Energy Performance Evaluation and Economical Analysis by Means of Simulation Activities for a Renovated Building Reaching Different Nzeb Definitions Targets

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Abstract

The nZEB target is increasingly becoming one of the main objectives in building renovation, but a unique nearly-Zero Energy Building definition is not explicitly available in the 31/2010 EU directive, the so-called "Energy performance of buildings directive". Nevertheless, the technical implementation of the nearly-Zero Energy Building concept into defined constraints and requisites is a determining factor for the consequences of energy-economic performance . In fact, in the renovation process of a building, different technical requirements lead to different design solutions that affect investment and operative costs, as well as energy performance. Through an optimization process based on dynamic simulations for energy and economic performance assessment, a comparison between different approaches for the nZEB building retrofit for a demo-case building has been performed. First, an energy target which is stricter than the nZEB standard is examined. In particular, the so-called "Positive Energy Building" approach, consisting of the design of a building that produces more energy than it consumes in the overall year, is evaluated. Then, the results of the Positive Energy Building target are compared to a nearly-Zero Energy Building approach in which self-sufficiency is promoted, instead of the energy production/consumption balance. Also, the nearly-Zero Energy Building target promoted by the Italian legislation has been evaluated, comparing the result of a plausible implementation with the other more stringent approaches. The simulation work has been aimed at comparing significant Key Performance Indexes, regarding both energetical and economical aspects. In particular, initial investment costs, expected net present value of the investment after 25 years and energy performance indexes have been evaluated. The discussion demonstrates that, according to the assumptions adopted for the investment and energy costs, the Positive Energy Building target is excessively economically inconvenient for a renovation intervention of this type. Moreover, designers should prioritize the self-sufficiency of the building energy system with respect to the production/consumption yearly ratio. Finally, the discussion demonstrates that a renovation design in accordance with the Italian nearly-Zero Energy Building target is economically sustainable but the PV system size to meet the minimum requirements could be non-optimal.

1. Introduction

1.1 Background

To achieve the goal of a strong reduction of building-related CO_2 emissions for the next decades in the EU, a significant contribution must come from acting on the existing residential building stock renovation. The target of nearly-Zero Energy Buildings (nZEB) for new buildings has been set by the EU Commission with the 31/2010 EU directive, the "Energy performance of buildings directive" (EPBD). Nevertheless, a unique approach for the definition of the technical requirements has not been defined,

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Pernigotto, G., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2023. Building simulation applications BSA 2022. bu,press.
https://doi.org/10.13124/9788860461919

since each country should take charge of the implementation of the directive (D'Agostino et al., 2021).
The nZEB as target performance also applies to major building renovation since 2021. Moroever, building deep retrofit is one of the key actions capable of decarbonizing the building sector to meet global targets to address climate change (D'Agostino et al., 2017). Reaching nZEB targets when renovating a building allows a greater reduction in fossil energy savings and greenhouse gas emissions compared with a traditional retrofit intervention (Holopainen et al., 2016). In the literature, cost-optimum calculations have been performed to identify which renovation interventions lead to the best economic benefits while meeting the nZEB target (Zangheri et al., 2018). Nevertheless, the renovation rate in Europe is around 1 % (A Renovation Wave for Europe, 2020) - still quite below the target of 2 %. In this framework, the trend of a prefabricated and industrialised retrofit is attracting more and more attention thanks to a set of research projects (D'Oca et al., 2018) and bottom-up national initiatives (e.g. EnergieSprong, ...). Prefabricated solutions could allow an increase of the annual renovation rate of the European building stock, also thanks to the integration of different functions and technologies in the same element (Pernetti et al., 2021; Pinotti, 2020).
After the introduction of the nZEB target, Positive Energy Buildings (PEBs) are somehow considered as the next phase for building sector sustainability. The requirements in terms of energy consumption efficiency are the same as the nZEB target, but a reinforcement of the building energy production is expected. Barriers and challenges in the Positive Energy Building implementation have been investigated by Ala-Juusela et al. (2021). PEBs also allow a significant contribution to the energy support of the local neighborhood, the so-called Positive Energy Neighborhood. Good et al. (2017), analysed this topic, highlighting its challenges and opportunities.

