# MODELING AND SIMULATION OF PHOTOVOLTAIC POWER GENERATION SYSTEMS FOR NET ZERO ENERGY BUILDINGS

Tatiane Stellet Machado
tatiane.stellet@gmail.com

Túlio Almeida Peixoto
tulioap@gmail.com

Joao Jose Assis Rangel
joao.rangel@ucam-campos.br

Universidade Candido Mendes
100 Anita Pessanha St, Pq. São Caetano
Campos dos Goytacazes, RJ, 28030-335, BRAZIL

Cássio Rangel Paulista
cassrangel@gmail.com

Instituto Federal Fluminense – Campus Campos Centro
R. Dr. Siqueira, 273 - Parque Dom Bosco
Campos dos Goytacazes, RJ, 28030-130, BRAZIL

## ABSTRACT

This paper has the purpose of evaluating the feasibility of utilizing a discrete event simulation tool for modeling and simulating a photovoltaic power generation system for residencies. Thus, two free and open source software, one for discrete event simulation and the other specifically designed for building energy simulation, were chosen to simulate the same model in order to compare the results obtained. There was no significant difference between both results, however, even though the energy simulation software provided a thorough analysis of the residence, it required much more information to run. Discrete event simulation may be a better option for modeling and simulating a group of residencies, as the model is easily expanded, or for the integration of a photovoltaic system to an industrial plant.

## 1 INTRODUCTION

Buildings have a great impact on the environment and energy use worldwide. In 2012, the building sector was responsible for consuming 30% of all energy worldwide and also 30% of the global energy-related CO2 emissions (IEA 2015a). However, in 2014, the carbon emissions started to decouple from electricity generation due to the rapid expansion of low-carbon energy sources (IEA 2015c). Renewable-based sources accounted for almost half of all new power generation in the same year, of which 37% was wind power, almost one-third solar power and more than a quarter hydropower (IEA 2015b).

Tsalikis and Martinopoulos (2015) believe that, of the various renewable energy systems that can be installed in the building sector in order to cover energy requirements (electrical and thermal loads), solar energy systems are currently the most widely used, mostly in the form of solar thermal and photovoltaic systems. As each day more people have access to proper housing and electricity (IPCC 2014), the two main strategies to keep energy and emission trends eco-friendly are, according to Sartori, Napolitano and Voss (2012), to optimize the efficiency of buildings and supply the remaining energy demand by means of on-site renewable energy sources.

Net zero energy buildings (NZEBs) present a good option for the climate change mitigation, following both strategies presented by Sartori, Napolitano and Voss (2012), as they have greatly reduced energy needs through efficiency gains such that the balance of the energy needs can be supplied by renewable technologies (Torcellini et al. 2006). The efficiency gains may be reached by adjusting various factors related to the building itself and its occupants. They include, among others, the optimization of the building's orientation and shape (Pacheco, Ordóñez, and Martínez 2012) and the building's envelope (Lin et al. 2016; Youssef, Zhai and Reffat 2016), the use of efficient HVAC (heating, ventilation and air-conditioning) systems (Safa, Fung and Kumar 2015; Zuo et al. 2015) and the identification of the drivers of energy use among occupants in order to target the energy saving strategies within the building (O'Neill and Chen 2002; Elnakat, Gomez, and Booth 2016).

The supply of the remaining energy demand is possible with the distributed power generation on site, specially by using solar power systems, that, according to Zhou et al. (2016), has gained wider implementation in NZEBs due to its accessibility and easy integration with existing building systems. Also, the photovoltaic (PV) panels are compact, require low maintenance and can be integrated to the building in various forms, divided basically into façade systems, as in the work of Agathokleous and Kalogirou (2016) and Aste, Del Pero and Leonforte (2016), and roofing systems, as presented by Yuan et al. (2016).

