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Design and construction of an nZEB in Piedmont Region, North Italy

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Abstract

Nowadays in nZEB designing it is fundamental taking into account both the energy and the economic perspective right from the preliminary phases of the project. Success in realizing nZEB lies in finding the right balance between energy performances, architectural quality and costs, which include investment, maintenance and running costs, incurred by the project owner during a defined period.

This paper analyzes CorTau House in terms of architectural aspects, energy performances and economic viability. It represents a significant Italian design experience in which the architectural quality of the refurbishment of a traditional rural building is combined with high-performing energy solutions.

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Keywords: nZEB; low energy building; cost-optimal analisys; energy dinamic simulation; economic evaluation; global cost; cost optimality

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1. Introduction

The EU Commission's Roadmap showed that greenhouse gas emissions in building sector should be reduced by around 90% by 2050 compared to 1990 [1]. The most immediate and cost-effective way of achieving this target is through a combination of cutting energy demand in buildings through increased energy efficiency and wider deployment of renewable technologies. The recast of the Directive on the Energy Performance of Buildings (EPBD) [2] represents a strong engagement for reducing energy consumptions and improving energy efficiency of the building stock. In particular, it defined all new buildings will be nearly-zero energy buildings (nZEBs) by the end of 2020; this represents a real step-change relative to the current way of designing and building, both from an

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architectural perspective and from the side of technical systems, including HVAC. In the Directive "nearly-zero energy building" means a building that has a very high energy performance; the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources produced on-site or nearby.

Due to criticalities which have arisen around the nZEBs cost efficiency, EPBD also tried to spread economic evaluations. It thus set a comparative methodology framework to guide Member States into the definition of minimum building energy performance requirements with a view of cost-optimality. Cost-optimal levels can be seen as a first step towards the achievement of nZEB target; they refer to the energy performance in terms of primary energy leading to the minimum life cycle cost. The extra-cost in terms of initial investment in realizing an nZEB could be recovered through fuel savings during building life cycle.

In this paper a single-family house located in Piedmont Region (North Italy) was analyzed in terms of architectural design, energy performances and economic restrictions. The case-study pursues the dual objective of combining cost-optimal and nZEB requirements with architectural quality principles. The aim is to illustrate the challenge of designing and building a nZEB, by examining how the purpose of costs control and the energy efficiency targets have influenced the architectural configurations and their evolution, since the first concept. In particular, cost-optimal methodology [3] was followed in order to identify nZEB configurations that represent the cost-optimality. Energy evaluation was performed by means of the dynamic energy simulation software EnergyPlus [4], while costs valuation was performed according to global cost method from EN 15459:2007 [5].

2. The case-study

CorTau House represents a significant Italian design experience in which the architectural quality in the refurbishment of a "curmà", a traditional rural building widely diffuse in Piedmont Region, is combined with using high-performing energy solutions. For this reason it represents a good example of the implementation and replicability of a high-performing building model at regional and national levels.

Building construction started in March 2014 and is still in progress. The single-family house, adapted to the preexisting structure, is all-electric and supplies its energy demand through self-generation of electricity from a solar photovoltaic system.

The traditional rural framework surely influenced the architectural project, whose aim is to preserve and to enhance the distinctive features of the existing rural building. The new volume is inserted under the preexisting roof, whose wooden structure and tiles covering were maintained, like the brick pillars (Fig. 1.a).

The first architectural concept (Fig. 1.b) consists of a split-level house characterized by an articulated frame of reinforced concrete bearing-walls and slabs [6]. This concept was put aside since too much expensive. Leading by wrapped economic restrictions the project was modified in the current single-storey volume (Fig. 1.c). Net floor area (130 m²) and volume (net conditioned volume = 390 m³) were reduced; interior spaces are thus optimized and compacted limiting energy losses through the envelope and, consequently, energy needs for space heating and cooling. This is a clear demonstration that, since the preliminary phase of the project, the architectural design was driven by energy targets together at the same time with owners' request of strictly cost control, both initial investment costs and future running costs.