1.2 Italian Framework for nZEB Buildings

In the Italian framework, the implementation of the EU directive for nZEB buildings has been carried out by the "Decreto ministeriale 26/06/2015". In both cases of new construction or renovation, the decree requires that the project building is compared with a reference building.
The reference building is a fictitious building that has identical geometrical shape (same volume, floor areas, envelope surfaces etc.), climatic conditions, orientation, destination of use and surrounding situation. The differences from the project building lie in the thermal characteristics of the envelope and in the energy system characteristics. These values are reported in specific tables.
A series of indexes that indicate the quality of the envelope and the efficiency of the energy system are calculated both for the project building and the reference building. Then, a comparison is made to assess whether the building can be considered as nZEB or not, considering the reference building as the minimum standard to be achieved by the project case.
Specifically, the previously mentioned indexes are:

- H'_T, which is the overall average coefficient of heat transfer by transmission
- $A_{sol,est}$/ $A_{sup\ utile}$, which is the so-called equivalent summer solar area per useful area unit
- Solar transmission factor, also considering the shadings
- Thermal inertia properties, such as superficial mass (Ms) and periodic thermal transmittance (Y_{IE})
- Thermal transmittance of the internal partition walls and of the outward-facing structures of non-air-conditioned rooms.
- Useful thermal performance indexes for heating ($E_{PH,nd}$) and cooling ($E_{PC,nd}$)
- Energy performance indices for winter space heating (E_{PH}) and summer space cooling (E_{PC}) and overall building performance, in non-renewable and total primary energy (E_{Pgl})
- Seasonal average efficiency of the system for winter space heating (η_H), summer space cooling (η_C) and domestic hot water production (η_w).

In addition, the building must accomplish some requirements in terms of renewable energy production. These requisites are reported in the "Allegato 3, DLgs 3 marzo 2011 n. 28". The building must guarantee:

- production of electrical energy by means of systems from renewable sources (mandatory installed on or inside the building or in its outbuildings) with a power measured in kW calculated according to the following formula:

$$P = \frac{1}{k} \cdot S\ [kW]$$

where:

S is the floor area of the building at ground level, measured in m²; k s a coefficient that takes the value K = 50 m²/kW if the application for the authorization is submitted after 1 January 2017.
- Contemporary coverage, by means of renewable energy sources, of the 50 % of the domestic hot water, space heating and cooling demand, and the 50 % of domestic hot water. In case the building is public, these percentages must be increased by 10 %.

1.3 Aim and Research Objective

The ambitious target of nZEB to be achieved by a prefabricated solutions approach for the renovation of a building is still lacking a technical feasibility analysis. In other words, from the literature it is still not clear which technical features of a retrofit action are compliant with the nZEB definition. Moreover, a techno-economic comparison between different nZEB definitions to be achieved with prefabricated technologies has not been performed. Such research questions are national-dependent and will be discussed in this paper for a case study in Italy. The case study is a residential building undergoing an innovative renovation process. The renovation intervention consists of the installation of prefabricated multifunctional envelope modules (façade and roof) that might integrate the following available technologies depending on needs: building-integrated photovoltaic or solar thermal panels (BIPV and BIST), mechanical ventilation machine units and green façade modules. Coloured BIPV panels are taken into consideration to optimize the building integration from an aesthetic point of view.

For the support activities in the preliminary design phase, dynamic simulations have been performed to examine the relationship between possible different renovation scenarios and the fulfilment of the nZEB definitions. In particular, a preliminary design of the BIPV system, with the possibility of integrating a Battery Energy Storage System (BESS), has been carried out.

The whole analysis aims at investigating how different renovation building scenarios – all targeting the nZEB level, perform from a techno-economic point of view.

2. Methodology

The building to be renovated is located in Greve in Chianti (Florence), and consists of two heated floors, with four apartments overall. The renovation aims to convert the building energy system into a full-electric system, producing electricity on-site to cover the energy demand. The heating and cooling services are set to be provided by an electric air-to-air heat pump, which will be, at least partially, fed by the BIPV system.