However, the system responsible to offset the energy imported from the grid needs to be properly sized in order to reach the net zero goal. Every building is a dynamic and complex system with multiple variables, granting its project with a high level of uncertainty that could be easily managed by a computer software. Thus, this paper aims to evaluate the feasibility of utilizing a DES (Discrete Event Simulation) tool for modeling and simulating a photovoltaic power generation system for residencies, as Frances, Escriva and Ojer (2014) believe that the DEVs formalism has many advantages that can be exploited within this field. Also, the results obtained will be compared to those generated by a software specifically designed for energy simulation.

## 2 NET ZERO ENERGY BUILDINGS

As the power demand of the residential sector continues to rise – 20% between 2000 and 2012 (IEA 2015a) – these self-sustainable buildings are already a realistic option for the mitigation of energy use and the related greenhouse gas emissions. NZEBs are efficient buildings, with low energy demand, that are able to generate at least as much power as it takes from the grid over a year through renewable sources (Machado et al. 2017). They are commonly divided into four categories: net zero site energy, net zero source energy, net zero energy costs and net zero energy emissions (Torcellini et al. 2006).

### 2.1 Net Zero Site Energy

A net zero site energy building produces on site as much energy as it uses, sending back to the grid at least the same amount of energy as it takes from it. This definition does not take into consideration the fuel used by the grid source to generate this power or the losses during transmission and distribution. Therefore, 1KJ of natural gas is equivalent to 1KJ of electricity, even though electrical equipment is more efficient when compared to those that run with gas.

Torcellini et al. (2006) find this definition the most consistent between all four as it is less vulnerable to external fluctuations.

### 2.2 Net Zero Source Energy

A net zero source energy building produces on site as much energy as it uses plus the amount of energy lost by the grid source during transmission and distribution. This greater power generation is determined by multiplying the end energy received from the grid to a conversion factor that depends mainly on the location of the building and type of energy (electricity, gas).

A limitation of this definition is that a project of a source NZEB might not meet its net zero energy goal if there is a significant change in the energetic matrix where the building is located due to a change in the conversion factors.

### 2.3 Net Zero Energy Costs

A net zero energy costs building receives as much financial credit from exporting the power generated on site through renewable sources as it is charged from using power from the grid.

One negative point about making the project of a building with the goal of zero energy costs is the drastic fluctuations of rates. That way, the building might achieve its goal one year but not the next.

### 2.4 Net Zero Energy Emissions

A net zero energy emissions building produces as much energy through emission free renewable sources as it takes from emitting sources.

Therefore, an all-electric building that has its electricity provided by a wind farm or hydroelectric/ nuclear power plant is automatically considered net zero energy emissions. On the other hand, there will be a great demand for energy production on site if the building is located where the main energy source is based on a highly pollutant fuel like the carbon-intense coal.

The embodied energy of the building can also be added to the energy balance to reach the definition proposed by Hernandez and Kenny (2010), a life cycle net zero energy building. Furthermore, if a building is able to generate more electricity than it consumes, as in the model proposed by Dávi et al. (2016), it can be categorized as a net plus energy building.

## 3 COMPUTER SIMULATION AND NZEBS

To choose the appropriate energy simulation software for this study, a survey has been conducted among publications regarding to NZEBs. The SCOPUS platform was used and the search was performed using the key words “net zero energy building*” OR “net-zero energy building*”, focusing on publications in English with the expression net zero spelled both with and without the hyphen and the asterisk to include the plural and singular forms of the word building. The research was performed in February/2018 and with the results restricted to articles or reviews, 208 documents were found, of which 128 have used a software for energy analysis. This data mining was performed by reading the publications or the abstract, if the full text was not available. As the purpose of this search is to determine the building energy software used by other authors, the publications using Monte Carlo simulation and Matlab were not accounted for. Figure 1 shows the number of publications per year.

