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Theoretical and actual energy behaviour of a cost-optimal based NZEB

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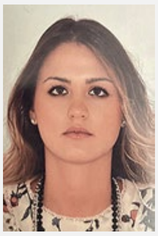

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Abstract

Building energy simulation proves to be an effective tool for the preliminary design phase to evaluate different retrofit scenarios. However, theoretical consumptions still differ from actual ones, especially in NZEBs, mainly due to occupants' presence and interaction with energy systems. This paper aims to verify the gap between theoretical and actual values for an existing Italian NZEB.

Introduction

Nowadays, the ambitious decarbonisation targets for the building sector, proposed by the European Commission, could be reached through the large-scale deployment of Nearly-Zero Energy Buildings (NZEBs). In NZEBs, the aim of reducing energy consumption and CO_2 emissions can be easily achieved since the planning stage, through the design and implementation of high-performing building envelopes coupled with efficient Heating, Ventilation and Air-Conditioning (HVAC) systems and appropriate renewable technologies. These concepts are the basis of the 2010 recast of the Energy Performance of Building Directive (EPBD, European Commission, 2010), which firstly introduced the concept of NZEB and stated that retrofit solutions for existing buildings need to be evaluated through a comparative methodology framework able to identify the cost-optimal levels of minimum energy performance requirements. During the planning phase, energy simulations are typically implemented to evaluate the energy performances of different technological scenarios; however, the theoretical energy consumptions are usually different from real ones. Two factors result to be the main cause of gap: the climate conditions considered in the simulation, as well as the presence of occupants in the building. First, the climatic files used by the simulation software, though plausible, are slightly different from real weather conditions. Moreover, occupant behaviour represents a key factor to uncertainty of building performance, due to its high impact on energy consumptions. For this reason, it is necessary to take into account not only the energy and the financial perspectives, but also to recognize the central role of occupants. To emphasize the importance of considering occupant behaviour within the energy analysis of buildings, the revised EPBD (European Commission, 2018), amended in 2018, introduced a new focus on indoor environmental quality (IEQ), stressing the need for optimizing occupants' health, comfort, and well-being.

In this paper, a single-family house, the so-called CORTAU House, located in Piedmont region, is analysed. Its requalification is of interest, being an example of energy retrofit in the Mediterranean area towards the NZEB targets achievement. Indeed, it is well known that the difference between NZEBs located in Northern and Southern European countries depends on climate conditions. On one hand, in Northern countries, the control of thermal loads in heating periods is crucial and the external climate conditions are favourable for free cooling. On the other hand, in Southern and Mediterranean areas, the goal is to minimize energy consumptions for both heating, in winter season, and cooling, in summer period. In many countries included in the Mediterranean climate area, due to the presence of a variety of climates (e.g. cold dry winters and hot wet summers), unknown in North Europe, there are extremely different scenarios that need to be faced.

In this work, once retraced the design procedure, which implemented the cost-optimal methodology to show to owners/private investors the most convenient retrofit solutions to reduce both energy consumptions and life-cycle costs, the theoretical results coming from the energy dynamic simulation of CORTAU House and from the energy certificate prepared before the occupancy period are compared with the actual consumptions during the year 2017 (as gathered from electricity bills). Moreover, given the key role played by occupants in the difference between theoretical and actual consumptions, a survey submitted to CORTAU final users allowed exploring the main criticalities and potentialities of living and operating an NZEB.

Materials and Methods

The paper aims to compare the theoretical and actual energy performance of an NZEB and to identify the major causes behind the discrepancies of the results. To do this, the work is divided into two stages. The first stage can be identified as the pre-occupancy phase; in particular, this stage consists in the preliminary study of the building through the performance of energy simulations (using EnergyPlus energy dynamic software) and the analysis of the building energy certificate, delivered prior to occupancy period, in order to obtain theoretical energy consumptions. The second stage, also identified as post-occupancy phase, considers the interaction of the occupants with the building systems, by collecting and critically analysing the energy bills, to compare the real consumptions with the simulated ones.

