Energy analysis of a nZEB standard residential building: case study in Rio de Janeiro

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Abstract. This research aims to identify the technical feasibility of the concept of Nearly Zero Energy Building according to Brazilian standards and climatic conditions. The analysis was performed under the most up-to-date normative references and through computational energy simulation via EnergyPlus software, focusing on the building envelope model of a residential building in Rio de Janeiro. A reference model and five other construction models common in the national market were analyzed in two scenarios: firstly, in terms of natural ventilation only, and then using natural ventilation alternating with artificial cooling. Although those models were shown to be in the scope of international benchmarks about energy consumption in warm climate areas, some models stood out. In this case, the model with the lowest energy consumption presented results 22% lower than the reference model. This model was then associated with a supply of solar photovoltaic energy in order to apply one of the fundamental requirements of nZEB: the use of renewable energy sources. The results show the potential for nZEB implementation in Brazil.

1. Introduction

Buildings today are responsible for more than a third of the global energy consumption and almost 40% of CO2 emissions. In order to minimize the energy consumption related to residential constructions, traditional building envelope sets have been analyzed in this paper according to the Nearly Zero Energy Building (nZEB) concept. The nZEB model is defined by the European Union in the Directive 2010/31/EU as a building with nearly zero energy needs and with very high energy performance, based on the annual energy calculated or actually consumed. Then the very low energy needs shall be covered to a large extent by energy from renewable sources, produced on-site or nearby [1].

Although the nZEB construction standard is being implemented in many places around the world, this type of construction is not widely used in Brazil. The present research aims to assess the technical feasibility of nZEB approach in Brazil by a building performance simulation and taking into consideration the current standards and the building materials that are most easily found in the national market.

The analysis was carried out using the application EnergyPlus (version 8.7.0) to model a residential building project located in Rio de Janeiro/Brazil. The evaluation focused on analyzing the impact of a set of envelope construction types on energy consumption of the building.
2. Literature review
The European Commission has set out not only to establish the concept of a Nearly Zero Energy Building, but also to specify building performance parameters for different climate zones in the EU. In Recommendation 2016/1318, it was established that in the case of countries situated in warm climates in the Mediterranean area, new single-family dwellings should fall within the range of 0-15 kWh/m² a year of primary energy. While these values are given for buildings in another continent, since this region has average temperatures close to those of Rio de Janeiro, these values were used as a parameter for the study [2]. The International Organization for Standardization (ISO) highlights important requirements to be considered for the nZEB approach in the standard ISO 52000:2017 - Energy Performance of Buildings. The first requirement is the assessment of the building performance related mainly to the building envelope and to the use of bioclimatic strategies. The second refers to the performance of building systems (ventilating, air conditioning, hot water or lighting) and the third is the evaluation of the amount of non-renewable energy use in relation to total energy consumption. In this standard, renewable energy generation is suggested to act as an offset to the non-renewable energy use. Thus, factors related to building performance and renewable energy use also apply for a nZEB [3].

Brazilian standards do not yet address nZEB although major changes are expected in the following years since most of the building performance standards are under revision. Nevertheless, it is possible to find technical references that apply to the subject and can be explored for the introduction of the concept in the national context of the construction sector. The standard NBR 15.220:2003 - Thermal Performance of Buildings - establishes a bioclimatic zoning for single-family houses with eight different zones. The division is made according to temperature and thermal comfort conditions, helping in the choice of construction strategies [4].

A recent standard related to the topic is NBR 15.575-1:2021 - Performance of residential buildings, which establishes requirements for constructions and establishes evaluation criteria for energy analysis using computer simulation. The standard specifies considerations for the occurrence of internal loads through the occupation of users in areas of prolonged stay (APS) and the use of artificial lighting and equipment. The energy analysis procedure of NBR 15.575-1: 2021 also specifies that it is mandatory to consider the use of natural ventilation. The evaluation is based on two requirements: percentage of hours of occupation of the APS within the operating temperature range (PHTRAPS) and maximum annual operating temperature (OTMAX) [5].

In the Brazilian literature, there are studies related to civil construction components that can be applied to the nZEB concept. For example, [6] simulated several scenarios of commercial buildings in Brasília and identified opportunities to reduce energy consumption by up to 46% for commercial buildings. Three cities located in different Brazilian climate zones were considered in the studies presented in [7]. In cities with cold climates, the proposed construction modifications had a greater reduction, between 60 to 80% related to cooling and heating, while the cities with hot climates presented a reduction of about 15%. The study then showed that an energy balance close to zero adapted to the region is a concept that can be applied in Brazil. Both researches, besides presenting significant energy reduction data, considered out of date normative references.