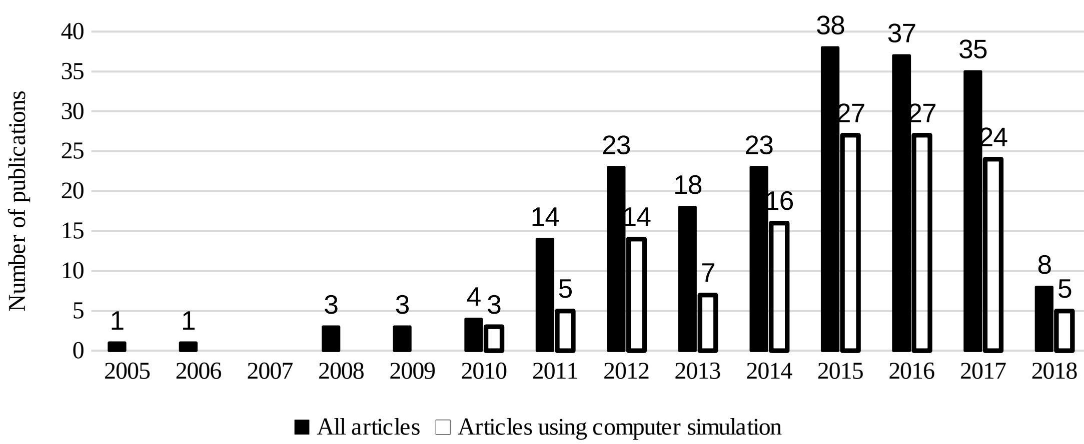



Figure 1: Number of publications per year. Source: Own elaboration.

There was an increase in the number of publications regarding to NZEBs starting in 2010, also when the first article of those found on this research using computer simulation was published. The number of publications reaches its peak in 2015, in which 38 articles were published – 27 using simulation tools. For reasons unknown, there were no publications in 2007. Figure 2 shows the most popular software.

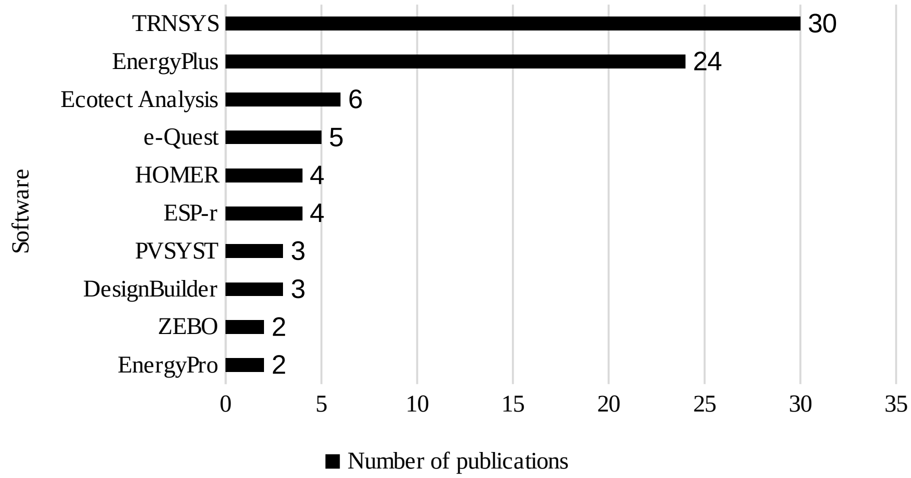



Figure 2: Most popular software by number of publications that have used it. Source: Own elaboration.

The majority of publications have chosen TRNSYS (Transient Systems Simulation Tool) as it is an extremely flexible graphically based software, commercially available for 35 years (Beckman et al. 1994). The second most used, EnergyPlus, is a free, open-source and cross-platform simulation engine without an interface, which can be used along with third party graphical interfaces if the user judges necessary (Crawley et al. 2001).

Although more publications have used TRNSYS as their simulation tool, this study has its energy simulation performed by EnergyPlus version 8.5.0, as it is free, resourceful and easily manageable. In addition, the 3D modeling software SketchUp and the OpenStudio plugin were used along with EnergyPlus.

The DES tool chosen, Ururau, is a free, open source and multiplatform software, developed in the Java language (Peixoto et al. 2017). Also, Ururau has been placed on the list of the ten most competent open source DES tools by Dagkakis and Heavey (2016).