Finally, considering that the occupant has become the centre of the concept of NZEB (European Commission, 2018), a survey was submitted to the inhabitants, to have feedback from the final users, highlighting benefits and criticalities of living in such a complex and high-performance building.

Case study

The case study for the pre- and post-processing of occupants' behaviour is CORTAU House (see **Figure 1**), an all-electric NZEB recently obtained from the retrofit of a traditional rural building (namely "*curmà*"). The building, located in Piedmont region, in the North-West of Italy (climate zone E), has a 147 m² floor area. Its construction started in March 2014 and finished in 2016.

In accordance with the afore-mentioned 2010 EPBD Recast, the building is a representative refurbishment example, since the cost-optimal methodology was implemented during the preliminary design phase, allowing to identify the package of retrofit measures able to minimize both primary energy consumption and global cost. In the case of CORTAU, different envelope and HVAC system configurations were evaluated on energy and financial basis. Four envelope strategies were considered (identified with progressive numbers from 1 to 4), each defined according to specific regulation requirements, in force at national (1), city (2), and international levels (3,4) (Barthelmes et al., 2015). Similarly, four HVAC system configurations were identified (with a letter from A to D), varying in terms of energy production system, as well as of installed renewable energy technologies. In particular, configurations A and B consider the use of condensing gas boiler and radiant floor for space heating, and multi-split air conditioner for space cooling. Configurations C and D, instead, consider the introduction of a water-to-water heat pump, coupled with radiant floors, for both space heating and cooling. Configurations A and C use natural ventilation, while configurations B and D assume the use of a controlled mechanical ventilation (CMV) system. Finally, all configurations consider the use of solar collectors for covering the domestic hot water (DHW) production, and of photovoltaic (PV) panels for matching part of the electricity demands (even if with different installed peak power: 2.6 kW_{peak} for configuration A, 3.4 kW_{peak} for configuration B, and 7 kW_{peak} for C and D). The combination of envelope and system strategies led to the definition of 16 energy design scenarios (see **Figure 2**), which were compared using the cost-optimal methodology. All scenarios were simulated using EnergyPlus software, for evaluating their energy performances, while the economic assessment was done based on the global cost calculation, as defined by (EN 15459-1:2017).

Based on the described methodology, the cost-optimal level for the refurbishment of CORTAU House is identified in the scenario 2C. However, in the design phase, team designer and owners have opted for the configuration 2D (see **Figure 2**), which differs from the cost-optimal level for the adoption of the CMV system (Barthelmes et al., 2015). Moreover, thanks to the use of PV panels and water-to-water heat pump, the national requirements in terms of Renewable Energy Sources (RES) coverage were largely met, thus not asking for the need to install the solar collectors on the roof. CORTAU House, today fully occupied, presents a water-to-water heat pump with 4.4 COP and 4.2 EER, coupled with radiant floor for space cooling and heating, and a CMV system equipped with heat recovery. A 6.3 kW_{peak} PV plant is installed on the roof. The thermal properties of the envelope are in line with Turin regulation (0.15 W/(m²K) for external walls and ceiling, 0.19 W/(m²K) for the slab and 0.96 W/(m²K) for the windows). Starting from the real characteristics of CORTAU House, a model was simulated with EnergyPlus, including standard occupants' behaviour in terms of heating and cooling set-points (20°C and 26°C, respectively), while schedules for occupancy, lighting and equipment usage were set according to existing standards (Barthelmes et al., 2016).

Results

The following section describes the results of the analysis, aiming to show and discuss the gap between theoretical and real consumption values. Theoretical results are assessed either with preliminary energy certifications of the building or with energy dynamic simulations during the design and operation phases. First, looking to the energy certification, performed at the end of 2015 (and thus during the pre-occupancy period), a primary non-renewable energy value of 11.08 kWh/(m²·year) was obtained, which considers only the energy consumption for space heating, space cooling, ventilation and domestic hot water production (being electricity consumption for

Figure 1. CORTAU House current architectural design (Barthelmes et al., 2015).

