ENERGY SIMULATIONS OF AN EXISTING VILLA CONVERTED INTO AN NZEB BUILDING: A CASE STUDY

Luís B. Martins[1], Ana C. Ferreira[1,2]*, Bernardino Pinto[1], Pedro Gonçalves[1], Nelson Rodrigues[2,3], José C. Teixeira[1] and Senhorinha Teixeira[3]

[1]MEtRICs - Centro de Engenharia Mecânica e Sustentabilidade de Recursos, University of Minho, Portugal
[2]COMEGI - Centro Investigação em Organizações, Mercados e Gestão Industrial, Universidade Lusíada, Portugal
[3]ALGORITMI, University of Minho, Portugal

*Corresponding Author: acferreira@dps.uminho.pt

ABSTRACT

The renovation strategy defined by the European Commission to improve the energy performance of buildings is crucial to achieve the climate-neutral targets by 2050. Accordingly, the undergoing revision of the Energy Performance of Buildings Directive will promote long-term renovation strategies to ensure the necessary progress towards the transformation of the existing housing stock into nZEB. This work aimed to energetically simulate a three-bedroom villa located in the city of Braga and compare the results after its conversion into an nZEB, leading it to a high-performance energy rating. To this end, two types of simulations were performed, a seasonal one using the National ITecons spreadsheets and another with multizone hourly dynamics, using the Energy Plus™ program. The seasonal methodology led to an energy Class F rating for the existing villa which passed to Class A after the implementation of improvement measures for the conversion into a nZEB. The dynamic simulations with the Energy Plus™ program showed different energy results with the detached house moving from Class C to Class A after the improvements. The discrepancies in the results obtained with the two types of simulations can be explained by the differences in complexity and philosophy of the two methodologies, but the multi-zone dynamic simulation methodology allows the prediction of the building heating and cooling needs in real-life dynamic situations.

1 INTRODUCTION

On the present date, about 75% of the European Union (EU) buildings are energy inefficient, with 35% being over 50 years old. A share of 85-95% of the stock is expected to still be standing in 2050 and more than 40 million Europeans are unable to properly heat their homes (Economidou et al., 2020; Zangheri et al., 2014). To reduce the overall emissions by at least 55% in 2030, as compared to 1990, and reach a carbon-neutral Europe by 2050, the European Commission launched the Renovation Wave Strategy for the building sector that aims to at least double the current 1% yearly renovation rate and, thus, renovate about 35 million inefficient buildings by 2030 (EU Monitor, 2020). Accordingly, the undergoing revision of the Energy Performance of Buildings Directive (EPBD), approved on the 14th of March 2023 by the European Parliament, will promote these long-term renovation strategies to ensure the transformation of the existing housing stock into nearly Zero-Energy Buildings (nZEB) (European Parliament, 2023).

The concept of energy efficiency must be combined with thermal comfort, enforcing measures to both reduce energy consumption and ensure human thermal comfort. Those measures aim for the rational use of energy, which leads to a reduction in GHG emissions and a lower energy dependency (Nastase et al., 2017; Suzuki et al., 2022). To achieve convenient energy efficiency objectives, it will therefore be essential to renovate a large part of the existing housing stock, if possible, to achieve the nZEB certification (Simson et al., 2021; Vitória et al., 2022). A nZEB building has a very high energy performance, and its low energy needs are mainly covered by renewable sources, preferably local or originating nearby from the building (Ascione et al., 2019; Resende & Corvacho, 2021).

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Portugal reinforced the importance of achieving more stringent targets with its Integrated National Energy and Climate Plan for the horizon 2021-2030 (NECP 2030): until 2030 there is a commitment to incorporate 47% of energy from renewable sources in the gross final energy consumption and reduce by 35% the primary energy consumption based on better energy efficiency and relative to forecasts by the 2007 PRIMES model. The sector targets for the reduction of greenhouse gas emissions with respect to 2005 are 70% and 35% for service buildings and households, respectively (NECP, 2030). In Portugal a vast housing stock was built before the 1990s, with few or no thermal requirements and most of those families do not have the financial capability for the high energy consumption associated with the eventual investment and use of Heating, Ventilation and Air Conditioning (HVAC) system, thus living in conditions of manifest thermal discomfort (Horta et al., 2019). The lack of comfort is particularly evident in traditional detached houses (Ghering et al., 2022). In Portugal and for certification purposes, the Building Energy Modelling (BEM) is made in three ways depending on the type of building and increasing complexity: using a spreadsheet with a seasonal model based on the heating degrees-day of the local climate; using a simplified time-dynamic software and detailed dynamic simulation programs. The seasonal model is applied to estimate the heating and cooling needs of residential buildings according to the Portuguese Regulation of Energy Performance for Residential Buildings as approved by the Decree-Law nº118/2013 and amended by DL nº101-D/2020, which transposed the European EPBDs nº 2010/31/EU and 2018/844/EU to the national legal system. This legislation establishes the minimum requirements for new or renovated buildings, as well as the methodology to characterize, evaluate and certificate the energy performance of all residential buildings, as a strategy to improve their thermal behaviour (ADENE, 2020). The Excel spreadsheet uses a stationary method (albeit with a thermal inertia term), based on the heating degree-days which means the heat transmission takes place in a steady state featuring the building as a single zone with constant reference indoor air temperature, ventilation rate and internal thermal gains. It is a simple method able to compare the quality of different buildings but unable to properly estimate the annual heating and cooling needs for the heating and cooling seasons. As the EPBD is again under review, this methodology will likely be abandoned as the certification of residential buildings will probably be also based on dynamic simulation programs (Esteves et al., 2021; Vaquero, 2020).