## 4 DESCRIPTION OF THE SYSTEM

A hypothetical all-electric family home located in Rio de Janeiro was idealized with 511m² of building area, divided into 3 bedrooms, 3 bathrooms, a living room, a kitchen and a laundry. The occupants include a middle-aged couple and two teenagers with a total of two men and two women. The gender and age diversity make the model more realistic, as Elnakat, Gomez and Booth (2016) have proven that they are strongly related to energy consumption. Figure 3 shows the 3D sketch of the building.

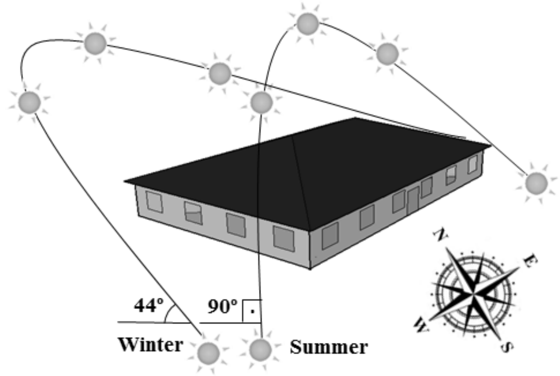



Figure 3: 3D sketch of the building. Source: Own elaboration.

The building's façade is oriented to the south and therefore the PV panels were installed at the back, facing north. The software covers the whole roof area with photovoltaics, but it has been set that only 20% of them are active with an efficiency of also 20%. The solar angle for the Rio de Janeiro region varies between minimum 44º, in June, and maximum 90º, in January, so the PV panels tilt angle was set for a better performance throughout the whole year. The energy simulation also requires a list of equipment and their schedule of usage. Table 1 lists the basic appliances, their average power consumption and daily schedule.

Table 1: List of equipment, average power consumption and daily schedule. Source: Machado et al. (2017).

| Quantity | Equipment | Power Consumption | Daily Schedule |
|---|---|---|---|
| **11** | LED light bulb | 12 W | 5 h |
| **04** | TV(42'' LED) | 203 W | 5 h |
| **03** | Air conditioner (10000 Btu) | 756.67 W | 8 h |
| **01** | Video game console | 24 W | 4 h |
| **04** | Laptop | 80 W | 4 h |
| **01** | Printer | 15 W | 20 min |
| **04** | Ceiling fan | 73 W | 4 h |
| **03** | Electric shower | 5500 W | 40 min |
| **02** | Hairdryer | 347.33 W | 20 min |
| **01** | Electric shaver | 10 W | 10 min |
| **01** | Stereo | 110 W | 1 h |
| **01** | Fridge | 55 W | 24 h |
| **01** | Electric stove | 60 W | 1 h |
| **01** | Electric oven | 500 W | 1 h |
| **01** | Microwave | 1398 W | 20 min |
| **01** | Coffee machine | 218.67 W | 15 min |
| **01** | Vertical freezer | 75 W | 24 h |
| **01** | Exhaust hood | 166 W | 1 h |
| **01** | Washing machine | 293.33 W | 2 h |
| **01** | Clothes iron | 600 W | 30 min |
| **01** | Vacuum cleaner | 717 W | 20 min |

Considering the location of the residence and its hot summers, a significant amount of energy is used for space cooling. However, there is no demand for space heating, another dominant energy end-use in cold climate countries (Guadalfajara, Lozano and Serra 2014).

A net zero energy building should interact with the power grid as shown in Figure 4.