lighting and electric equipment excluded). In order to compare the value with the real consumptions in the post-occupancy phase, electricity bills were collected for the year 2017 (total electricity from the grid equal to 4 457 kWh/year), while thanks to the on-going monitoring campaign of the PV production, the electricity locally produced in 2017 was gathered (equal to 6 513 kWh/year). Moreover, by estimating the usage profiles of the main interior electrical equipment installed within the building, it was possible to isolate the real electricity consumption for space heating, space cooling, ventilation and domestic hot water production (equal to 7 663 kWh/year). Therefore, parallelly to what assumed for the energy certification (namely to consider the PV production as available for matching the climatization consumption only), it was possible to obtain an overall electricity consumption from non-renewable sources equal to 7.82 kWh/(m²·year). The correspondent value of primary non-renewable energy of 15.3 kWh/(m²·year) was obtained (with a 1.95 conversion factor). As expected, this value is higher than the value shown in the energy certification, showing a percentage discrepancy of 38% between theoretical and real value.

Similar comparison was performed, considering the ideal results coming from the simulation of the EnergyPlus model. The differences between model and real values, in terms of electricity consumption, PV production and purchased electricity from the grid, are shown in **Figure 3**.

Ideal results from simulations are influenced by standard settings in terms of occupancy schedules, lighting and electrical equipment densities and schedules of usage. For this reason, it is well known that energy dynamic simulations, besides being fundamental to understand the energy behaviour of a building, represent ideal situations, far from the reality. Indeed, electricity consumptions reported in the energy bills, gathered from CORTAU occupants, show that the electricity purchased from the grid in the real situation is higher than what expected from simulations.

The differences between theoretical and real results might be conducted to two main causes. The first one can be defined as external climate, since irradiation, external temperature and humidity vary year by year (and thus differing from climatic data used for the simulations),

