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Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimization towards nearly zero-energy performance

Fabrizio Ascione [a,*], Nicola Bianco [a], Rosa Francesca De Masi [b], Gerardo Maria Mauro [a], Giuseppe Peter Vanoli [c]

[a] Università degli Studi di Napoli Federico II, DII – Department of Industrial Engineering, Piazzale Tecchio, 80, 80125 Napoli, Italy
[b] Università degli Studi del Sannio, DING – Department of Engineering, Piazza Roma, 21, 82100 Benevento, Italy
[c] Università degli Studi del Molise, Dipartimento di Medicina e Scienze della Salute "Vincenzo Tiberio", Via Francesco De Sanctis, 1, 86100 Campobasso, Italy

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ABSTRACT

Building activity is the sector that affects for the most part the anthropogenic climate change. Indeed, even if differences can be found among countries, according to the level of development and climates, buildings require about 30–40% of the overall energy demand, with similar share concerning the greenhouse emissions. According to the more recent EU Directives in matter of energy efficiency in energy use, a great attention has to be paid to energy refurbishments of existing buildings. Indeed, the turnover rate of the EU building stock is generally low in fully-developed countries, so that the energy retrofits are also more important compared to new nearly zero-energy buildings. The proposed investigation concerns the demonstrative role of the public hand, whose necessity is underlined by the EU Directives 2010/31/EU and 2012/27/EU, through a multi-step and multi-objective optimization of an educational building of an Italian University. All preliminary investigations aimed at a reliable modelling, the iterative method that combines genetic algorithms and transient energy simulations tailored on calibrated numerical models make the investigation complete and repeatable. All levers of energy efficiency have been pressed, and thus the refurbishment of building envelope, HVAC systems, integration of energy supply by renewables. The multi objective optimisation concerns costs, incentives, indoor comfort, energy demands for heating and cooling and a novel approach is proposed for choosing the best configuration of retrofit. It is resulted that the most profitable energy efficiency measures involve the modernization of energy systems, even if also the retrofit of the building envelope can be profitable under favourable financial conditions. The cost-effective refurbishment reduces the primary energy demand up to a value of 12 kWh/m^{2}a, so that the building can be surely considered as nZEB.

1. Introduction

Space heating and cooling are the prevalent energy usages of European Union (EU) [1], with 50% (546 Mtoe) of final energy consumption in 2012, and it is expected that these will remain quite high. Thus, energy-efficient and low/zero-carbon energy technologies for heating and cooling in buildings will play a key role to achieve a significant reduction of greenhouse gas emissions at European level, as well as to meet the targets of the COP21 climate conference 2015 of Paris. In this frame, the Energy Performance of Buildings Directive (EPBD) Recast (2010/31/EU) [2] showed a framework for improving energy performance of European buildings and for increasing the exploitation of renewable sources. A key element of the EPBD Recast, in order to achieve long-term efficiency objectives, is the introduction of the standard of 'nearly zero-energy building (nZEB)'. According to the mentioned Directive, a nZEB is "a building that has a very high energy performance, for which the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby".

More in detail, the European Directive 2010/31/EU [2], established that the definition of nZEB is a task that should be defined

* Corresponding author.
E-mail addresses: fabrizio.ascione@unina.it (F. Ascione), nicola.bianco@unina.it (N. Bianco), rfdemasi@unisannio.it (R.F. De Masi), gerardomaria.mauro@unina.it (G.M. Mauro), giuseppe.vanoli@unimol.it (G.P. Vanoli).

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Nomenclature

Symbols

a	Absorptance to solar radiation [–]
cov	Percentage of roof area covered by PV panels [–]
dGC	Difference in GC compare to BB [€
dPEC	Difference in PEC compare to BB [Wh_p/m^2 a] [–]
e	Thermal (infrared) emissivity [–]
g_{max}	Maximum number of GA generations [–]
r	discount rate [%]
s	Population size of the GA [–]
t	Thickness of thermal insulation layer [m]
x	Vector of design variables [–]
A	Surface of envelope compenents [m^2]
COP	Coefficient of performance of heat pumps [W_t/W_{el}]
DH	Percentage of discomfort hours [%]
EER	Energy efficiency ratio of chillers [W_t/W_{el}]
F	Objective functions [–]
GC	Global cost [€]
IC	Investment cost [€]
PEC	Primary energy consumption per unit of conditioned area and year [Wh_p/m^2 a]
P	Power [W]
SHGC	Solar heat gain coefficient [–]
T_{vis}	Transmittance to visible radiation [–]
TED	Thermal energy demand for space conditioning [Wh/m^2 a]
U	Thermal transmittance [W/m^2 K]
η	Efficiency of boilers [W_t/W_p]