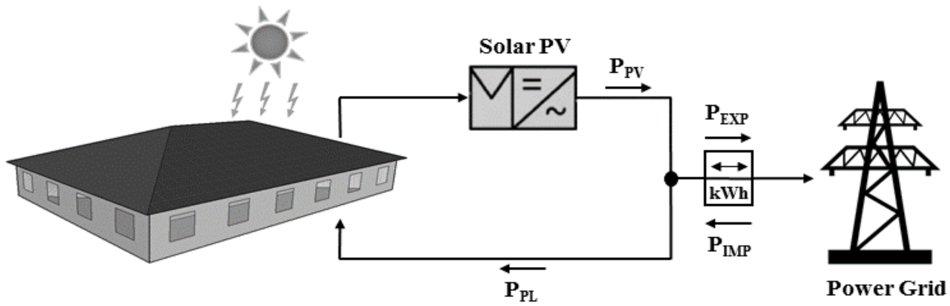



Figure 4: Interaction between the NZEB and the power grid. Source: Adapted from Dávi et al. (2016).

Electricity is generated by PV cells ($P_{PV}$) and runs through an inverter that converts the direct current into a utility frequency alternating current. This electricity will feed the building's power demand ($P_{PL}$) while the excess can be exported to the power grid, as the house is connected to it with a bidirectional feeder, allowing the energy to flow both ways. Electricity can also be imported from the grid ($P_{IMP}$) when PV generation does not meet the building's energy needs. Thus, the balance between $P_{PL}$ and $P_{PV}$, at the end of one year, should be at least zero, as the exceeding PV electricity generated in the summer compensates what is imported from the grid on winter days, when PV generation is low.

The total energy consumption ($P_{PL}$) over a period τ1 and τ2 is represented in Eq. 1, which is the sum of the electricity generated by PV and directly consumed by the residence ($P_{PV\rightarrow L}$) and the electricity imported from the grid ($P_{IMP}$) (Dávi et al. 2016).

$$\int_{\tau_1}^{\tau_2} P_{PL}(t)\,dt = \int_{\tau_1}^{\tau_2} P_{PV\rightarrow L}(t)\,dt + \int_{\tau_1}^{\tau_2} P_{IMP}(t)\,dt \qquad (1)$$

However, in the ideal scenario, the electricity generated by the PV cells ($P_{PV}$) would be sufficient to meet the residence's needs ($P_{PV\rightarrow L}$) with a surplus that can be exported to the grid ($P_{EXP}$), as shown in Eq. 2 (Dávi et al. 2016).

$$\int_{\tau_1}^{\tau_2} P_{PV}(t)\,dt = \int_{\tau_1}^{\tau_2} P_{PV\rightarrow L}(t)\,dt + \int_{\tau_1}^{\tau_2} P_{\exp}(t)\,dt \qquad (2)$$

## 5 SIMULATION MODELS

The simulation model was built in order to achieve the net zero goal, based on the PV electricity and the average power consumption of equipment and lighting. The steps proposed by Banks et al. (2010) for a thorough and sound simulation study were followed. For the steps concerning the model conceptualization and verification/validation, the techniques proposed by Montevechi et al. (2010) and Sargent (2013), respectively, were used. Figure 5 shows the simulation model, using the IDEF-SIM technique presented by Montevechi et al. (2010).

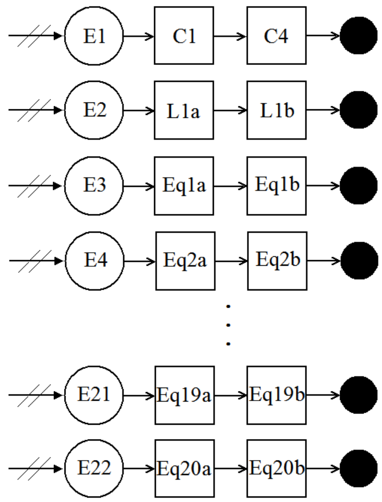


Figure 5: IDEF-SIM model of the simulation. Source: Machado et al. (2017).