The simplified time-dynamic software is applied to estimate the heating and cooling loads for commercial and service buildings of limited size. This software estimates heating and cooling needs by defining the building as a single zone and calculating energy balances on an hourly basis and for the Typical Meteorological Year (TMY) as described in the EN ISO 13790 standard. The estimation of the total energy consumption is made through an annual calculation, based on rules and orientations presented in the Regulation of Energy Performance for Commercial and Services Buildings (RECS), also approved by the DLs nº118/2013 & nº 101-D/2020. Several Excel spreadsheets have been developed by two institutes, ITeCons and PTnZEB, to facilitate the previously described methodologies. ITeCons has one Excel spreadsheet for residential buildings and a simplified dynamic software (converted to an Excel spreadsheet) for small Commercial and Services Buildings. PTnZEB developed a single spreadsheet that includes both methodologies. They allow the direct fulfilment of all information necessary for the emission of energy building certificates.

The evaluation of the energy consumption for a multizone building is made by computational simulations using programs accredited by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) through the standard number 140. This detailed methodology is compulsory for large commercial buildings (ASHRAE, 2001). Many software tools are available, *e.g.*, TRNSYS, TRACE 700, Energy Plus™ and HAP by Carrier (Cetin et al., 2019; Crawley et al., 2001). Usually, there is less information regarding the complex calculation methodologies used and difficulties in accessing very detailed results.

The choice between seasonal methodology and detailed dynamic hourly simulation depends on the specific goals of the analysis, the level of detail required, and the available computational resources. While simplified seasonal approaches provide energy estimates, this methodology cannot capture the full range of building energy dynamics. On the other hand, the detailed dynamic hourly simulation is typically preferred for in-depth studies of building performance, energy efficiency measures, and HVAC operation optimization. Thus, research is needed to compare and assess the differences when developing and applying different methods, balancing accuracy and computational efficiency.

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These methods could help to improve the energy performance prediction of buildings while being practical for use in real-world projects. The objective of this work is to simulate the energy performance of a three-bedroom villa located in the northwest of Portugal, 30 km away from the coastline, and compare the results after the conversion into an nZEB, leading it to a high-performance energy rating. To this end, two types of simulations were performed, a seasonal one using the National ITecons spreadsheets and another with multizone hourly dynamics, using the Energy Plus™ program. This study aims to overcome a gap in the literature related to the need to evaluate and compare the results of different methodologies for evaluating a building energy performance. The residential building should be straightforward enough for easy implementation of different commercial software.

2 CASE STUDY

This section presents the characterization of the three-bedroom existing villa and the suggested five improvement measures required to achieve an nZEB rating.

2.1 Characterization of the Existing Villa

The building under study consists of a single-family house, located in the city of Braga - Portugal. Adjacent buildings were considered not to cause any significant obstructions to its horizon. It can be considered a typical Portuguese family house built before the 1990s, usually without any worries concerning energy conservation, resulting in a lack of insulation materials and total negligence concerning the building's solar orientation and corresponding glazing areas.

The main front of the building is North facing with the rear facing South and the longer sides facing East and West. The building is of type T3 (Portuguese terminology for a three-bedroom house or flat) and consists of a basement, a ground floor and a 1st floor. It has an average ceiling height of 2.67 m and interior areas with the following dimensions: basement – 108 m^2; ground floor – 103 m^2 and 1st floor – 95 m^2. The basement includes a garage, a cellar, a service bathroom and a laundry room. The ground floor comprises a living room, a kitchen, a guest bathroom, a waiting and a dining room. The 1st floor consists of 3 bedrooms, one of which is a suite, a bathroom that serves the other 2 bedrooms, a small room and a hall. Only the ground floor and the 1st floor will be air-conditioned and are therefore considered useful spaces in terms of thermal energy use, with a total area of 198 m^2. The basement is a separate non-useful and non-air-conditioned zone, as is the case with the non-habitable and non-insulated attic.

