8.

Ph.D. publications

Paper I

S.P. Corgnati, E. Fabrizio, M. Filippi, V. Monetti, *Reference buildings for cost optimal analysis: Method of definition and application*, Applied Energy, Volume 102, February 2013, Pages 983-993, doi:10.1016/j.apenergy.2012.06.001.

Applied Energy 102 (2013) 983–993

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Reference buildings for cost optimal analysis: Method of definition and application

Stefano Paolo Corgnati [a,*], Enrico Fabrizio [b], Marco Filippi [a], Valentina Monetti [a]

[a] Dipartimento di Energia (DENERG), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] Dipartimento di Economia e Ingegneria Agraria, Forestale e Ambientale (DEIAFA), Università degli Studi di Torino, Via Leonardo da Vinci 44, 10095 Grugliasco (TO), Italy

HIGHLIGHTS

- ▶ We analyze the problem of reference building models for cost optimal analysis.
- ▶ We present the international state of the art on reference buildings.
- ▶ Three methodologies to define a reference building models (example, real and theoretical).
- ▶ We present the energy performance of an Italian office reference building model.

ARTICLE INFO

Article history:
Received 22 March 2012
Received in revised form 1 June 2012
Accepted 1 June 2012
Available online 26 July 2012

Keywords:
Reference buildings
Nearly zero energy building
Cost optimal analysis
Energy performance
Office building

ABSTRACT

The Energy Performance of Buildings Directive (EPBD recast, 2010/31/EU) requires Member States to define minimum requirements of energy performance of buildings and building components with a view to achieving cost-optimal levels. In order to calculate the cost optimal level of minimum energy performance, Member States are required to create a set of reference buildings, at national or regional level, to be used in the calculations. This paper introduces to the concept of reference buildings and to the state of art at an international level. In particular, a general methodology for the creation of reference buildings is illustrated. A case study of an office building as a reference building for the Italian existing building stock is then shown. The process concerning the building definition and modeling was carried out by means of dynamic energy simulation program EnergyPlus.

1. Introduction

Building sector is responsible for 40% of the total energy consumption at European level.

In order to have a practical impact on the reduction of building energy consumptions, the Energy Performance of Buildings Directive (EPBD recast, 2010/31/EU) [1] requires Member States (MSs) to define minimum requirements of energy performance of buildings and buildings components with a view to achieving cost-optimal levels using a comparative methodology framework.

Since it is not possible to calculate the cost-optimality for every single building, the comparative framework illustrated in the accompanying Guidelines [2] of the EPBD requires of MSs to define a set of reference buildings (RBs), as typical national or regional buildings. Due to the EPBD request, RBs have hence become a crucial topic for studies assessing the energy performance. In particular two recent projects within the “Intelligent Energy Europe” program (IEE), TABULA [3] and ASIEPI [4], holds a reference position with regard to the definition of typical residential buildings.

In the past, many studies pursed the definition of typical buildings but with different final targets. While some works were aimed to the creation of representative buildings to be used for the evaluation of energy saving possibilities in existing dwellings [5–7] others pursued the definition of typical buildings in order to develop benchmark energy consumption of certain categories of buildings [8–11].

At international level one of the largest database of benchmark building models for commercial buildings is the one of the Department of Energy (DOE) of United States, where RB models are defined for 16 building typologies across 16 locations (representative of US climate zones) and three construction periods (pre-1980, post-1980, new buildings).

The EPBD establishes also a strong step forward into the economic evaluations. Before referring to the cost-optimality methodology, energy saving measures were often compared by taking into account only the energy consumption and neglecting the economic evaluation. Recently economic evaluations made use of the life cost analysis [12] as well as through the total net present value in a

---

* Corresponding author. Tel.: +39 011 0904507; fax: +39 011 0904499.
E-mail address: stefano.corgnati@polito.it (S.P. Corgnati).

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.06.001

defined building lifecycle [13]. Indeed, according to art. 12 of the EPBD, cost optimal level refers to the energy performance that leads to the lowest cost during the estimated economic lifecycle. The main reference for the economic calculation methodology is the global cost calculation from the European Standard EN 15459 [14]. In particular the global cost calculation allows to compare different energy saving measures, applied to different buildings, taking into account both the energy consumption and the economic performance. Some applications of the global cost calculation on different packages of measures applied to office buildings and residential buildings have been made [15,16].

After drawing a common picture about the state of art of RBs, this paper illustrates an harmonized methodology for the creation of RBs. Considerations and challenges about the definition of the concept of RBs at European level are also presented. Moreover the first results on the activities on-going about the definition of some RBs of the authors are here provided. In particular, a case study of an office RB for the existing building stock is shown. The process concerning the building definition and modeling by means of dynamic energy simulation through EnergyPlus program is illustrated.