Subscripts or Superscripts

BB	Referred to the base building configuration
C	Referred to space cooling
el	Referred to electrical energy or power
f	Referred to the external floor
H	Referred to space heating
p	Referred to primary energy or power
r	Referred to the roof
t	Referred to thermal energy or power
v	Referred to the external vertical walls
w	Referred to the windows

Acronyms

BB	Base building configuration
DHW	Domestic hot water
ERM	Energy retrofit measure
GA	Genetic algorithm
HVAC	Heating, ventilating and air conditioning
PV	Photovoltaic
RES	Renewable energy source

at national level. Today, where a numerical indicator is set, the requirements – in terms of primary energy – range rather widely from 0 to 270 kWh/m^{2}a. For residential buildings, the higher energy demand ranges between 33 kWh/m^{2}a in Croatia and 95 kWh/m^{2}a in Latvia, with a majority of countries aiming at 45–50 kWh/m^{2}a. Few Member States mentioned objectives that go beyond nZEB requirements, and thus the targets of net zero-energy buildings (ZEB) in the Netherlands, positive-energy buildings in Denmark and France, climate neutral new buildings in Germany and the zero-carbon standard in the UK [3]. In Italy, the definition of nZEB standard has been completed by the Ministerial Decree 06/26/2015 [4]. The Italian procedure consists of determining the building energy class, assuming conventional boundary conditions (i.e., "asset rating"). The energy class is derived from the value of the overall energy performance index $EP_{gl,NREN}$ which represents the annual amount of non-renewable primary energy needed to meet the different needs associated with a standardized use of the building, divided by the useful area of building [kW/m^2], and thus heating, cooling, sanitary hot water, illumination, ventilation, and electrical consumption for people moving inside the building. In detail, building under examination must achieve energy class IV, the best one, to be classified as NZEB. This means that $EP_{gl,NREN}$ should be lower than 40% (at least) compared with $EP_{gl,NREN}$ index calculated for reference building. This is defined as the one characterized by same geometry, orientation, functionality, climatic conditions and geographic location of the building under investigation, and it respects for the building envelope and the systems, the minimum requirements defined by [4] from 1 January 2019 for public buildings, and from 1 January 2021 for all others.

However, new buildings are few in all EU developed countries (a reasonable range is 0.4–1.2% per year) and thus the major way for achieving de-carbonization targets is the renovation of the existing building stock. About it, two thirds of the EU's buildings were built when mandatory energy efficiency requirements were poor or absent. For instance, almost half of buildings have individual boilers installed before 1992, with efficiency equal to 0.60 or less, and, moreover, 22% of individual gas boilers, 34% of direct electric heaters, 47% of oil boilers and 58% of coal boilers are older than their technical lifetime. Thus, large savings can be achieved through simple retrofits of building envelope and HVAC systems. For what concerns the Italian building stock, Corrado et al. [5] elaborated data of the national pilot action for the IEE-EPISCOPE project, concerning the residential buildings of Piedmont region (North Italy). The analyses underlined that the current trend of the average yearly refurbishment rate, included in the range 0.06–1.05%, is not sufficient to achieve the CO2-eq emissions' reduction target. In Europe, offices and educational buildings account for about 40% of the entire non-residential floor space, such as specified by the first version of the EPBD. In the non-residential sector, since 1990, electricity consumption has increased by a remarkable 74%. Non-residential average specific energy consumption was estimated around 280 kWhp/m^2 a (with reference to all end-uses) [6]. More in detail, educational buildings and sport facilities account for a further 18% of the energy use [6]. In China, surveys on energy consumption of colleges and universities in Guangdong province [7] showed that campuses are among the major energy consumers. Chung and Rhee [8] established that potential energy savings, in the range 6–29%, can be reached in university buildings of Seoul, South Korea. As underlined by Santamouris [9], high-energy consumption of the building sector, local climate change and energy poverty are strongly interrelated. According to the author, the innovation of the built environment of Europe can contribute to the minimization of consumption of the building sector, eradication of energy poverty and mitigation of urban heat island effect and local climate change.

The study here presented concerns the energy retrofit of an educational (i.e., university) building located in South Italy, by showing that the application of a rigorous optimization methodology provides robust cost-optimal retrofit solutions that ensure very high levels of energy performance, near to those typical of nZEBs. Thus, this study aims to demonstrate that the cost-optimal building retrofit towards nZEBs is possible, thereby coupling the drastic reduction of energy consumption, and thus of environmental impact, with cost-effectiveness and economic feasibility. The methodology is applied after the calibration of the building energy model by means of energy audit and measured data. Before the description of methodology and outcomes, the following lines propose a brief review of research in matter of building energy retrofitting aimed at the achievement of the nZEB goal. Since the proper selection of the best packages of energy retrofit measures