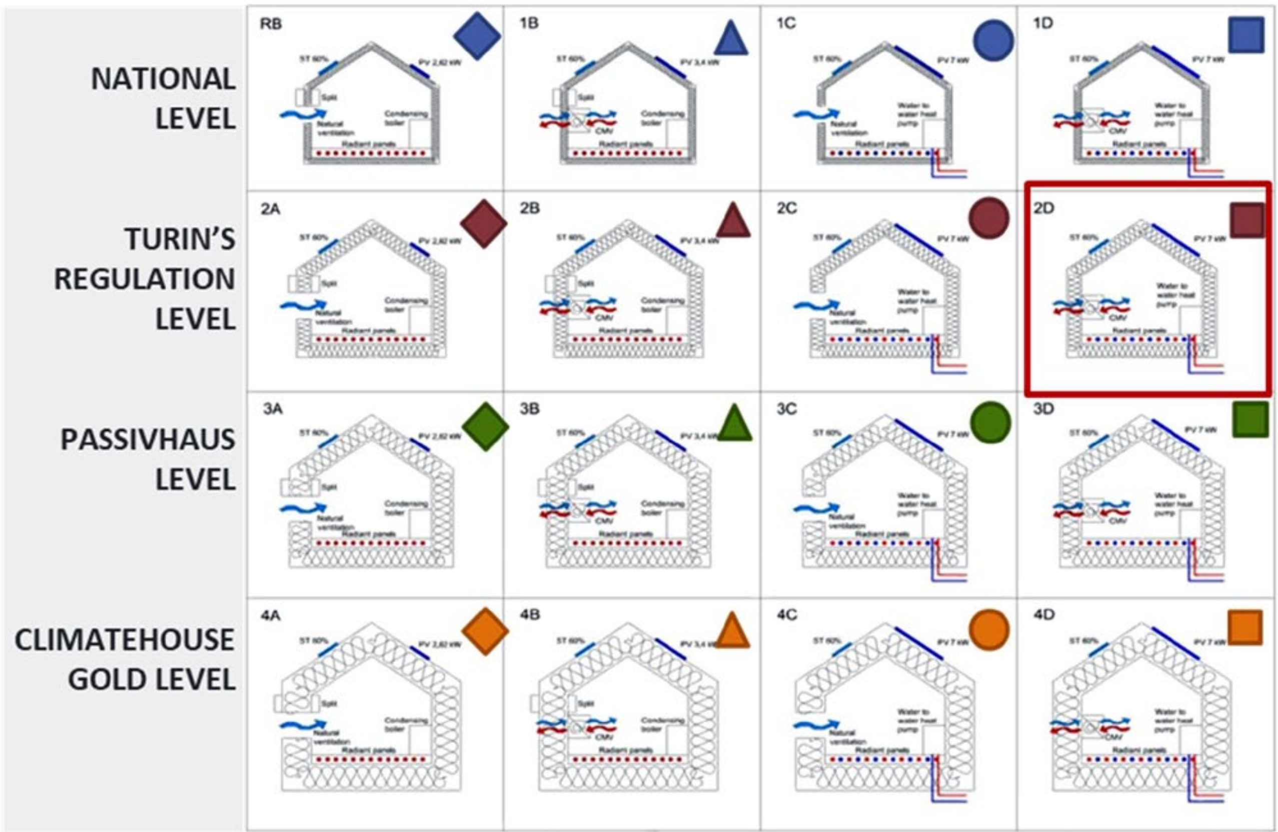

Figure 2. Matrix of 16 energy design scenarios for CORTAU House retrofit (Barthelmes et al., 2014).

influencing the real consumptions of the building. This result is shown in **Figure 3**, since the electricity produced by the PV system in 2017 is higher than what simulated in the EnergyPlus model. Furthermore, the second cause of discrepancy is represented by occupants, whose real behaviour can be very different from existing standards, due to different perceptions in terms of thermal comfort, and therefore different settings in terms of temperature set-points or ventilation requirements. The effect that occupant behaviour can have on consumptions was well captured in (Barthelmes et al., 2016), where different lifestyles were simulated in EnergyPlus, showing that a low consumer profile (representative of an occupant attentive to energy matters) could reduce overall energy use up to 28%, just operating electrical equipment in a more conscious way.

In this framework, given the importance that occupant behaviour plays in the overall building consumptions, it is important to better capture which are the feelings that occupants have when dealing with an NZEB, as well as the difficulties they may feel in case of smart buildings, in which their control over the building systems could be reduced. Thanks to an interview submitted to CORTAU occupants, it was possible to identify the main pros and cons perceived by NZEB users. The main criticalities emerged from users' feedbacks are mainly related to the interaction with the HVAC systems installed within the building:

- Difficulty in getting used to a DHW temperature different from that produced by a boiler system;
- Difficulty in getting used to the CMV system;
- Understanding the crucial role of dehumidification associated with the use of radiant floor cooling system during summer season, in order to reduce air humidity and to avoid condensation on the surfaces;
- Difficulty in getting used to the thermal inertia of the floor radiant system.

Conversely, the main potentialities defined by CORTAU occupants derive from a better thermal comfort within the internal spaces, achieved thanks to the use of radiant system coupled with CMV:

- Feeling of a better indoor comfort and air temperature distribution thanks to the presence of the radiant system;
- Possibility to maintain a lower indoor air temperature during the heating season, obtaining energy savings;
- Perception of a pleasant indoor temperature in winter season thanks to solar load;
- Use of shading systems to reduce the solar radiation entering the building, obtaining energy savings.

