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A new methodology for investigating the cost-optimality of energy retrofitting a building category

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ABSTRACT

According to the Energy Performance of Buildings Directive (EPBD) Recast, building energy retrofitting should aim "to achieving cost-optimal levels". However, the detection of cost-optimal levels for an entire building stock is a complex task. This paper tackles such issue by introducing a novel methodology, aimed at supporting robust cost-optimal energy retrofit solutions for building categories. Since the members of one building category provide highly different energy performance, they cannot be correctly represented by only one reference design as stipulated by the EPBD Recast. Therefore, a representative building sample (RBS) is here used to consider potential variations in all parameters affecting energy performance. Simulation-based uncertainty analysis is employed to identify the optimal RBS size, followed by simulation-based sensitivity analysis to identify proper retrofit actions. Then post-processing is performed to investigate the cost-effectiveness of all possible retrofit packages including energy-efficient HVAC systems, renewables, and energy saving measures. The methodology is denoted as SLABE, 'Simulation-based Large-scale uncertainty/sensitivity Analysis of Building Energy performance'. It employs EnergyPlus and MATLAB®. For demonstration, SLABE is applied to office buildings built in South Italy during 1920–1970. The results show that the cost-optimal retrofit package includes the installation of condensing gas boiler, water-cooled chiller and full-roof photovoltaic system.

1. Introduction

In recent years, the interest of the scientific community toward building energy performance is more and more increasing because the building sector accounts for around 40% of energy demand in the European Union (EU) and 32% in the world [1]. This leads to international calls for achieving net/nearly zero-energy buildings in order to reduce the energy consumption of the future building stock. However, it is well known that the building turnover rate is quite low, especially in the industrialized countries, which are responsible of a wide part of world consumption. Therefore, building energy retrofitting is a key-strategy to achieve tangible results in the reduction of world energy demand and thus polluting emissions. For instance, Nemry et al. [2] showed that, concerning the residential category at EU level, the potential reduction of the environmental impact of new buildings can be neglected compared to that of existing ones. Similar conclusions are valid for other categories, such as office buildings [3,4].

The scientific community supports the necessity of acting on the existing building stock as shown by Ma et al. [5], who proposed an admirable review of worthy studies in the field of building energy retrofitting. Such studies are subdivided into two groups: those focused on residential buildings and those focused on office buildings. This distinction is made because the best energy retrofit packages for heterogeneous building types and uses generally differ. The attention is directed to these two categories because they cover the vast majority of the building stock of any country.

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Nomenclature

$a, b, \ldots, g, h$	labels of the EEMs[d]
a	absorption coefficient for solar radiation
c	specific heat [J/kg K]
d	density [kg/m^3]
e	number of parameters describing the EEMs[d]
k	thermal conductivity [W/m K]
n	number of characteristic parameters describing the existing building stock
p_i	ith parameter
r	ratio between the number of sampled cases and the number of characteristic parameters
$r_{\min}$	minimum value of r for achieving a reliable RBS
t	thickness [m]
ACC	efficient air-cooled chiller
BPS	building performance simulation
CB	condensing boiler
COP	coefficient of performance of heat pumps [$W_{\mathrm{th}}/W_{\mathrm{el}}$]
DH	percentage of discomfort hours [%]
DHW	district hot water
EB	efficient boiler
ED	thermal energy demand [kWh/m^2 a]
EEM[d]	energy efficiency measure for the reduction of thermal energy demand
EER	energy efficiency ratio of chillers [$W_{\mathrm{th}}/W_{\mathrm{el}}$]
GC	global cost [€ per building]
HP	heat pump
HVAC	heating, ventilating and air conditioning
LHS	latin hypercube sampling
N	number of cases included in the RBS (RBS size)
$N_{\min}$	minimum value of N for achieving reliable results
PEC	primary energy consumption [kWh/a per building]
PI	performance indicator
PV	photovoltaic
R	thermal resistance [m^2 K/W]
RB	reference boiler
RBS	representative building sample
RefB	reference building
RC	reference chiller
RES	renewable energy source
S_1	sample set representing the existing building stock (RBS)
S_2	sample set representing the renovated building stock
S_3	sample set representing the packages of the most important EEMs[d]
SA	sensitivity analysis
SLABE	simulation-based large-scale uncertainty/sensitivity analysis of building energy performance
SRRC	standardized rank regression coefficient
U	thermal transmittance [W/m^2 K]
U_{w}	thermal transmittance of the windows (glass + frame) [W/m^2 K]
UA	uncertainty analysis
WCC	water-cooled chiller
μ	mean value
σ	standard deviation