Portugal is divided into three winter (I1, I2, I3) and three summer (V1, V2, V3) climate zones, according to the local climate severity. The location corresponding to the Braga area is classified as of medium severity, both for winter and summer (zones I2 and V2). For the reference altitude of 171 m, its winter season is characterized by 1491 heating degrees-day at 18 ºC, a duration of 6.8 months, an average temperature for the coldest month of 9 ºC, and 125 kWh/m^2 per month of average global solar energy on a vertical south-facing surface. The 4 months' summer season is characterized by an average air temperature of 20.7 ºC and 795 kWh/m^2 of accumulated solar energy from June to September on a horizontal surface.

For the building envelope, the exterior walls are assumed to be made of traditional clay bricks and concrete without insulation, with a thermal transmittance *U*-value likely exceeding 2.0 $W.m^{-2}K^{-1}$ (exact value unknown). The corresponding *U*-value for the uninsulated and non-ventilated attic roof is expected to be about 1.5 $W.m^{-2}K^{-1}$. These high *U*-values are considered to be the major contributors to the energy inefficiency and discomfort of traditional houses in Portugal. Namely, the 1st floor bedrooms are typically the most uncomfortable spaces, particularly in summer, with the ceiling working as an infrared radiator as very high temperatures can be achieved in the unvented attic space.

The Energy Regulation for Residential Buildings (REH) seasonal method stipulates a constant use of the building corresponding to permanent set point temperatures of 18 ºC for winter and 25 ºC for summer and a continuous internal energy gain of 4 W/m^2, including lighting and other equipment. In the Energy Plus™ dynamic simulation, more realistic hourly utilization profiles will be used for the HVAC useful space working hours (ground floor and 1st floor) and for room-specific profiles for

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lighting and equipment use, which translate into heat gains. In addition, the certification process includes the conversion of all forms of final energy consumption into primary energy.

Regarding occupation, the regulation defines it as permanent occupation when the human presence is at least on average, two hours per day during the period of operation of the space and which, cumulatively, has a density greater than 0.025 occupants/m^2. Therefore, it is necessary to consider all compartments belonging to the basement and roof spaces as non-useful spaces, *i.e.*, not occupied and thus, not requiring air-conditioning. The occupancy profile shown in Table 1 was adopted. Occupancy was divided into villa divisions and only the periods when spaces were occupied were described.

Table 1: Occupancy hours of the different divisions

Division	Week days	% Occupancy	Weekend days	% Occupancy
Kitchen	7 a.m. – 8 a.m. 7 p.m. – 8 p.m.	0.50 0.50	8 a.m. – 9 a.m. 1 p.m. – 2 p.m. 8 p.m. – 9 p.m.	0.25 0.50 0.50
Dinner Room	7 p.m. – 8 p.m. 8 p.m. – 9 p.m.	0.50 1	1 p.m. – 2 p.m. 7 p.m. – 8 p.m. 8 p.m. – 9 p.m.	0.50 0.50 1
Double Room	10 p.m. – 7 a.m.	0.50	12 p.m. – 8 a.m.	0.25
Individual Room	9 p.m. – 7 a.m.	0.25	12 p.m. – 8 a.m.	0.25
Hall	9 p.m. – 10 p.m.	0.50	9 p.m. – 11 p.m.	0.50
Bathroom	7 a.m. – 8 a.m. 8 p.m. – 9 p.m.	0.25 0.25	8 a.m. – 9 a.m. 8 p.m. – 9 p.m.	0.25 0.25

2.2 Suggested improvements to achieve nZEB rating

The objective is to convert the building under study into an nZEB, with almost zero energy needs that should be mainly covered by renewable energy sources produced on-site or nearby. The main suggested measures are as follows:

- Measure I - Reduction of the *U*-values for opaque envelope elements and windows. Traditional Portuguese houses built before 1990 usually have non-insulated exterior walls and roofs, and single glazing windows. Thus, it is crucial to severely reduce the thermal transmittance *U*-values of all these envelope elements, by applying adequate external insulation to maintain the traditional high thermal inertia, not forgetting the change for high-quality windows and doors.
- Measure II – High building airtightness with controlled ventilation and free cooling.
- Measure III – Fixed and variable geometry automatic shading devices. To allow the entrance of ‘free’ solar energy to heat the building in winter and avoid it during the summer, appropriate window shading is essential and a combination of fixed geometry and automatic variable shading devices will be used.
- Measure IV - Increased efficiency of technical systems and more efficient lighting. To make the building even more efficient, better HVAC and hot water systems must be used, together with the adoption of energy efficiency measures for general equipment (electric and gas), including the careful design of an LED-type lighting system.
- Measure V - Use of renewable energy.

In Portugal, at least 50% of the primary energy needs of a nZEB must be supplied by renewable energy sources. The systems that should be preferred are: solar thermal for hot water supply, solar Photovoltaics (PV) for electricity and the HVAC system should be based on highly efficient heat pumps such as a geothermal heat pump or a geothermal/water source heat pump.

