COBEM 2021
26th International Congress of Mechanical Engineering
ABCM
Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

# EVALUATION OF THE ENERGY 3D POTENTIAL USE AS A SIMULATION TOOL FOR UNDERGRADUATE STUDENTS: A CASE STUDY ON ENERGY EFFICIENCY AND PV GENERATION

**Pedro Henrique Regina Canali**
**Letícia Jenisch Rodrigues**
Universidade Federal do Rio Grande do Sul, Escola de Engenharia, Departamento de Engenharia Mecânica, Rua Sarmento Leite, 425 - 90046-902 Centro Histórico - Porto/Alegre RS - Brasil
pedrohenrique.canali@hotmail.com
leticia.jenisch@mecanica.ufrgs.br

***Abstract.*** *The main objective of this paper is to evaluate the potential of using Energy 3D software for engineering undergraduate students in courses involving solar energy and energy efficiency. A specific case study on photovoltaic(PV) generation and energy efficiency was selected involving a hypothetical single-family residential building in Porto Alegre, Brazil. Contrary to the usual, cases were simulated in which the PV modules were installed on the façade. The results of the simulations are presented, discussed, and then evaluated in terms of the potential to use in specific courses as a didactic support tool. This potential considers the outputs of the software, the relevance and quality of graphics, and data export. It is expected to demonstrate the software's potential to encourage its use in different stages of an engineering course through its use and the analysis of the results obtained.*

***Keywords:*** *façade PV modules, Energy 3D software, single-family residential building, didactic support tool*

## 1. INTRODUCTION

The Energy3D software is a CAD tool developed from scratch and directions of the three advancements to support engineering research and education: system integration, machine learning, and computational design (Xie et al., 2018). This software allows students to develop design tasks without worrying about expenses (prototypes), accidents (involving electricity, for example), and other challenges that an experimental project imposes. According to the developers (Xie et al., 2018), CAD software can become a powerful tool for engineering education by providing quantitative results and helping students make design decisions. This transformation is possible due to two characteristics of the software: an intuitive and user-friendly interface and graphical outcomes. In addition, according to Hatherly (2017), simulations and games help to understand concepts that traditionally could be a little more difficult to understand.

From a physical perspective, the software allows combining concepts of solar radiation with aspects that involve heat transfer in buildings and the use of renewable energy (solar thermal and photovoltaic). Furthermore, it offers optimization options (using genetic algorithms): building location, building orientation, window size, solar panel tilt angles, and solar panel array.

This article seeks to assess the potential use of this educational CAD tool in engineering education, focusing on aspects related to the energy efficiency of a hypothetical building and PV generation. In the last case, this generation is evaluated both on the building's roof (usual configuration) and on the façades. This building is located in Porto Alegre, in southern Brazil, based on Carilho's building (Carrilho da Graça et al., 2012) and adapted to Brazil by Caus (2019). This potential considers the outputs of the software and the relevance and quality of graphics.

## 2. CASE STUDY

The building, Figure 1a, initially developed by Carrilho da Graça et al. (2012), was chosen for this case study. We selected one of the two buildings studied by the authors: the passive house, Figure 1a. Figure 1b shows its internal configuration and orientation. There were made two modifications: (1) removing the horizontal *brises* in the kitchen (KIT) and living room (LR) windows; (2) the building rotation by 180º - so, the façade with the largest window area is now oriented to the North (Caus, 2019), Figure 1c.

The simulated building model has no internal divisions for simplicity's design sake. In addition, the software does not make assessments in terms of thermal zones, such as Energy Plus$^{TM}$ (Crawley et al., 2001), for example. It is just the envelope, Figure 2a. The general characteristics of the building are as follows: floor area of 110 m$^2$, the volume of 330 m$^3$, white external walls, and flat gray roof, Figure 2b. There are six windows: one of 6 x 1.5 m (in the living room - LR), two of 0.6 x 0.5 m (in the bathroom 1 and 2 – WC1 and WC2), and three of 3 x 1.5 m (in the kitchen, bedroom 1, and bedroom 2 – KIT, BR1, and BR2).

The roof ($U = 0.23$ W/m$^2$K) thickness is 0.36 m, the external walls ($U = 0.32$ W/m$^2$K) thickness is 0.38 m, and the floor ($U = 0.48$ W/m$^2$K) thickness is 0.23 m. The roof insulation thickness is 0.15 m (polystyrene insulation $U = 0.14$ W/m$^2$K), external walls insulation thickness is 0.10 m (polystyrene insulation $U = 0.24$ W/m$^2$K), and floor insulation thickness is 0.08 m (polystyrene insulation $U = 0.15$ W/m$^2$K). All windows have double glass ($U = 1.8$ W/m$^2$K) and the Solar Heat Gain Coefficient is SHGC = 0.63. The volumetric heat capacity values are as follows: 0.14 kWh/m$^2$K (roof), 0.10 kWh/m$^2$K (external walls), and 0.03 kWh/m$^2$K (floor).