Subscripts

c	referred to the cooling season
h	referred to the heating season

Concerning residential buildings, their energy performance is highly affected by the characteristics of the building envelope, mainly because of the low ventilation needs. Thus, the thermal insulation of the building shell [6–8] can induce high energy and economic savings. Furthermore, if this measure is combined with the use of more efficient building HVAC systems and with the exploitation of renewable energy sources (RESs), especially photovoltaic panels, the energy retrofit of existing buildings to nearly zero-energy ones is possible [9]. However, this outcome is valid only for heating-dominated climates (e.g., North Europe), whereas in presence of cooling-dominated climates (e.g., Mediterranean area) a deeper analysis is necessary in order to take into account the issue of summer overheating. In this regard, two macro-strategies can be identified for reducing the cooling need and avoiding the overheating effect in warm climates: (a) the reduction of the solar gain by means the use of solar shadings [10,11] and/or reflective coatings [12]; (b) the adoption of techniques for discharging the building envelope, thereby operating a passive cooling of indoor spaces [13–15].

Concerning office buildings, they are characterized, compared to dwellings, by a higher demand for lighting and various electric uses, as well as by a much larger ventilation need and endogenous heat gain that increases the energy demand for space cooling. Therefore, also in heating-dominated climates, the main components of annual primary energy consumption, i.e., space heating, space cooling, lighting and electric uses, are more balanced [16] compared to residential buildings, whose consumption is highly affected by space heating. This determines major issues in the design of retrofit strategies, which simultaneously should take into account environmental, sociocultural and economic criteria [3]. In this vein, Hestnes and Kofoed [17] investigated ten existing office buildings by exploring the impact of different retrofit strategies, including measures addressed to building envelope, HVAC system and lighting. The outcomes confirmed the complexity of energy retrofitting the considered building category, since the optimal strategy significantly depends on the specific building characteristics. Definitely, the energy retrofit of office buildings should be designed ‘ad hoc’ by taking into account all levers affecting energy performance [18,19]. In this regard, different interactive decision support tools have been conceived [20,21] in order to detect optimal energy retrofit packages for office buildings, based on the trade-off among different performance indicators, such as energy consumption, investment and operating costs, environmental impact.

As shown by the mentioned studies, the design of building energy retrofit is a challenging task that requires a holistic and integrated team approach [22] because conflicting objectives generally subsist. The two main objectives are the minimization of energy consumption and the maximization of economic benefits. Since they are generally conflicting, multi-objective optimization is recommended [23–35]. In order to harmonize such objectives, the Energy Performance of Buildings Directive 2010/31/EU (EPBD Recast) [36] focuses on the concept of ‘cost-optimality’. More in detail, this directive has introduced a new comparative methodology framework in order to assess building energy performance “with a view to achieving cost-optimal levels”. The energy retrofit actions should be effective by minimizing the global cost over the lifecycle of the building. Since the cost-optimal analysis cannot be performed to each building, for reason of complexity, reference buildings (RefBs) have to be defined to represent the national building stock. They should cover all the building categories, where a category is meant as a stock of buildings that share climatic conditions (location), functionality and construction type. Thus, the cost-optimal analysis should be applied to these RefBs in order to detect cost-optimal packages of energy measures [37,38]. Then,