The entities (E1 to E22) are responsible for the discretization of energy consumed by equipment and lighting or generated by PV cells. C1 accounts for the 2350W of electricity generated in 1 hour (3600 seconds), considering the average insolation for Rio de Janeiro city of 6 hours a day (Tiba, 2000). All the equipment from Table 1 are represented as Eq1 to Eq20. The calculation of their average electricity consumption is divided in two parts. First, it is taken into consideration their daily schedule, also presented on Table 1, by configuring the attribute "on". This is done in all equipment tags followed by the letter "a", by setting the percentage of the day in which the equipment is on and off. For example, TV is on for 5 hours a day, that is, 79% off (0) and 21% on (1). Then, this attribute "on" generates a random value of zero or one according to its probability that will be used to calculate the equipment's final electricity consumption on the "Eq" tag followed by the letter "b". The same is used to calculate the amount of energy used for lighting, represented in the model as "L1a" and "L1b".

Ultimately, all variables are added to C4, which accounts for the electricity generated and consumed. The positive end value can be interpreted as the building consuming more energy than it produces. Moreover, the negative end value shows that the building has achieved a net-plus energy status, generating more electricity than it consumes. The complete model can be found on Appendix A for further analysis.

This simulation model can be easily expanded to fit new equipment. Also, the whole model can be replicated to represent a new building in order to observe the behavior of an entire neighborhood or city. Moreover, the system can be integrated to an industrial plant.

## 6 RESULTS AND DISCUSSION

Both results show the energy balance for one year (8760 hours). The simulation executed with Ururau used 35 replications and ran for 7 minutes and 44 seconds on an Intel Core i7 computer with 8GB of RAM. EnergyPlus ran its simulation in 41 seconds on the same computer.

Table 2 shows the simulation results from Ururau and EnergyPlus for the simulation model represented on Figure 6.

Table 2: Simulation results from Ururau and EnergyPlus. Source: Own elaboration.

| | **Total Generated by PV (GJ)** | **Total Consumed by Lighting (GJ)** | **Total Consumed by Equipment (GJ)** | **Balance (GJ)** |
|---|---|---|---|---|
| **EnergyPlus** | 22.80 | 0.87 | 54.51 | -32.58 |
| **Ururau** | 22.85 | 0.87 | 54.46 | -32.47 |
| **Half-width*** | 0.01 | 0.01 | 0.37 | 0.37 |

*The half-width values are applicable only to Ururau's results as EnergyPlus only provides the user with an absolute value for each variable.

There is no significant difference between the results from both software, showing that Ururau was able to perform the building energy simulation satisfactorily. Annex I shows the screenshot of the results report generated by Ururau and EnergyPlus.

Ururau's report, like all DES software, provides the user with the mean, standard deviation, half-width, minimum and maximum, considering the results of each of the 35 replications. EnergyPlus does not work with replications, therefore giving its results as absolute values. Its report is extensive and detailed, including the building's envelope information, its performance, demand end use by fuel, the life-cycle cost report, among others.