To achieve the goal of evaluating different renovation scenarios and their impacts in terms of nZEB definitions, energy performance and costs, the following methodology has been defined. First, the target scenarios have been defined:

- Scenario 1, based on the Positive Energy Building (PEB) target d1, for which the building produces more energy than it consumes in a yearly balance. As a consequence, the BIPV system has been sized to cover more than 100 % of the building's electric demand.
- Scenario 2 assumes that the system has to guarantee a level of self-sufficiency equal to the one resulting in Scenario 1 while minimizing the cost per kWh produced (Levelized Cost Of Electricity, LCOE). It means the BIPV system is optimized in a way that a specified portion of the energy demand is covered by self-produced electricity, also considering the support of a battery storage system.
- Scenario 3 assumes that the system has to guarantee self-sufficiency equal to 30 %, i.e., a typical value achieved in residential applications (McKenna et al., 2017).
- Scenario 4 aims to meet the Italian nZEB target described in Section 1.2. Unlike in the previous scenarios, here the PV configuration is an input of the BIPV optimization tool, which is used in

simulation mode, and the building electric load is not taken into account for the sizing of the components. In particular, the PV nominal power is the result of a previous calculation (UNI/TS 11300 and “Allegato 3 del D. Lgs. 28/2011”), aimed at ensuring the minimum compliance with the Italian regulation; the PV module position is determined considering the most irradiated building surfaces, i.e., in this case, the south-facing roof pitch.

These scenarios are summarized in Table 1.

Table 1 - nZEB scenarios for the simulations

Scenario	**nZEB approach**	**Energy target**
1st scenario	Zero Energy Building	Energy produced is equal to energy consumed in a yearly balance
2nd scenario	Prioritization of self-sufficiency	Same self-sufficiency of the 1st scenario, but the Levelized Cost of Electricity is minimized
3rd scenario	Prioritization of self-sufficiency	Self-sufficiency is lower than in 2nd scenario, Levelized Cost of Electricity is still minimized
4th scenario	Italian nZEB standard	Requirements of the “Allegato 3 del D. Lgs. 28/2011” and other technical requisites

Then, the final Key Performance Indicators to compare the renovation scenarios against been defined as the following:

- Initial investment costs for the BIPV system (including the battery cost)
- Expected NPV (Net Present Value) after 25 years
- Self-sufficiency (i.e., the portion of building demand directly covered by self-consumed PV electricity)
- Self-consumption (i.e., the portion of PV-produced electricity directly consumed or stored in the building)
- Annual cumulative production – consumption rate

The electrical energy demand for the different renovated building scenarios has been calculated with an energy dynamic model (TRNSYS). After that, the electrical demand curve is considered as input in a “BIPV optimization tool”, able to find optimal BIPV-battery configurations to meet the previously described requirement scenarios. The outcomes of the optimization are processed and evaluated in terms of energy and economic performance through the set of KPIs that have been previously described. Hence, the solutions suggested for the BIPV and battery system design are compared. Considerations regarding different nZEB approaches and requisites are also reported.

2.1 Electrical Energy Demand Calculation

For the purposes of this work, the dynamic energy modeling tool TRNSYS (Thermal Energy System Specialists) has been used to model and simulate the building thermal behavior, calculating the space heating and cooling energy demands, the indoor thermal comfort and the electrical energy consumption needed by the heating/cooling and ventilation systems (plug loads are not considered). The required input data are reported in Table 2. Specifically, a 3D model is produced to represent the geometry of the building (Fig. 1). Information regarding the actual thermal characteristics of the envelope, as well as the ones related to the energy system are retrieved from a previous building energy audit. The characteristics of the existing building are then crossed with the planned renovation project, defining the future building energy model. In fact, the thermal transmittance of the envelope-renovated portion is updated to the designed conditions and the new Heating, Ventilation and Cooling (HVAC) system is implemented, using a heat pump TRNSYS type developed at Eurac Research. This type has been developed as a grey-box model, in which the generated heat and the electrical consumption are determined by developed algorithms out of performance maps provided by manufacturers. Generated heat and electrical consumption of the heat pump are calculated as a function of boundary conditions. After the boundary conditions of the simulation are set, together with the expected building occupants' behavior and the expected internal gains (SIA 2024:2015), the total electrical energy demand is calculated.

