} C_p \left(T_{out} - T_{in} \right) \tag{7}$$

Where T is the fluid temperature.

The TRNSYS model type 50a is based on this description of the equation model. Consequently, several parameters that characterize the PV/T technology have to be computed, for instance:

- F' referred to as the "collector fin efficiency factor"
- U_L referred to as the "collector loss coefficient"

Other parameters are the physical properties of the PV/T components (α, τ, β_r and η_r). Considering a linear approximation of the temperature profile, the average and the outlet fluid temperatures can be computed with the inlet temperature as an input value.

2.3 Computation of the TRNSYS parameters F' and U_L

Based on Figure 5, we have:

$$U_L = \frac{1}{\frac{e_g}{\lambda_g} + \frac{1}{h_{rad} + h_{conv}}} \tag{8}$$

Where e_g and λ_g are, respectively, the thickness and thermal conductivity of the glass (laminated on the cell). As recommended by (Bhattarai, 2011), the convective coefficient in forced flow for a tilted surface can be calculated with the following equation:

$$h_{conv} = 2.8 + 3U_{wind} \tag{9}$$

The radiation coefficient is computed as:

$$h_{rad} = \frac{\sigma \varepsilon_{glass} \left(T_{glass} + T_s \right) \left(T_{glass}^2 + T_s^2 \right) \left(T_{glass} - T_s \right)}{T_{glass} - T_a} \tag{10}$$

Where T_{glass} is considered equal to the NOCT temperature (313 K in this case). This approximation allowed us to consider a constant radiation coefficient and is 5% accurate for the considered temperature. T_s is the sky temperature defined by (Swinbank, 1963)

$$T_{sky} = 0.0552 T_a^{1,5} \tag{11}$$

This leads to the following value for the modified overall loss coefficient: $\tilde{U}_L = 15.65 W/m^2K$.

According to the Figure 5, we have:

$$U_0 = \frac{1}{\frac{1}{\tilde{U}_L} + \frac{1}{U_{col}}} \tag{12}$$

Where U_{col} contains the convective heat transfer between the heat exchanger and the fluid as well as the conductive heat transfer in the lower part of the cell of the PV/T system. The convective heat transfer coefficient is calculated according to the equation proposed by (Bejan, 2013) for laminar flow and is 1077 W/m^2K. The equivalent conductance of the lower part of the PV/T system is 210 W/m^{2}K. This value is strongly dependent on the PV/T technology.

Thus, $U_0 = 14.37 W/m^2K$ and consequently, $F' = 0.92$.

2.3 Summary of the reference parameters used for the simulation

Table 1 – Main design parameters used in TRNSYS

DESIGN PARAMETERS	VALUES
Collector area	1.6 m^2
Number of collectors	3
Water consumption	150 L/day
Tank volume	= Water consumption
Water temperature for consumption	45°C
Pump flow rate	50 kg/m^{2}h
Pump running time	7-18 h
Collector efficiency factor F’	0.92
$(\tau\alpha)$	0.8464
Overall heat loss coefficient U_L	15.65 W/m^2.K
Packing factor	0.95
Cell efficiency$_{STC}$	16.7%
Slope of surface	Local latitude + 10°
Temperature coefficient	0.45%/°C

3 RESULTS AND DISCUSSION

The Brazilian National Agency for Electric Power (ANEEL) establishes that the average monthly power consumption of a residence must be below 120 kWh in order to receive tariff benefits. Therefore, the photovoltaic installations for modest residences are usually dimensioned to provide 120 kWh/month and each unit has 1.6 *m*2.

3.1 PV/T vs PV: Comparison of the monthly electricity production values for a PV/T system and a PV system.

Performing the simulation in the TRNSYS software for an entire typical year and integrating the monthly output power, it is possible to generate a graph which shows how much electrical and thermal energy is generated each month depending on the tank volume and the panel quantity. The simulation was carried out for one year and the values for the electricity production of the PV/T and PV systems were compared, for the configuration shown in Table 1. The result is shown in Figure 6.

The resulting average power generation for the year is 120.30 kWh, which shows that the use of 3 PV/T collectors meets the electricity demand for low-income residences located in Belo Horizonte, Minas Gerais State, Brazil.

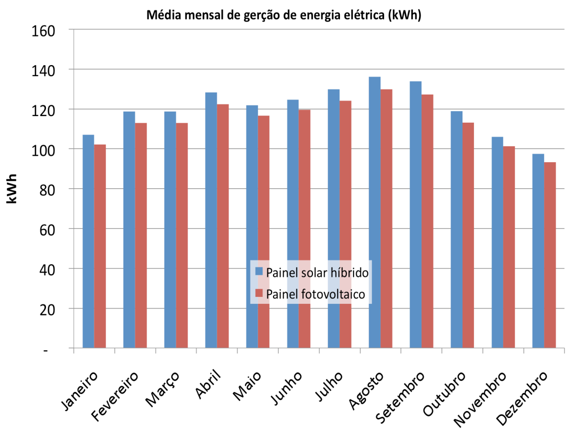

Figure 6- PV/T vs PV power output during one year

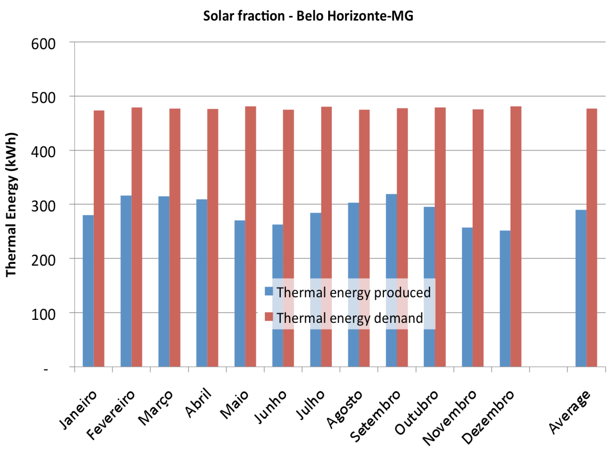

Figure 7- Solar Fraction during one year for Belo Horizonte city

It can be observed in Figure 6 that the power generation of the PV/T system is higher than that of the conventional PV system during a period of one year, resulting in an electrical efficiency gain of 4.70%.