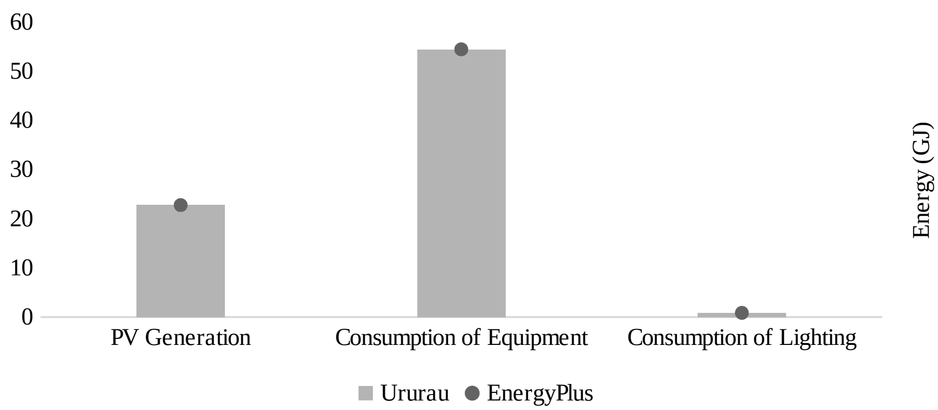
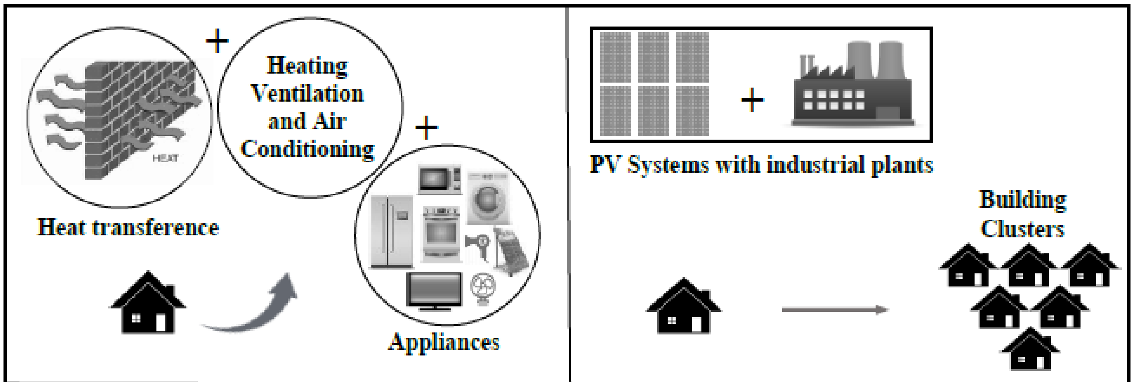



Figure 6: Comparison between the results from Ururau and EnergyPlus. Source: Own elaboration.

Furthermore, Figure 7 presents a brief comparative analysis based on the results obtained from the simulation with Ururau and EnergyPlus.




| EnergyPlus | Ururau |
|---|---|
| • Thorough analysis of the system as the user provides information on the design days like temperature, humidity, pressure, wind, precipitation, among others;<br>• Allows the user to set a detailed schedule for equipment, including one for winter days and another for summer days;<br>• The weather files as well as the design days are easily obtained on EnergyPlus' website;<br>• No graphic interface, making the simulation process harder for beginners;<br>• Since it requires too much information on the building, the simulation is time consuming. | • The simulation model can be easily expanded to analyze a group of residencies;<br>• The PV system can also be integrated to an industrial process, a usual environment in which DES is utilized;<br>• User-friendly graphic interface and explanatory videos available on the website;<br>• Does not take into consideration heat transfer parameters;<br>• It does not provide results as detailed as EnergyPlus' as the input information only covers the system generating electricity and the equipment consuming it. |

Figure 7: Brief comparison between Ururau and EnergyPlus. Source: Own elaboration.

## 7 CONCLUDING REMARKS

The results obtained in this work have confirmed the hypothesis that discrete event simulation can be used for modeling and simulating photovoltaic generation systems. This confirmation was possible by simulating the same model with the discrete event simulation software Ururau and EnergyPlus, a simulation engine for building energy, and comparing the results obtained.

There was no significant difference between both results; however, a brief comparison showed that discrete simulation has a better performance while analyzing ample systems. While EnergyPlus provides a thorough calculation of a single building's performance, a discrete event simulation tool would be a better choice when simulating multiple residencies or integrating a photovoltaic system to an industrial plant.

The purpose of this work was not to simply compare the performance of two software, but to present the modeler an alternative by showing the characteristics and better application of these two types of simulation for buildings. Moreover, the utilization of two options of free and open-source software for energy analysis may broaden the use of simulation by homeowners and small companies for the same purpose, as they do not require the purchase of a license.