Table 2 - Input for the TRNSYS model

Input data	Source
Geometry of the building	SketchUp 3D model
Thermal properties of the building envelope	Energy audit report; thermal characteristics of the prefabricated panels and new windows
HVACS characteristics	Properties of the system that is expected to be installed during the renovation process; heat pump performance is simulated with a black-box model developed by EURAC Research
Boundary weather conditions	Typical meteorological year (TMY) of the building location
Occupancy schedule and internal gains	SIA 2024:2015

Simulating the behavior of the building in hourly time-steps, the electrical energy consumption is calculated in TRNSYS. This electricity curve is later used as input in the "BIPV optimization tool".

2.2 BIPV Optimization

For the BIPV system optimization, a Python-based tool (EnergyMatching) (Lovati et al., 2019) has been used.

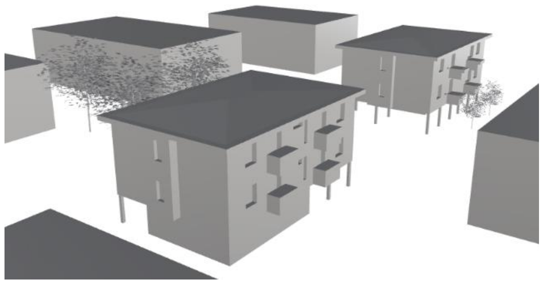

Fig. 1 - 3D model of the building case study

This has been developed by Eurac Research to support designers and other professionals who want to integrate a photovoltaic system in buildings or districts. The tool is based on a direct search algorithm applied to a minimization/maximization problem, which can be constrained or unconstrained, depending on the target function selected (minimization of the Levelized Cost of Electricity, Maximization of the Net Present Value, etc.). As a solution, it suggests the optimal BIPV configuration, i.e., how many PV modules and where to integrate them over the building envelope (on roofs, façades, shading devices, balustrades, etc.). It can also suggest including an electric storage system to increase the ratio of self-consumed energy. The BIPV configurations are optimized according to the specificities of the cases (building geometry, local weather, surrounding shade, unitary costs of the system and current benefits to produce electricity, sold or self-consumed), also considering how much energy is indeed needed by the building throughout the day and the seasons. Moreover, different target functions can be assigned to the tool, to achieve energy, economic and/or environment-related goals. Based on hourly time-step calculations that allow evaluation of the energy fluxes between the photovoltaic system, the battery, the load and the grid, the tool can provide a set of KPIs showing the expected performance of the photovoltaic system, from energy, economic and environmental points of view. Further information and details on the BIPV optimization tool calculation model are available in (EnergyMatching, 2022).

The assumptions and input data for the BIPV-BESS optimization are reported in Table 3. It has to be noted that the technology prices are higher than benchmark on-the-market PV modules because it refers to aesthetically appealing glass-glass BIPV modules able to comply with the requirements of façade integration also in culturally preserved urban contexts.

Table 3 - Assumptions and input data for BIPV optimization

Price of electricity bought from the grid	0.215	[€/kWh]
Price of electricity sold to the grid	0.05	[€/kWh]
BIPV module efficiency	0.13	[%]
BIPV cost	2800	[€/kWp]
BESS cost	800	[€/kWh]

3. Results Analysis and Discussion

The results obtained for the four renovation scenarios considered are shown in Table 4 and discussed case-by-case in this section.