As explained previously, the higher power efficiency is a consequence of the lower cell temperature in the case of the PV/T system due to the cooling effect of the heat exchanger.

3.2 Thermal generation of PV/T system

The amount of thermal energy that a residence needs can be calculated based on the water consumption, the required water temperature, the water supply temperature and the ambient temperature. Assuming a fixed water supply temperature of 20°C during the year, the average thermal energy demand was calculated for each month. The thermal energy rate provided by the boiler in the PV/T collector system is also integrated monthly. Figure 7 shows the ratio between the thermal energy produced by the system and the total thermal energy demand, known as the solar fraction. It is recommended that the average solar fraction during the year is between 60 and 70 per cent. The resulting solar fraction for the configuration shown in Table 1 in Belo Horizonte- MG is therefore 62.4%.

It can be concluded that the installation of three PV/T collectors meets the electricity demand (120 kWh) and provides the recommended thermal energy (solar fraction 60-70per cent) for a low-income residence located in Belo Horizonte, Minas Gerais State, Brazil.

3.3 Recommended PV/T installation for low-income residences in Brazil

The analysis will now be extended to several cities in Brazil according to the design recommendations for solar collectors for low-income residences (Table 2). Maintaining the parameters shown in Table 1, simulations were performed in the TRNSYS program for various cities and with different numbers of PV/T collectors. The configuration which best meets the energy demands was then identified and the results are shown in Figure 9.

As can be seen on the map, the installation of only three PV/T collectors meets the demand for the Brazilian cities of Brasília (Federal District), Belo Horizonte (Minas Gerais State) and Campo Grande (Mato Grosso do Sul State). In cities with lower levels of incident radiation, such as Florianópolis (Santa Catarina State) and Santa Maria (Rio Grande do Sul State) 5 PV/T collectors are needed to meet the thermal energy demand, resulting in the power generation exceeding the recommended value.

Table 2 – Design recommendations

Average power generation over one year	120 kWh/month
Solar fraction	60-70%

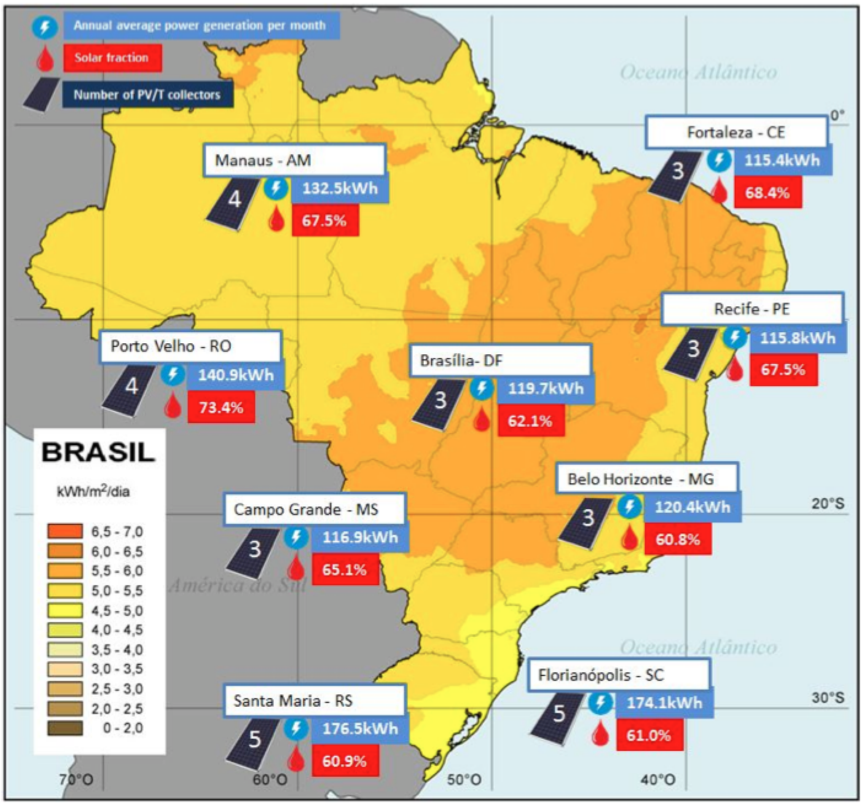

Figure 7– Recommendations for PVT installation for low-income residences in Brazil

4 CONCLUSIONS

The combined PV/T system technology for solar energy generation is able to provide both electricity and hot water in only one integrated and more efficient component. A TRNSYS simulation method was described based on a physical model to determine the input parameters for the TRNSYS software. These parameters are dependent on the PV/T design technology.

The PV/T technology proved to be an excellent option for low-income residences in Brazil. It was shown that, depending on the latitude, between 3 and 5 PV/T panels per roof is sufficient to satisfy the monthly hot water (60 %, reference value for solar design) and electricity demands of a low-income family residence. A comparison with the classical PV technology highlights that the PV/T system will produce 4 to 8 % more electricity, due to the cooling of the cell. More than that, the use of the combined PV/T technology would result in space savings and cost reductions in comparison with the use of the two systems separately.

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