Old Portuguese buildings are notorious for their massive external envelope gaps and corresponding air leaks. Thus, it is also important to make the building airtight and promote efficient ventilation. Individual space-controlled ventilation should be promoted and free cooling by natural convection during the summer nights is an adequate mechanism for the local climate. Heat Recovery Ventilation (HRV) or Enthalpy Recovery Ventilation (ERV) might also be used.

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3 ENERGY SIMULATIONS

In this section, both methodologies used for energy performance simulations are described, as well as the respective input and boundary conditions.

3.1 Seasonal energy assessment

As a residential building, for its energy assessment and certification and according to the REH, the seasonal methodology has been used up till now. The ITecons spreadsheet was used and the input parameters of the existing building were inserted. To calculate the heating energy needs, the required local climate data includes the Heating Degree Days (HDD) at 18 ºC and the heating season duration, as well as the medium solar energy received in a south-facing vertical surface. The cooling needs require the medium air temperature and the accumulated solar energy received on horizontal and 4 vertical surfaces during the summer season. The annual nominal needs of useful heating energy in the heating season N_{ic}, per unit floor area of the building, is calculated as in equation (1):

$$N_{ic} = \left(Q_{tr,i} + Q_{ve,i} - Q_{gu,i}\right) / A_p \qquad [\text{kWh.m}^{-2}.\text{year}^{-1}] \qquad (1)$$

where $Q_{tr,i}$, $Q_{ve,i}$, and $Q_{gu,\mathrm{i}}$ are respectively, the transmission heat transfer losses through the building envelope, heat required by air ventilation and heat from useful internal gains plus useful solar gains, in kWh/year. A_p is the useful interior area of the building (m^2).

The useful internal gains are obtained from the gross internal thermal loads (equipment, lighting), considered constant in time with a specific value of 4 W/m^2 based on the useful interior area, and a useful gains factor dependent on thermal inertia. The useful spaces of the building are assumed to be kept at a minimum temperature of 18 ºC throughout the heating season. The value of the annual nominal needs of cooling useful energy in the cooling season, N_{vc}, is calculated as in equation (2):

$$N_{vc} = \left(1 - \eta_v\right) Q_{g,v} / A_p \qquad [\text{kWh.m}^{-2}.\text{year}^{-1}] \qquad (2)$$

where $Q_{g,v}$ is the gross thermal gains in the cooling season (kWh/year) and η_v is the thermal gains utilization factor. The weak point of this method is that it does not use the concept of Cooling Degree Days (CDD) for cooling, although HDD is used for the winter season.

3.2 Detailed hourly dynamic energy simulation software

The detailed dynamic simulations were accomplished with the Energy Plus^{TM} program. The Energy Plus^{TM} package is a collection of programming modules that work together to calculate the energy required for heating and cooling a building with the option for using various systems and energy sources. The Energy Plus^{TM} software was approved by the American Society of Heating, Refrigerating and Air-Conditioning Engineers through ASHRAE 140-2017 standard and it is based on two tools developed during the 1970s after the oil crisis: BLAST and DOE-2. The software can model radiant, convection and conduction heat fluxes through any building element, the ventilation airflows, the heat exchanges with the ground, the HVAC systems performance and thermal comfort in any room (Esteves et al., 2021). The dynamic transient simulations allow user-defined time steps between 1 minute and 1 hour, but typically an hourly representative year is used. After the simulation process, the heating and cooling demands are obtained.

The simulation is based on the solution of the heat balance equation through the envelope elements of the building. Each wall conduction transient analysis uses a 1D model with the option for two numerical methods: the analytical Conduction Transfer Functions (CTF) method or the finite-difference method (Alghoul et al., 2017). It is essential to point out that the building 3D model was made in *SketchUp* 2017 and linked to the *OpenStudio* (OS) application via a dedicated plug-in. Conceptually, the OS provides an Application Programming Interface (API) to access the Energy Plus^{TM} modelling engine. All building surfaces were defined as well as their boundary conditions.

3.2.1. Building 3D modelling in SketchUp

The 3D villa drawing was made with *Sketchup* graphical interface as shown in Figure 1. The modelling included the definition of envelop-space boundary conditions and building orientation. The model was then imported into the OS software and used as the input/output interface to the Energy Plus^{TM}.

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All the subsequent input data were introduced via OS, before starting the simulation procedure, such as climate zone data, building thermal zones, materials, occupation profiles, equipment and lighting loads and setpoint temperatures.