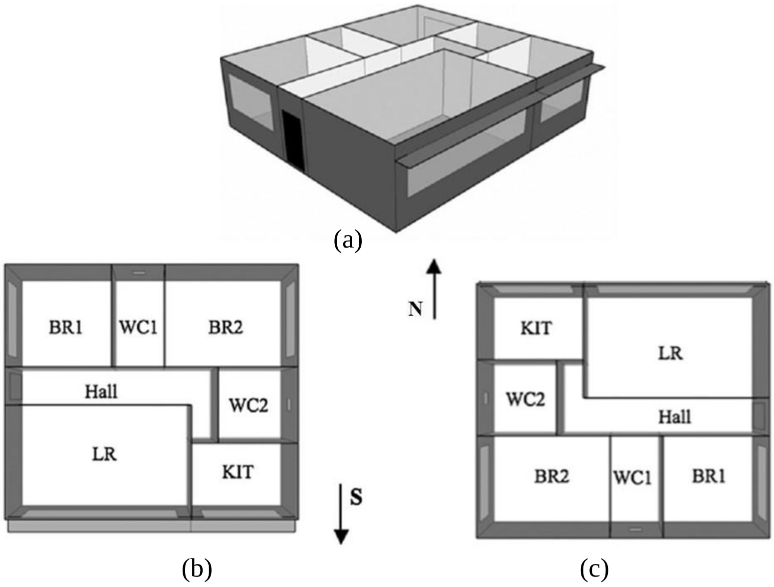



Figure 1. Selected building: (a) original house with *brise* and oriented to the South; (b) upper view; and (c) case studied - without *brise* and oriented to the North. Adapted from Carrilho da Graça et al. (2012) and Caus (2019).

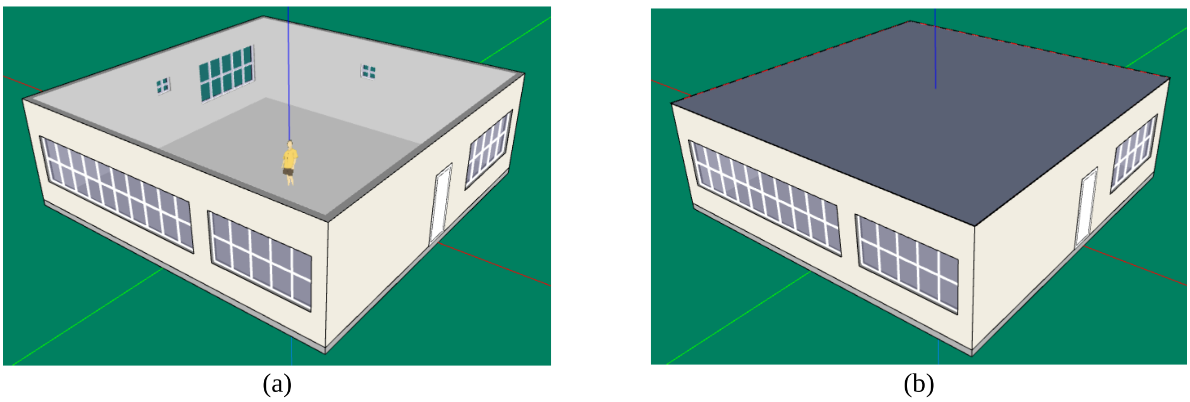


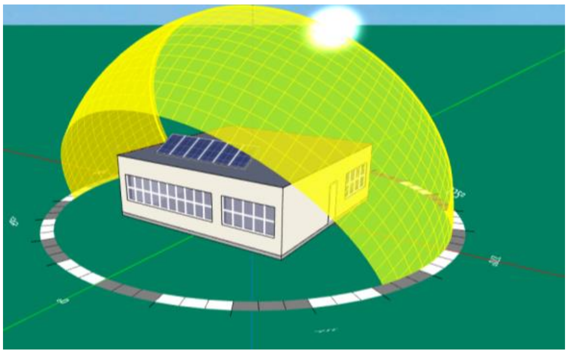

Figure 2. Simulated building: (a) interior without divisions and (b) flat roof.

Five scenarios were evaluated for the place of PV generator: (A) on the roof, (B) on the South wall, (C) on the West wall, (D) on the East wall, and (E) on the North wall. In this last scenario, the kitchen window had to be moved to the West wall, Figure 3e. All designs are illustrated in Figures 3a to 3e, respectively, and six photovoltaic modules are used - with the same characteristics, Table 1. The PV modules on the roof are oriented to the North with a 30° of inclination, the same value as the local latitude 30ºS (Porto Alegre, Brazil). The inverter has 97% efficiency. These data are enough to characterize the module used in the simulation. Although the software has a diverse library of PV modules, we chose to declare it in this work. Precisely to show which parameters are necessary for the PV system configuration.

The number of modules (six) was determined from a simplified model, i.e.,

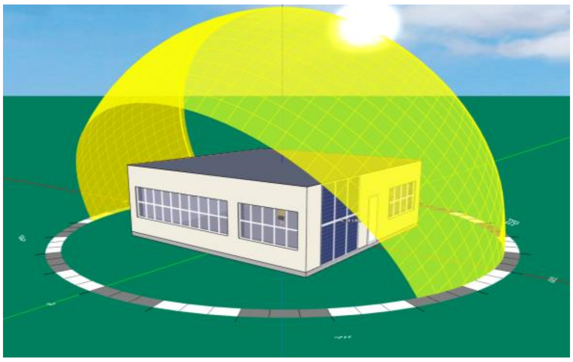
$$P_{PV} = \frac{E\,G_{STC}}{30\;(TD\;H_{TOT})} \tag{1}$$

where $P_{PV}$ is the generator power (Wp), E is the consumed energy (Wh), $G_{STC}$ is the standard irradiance (1000 W/m$^2$), $H_{TOT}$ is the annual average total daily irradiation (Wh/m$^2$), TD is the performance ratio (from 0.7 to 0.85), and 30 is the number of days in a month.