Table 4 - Results of BIPV optimization tool in the four scenarios

Scenarios	1	2	3	4
Suggested PV capacity [kWp]	15.7	11	5.4	4.4
Suggested electric storage capacity [kWh]	0	3.4	0	0
Investment costs [€]	44045	33533	14976	12333
Expected NPV after 25 years [€]	-18018	-10034	-60	571
Self-sufficiency [%]	48	48	30	27
Self-consumption [%]	46	66	86	91
Annual cumulative ratio production/consumption	1.03	0.73	0.36	0.29

Scenario 1: considering the design target of a ratio production/consumption (on a yearly basis) higher than one, the photovoltaic nominal power suggested by the BIPV optimization tool is the highest among the scenarios considered and is equal to 15.7 kWp. On the contrary, the electric storage capacity is 0 kWh, since it does not contribute towards achieving the design target. From an economic point of view, this solution is the less cost-effective, from both the investment and NPV perspective.

Scenario 2: results obtained show the same performance in terms of self-sufficiency as Scenario 1 (because it has been set as optimisation target for this scenario) but with lower investment costs and a better NPV, due to the presence of a battery storage. As the suggested PV capacity is lower, the annual ratio production/consumption decreases to 0.73.

Scenario 3: in this scenario, the annual cumulative ratio production/consumption is lower compared with Scenario 1 and 2 (below 0.4) but the investment payback is achieved during the system lifetime of 25 years considered. Self-sufficiency is only 30 %, meaning that the BIPV system contributes less compared with the previously described scenarios to cover the electricity demands of the building.

Scenario 4 achieves similar results in terms of annual balance and self-sufficiency compared with the ones obtained in Scenario 3.

The best BIPV configuration obtained for Scenario 1 turns out to be less cost-effective than the ones obtained with the other approaches from both the investment and NPV perspective.

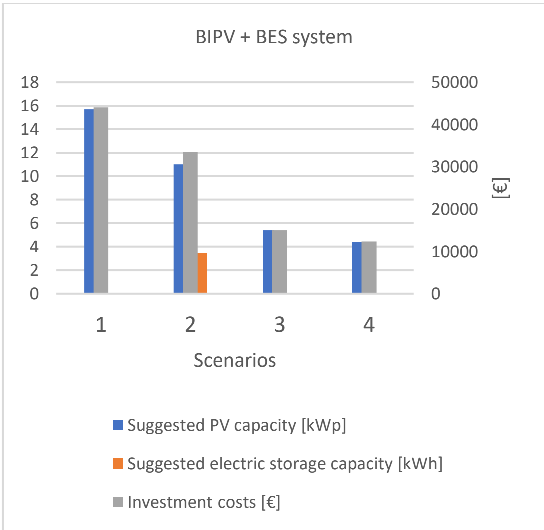

Fig. 2 - BIPV and BESS characteristics

Moreover, considering that the only design constraint is obtaining the target yearly energy production, the electric storage capacity is equal to 0, at the cost of a low self-consumption (46 %), as seen in

Fig. 3. On the contrary, results obtained for Scenario 2 confirm that the same self-sufficiency can be achieved by installing a more balanced system. This is confirmed by the self-consumption index (SC), which is increased to 66 % by decreasing the nominal power of the photovoltaic system and favoring the installation of an electric energy storage (3.4 kWh), as seen in Fig. 2. Also from an economic point of view, Scenario 2 can be considered a better approach, since the investment costs are decreased by 24 % and the NPV also improves. Due to the lower nominal power installed, the ratio consumption/production decreases to 0.73, meaning that, on an annual basis, the building does not produce the same electrical energy that is consumed.

Regarding Scenario 3, the annual cumulative ratio of production/consumption decreases significantly (below 0.4) but the payback of the system is achieved after 25 years. This is caused by the fact that a small system is installed and no battery is needed to meet the energy target. This is confirmed by the high value of self-consumption (86 %), meaning that most of the energy produced is directly self-consumed by the building. However, high values of self-consumption and low values of self-sufficiency mean that the system covers only a small fraction of the total energy consumption even if most of the energy produced is self-consumed. This usually indicates that the system is slightly undersized compared with the building energy consumption.