3. Materials and methods
The requirements of the mentioned standards were considered in the design and energy analysis of the nZEB case study presented in this work. The single-family dwelling construction information was modelled in a 3D platform and the information imported to the energy analysis application. The energy consumption output was the basis for the design of the PV generation.

3.1. 3D Model
The model represents a low standard family residence: two bedrooms, two bathrooms, a living room, kitchen and circulation area. For the energy analysis, the building was modeled in 3D in Sketchup (2017) using Plug-in Euclid (9.3.0), as shown in Figure 1.
According to the categorization presented in NBR 15.220:2003, since this building is located in Rio de Janeiro, it belongs to bioclimatic zone 8. Thus, all the construction guidelines for this zone regarding the size of openings, shading and material properties were applied in the model.

Figure 1. 3D model of the building: (a) external view, (b) internal view.

Figure 2. Different fields of energy modeling in EnergyPlus: (a) compact schedule, (b) building layers, (c) materials used, (d) natural ventilation.
3.2. Energy modeling of the building

The energy modeling was performed in EnergyPlus 8.7.0. Some data were automatically imported from the 3D model, such as the building surfaces, windows and shading defined according to NBR 15.575-1: 2021, indicated in Figure 2 (a) and (c).

The physical and thermal properties of the materials indicated in Figure 2 (b), such as absorptance, thermal conductivity, density and specific heat, were defined according to the values indicated in NBR 15.220:2003 for each material.

The natural ventilation fields, as shown in Figure 2 (d) were filled according to the control of openings specifications of NBR 15.575:2021. The control mode depends on the category of the room and can be configured as one of the following modes always closed, always open, temperature dependent and occupation dependent.

3.3. Reference model

Energy analysis was performed by a comparison between a reference model and a set of alternative models. The reference building has the thermal properties specified in NBR 15.575-1: 2021 for areas with prolonged stay. In this case, the reference model (RM) has concrete block walls (9x19x39cm), with no internal and external coating, a concrete slab ceiling (10 cm), an air chamber of 0.2167 m²K/W, thermal insulation of 0.67 m²K/W, ceramic tiles and common 3mm glass in the windows.

3.4. Alternative models

The building envelopes of the other five models analyzed were defined based on the most common building systems components available in the national market. The first roofing model studied is composed of a 10 cm solid concrete slab ceiling, an air chamber greater than 5 cm, and 1 cm light-colored painted ceramic tiles (SSAT). The second model has a combination of ceramic tiles, an air chamber and PVC ceiling cladding (PAT); and the third model has tiles, air and wooden lining closure (WAT). The fourth model makes use of a 12 cm pre-molded EPS slab, air and ceramic tiles (PMSEAT). The fifth model has a green roof (GR): a 10 cm solid slab, 40 cm dry clay soil and vegetation. All models are composed of ceramic block walls (9x19x19 cm), 2.5 cm of mortar on the inner and outer sides, and the same common 3 mm glass for the glazing. The summary of all the models studied and their specific properties is shown in Table 1.

| Element | Materials and thickness (cm) | Code | Thermal properties |
|---------|------------------------------|------|--------------------|
|         |                              |      | Transmittance (W/m²K) | Heat capacity (kJ/ m²K) |
| Roof    | Solid concrete slab (1) + air chamber (>5) + ceramic tile (1) | (SSAT) | 2.05 | 238 |
|         | PVC ceiling (1) + air chamber (>5) + ceramic tile (1) | (PAT) | 1.75 | 21 |
|         | Wooden lining (1) + air chamber (>5) + ceramic tile (1) | (WAT) | 2.02 | 26 |
|         | Pre-molded EPS slab (1) + air chamber (>5) + ceramic tile (1) | (PMSEAT) | 1.26 | 150 |
|         | Solid concrete slab (1) + dry clay soil (40) + vegetation | (GR) | 0.96 | 791 |
| Wall    | Pierced Ceramic Block (9) + internal and external mortar (2.5) | All models | 2.37 | 151 |
| Glass   | Glass (0.3) with F.S= 0.87 | All models | 5.7 | Not specified |
4. Results and discussion

4.1. Natural ventilation

As it is compulsory to assess natural ventilation in the building, the two criteria of NBR 15.575-1:2021 were applied. The first criteria are related to the annual average dry bulb temperature (23.5°C for Rio de Janeiro) and the operating temperature range (18°C to 26°C). PHTR\textsubscript{APS} were calculated and all the alternative models obtained a percentage greater than 90% of the reference model, meeting the performance criteria.