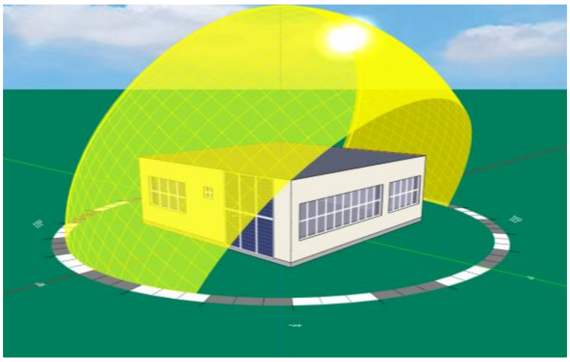


(a) Scenario A

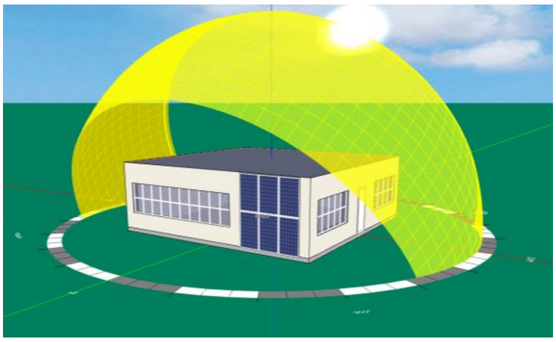
(b) Scenario B



(c) Scenario C



(d) Scenario D



(e) Scenario E

Figure 3. The five scenarios: PV generator (A) on the roof, (B) on the South wall, (C) on the West wall, (D) on the East wall, and (E) on the North wall.

Table 1. Input data: general characteristics of the module used, CS6P-P Canadian – 255 Wp (MRSolar, 2021).

| **Characteristics** | **Value** | **Characteristics** | **Value** |
|---|---|---|---|
| Dimensions | 0.99 m x 1.65 m | NOCT(1) | 43ºC |
| Efficiency | 15.85% | Number of cells | 60 |
| Cell type | polycrystalline | Color | Blue |

(1) Nominal Operation Cell Temperature

According to Fedrigo et al. (2009), the average monthly consumption of a single-family residence located in southern Brazil is approximately 273.09 kWh in summer and 261.26 kWh in winter. Therefore, we assume a constant monthly average: the consumption is about 267 kWh. So, for simplification purposes, this average consumption will be regular throughout the year. However, it should be noted that the software allows the user to declare different monthly consumptions.

Defining a three-phase system, whose availability fee in Porto Alegre is equivalent to 100 kWh, the consumed energy, E, is 167 kWh. Table 2 presents the parameters associated with the PV array sizing.

Table 2. PV array sizing.

| Characteristics | Value | Characteristics | Value |
|---|---|---|---|
| Average consumption | 267 kWh | $H_{TOT}$ | 4.89 kWh/m$^2$ |
| Availability fee | 100 kWh | TD | 0.77 |
| Consumed energy - E | 167 kWh | $P_{PV}$ | 1479.2 Wp |

The weather file comes with the software, and it is not possible to change it or insert a new file. Thus, only available cities can be chosen - Porto Alegre is one of them. Little information is available. There are four graphs available: monthly sunshine hours (Figure 4a), maximum and minimum ambient temperatures (Figure 4b), average ambient temperature (Figure 4c), and the ground temperature for depths of 0.5, 1.0, 2.0, and 6.0 m (Figure 4d).

From Figure 4a, it is possible to observe that the monthly sunshine hours are the same for July, August, and September. That doesn't happen. Thus, the weather file used by the software for Porto Alegre has at least one inconsistency.