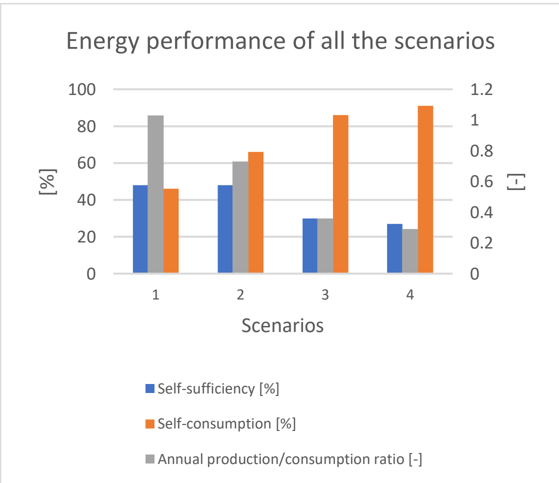

Fig. 3 - Self-sufficiency and self-consumption for the scenarios considered

For Scenario 4, the system was not optimized to obtain a specific target but designed to respect the Italian regulation for the installation of photovoltaic panels in nZEB buildings. Results obtained are similar to the ones obtained for Scenario 3 and the same considerations can be applied. However, the main limitation of this approach is that it suggests reasonable solutions only for a limited number of cases. In fact, as discussed in the paperwork by Lovati et al. (2020), the same photovoltaic nominal power is suggested for a fixed building gross area and it does not depend on the building floors (and as a consequence on the building energy consumption).

Numerical results can change if investment costs or if the price of electricity are different. There are important aesthetic advantages to the selected BIPV panels, but they lead to higher investment costs and lower efficiency compared with standard solutions. This means that the payback time of the investment is also longer.

All the analyzed have proved to be compliant with the nZEB Italian definition, which is the minimum required by law. Nevertheless, actual foreseen energy performances are very different among the scenarios and underline relevant discrepancies in the energy behavior. In particular, Scenario 1 can be-called "yearly zero energy balance", but requires the electric grid to perform the electric energy exchange and is the most expensive in terms of initial investment with the longest payback time. Scenario 2 can be considered a "low grid dependency" nZEB target. In fact, it prioritizes self-sufficiency, which considers the energy produced in situ, which is directly consumed (or stored) without exchange with the grid. This approach presents better economic results if compared with Scenario 1, having lower investment costs and shorter payback time. Decreasing the self-sufficiency target, in Scenario 3, the economic KPIs are improved and the Italian nZEB requisites are still accomplished.

4. Conclusions

Observing the results of the dynamic simulations, which assess the expected energy and economic consequences of renovating a building according to different nZEB approach targets, it is possible to assert that the implementation choice of the nZEB definition has a strong impact. Since the European guidelines are not very well defined in terms of technical requisites and energy performance targets, each EU Country has decision space to set its own technical requirements for the nearly-Zero Energy Building assessment. Because of the elevated number of factors that occur in the energy sector, identifying an optimal nZEB definition is not simple. Nevertheless, the authors consider that the renovation design for a nearly-Zero Energy Building should lead to an energy-efficient building, capable of supplying its own energy demands through the implementation of economically and environmentally sustainable solutions.

The simulation outcomes indicate that prioritizing the energy production/consumption yearly balance, having as the Positive Energy Building target as an objective, could lead to an oversized system in terms of energy generation and, consequently, to an excessive investment cost compared with the economic benefits over time. On the other hand, prioritizing the self-sufficiency of the building energy system could lead to the design of more balanced systems and a significant improvement in the energy and economic KPIs.

The current Italian nZEB target, which has also been examined, seems to be economically sustainable for this specific case-study, but it could lead to not-optimal designs in case of multi-floor buildings.

Prioritizing the self-sufficiency target instead of the yearly ratio production/consumption will become particularly relevant and crucial in the next years, when subsidies such as net billing and net metering will be abolished in many European countries. In this view, the results presented in this article should be considered when the requirements for the PEB and nZEB standards are updated.

The fluctuations of the electricity price and the increase of the cost of raw materials could have an impact on the results. It would be interesting to carry out further research regarding the impact of cost variability on the analysis considerations performed.

This paper is part of the research activities of the INFINITE project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 958397.

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