Regarding OT\textsubscript{max}, the values for each APS the Brazilian standard specifies that the models must have a temperature lower than that of the reference model (tolerance of 2 ° Celsius for single-family homes). All models met the criteria and presented temperature below 38.41°C. Table 2 presents PHTR\textsubscript{APS} and OT\textsubscript{max} of the models.

| Model | PHTR\textsubscript{APS} (%) | OT\textsubscript{MAX} |
|-------|-----------------|------------------|
| RM    | 58.78           | 36.41            |
| SSAT  | 60.48           | 37.48            |
| PAT   | 79.55           | 34.56            |
| WAT   | 79.37           | 34.61            |
| PMSEAT| 65.63           | 36.02            |
| GR    | 65.15           | 34.7             |

All building models presented acceptable thermal performance using natural ventilation only, with comfortable temperatures for most of the year. However, for the purpose of the energy study, the building was analyzed with the use of natural ventilation during the day and artificial cooling in the bedrooms at night, from 10pm to 8am.

4.2. Natural ventilation and artificial cooling

The simulation allowed the identification of the annual consumption for the models, as can be seen in table 3. The building model that presented the lowest energy consumption was the model composed of ceramic blocks with mortar on both sides and roofing with ceramic tiles and PVC ceiling. Its consumption was 22% lower than the reference model, a difference related to room air conditioning, highlighting the importance of carefully choosing materials in the building envelope.

| Model | Heating  | Cooling | Illumination | Equipment | Ventilation | Total energy consumption (kWh) | Energy consumption by area (kWh/m²) |
|-------|----------|---------|--------------|-----------|-------------|---------------------------------|-----------------------------------|
| RM    | 0        | 1436.44 | 819.52       | 598.02    | 206.59      | 3060.57                         | 10.07                             |
| SSAT  | 0        | 1168.55 | 819.52       | 598.02    | 168.92      | 2755.01                         | 9.07                              |
| PAT   | 0        | 850.75  | 819.52       | 598.02    | 120.14      | 2388.43                         | 7.86                              |
| WAT   | 0        | 858.0   | 819.52       | 598.02    | 120.21      | 2395.86                         | 7.89                              |
| PMSEAT| 0        | 1020.37 | 819.52       | 598.02    | 131.91      | 2571.63                         | 8.46                              |
| GR    | 0        | 1021.59 | 819.52       | 598.02    | 132.49      | 2569.83                         | 8.46                              |

4.3. Renewable energy generation and energy balance

Using the consumption outputs for the best performing model, the analysis of the renewable energy supply was performed. Due to the favorable conditions for solar energy generation in Brazil, a solar photovoltaic system connected to the electrical grid was designed [8]. The demand-compliant system has a 2 kW PV generator composed of six 340W modules facing north and tilted 23°. Figure 3 presents the energy balance of the most efficient building obtained from the EnergyPlus simulation. It resulted
in a positive annual balance of 308.8 kWh, demonstrating that besides generating energy to cover the building's energy needs, the system has the capacity to export energy to the grid.

![Figure 3. Energy balance.](image)

5. Conclusion
The study explored the technical feasibility to apply minimal actions in order to obtain nZEB domestic buildings under the current context of Brazilian standards and the materials available on the market. Regarding the performance of the materials, an important point is that the choice of envelope materials had a great impact on total energy consumption and must be carefully analyzed in the building design stage.

The use of the bioclimatic strategy of natural ventilation, in regions with similar conditions to Rio de Janeiro, can provide environmental comfort during most of the year. Moreover, even when using artificial cooling, the consumption data is still acceptable with values of annual energy consumption per area up to 15 kWh/m², which is within the expected consumption margin for countries in warm regions of the EU. This could be an indication that the Brazilian construction systems have promising potential for nZEB considering the local climatic conditions.

Furthermore, it was possible to identify that buildings located in Rio de Janeiro have the available resources to obtain renewable energy production compatible with the demand for a low standard residential building by using a small photovoltaic system.

The study demonstrates that the existing building technologies associated with renewable energy supply can result in a favorable energy performance that allows the application of the nZEB concept in the Brazilian constructions directives.

6. References
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