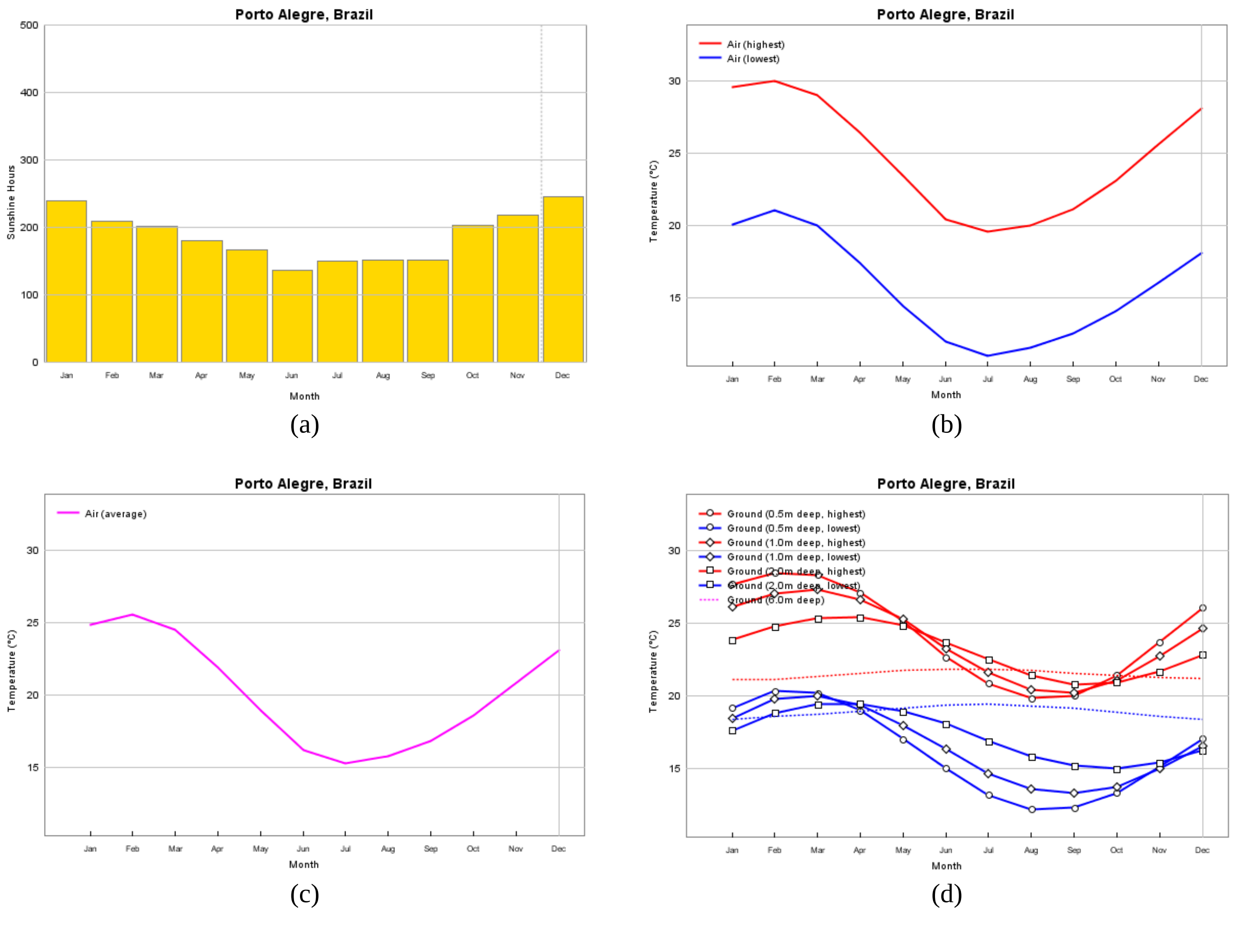



Figure 4. Weather file available data: (a) monthly sunshine hours, (b) maximum and minimum ambient temperatures, (c) average ambient temperature, and (d) ground temperature for depths of 0.5, 1.0, 2.0, and 6.0 m.

Among the various qualities of the software, the visual issue stands out. It is possible to observe the apparent movement of the Sun at different times of the year, Figures 3, 5, and 6, as well as the solar angles (altitude and azimuth). In addition, a solar irradiance heat map is available, Figures 5 and 6. The magnitude of the irradiance is expressed qualitatively in terms of a color gradient. High values tend towards red, Figure 5, while low values are shown in blue, and intermediate values in orange, yellow, or green.

Furthermore, it is possible to visualize the heat fluxes on different building surfaces, Figure 5. The flux vector size indicates how large its magnitude is. These heat fluxes allow us to assess which building components transmit more or less heat for different times of the year. For educational purposes, this information is highly relevant.

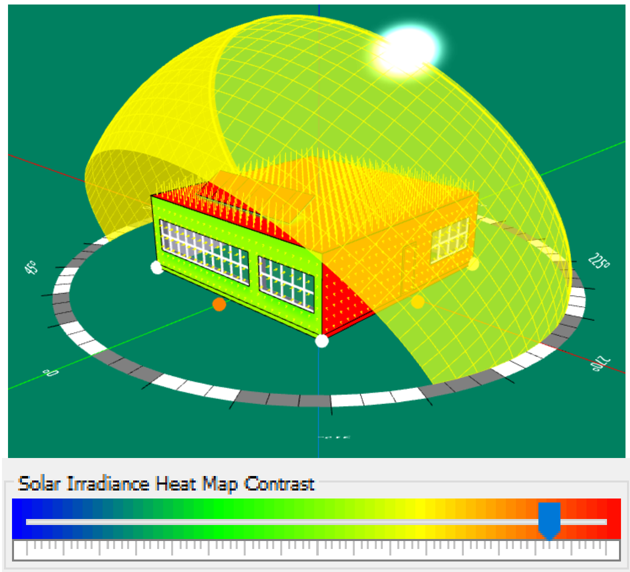
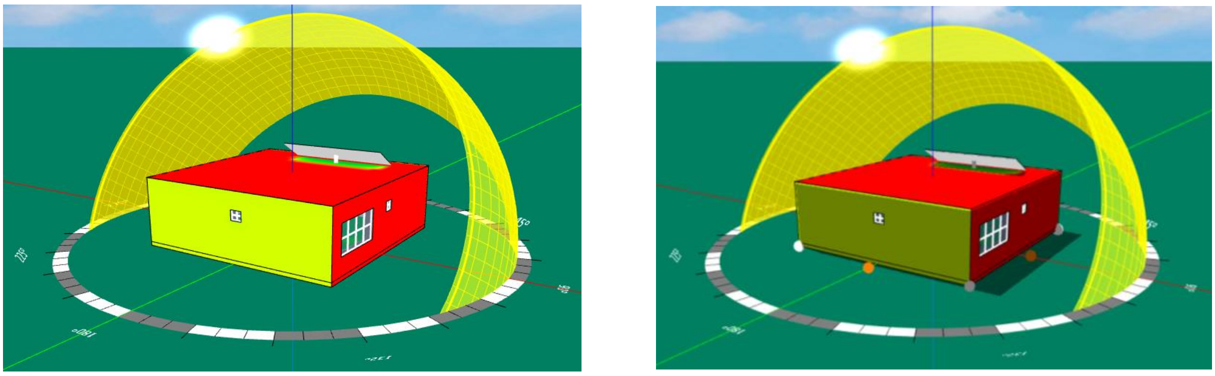