An ancient intuitive know-how consisting in bioclimatic architecture principles guided the architectural design team in the new building planning. Indeed, as the preexisting rural building presented a fully-open southern façade and a blind northern façade, the new volume is characterized by a mostly glazing southern façade while the northern one presents few little windows (Fig. 1.b). On the South side windows are equipped with exterior horizontal overhangs carefully designed in order to maximize useful solar gains in winter and avoid overheating in summer; the arrangement of some tree and hedges was studied accurately with the dual function of acoustic protection and solar control. In the analyzed Mediterranean climate (Italian Climate Zone E, 2549 Degree Days), indeed, nZEB design challenge can be summarized in a careful building planning that permits to obtain indoor comfort conditions in both winter and summer with very low energy consumption. The adopted strategies consist of a strongly insulated building envelope that is also very tight with low infiltration airflow; the thermal insulation layer is placed on the external surface of the walls, in order to increase the inside thermal inertia of the house; a mechanical ventilation system equipped with high efficiency heat recovery exchanger guarantees good indoor air quality.

Fig. 1. (a) The preexisting rural building, south front; (b) the first design concept; the current architectural design.

2.1. Building envelope and HVAC system features

The house structure is characterized by reinforced concrete bearing-walls oriented in North-South direction, which have the dual function of acting as structural elements and including building systems in dedicated cavities. Plasterboard partition walls placed between living and sleeping areas provide the acoustic insulation among these two house macro-areas thanks to inserted acoustic insulating material. All the reinforced concrete bearing-walls and slabs were cast on-site; a custom wooden formwork was realized expressly for the fair-faced concrete roof slab due to the need to obtain a homogenous smooth surface.

The whole vertical envelope, constituted by both reinforced concrete bearing-walls and infill masonry walls, is covered with a 16-cm exterior insulation layer made of rock-wool panels ($U_{wall} = 0.15$ W/m²K). The same insulating material was adopted also for the slabs ($U_{floor\ slab} = 0.19$ W/m²K, $U_{ceiling} = 0.15$ W/m²K), having the wisdom to choose high-density compression resistant panels ($\lambda = 0.037$ W/mK; $\rho = 150$ Kg/m³). The floor slab consists of a concrete casting incorporate disposable formworks in recycled plastic realizing a ventilated under-floor cavity for one portion; in the remaining part the casting is realized on a gravel layer as damp proofing. The thermal bridge between external infill masonry walls and floor slab is eliminated with an intermediate 8-cm cellular-glass insulation layer, which provides also excellent barrier to rising damp.

Windows are composed by aluminum frame with thermal break with low-e triple-pane glass with argon ($U_{window} = 0.96$ W/m²K). Thermal bridges are eliminated through a careful study of anchoring and joints between external insulation layer and window wooden sub-frames.

Fig. 2. (a) casting of the floor slab above disposable formworks; (b) structure of the house with insulation layers; (c) roof details.

With regard to the building primary system, a controlled mechanical ventilation (CMV) system with heat recovery and dehumidifier is combined with radiant floors for space heating and cooling in all areas with the addiction of electric radiators in the bathrooms. Space heating and cooling is provided by a water-to-water heat pump that supplies also domestic hot water (DHW) production. As explained previously, the CorTau House represents a model of all-electric building (the kitchen indeed is furnished with electric stove and oven); according to nZEB definitions a distinctive element of the building is thus the possibility to ensure the energy independence from fossil energy sources. All electricity needs of the building for space heating and cooling, ventilation, lighting, equipment, is covered by a 7 kW_{peack} grid-connected PV system installed on the roof.

3. Cost-optimal methodology as a design tool

As previously explained, in the preliminary design phase cost-optimal methodology was followed in order to identify nZEB energy configurations that represent the cost-optimality; specifically, the methodology was exploited as decision-making tool equipped to guide design team and owners' choices.

Cost-optimal analysis bands together energy and economic performances of different design configurations and identifies the so-called cost-optimal level that represents the energy performance level which leads to the lowest cost during the economic building lifecycle.

In the specific case of CorTau House, after fixing the architectural appearance different energy design configurations for both building envelope and HVAC system were hypothesized and assessed in terms of energy consumptions and costs. In detail, four building envelope design configurations with various thermal insulation levels were chosen to fulfil different energy performance requirements for space heating need. The first level (number 1 in Table 1 and Fig. 3) refers to the national requirements for climate zone E (where the house is located) [7]; the second one (number 2) refers to the Turin city regulation optional values [8]; the third one (number 3) refers to minimum values required by national regulation for the subsidized level [9]; the last level (number 4) refers to the Climate House A requirements [10].