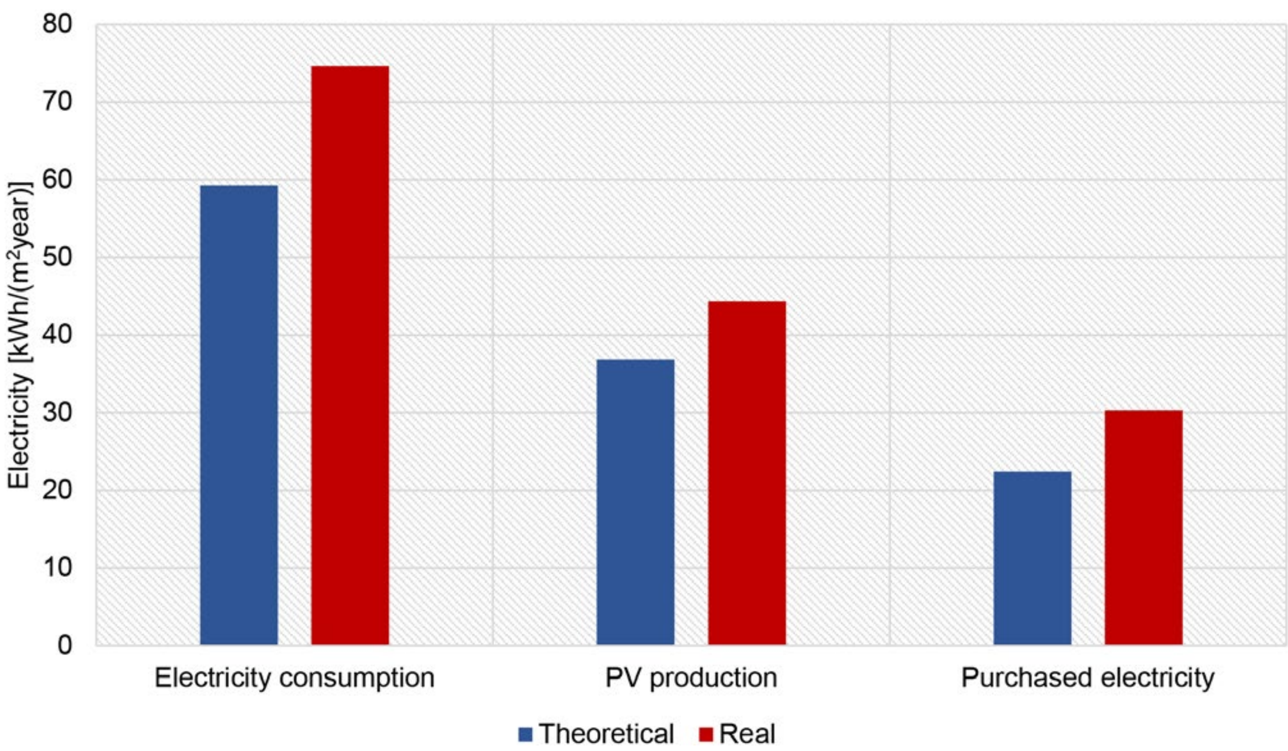

Figure 3. Comparison of electricity features between theoretical and real values.

Conclusions

Nearly-zero energy buildings represent sustainable solutions to reach the ambitious decarbonization targets suggested by the European Union for the building sector. Nowadays, although efficient design and existing technologies allow to reach the NZEB targets, the role of occupants in the final consumptions is considerable. For the above-mentioned reasons, it is necessary to realize an accurate preliminary design phase to evaluate consciously the effect of different system technologies and envelope solutions. Moreover, an estimation of the possible causes of energy consumption diversions due to the modification of the condition of use, caused by different occupant behaviours, should be performed.

In this paper, the single-family CORTAU House was analysed in order to compare the theoretical energy consumptions estimated from the dynamic simulation of EnergyPlus and from the preliminary energy certification of the building during the pre-occupancy period, with the actual consumptions reported in the electricity bills. Results show a discrepancy of 38% between the certification value and the real one, in terms of primary non-renewable energy. Moreover, the comparison between energy simulation and electricity bills shows a real electricity consumption of 26% higher than the simulated value. Besides the effect that climate external conditions can have on results, a significant gap is due to occupant behaviour.

It is necessary to underline that the comparison between theoretical and actual energy consumption is based on an annual assessment. In order to achieve a more complete view, it would be interesting to consider more years in the evaluation of the energy bills, to potentially explore the effects of diverse climate conditions on overall results, as well as to increase the temporal granularity of the analysis, including monthly reports from energy bills.

To conclude, it can be said that the NZEB market is ready to be successful from a technology standpoint, however, there are still some critical issues to be carefully addressed, from design and construction phases, to the operational one. First, it is fundamental to find trained manpower able to concretely realize the NZEB project. Moreover, it is extremely important to have an occupants' education phase, before their entrance into the house. Indeed, NZEB building could be seen as a complex machine to be managed, which misuse can lead to excessive energy consumptions, despite the high-performance level of technologies and envelope components installed. ■

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Conflict of interest

Authors declare that there are no economic or other conflicts of interest on the presented article.

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