Figure 5. Sun's apparent trajectory, solar irradiance heat map (summer day), and heat fluxes (white vectors).

A shading option is also available, Figure 6b. All of the possibilities mentioned above can be "turned on" or "turned off" by the user.



(a) (b)

Figure 6. South façade: (a) solar irradiance heat map and (b) shading.

## 3. RESULTS AND DISCUSSIONS

This section presents the obtained results organized as follows: PV generation and solar heat gain through windows and the consumption from air conditioning and heating systems, followed by the evaluation of the educational potential of the software.

### 3.1 PV Generation and Solar Heat Gain

The PV system generates approximately 1,909 kWh throughout the year, while consumption is 2,004 kWh, i.e., the generation corresponds to 95% of consumption (Scenario A - PV on the roof). Figure 7 shows the monthly behavior of the PV generation. The PV generation in February is lower than the PV generation in March, and the PV generation in October is larger than the PV generation in November. It doesn't happen. Thus, another inconsistency was found in the weather data since the PV generation is directly linked to solar radiation.

As already expected, the PV system generation is the same when installed in the East or West direction (Scenarios D and C, respectively), Table 3, due to the symmetry of the apparent Sun path. For these cases, the PV generation is equivalent to 60% of PV generation on the roof. It is also observed that the generation is privileged in the summer months, early spring, and early fall. In such cases, the PV generation is greater than or equal to half the consumption (yellow cells), Table 3. On the other hand, the PV generation is less than half the consumption (red cells), Table 3, during the winter months and adjacent ones.

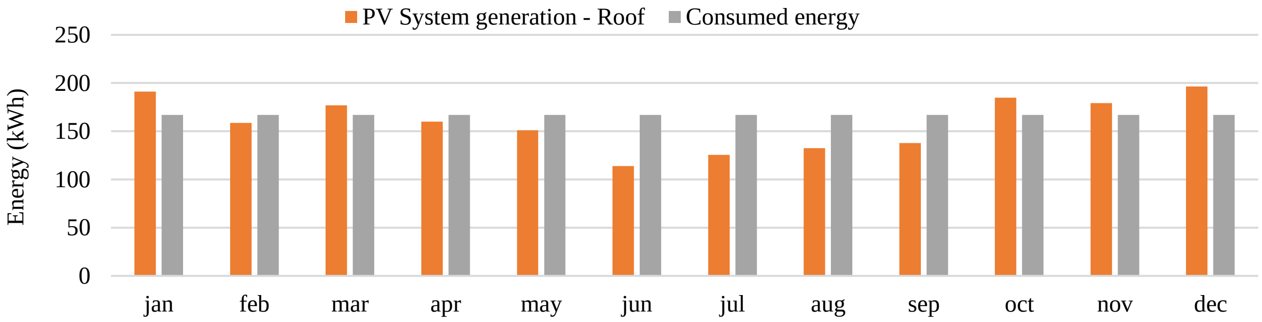



Figure 7. Monthly behavior of the PV generation (Scenario A – PV on the roof).

For the North facing orientation (Scenario E), the behavior is inverted. The PV generation is considerably higher in the winter and surrounding months. When the Sun passes 7° from the zenith in summer, the North façade receives less solar radiation. In this scenario, the PV generation corresponds to 64% of the generation in Scenario A (on the roof). Finally, in scenario B, it is observed that PV generation is below half of the consumption throughout the year. In this configuration, the summer months also have the highest generation values. In scenario A, PV generation exceeded consumption (green cells), generating credits – net metering model. As in the other scenarios, the characteristics of this PV generation profile are due to the Sun's apparent path throughout the year.

Regarding solar heat gain, the change in the kitchen window orientation in scenario E (Windows E – Table 3) did not significantly affect the annual value. However, it is possible to observe a decrease in the winter months when the Sun is at its lowest position.