Furthermore, four design configurations for the HVAC system characterized by different efficiency were defined. Two of them provide for supplying heating use with natural gas originating a not all-electric building; however they were considered in the analysis for further information and in order to give a clear view to owners and design team in making decisions. The first configuration (A in Table 1 and Fig. 3) consists in a condensing boiler (nominal efficiency = 0.95) with radiant floor for space heating and a multi-split air conditioner for space cooling. The second configuration (B) is equal to the first one with CMV with heat recovery in addiction. The third (C) and the fourth (D) configurations are constituted by a water-to-water heat pump (nominal efficiency for heating COP = 4.75; nominal efficiency for cooling EER = 5.65) with floor radiant floors for space heating and cooling associated respectively with natural ventilation and CMV with heat recovery.

According to the nZEB definition, it is necessary to largely supply energy by renewable sources in order to reach nearly-zero energy targets. Therefore solar collectors covered 60% of domestic hot water (DHW) production were taken in account. Various power values for photovoltaic (PV) system were hypothesized; in accordance with Italian Directive [11], the peak power of PV system in configuration A is equal to 2.6 kW_{peak}, in configuration B 3.4 kW_{peak}, while in configuration C and D peak value of 7 kW_{peak} was defined in order to cover whole electricity consumptions and obtain a production surplus.

Combining the four different design configurations hypothesized for the building envelope and for the HVAC systems, 16 energy design scenarios were created and compared in terms of economic and energy performances.

3.1. Energy evaluation

Energy evaluation was performed by means of the dynamic energy simulation software EnergyPlus (version 8.1) [4]. The annual overall delivered primary energy includes energy use for heating, cooling, DHW production, lighting, equipment, ventilation and PV production taking in account on-site consumption and surplus electricity going to utility grid. Primary energy values were calculated using Italian primary energy factors (e.g. 1.09 for natural gas and 2.17 for electricity).

Energy evaluation results (Table 1) show that in order to reach nZEB target (with a primary energy consumption lower than 10 kWh/m^2y) it is necessary to choose a strongly insulated building envelope and an HVAC system consisted in water-to-water heat pump with radiant floors for space heating and cooling, eventually coupled with CMV. By energy evaluation it is confirmed that it is indispensable in all-electric configuration to cover a large energy supply by renewable sources (systems C and D) in order to reach nZEB performance as previously mentioned. In Table 1, it is worth noting that scenario 4D represents a positive-energy building in which the energy production over the year from renewable sources is superior to the energy importation from external grid.

Table 1. Primary energy consumptions (kWh/m²y) and possible nZEB configurations (grey cells).

Scenario	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B	3C	3D	4A	4B	4C	4D
Primary Energy (kWh/m²y)	114	87	41	32	79	56	12	6	72	49	7	0.03	65	46	3	- 5

3.2. Economic valuation

Economic valuation was performed according to global cost method from European Standard EN 15459:2007 [5]. For each energy design scenario global cost was valuated; it consists in the estimation of the net-present value of all costs incurring in a defined calculation period, taking into account the residual values of components with longer lifetime. In detail, global cost is determined by summing up the global costs (that means actualized with an appropriate discount rate) of initial investment costs, periodic and replacement costs, annual costs and energy costs and subtracting the global cost of the final value; it can be written as:

$$C_G(\tau)=C_I+\sum_J\left[\sum_{t=1}^{\tau}\left(C_{a,i}(j)*R_d(i)\right)-V_{f,\tau}(j)\right] \qquad (1)$$

where $C_G(\tau)$ represents the global cost referred to starting year τ_0, C_I is the initial investment cost, $C_{a,i}(j)$ is the annual cost for component j at the year i (including running costs and periodic or replacement costs), $R_d(i)$ is the discount rate for year i, $V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period (referred to the starting year τ_0).

In CorTau House economic valuation the duration of the calculation period was set to 30 years while the discount rate was fixed at 3%. Results stability was tested through some sensitivity analyses that confirmed the outcome obtained in terms of cost-optimal level.