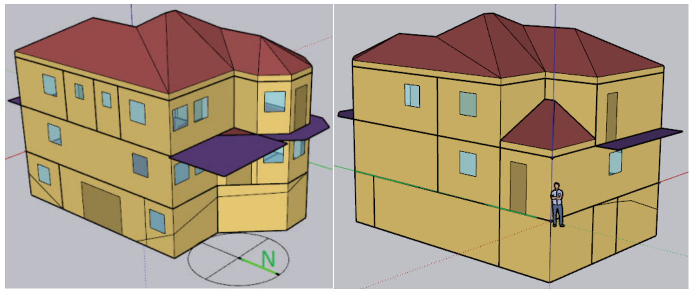

Figure 1: 3D modelling of the building in SketchUp 2017.

The building energy performance is influenced by the geographic location due to factors such as atmospheric air temperature and humidity, altitude, prevailing wind direction and velocity, and solar radiation. The building was located in Braga at an altitude of 171 meters, at a distance from the coast greater than 5 km. For this purpose, an Energy Plus Weather (EPW) data file was created, with hourly climate data based on the local Typical Meteorological Year (TMY) by using the CLIMAS-SCE software. The building was divided into three Thermal Zones (TZ), according to the space utilization:

- TZ 1: Comprises the climatized useful area, equivalent to the ground floor and the 1st floor;
- TZ 2: Corresponds to the basement, considered another thermal zone as it is not climatized. It is mainly a garage with sporadic human presence, thus considered a non-useful space;
- TZ 3: Corresponds to the closed and non-used attic, treated as another thermal zone with no thermal insulation and non-ventilated, thus prone to extreme temperatures.

3.2.2. Materials and constructive

The main materials used in Portuguese masonry construction (walls, floors and roofs) are concrete or stone with perforated clay bricks. This results in high thermal transmittance *U*-values so that when renovating an old house, the major measure towards nZEB is to apply appropriate insulation to the full building envelope. The common options are the use of an External Thermal Insulation Composite System (ETICS) for the exterior walls and a thick insulation board on the attic floor. ETICS is a compact multilayer insulation solution, designed to improve the energy efficiency of both new and existing buildings (known in Portugal as "Capoto"), preserving the thermal inertia. To achieve *U*-values below 0.5 $W.m^{-2}K^{-1}$, the insulation layer should be about 10 centimetres thick. Table 2 presents all the envelop *U*-values for the existing house, together with the ones proposed for the nZEB renovated building.

Table 2: Thermal transmittance *U*-values for building envelop: existing and proposed nZEB

Building element	$U_{Existing\ villa}$ [$W.m^{-2}K^{-1}$]	U_{nZEB} [$W.m^{-2}K^{-1}$]
Exterior walls	2.43	0.37
Basement walls (soil contact)	4.54	0.38
Walls in contact with non-useful spaces	1.96	0.36
Interior walls	2.50	2.50
Ground floor	1.22	0.31
Basement floor	1.86	0.29
First floor	2.46	2.46
Roof (Attic included)	1.48	0.29
Windows	5.80	1.10

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3.2.3. Thermal loads

For the REH seasonal methodology, the total internal thermal loads were considered constant in time with a specific value of 4 W/m^2 based on useful floor area, or about 800 W in total. Also, the HDD methodology implicitly considers that the building is always in use, with fixed setpoint temperatures for the winter (18 ºC) and summer seasons (25 ºC). However, in the case of the dynamic simulation, a set of equipment and lighting was defined with the respective usage and occupancy profiles, defined in the Energy Plus™ through the OS interface. The set-point temperatures for the HVAC system were 18 ºC (winter) and 25 ºC (summer) from 7 p.m. to 8 a.m. on week days (the building was considered vacant during the day) and from 8 p.m. to 3 p.m. on weekends (vacant from 3 p.m. to 8 p.m.). As for the equipment lighting and number of occupants, each room had its own utilisation profiles.

The lighting characteristics are presented in Table 3. The baseline Lighting Power Density (LPD) for each space is estimated based on the illuminance recommended values in lux (lx), to allow safety and comfort in the different compartments of the building. Illuminance is the incident luminous flux per area unit (1 Lux = 1 Lumen/m^2). As for the electric and gas equipment, the items and respective nominal loads are shown in Table 4.

Table 3: Lighting system characteristics

Division	Illuminance [lx]	LPD [W/m^2]
Kitchen	300	15
Dinner Room	200	36
Double Room	150	7
Individual Room	150	8
Hall	150	14
Bathroom	150	8

Table 4: Equipment nominal power and energy source

Appliance	Energy Source	Power [W]
Refrigerator	electricity	300
Microwave	electricity	700
Washing Machine	electricity	1000
LED TV (x2)	electricity	230
Oven & stove	natural gas	7300
Computer	electricity	150
Dishwasher and remaining items	electricity	1200

The building under study has two shading systems *i.e.*, a fixed horizontal canopy type (top floor windows and ground floor south facade and north facade windows) and exterior mobile blinds (all windows). The air-conditioned space comprised the ground floor and the 1st floor. Different considerations were taken to perform the simulations:

- For the existing building, a system with multiple split-ductless air-to-air units was considered with a COP of 2.8 and EER of 2.4., respectively. An electric heater was chosen for Domestic Hot Water (DHW) with an efficiency of 0.90 (poorly insulated tank). Also, it was considered natural ventilation with an estimated rate of 1.0 Renovations Per Hour (RPH).
- For the nZEB case, a centralized VRF system was considered with COP/EER values of 6.0/5.0. Also, systems with better efficiencies were used, *i.e.*, a solar-thermal system for hot water production and a lower air renovation rate of 0.6 RPH.