Table 3. Energy gain through windows and PV generation.

| Month | Windows (A, B, C e D) | Windows (E) | PV Roof (A) | PV West (C) | PV East (D) | PV North (E) | PV South (B) |
|---|---|---|---|---|---|---|---|
| jan | 986.69 | 1129.80 | 191.05 | 132.88 | 132.88 | 65.88 | 80.67 |
| feb | 851.70 | 941.28 | 158.71 | 105.37 | 105.37 | 63.47 | 54.00 |
| mar | 1057.37 | 1091.58 | 177.04 | 109.67 | 109.67 | 93.92 | 48.02 |
| apr | 1113.53 | 1059.03 | 160.01 | 91.07 | 91.07 | 117.26 | 40.24 |
| may | 1175.01 | 1058.46 | 151.07 | 80.35 | 80.35 | 136.39 | 37.69 |
| jun | 934.98 | 817.91 | 113.87 | 57.88 | 57.88 | 115.25 | 28.58 |
| jul | 1043.13 | 908.59 | 125.61 | 63.54 | 63.54 | 129.38 | 31.70 |
| aug | 1045.18 | 929.02 | 132.49 | 69.03 | 69.03 | 125.94 | 33.08 |
| sep | 975.46 | 907.92 | 137.69 | 76.14 | 76.14 | 109.36 | 34.06 |
| oct | 1143.58 | 1144.22 | 184.74 | 110.98 | 110.98 | 111.08 | 47.75 |
| nov | 968.79 | 1052.61 | 179.20 | 116.88 | 116.88 | 77.07 | 56.73 |
| dec | 1015.50 | 1156.21 | 196.61 | 135.73 | 135.73 | 69.52 | 79.74 |
| **AVERAGE [kWh]** | 1025.91 | 1016.39 | 159.01 | 95.79 | 95.79 | 101.21 | 47.69 |
| **TOTAL [kWh]** | **12310.93** | **12196.62** | **1908.08** | **1149.52** | **1149.52** | **1214.52** | **572.25** |
| **PERCENTAGE** | 100% | 99.07% | 100% | 60.24% | 60.24% | 63.65% | 29.99% |

### 3.2 Air conditioning and Heating

The software has a limitation regarding air conditioning (AC) and heating systems. Both systems are kept "on" as long as necessary to keep the internal temperature equal to the setpoint temperature. The user is unable to configure schedules. Consequently, the systems are "turned on" every day, i.e., both AC and heater are used on the same day. The energy consumption for these systems schedules proved to be very high. So, it was decided to evaluate them "qualitatively" - reference values were chosen to compare the results. These values refer to scenarios A, B, C e D, which have two windows on the North façade. This assessment is crucial because it shows the impact of changing the windows' orientation on consumption for cooling and heating. Moreover, the setpoint temperatures were 22ºC for winter and 24ºC for summer, in this case.

Table 4 presents the normalized consumption values for AC and heating systems as a function of their maximum values. There was no change in month values for the heating system, whose most significant consumption was in July (blue cells). So, changing the number of windows on the North facade did not significantly impact this system.

Table 4. Normalized AC and heating systems consumption.

| Month | Scenarios A, B, C e D | | | Scenário E | | |
|---|---|---|---|---|---|---|
| | Heater | AC | H+AC | Heater | AC | H+AC |
| jan | 0,00 | 1,00 | 0,97 | 0,00 | 1,00 | 1,00 |
| feb | 0,00 | 0,86 | 0,83 | 0,00 | 0,84 | 0,84 |
| mar | 0,00 | 0,97 | 0,94 | 0,00 | 0,91 | 0,91 |
| apr | 0,00 | 0,95 | 0,92 | 0,00 | 0,84 | 0,84 |
| may | 0,59 | 0,86 | 0,98 | 0,59 | 0,73 | 0,87 |
| jun | 0,86 | 0,53 | 0,73 | 0,86 | 0,44 | 0,64 |
| jul | 1,00 | 0,55 | 0,78 | 1,00 | 0,44 | 0,67 |
| aug | 0,92 | 0,58 | 0,79 | 0,92 | 0,50 | 0,71 |
| sep | 0,76 | 0,62 | 0,79 | 0,76 | 0,54 | 0,71 |
| oct | 0,59 | 0,88 | 1,00 | 0,59 | 0,81 | 0,95 |
| nov | 0,00 | 0,88 | 0,85 | 0,00 | 0,86 | 0,86 |
| dec | 0,00 | 0,97 | 0,94 | 0,00 | 0,97 | 0,97 |
| **AVERAGE** | 0,39 | 0,81 | 0,88 | 0,39 | 0,74 | 0,83 |
| **PERCENTAGE** | 100,00% | 100,00% | 100,00% | 100.00% | 91,95% | 94,90% |

Regarding the AC system, the month with the greatest consumption was January, in all scenarios (orange cells). However, unlike the heating system, it is possible to observe a decrease in monthly consumption throughout the year in scenario E. Consequently, the average annual consumption was 91.95% lower than the scenarios with two windows to the North. The difference was approximately 2% for the summer months.