3.3. The cost-optimal level

After energy and economic assessing, it was possible to draw cost-optimal graph in which primary energy consumption (kWh/m²year) on the x-axis was plotted versus global cost on the y-axis (€/m²) (Fig. 3). Each point on the graph represents a different design scenario in terms of energy and economic performance. The positions of the different scenarios allowed drawing the trend of the dotted broken line representing the so-called cost-curve, the minimum of which represents the cost-optimal level.

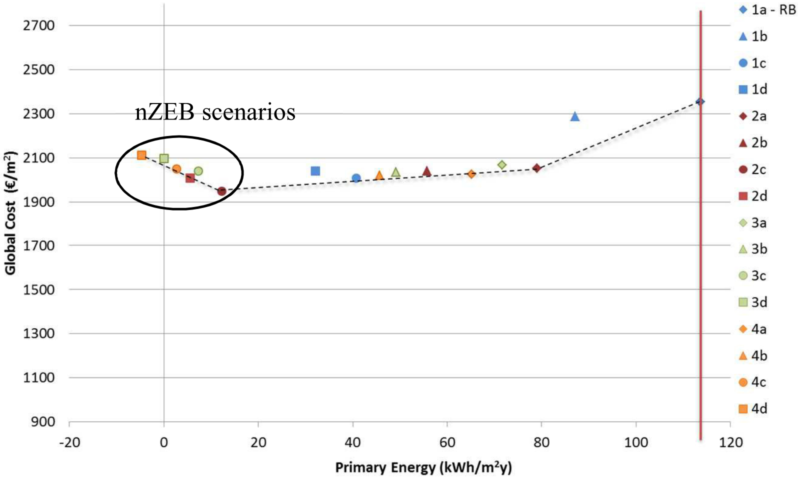

Fig. 3. Cost optimal graph and nZEB configurations.

Absolutely the cost-optimal level is marked by the energy design scenario 2C (Turin city regulation thermal insulation level, water-to-water heat pump, radiant floors for space heating and cooling, natural ventilation; primary energy consumption = 12 kWh/m²y) that hits simultaneously nZEB targets and cost optimality. It is useful to outline that there are other several scenarios characterized by energy consumption lower than scenario 2C but with similar global cost: 2D, 3C, 3D, 4C, 4D. All these scenarios are characterized by a strongly insulated envelope and a water-to-water heat pump with radiant floors for space heating and cooling, eventually coupled with CMV; all of them have installed PV system with the uppermost pick power underlining that renewable sources contribution is fundamental for reaching nZEB target in terms of both energy and economic effectiveness. Global cost difference between scenario 2C, that represents cost-optimal level, and 4D, that is the nZEB configuration with the highest global cost value, is not so high and is equal to 165€/ m². Indeed, team designer and owners chose the configuration 2D (Turin city regulation thermal insulation level, water-to-water heat pump, radiant panels for space heating and cooling, CMV, PV with 7 kW_{peak}) that provide lower energy consumptions thanks to CMV system (whose dehumidification function is essential with radiant floor during summer) than scenario 2C with a little increase of 60 €/m² in global cost.

4. Conclusions

In this paper the challenge of designing and building a nZEB, by examining how the purpose of wrapped control of costs and the high energy efficiency targets have influenced the architectural configurations and their evolution, since the first concept, is illustrated. The single-family CorTau House located in Piedmont Region (North Italy) was analyzed in terms of architectural design, energy performances and costs. In detail, cost-optimal methodology was applied in order to identify nZEB configurations that represent the cost-optimality.

By means of analysis the cost-optimal level consists of energy design scenario 2C (Turin city regulation thermal insulation level, water-to-water heat pump, radiant panels for space heating and cooling, natural ventilation; primary energy consumption = 12 kWh/m²y). Team design and owners chose scenario 2D that provide still lower energy consumptions (thanks to CMV, dehumidifier function is fundamental in summer coupled with radiant floors) than scenario 2C with a little global cost increasing of 60 €/m².

Finally, cost optimal graph highlights that the same global cost value is associated to divergent energy performance. For example, scenario 4C and scenario 2A have the same global cost (2050 €/m²) with a primary energy consumption respectively equal to 3 kWh/m²y (nZEB scenario) and 79 kWh/m²y. Therefore nowadays designing and building an nZEB is technically feasible; considering only investment cost it is not viable, but it reveals to be cost efficient taking into account the costs incurred during whole building life cycle.

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