The DHW useful heat needs were calculated to be 2377 kWh per year, based on a water temperature increase of 35 °C and 160 litres per day for 4 individuals.

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4 RESULTS AND DISCUSSION

The energy performance results of a three-bedroom existing villa, before and after a proposed renovation towards nZEB status, using a simplified seasonal methodology and a multizone hourly simulation with the Energy Plus^{TM} program are presented and discussed in this section.

4.1 Seasonal energy assessment

In this section, the energy needs for seasonal methodology results are presented. As previously stated, the building occupants are in comfortable conditions when the air temperature is above 18ºC (winter) and below 25 ºC (summer). Thus, the heating and cooling energy values, N_{ic} and N_{vc}, are regarded as indirect comfort indicators, as they represent the specific thermal energy requirements to keep the building useful spaces between those two temperatures. High values of N_{ic} and N_{vc} are an indication that without an HVAC system, the building will be uncomfortable most of the year. N_{tc} is obtained from the sum of N_{ic}, N_{vc}, and specific hot water needs, after conversion to primary energy (Primary Energy Factors (PEF)). For electricity and natural gas, PEFs of 2.5 and 1.0 were used, respectively. The existence of these energy indicators allows objective comparisons between buildings with very different sizes (useful areas).

For residential buildings, the energy class is determined according to the ratio ($R_{Nt}= N_{tc}/ N_t$) that results from the relationship between the total needs of predicted primary energy N_{tc} (for the existing building or the proposed nZEB) and the reference N_t. Thus, the R_{Nt} value is defined in class intervals (for example, for Classe A+: $R_{Nt} \leq 0.25$; Class A: $0.25 < R_{Nt} \leq 0.50$; and Class F: $R_{Nt} > 2.50$).

The values for the different specific energy needs based on useful space area (heating N_{ic}, cooling N_{vc}, hot water and total primary energy, N_{tc}) for the existing villa and the proposed renovated villa as nZEB were calculated considering the seasonal energy assessment method (Table 5). The energy needs results of the nZEB with the existing villa are also compared. The building energy performance evaluation process culminates with the determination of the energy class, based on the comparison of these energy indicators.

Table 5: Energy needs for seasonal methodology (specific energy needs in kWh/m^2.year)

Building	**N_{ic}**	**N_{vc}**	**DHW**	**N_{tc}**	**R_{Nt} [-]**	**Class**
Existing	154.9	20.8	12.0	193.4	2.65	F
Proposed nZEB	27.6	9.8	4.1	29.0	0.40	A
Differ. [%]	- 82	-53	-66	-85	-85	-

Regarding the results for the existing villa, and according to the tabled values, an $R_{Nt} = 2.65$ is in the interval corresponding to class F, the worst energetic classification, which results from the high energy consumption, mainly in the heating season. It is also a direct consequence of the non-insulated walls and single-glazed windows typical of old Portuguese houses.

After the improvement measures for the proposed nZEB, the renovated villa will have a 6.6-fold reduction in primary energy needs, resulting in an A classification. It is clearly noted that the improvement measures applied promoted a very significant reduction in energy consumption, mainly in the heating season with a reduction of 82%, while in the cooling season there was a reduction of 53%. This effect is mainly due to the introduction of thermal insulation in the building envelope.

In accordance with the REH, for a residential building subjected to a major renovation, its consideration as nZEB requires its compliance with the thermal comfort and energy performance requirements of a new building for the respective climate zone. The simulated villa is located in the climate zone I2: heating needs below 85% of the reference building ($N_{IC}/N_I \leq 0.85$); cooling needs below the reference building ($N_{VC}/N_V \leq 1.0$); primary energy needs under 50% of the reference ($R_{Nt} \leq 0.5$); and renewable energy self-supply above 50% of the hot water energy needs. The presented renovated villa fulfils all these criteria and it is thus entitled to be certified as nZEB.

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4.2. Dynamic methodology results

Once the existing villa and the nZEB have been simulated using the hourly dynamic methodology, it is possible to obtain all the required energy data and determine the class rating for the existing villa and the proposed renovated nZEB. The procedure for energy rating is done in the same way as the seasonal method, *i.e.*, based on the R_{Nt}, which is based on the ratio between the primary energy needs of the existing or predicted renovated nZEB, and the primary energy needs of the reference building.