When a global assessment involves the two systems, the maximum consumption does not occur in the same month. In scenarios A to D, windows to the North, the maximum consumption is observed in October, while for scenario E, the maximum consumption is in January (purple cells). In this situation, the average annual consumption was 94.90% lower than the scenarios with two windows to the North.

### 3.3 Discussion: the potential of using the free Energy 3D software for Engineering undergraduate students

In building science, many concepts are invisible to the human eye (Hatherly, 2017), including the most important of all: heat transfer through walls, windows, roof, and floor. Heat transfer and associated fluxes are not constant over days and months. In addition, external situations, such as shading by trees and buildings, orientation, and localization, also influence it. Also, the size and orientation of windows play a central role in the thermal behavior of the building.

In cold climate locations, the building tends to lose more thermal energy through the windows during the winter than in buildings in hot climate locations. Furthermore, the amount of solar heat gain through them during summer and winter days is different. The latter knowledge is essential to guide the selection of passive solar solutions, which directly impact AC and heating systems consumption (Xie et al., 2018).

At first, it can be difficult for the student to understand external factors, the material used in the construction, solar radiation, orientation, and location, on the building's thermal behavior. In this sense, we have several abstract concepts, such as heat, relative humidity, the apparent path of the Sun, Fourier's law (conduction of heat), Newton's law of cooling (convection), Stefan Boltzmann's law (thermal radiation), etc.

In this context, Energy 3D software allows students to build and modify buildings and, at the same time, visualize these effects over a day, a month, or a year. Heat fluxes, for example, are represented by arrows, whose size varies according to their magnitude. Thus, they can observe the flow direction and value during the day and the night and in winter and summer, in different building elements.

The behavior of solar radiation throughout the year can also be seen. The software shows the Sun's apparent path across the sky, illustrating the variation in the sun altitude, sun azimuth, location, and sunrise and sunset hours throughout the year. The amount of radiation received by surfaces is also illustrated in terms of a heat map, whose color gradients are associated with the magnitude of the energy received. This type of information allows the student to make decisions regarding orientation, materials, insulation systems, shading strategies, and window sizes. A window size optimization using genetic algorithms is also available.

In addition to the thermal evaluation of the building and of AC and heating systems, the software also allows the study of electric energy generation systems using solar thermal and photovoltaic energy. Concerning PV power generation, it is possible to configure systems on roofs and facades, a solar canopy, solar *agrivoltaics* (greenhouses), and solar farms – with or without solar tracking. An optimization related to photovoltaic array inclination in static systems - without tracking - is available in these cases.

Regarding concentrated solar power (thermal energy to electricity), it is possible to design the following types of system: parabolic trough, parabolic dish, linear Fresnel reflectors, and concentrated solar power tower and its heliostats. However, due to the scope of this work, these options were not used.

All graphs allow export values to tables, Figure 8, except for those associated with the weather file. These can be pasted and later processed in spreadsheet software. Depending on the choice made by the user, the data can be evaluated daily or monthly - PV generated energy, energy gain through windows, AC and heating consumption. The software also allows declaring the monthly consumption of energy used by other equipment. Sun hours values can be obtained for any day of the year. Outside temperature values too.

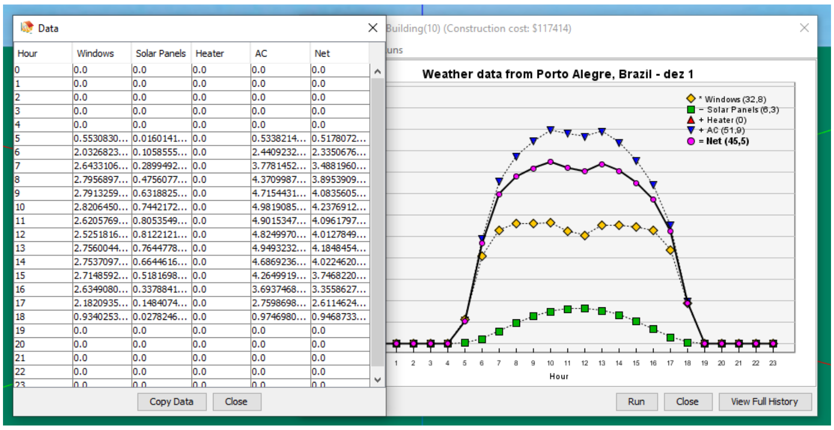



Figure 8. Daily graph and respective table.

It is possible to declare the value of the materials used in the building construction. Thus, the software calculates the cost of construction. This option is interesting to visualize that the cost varies depending on the chosen materials. For example, how worthwhile is the increase in wall insulation? Is it compatible with the reduction of expenses with an AC and heating system? I.e., according to Xie et al. (2018), "*engineering design is not just about 'how it works' (qualitative conceptual understanding), but 'how much it should be' (quantitative decision making)*."

In the case evaluated, there are five optimizations available: building location, building orientation, window sizes, solar panel tilt angles, and solar panel array, Figure 9. Optimizing the building's orientation led to the configuration in which the most extensive window area faces North. Window size and building location optimization were not used. The latter would help to optimize the location of the building in terms of adjacent buildings, Figure 10. All options discussed here are based on the solar gain and energy savings ratio.