## ACKNOWLEDGMENTS

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## APPENDIX A

| Code | Description | Parameter |
|---|---|---|
| **E1 to E22** | Discretization of energy | 1 unit of energy per hour |
| **C1** | Photovoltaic energy generated | total_gen +2.350*3600*NORM(6,1)/24 |
| **C4** | Total energy generated by PV minus total energy used | total_gen - (total_ilum+total_equip) |
| **L1a** | Lights on/off | DISCRETE(0.792,0,0.208,1) |
| **L1b** | Electricity used by lighting | total_ilum +0.012*3600*on*11 |
| **Eq1a** | TV on/off | DISCRETE(0.79,0,0.21,1) |
| **Eq1b** | Electricity used by TV | total_equip +0.203*3600*on*4 |
| **Eq2a** | Air conditioner on/off | DISCRETE(0.66,0,0.33,1) |
| **Eq2b** | Electricity used by air conditioner | total_equip +0.75667*3600*on*3 |
| **Eq3a** | Videogame on/off | DISCRETE(0.84,0,0.16,1) |
| **Eq3b** | Electricity used by videogame | total_equip +0.024*3600*on |
| **Eq4a** | Laptop on/off | DISCRETE(0.82,0,0.16,1) |
| **Eq4b** | Electricity used by laptop | total_equip +0.08*3600*on |
| **Eq5a** | Printer on/off | DISCRETE(0.9861,0,0.0138,1) |
| **Eq5b** | Electricity used by printer | total_equip +0.015*3600*on |
| **Eq6a** | Ceiling fan on/off | DISCRETE(0.84,0,0.16,1) |
| **Eq6b** | Electricity used by ceiling fan | total_equip +0.073*3600*on*4 |
| **Eq7a** | Electric shower on/off | DISCRETE(0.972,0,0.027,1) |
| **Eq7b** | Electricity used by electric shower | total_equip +5.5*3600*on*3 |
| **Eq8a** | Hairdryer on/off | DISCRETE(0.9861,0,0.0138,1) |
| **Eq8b** | Electricity used by hairdryer | total_equip +0.34733*3600*on*2 |
| **Eq9a** | Electric shaver on/off | DISCRETE(0.9930,0,0.0069,1) |
| **Eq9b** | Electricity used by electric shaver | total_equip +0.010*3600*on |
| **Eq10a** | Stereo on/off | DISCRETE(0.958,0,0.042,1) |
| **Eq10b** | Electricity used by stereo | total_equip +0.11*3600*on |
| **Eq11a** | Fridge on/off | DISCRETE(0.001,0,0.999,1) |
| **Eq11b** | Electricity used by fridge | total_equip +0.055*3600*on |
| **Eq12a** | Electric stove on/off | DISCRETE(0.958,0,0.041,1) |
| **Eq12b** | Electricity used by electric stove | total_equip +0.060*3600*on |
| **Eq13a** | Electric oven on/off | DISCRETE(0.958,0,0.041,1) |
| **Eq13b** | Electricity used by electric oven | total_equip +0.500*3600*on |
| **Eq14a** | Microwave on/off | DISCRETE(0.9862,0,0.0138,1) |
| **Eq14b** | Electricity used by microwave | total_equip +1.398*3600*on |
| **Eq15a** | Coffee machine on/off | DISCRETE(0.9861,0,0.0138,1) |
| **Eq15b** | Electricity used by coffee machine | total_equip +0.21867*3600*on |
| **Eq16a** | Vertical freezer on/off | DISCRETE(0.001,0,0.999,1) |
| **Eq16b** | Electricity used by vertical freezer | total_equip +0.075*3600*on |
| **Eq17a** | Exhaust hood on/off | DISCRETE(0.958,0,0.0416,1) |
| **Eq17b** | Electricity used by exhaust hood | total_equip +0.166*3600*on |
| **Eq18a** | Washing machine on/off | DISCRETE(0.9166,0,0.0833,1) |
| **Eq18b** | Electricity used by washing machine | total_equip +0.29333*3600*on |
| **Eq19a** | Clothes iron on/off | DISCRETE(0.979,0,0.02083,1) |
| **Eq19b** | Electricity used by clothes iron | total_equip +0.600*3600*on |

| | | |
|---|---|---|
| **Eq20a** | Vacuum cleaner on/off | DISCRETE(0.9792,0,0.0208,1) |
| **Eq20b** | Electricity used by vacuum cleaner | total_equip +0.717*3600*on |

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