Table 6 presents the main energy results obtained with dynamic simulations for both cases. It should be noted that while with the seasonal methodology the house is considered to be permanently occupied (24 hours per day), with the dynamic simulations the occupation profile was mainly during the nights so that the building was vacant from 8:00 am to 7:00 pm on weekdays and from 3:00 pm to 8:00 pm on weekends (HVAC off). Also, instead of the previously used constant gains of 4 W/m^2, utilization profiles were added for the lighting system and diverse equipment (mostly electric but also gas equipment in the kitchen) and that were room dependent. As before, the HVAC set-point temperatures were 18°C and 25 °C, but were only active when the building was occupied (HVAC on). The DHW energy needs were calculated as before, nevertheless the N_{tc} (the amount of total primary energy needed to guarantee all the energy needs of the dwelling) includes the lighting system and the equipment (electric and gas).

Table 6: Energy consumption indicators and efficiency for the dynamic simulation (in kWh/m^2.year)

Building	N_{ic}	N_{vc}	DHW	Lighting	Equipment	Ventilator	N_{tc}	R_{Nt} [-]	Class
Existing	36.8	20.6	12.0	3.22	9.58	0.81	116. 4	1.32	C
nZEB	10.2	18.6	3.29	1.61	9.25	0.42	42.3	0.47	A
Differ. [%]	-72	-9.7	-73	-50	-3.4	-48	-64	-53	-

As expected, the heating needs N_{ic} are significantly lower when compared with the seasonal methodology for two main reasons: the lower period of occupation considered in the dynamic simulations versus the continuous occupation in the seasonal method; the relatively high equipment and lighting system loads (that also affect the final energy indicator N_{tc}), which was not considered in the previous method.

The opposite is observed with the cooling needs, N_{vc}, which are somehow higher in the dynamic simulations results. Again, the explanation lies in the high lighting and equipment loads that translate into higher HVAC thermal loads during the summer season. Also, the simplified seasonal methodology is well known for its poor precision and underestimated summer results. In both cases, the nZEB achieves a Class A rating (and fulfils all criteria to be rated as nZEB), but with a R_{Nt} of 1.32, the existing villa is rated as Class C, compared with the previously Class F. Again, the main reason is related with the lighting and equipment loads.

Figure 2 and Figure 3 present the annual final energy consumption shares by application, for the existing villa and proposed renovated villa as nZEB, respectively. All items correspond to electricity consumptions with the exception of the equipment item, which includes the gas stove/oven.

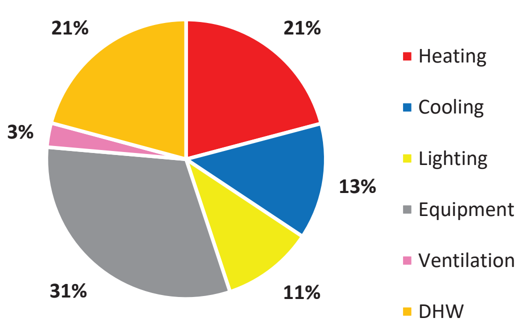

Figure 2: Annual final energy consumption shares for the existing villa.

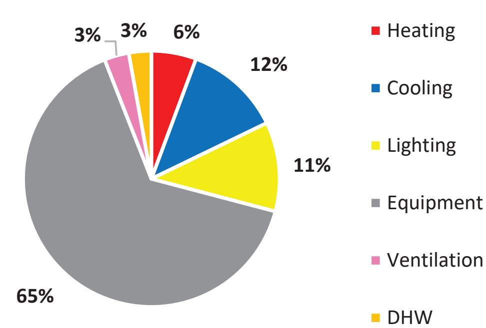

Figure 3: Annual final energy consumption shares for the renovated villa.

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It can be observed that as the building becomes more energy efficient (evolution from existing towards nZEB) the HVAC consumption share during the heating season diminishes significantly, whereas the fixed equipment shares increases.

Figure 4 and Figure 5 present the estimated monthly HVAC electricity consumption. The monthly atmospheric mean temperature is also plotted. As can be observed in Figure 4, the most critical months for the heating and cooling seasons are January and July, when consumption reaches approximately 900 kWh and 550 kWh, respectively. It can also be seen that consumption is higher in winter than in summer with totals of 2622 kWh and 1773 kWh, respectively.

For the heating season, a lower outside temperature correlates relatively well with a higher energy consumption. Nevertheless, December with an outside temperature of 10.1 ºC has a higher energy consumption than February with 9.9 ºC. A similar outcome is observed by comparing November with March. The opposite happens for the cooling season, as higher outside temperatures correspond to higher electricity consumptions to cool the building, but again with slight mismatches when comparing June with September and May with October.