Thus, Energy 3D can be applied in courses on energy efficiency and solar energy. Given its user-friendly interface and the characteristics of the generated graphics and data, it can be mainly used at the beginning of the engineering course.

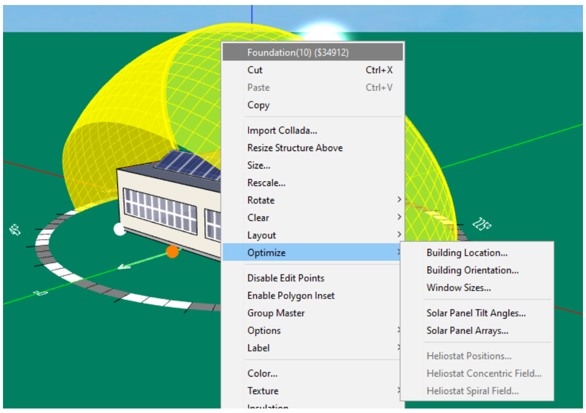



Figure 9. optimization options.

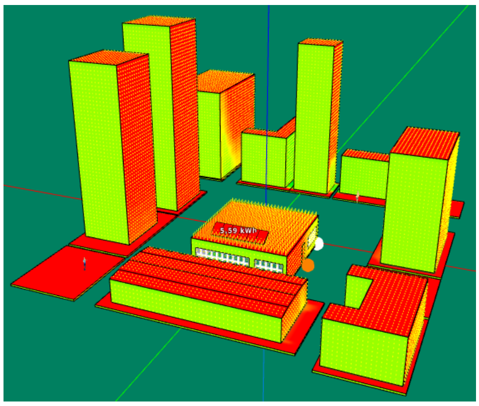


Figure 10. Optimization: building location.

## 4. CONCLUSIONS

This work aimed to analyze the potential of using the free Energy 3D software for engineering undergraduate students in solar energy and energy efficiency courses. A specific case study on photovoltaic generation and energy efficiency was selected involving a hypothetical single-family residential building in Porto Alegre, Brazil. Contrary to the usual, cases were simulated in which the PV modules were installed on the façade.

It was possible to evaluate the difference in the PV generation in terms of the location of the module arrangement. As expected, the best performance was from the roof configuration. However, if it is not an option, installations on the East, West, or North façades allow generating around 60% of the optimal value, showing themselves as viable alternatives. In the case of the North façade, the relocation of the kitchen window does not impact the consumption of the heating system. However, in the AC system, this configuration leads to a decrease in consumption of around 10%.

In general, the software allows you to build, declare building materials and electricity consumption, analyze expenses with AC and heating systems, etc. Furthermore, it will enable the user to "see" abstract concepts in graphic form, using arrows (vectors) and heat maps (solar radiation). Optimization tools make it possible to "discover" optimal settings and investigate other possibilities for project design. In this sense, perhaps the most important is the opportunity to visualize the effect of the decisions taken during the project's development. In this way, students become protagonists in their learning.

## 5. ACKNOWLEDGEMENTS

The first author thanks UFRGS (Federal University of Rio Grande do Sul) and CNPq (National Council for Scientific and Technological Development) for the Scientific Initiation scholarship. Both authors would like to thank UFRGS and LAFRIG (Laboratory of Steam and Refrigeration).

## 6. REFERENCES

Carrilho da Graça, G.; Augusto, A.; Lerer, M. M., 2012. "Solar powered net zero energy houses for southern Europe: Feasibility study". *Solar Energy*, Vol. 86, No. 1, pp. 634–646. DOI: 10.1016/j.solener.2011.11.008

Caus, A.B., 2019. *Viability Study of a Model House for Residential Homes in Porto Alegre* (in Portuguese). Mechanical Engineering End of Course Monography – Mechanical Engineering degree, Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

Crawley, D.B., Lawrie, L.K., Winkelmann, F.C., 2001. Energy plus: A New-Generation Building Energy Simulation Program (2001), https://www.researchgate.net/publication/222517509_EnergyPlus_Creating_a_New-Generation_Building_Energy_Simulation_Program. Accessed 10 March 2021. DOI: 10.1016/S0378-7788(00)00114-6

Fedrigo, N.S., Gonçalves, G., Lucas, P.F., Ghisi E., 2009. *Final Uses of Electric Energy in the Brazilian Residential Sector* (in Portuguese). Scientific Initiation Report. Energy Efficiency In Buildings Laboratory, Federal University of Santa Catarina, Florianópolis, Brazil.

Harthely, A., 2017. "Teaching Building Science with Simulations". *Community College Journal of Research and Practice*, Vol. 41:6, pp. 363-365. DOI: 10.1080/10668926.2016.1268079

MRSolar, 2021. CS6P-255P PV Module datasheet, https://www.mrsolar.com/content/pdf/Canadian/CS6P-250P255P.pdf. Accessed 30 January 2021.

Xie, C., Schimpf, C., Chao, J., Nourian, S., Massicotte, J., 2018. "Learning and teaching engineering design through modeling and simulation on a CAD platform". *Computer Applications in Engineering Education*, Vol. 26, Issue 4, pp. 824-840. DOI: 10.1002/cae.21920

## 7. RESPONSIBILITY NOTICE

The authors are the only ones responsible for the printed material included in this paper.