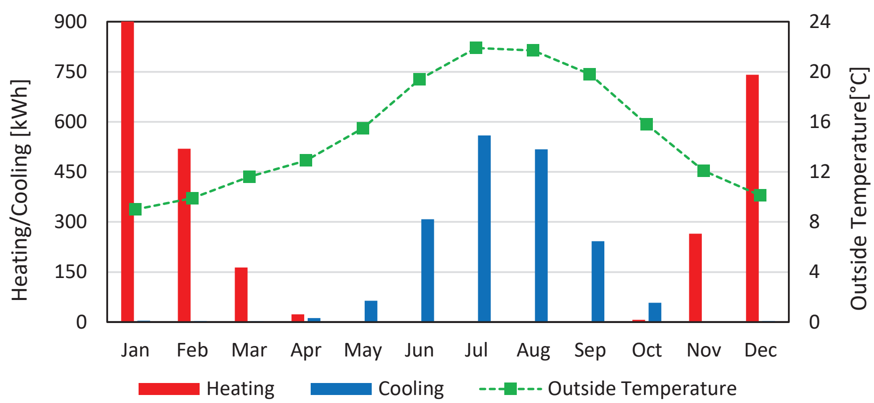

Figure 4: Monthly estimated HVAC electricity consumption for the existing building.

Dramatic decreases in winter energy consumption are observed when comparing Figure 5 (nZEB) with Figure 4 (existing build.). This is mainly due to the introduction of proper insulation in the building envelope, but also to efficiency improvements in the HVAC systems.

In particular, the very low nZEB heating needs are also due to the use of a high efficiency thermal/water source heat-pump with a COP of 6.0. The decrease in summer energy consumption is less evident as the improvements in the insulated envelope tend to increase the effect of the internal thermal gains from equipment and solar radiation.

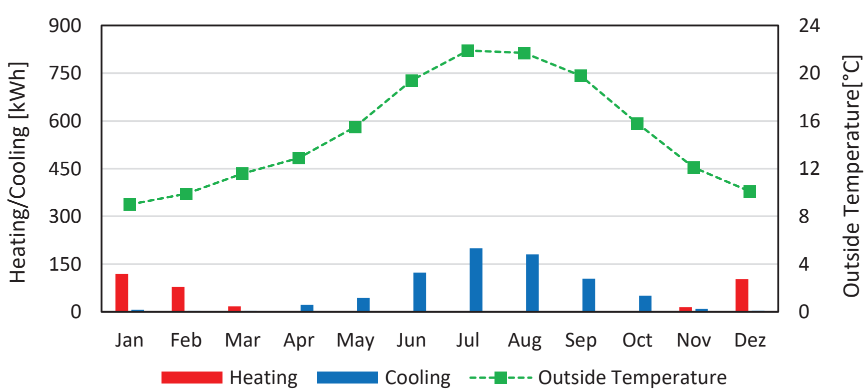

Figure 5: Monthly estimated HVAC electricity consumption for the nZEB.

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5 CONCLUSIONS

The energy performance of a three-bedroom existing villa was evaluated, before and after a proposed renovation towards nZEB status, using a simplified seasonal methodology and a multizone hourly simulation with the Energy Plus^{TM} program. The renovation mainly consisted in the proper insulation of the building envelope from the outside, thus keeping unscathed the typical high thermal inertia of Portuguese buildings. Doubled glazed windows with suitable shading were also included.

The seasonal methodology led to an energy Class F rating for the existing villa, improving to Class A after the proposed renovation, while the corresponding results with the dynamic simulation led to a Class C energy rating improving to Class A. The discrepancies in the energy results can be explained by the differences in complexity and philosophy of the two methodologies, *e.g.,* with the building considered permanently occupied with low and constant thermal gains in the seasonal methodology *versus* an only evening-night occupation profile but higher equipment and lighting loads (translated in thermal gains, favorable in winter but undesirable during the summer season) with the dynamic simulation.

The seasonal methodology is currently adequate for the REH and is used in the Portuguese certification of residential buildings. It can be considered a reasonable methodology for comparing different buildings in terms of energy performance and qualitative comfort but is inadequate to predict the building heating and cooling needs in real-life dynamic situations as permitted with the Energy Plus^{TM} simulation program. In addition, detailed multizone dynamic simulations are essential for quantitative thermal comfort analysis in the individual spaces and is likely to become the norm even for residential buildings after the undergoing recast of the EPBD.

Future work should consider the first-floor as a separate thermal zone and the thermal comfort should then be assessed by taking into account the multiple thermal zones of the simulated building and by estimating the Predicted Mean Vote (PMV) index. It is believed that the cooling needs for the nZEB can be significantly reduced by implementing an adequate free-cooling system during the summer nights (preferably promoting natural convection ventilation) which was not considered in the present study. In addition, a cost-benefit analysis of the renovations should be performed to get a more comprehensive understanding of the practical implications of converting existing buildings into nZEB.

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