2. How to define RBs

In past and recent years several studies using RBs as a starting point, were carried out, hence RBs do not represent a new area of interest at all. However, MSs follow approaches that are very unlike in terms of methodology and degree of detail in the creation of RBs [17–19] since there is still no standardized methodology to refer to. Some MSs have developed a comprehensive catalogue (Germany), others are dealing with example buildings (Denmark), others are defining them just for a few building categories and others still do not have them in a project development. This paragraph attempts to draw a comprehensive and common picture of the state of art of RBs and also to outline a fair and harmonized methodology to be used to determine them.

2.1. Towards a common definition

Before discussing the methodology it is essential to dwell on the theme of RB, to introduce it properly with a few simple questions in order to establish good basics.

2.1.1. What are RBs?

Currently there is no well-known and uniformed definition to refer to, hence it is essential to set a recognized and harmonized definition at European level to be used. According to Annex III of the EPBD recast, RBs are "buildings characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions". They aim to represent the typical and average building stock in terms of climatic conditions and functionality (e.g. residential buildings, schools, etc.). Different points of view [17] related to that topic emerged during the European Commission's meeting for the supplementing regulation to Directive 2010/31/EC. Some experts believe RBs for the existing stock should be as accurately as possible to the present average building stock, but national experts reckon this kind of models would be very complex and unrealistic, even if built on statistical basis. Moreover the level of detail considered for the building envelope and the system in RBs for the new construction represent another subject for discussing between experts.

2.1.2. What is the target pursued with RBs? How can RBs reflect on building energy performance and how are they connected with the EPBD recast?

Generally speaking RBs aim to characterize the energy performance of typical building categories under typical operations. In particular, in compliance with the EPBD recast, RBs are required for the purpose of cost-optimal methodology. They need to reflect as accurately as possible the actual national building stock to ensure that results from cost-optimal calculations are representative. Moreover they can be used to evaluate the achievable reduction on energy consumption under a certain energy policy applied to a selected building category in a national territory.

Especially EPBD recast demands MSs to define at least two RBs for the existing buildings subjected to renovation and one for new buildings. The building categories considered are Single-family buildings, Apartments blocks/Multi-family buildings, Office buildings and the other non-residential buildings listed in Annex I of the EPBD recast. MSs can choose to define a RB for each non-residential building category or define a RB can be considered representative of two or more building categories. Overall the number of RBs demanded to each MSs has to be equal or superior to 9.

2.2. Methodology

Once established a definition for RBs, it is important to carry out an accepted methodology for the creation of RBs. European building stock is very heterogeneous in terms of climatic zones, building styles and usage. In fact within the same category, building use can vary widely if analyzed into different MSs. Climate conditions have a relevant influence into the construction technologies and the energy needs that characterize the building. It is thus important to take these differences into account in order to identify a proper methodology to be used by all MSs.

2.2.1. How can a RB then be defined? What problems may be faced during its creation?

These two questions do not have easy answers. To create a RB is a quite complex operation and its accuracy mostly depends on the level of detail pursued in defining the building. In fact a common and main problem usually faced is the lack of information requested for defining properly RBs as it is difficult to find reliable sources to refer to. Usually a common approach is to extract, when available, data from official statistics at national or regional level. The high need of information, relies also on the methodology used for the assessment of energy performance in buildings. In order to achieve reliable results, the Guidelines suggest MSs to perform calculation using a dynamic method. It is thus recommended to carry out calculations by means of dynamic energy simulation with appropriate calculation programs (e.g. EnergyPlus). Dynamic energy simulation requires detailed building energy models and faces several problems associated mostly with the several pieces of information necessary as input data for the modeling process. Thereby, as the level of information required is high, a solid foundation of data about the building stock is the starting point to create RBs, especially when using dynamic energy simulation.

The data collected for creating RBs, can be gathered into four main areas of investigation as listed below:

1. Form.
2. Envelope.
3. System.
4. Operation.

Data from each one of these four area form a sub-set of the features of a building. All four sub-sets gathered together constitute a wider set of features, that match with a RB model. The subset "Form" regards the building type (e.g. office, school, etc.), size and general geometry of the building. The second sub-set, "Envelope", regards the construction technologies and the material used in the building, providing a description of the thermophysical proprieties of building envelope. The sub-set "System" concerns the heating and cooling systems, the mechanical ventilation systems (when applicable), the generation systems and the production from renewable sources within the building. In conclusion "Operation" sub-set consists of the operational parameters affecting the usage of the building and it is also expressed through a set of schedules (i.e. lighting schedule, equipment schedule, heating temperature schedule, etc.). The structure of the four sub-set of features is reported in Fig. 1 and takes inspiration from the methodology [20] for establishing RBs used by the Department of Energy (DOE) of United States. In fact DOE RB models are defined gathering the data into four main area of investigation: program, form, fabric and equipment, that match respectively with the sub-set operation, form, envelope and system outlined above.

Moreover, as also recommended into the Guidelines, collected data are subsequently gathered in terms of age, location and type.

Once collected the data within the 4 sub-sets, in order to create RBs, the process of gathering all data together is a crucial task. It is important to understand the typology of data available depending on the sources used. It is possible to collect data from statistical analyses or to base RBs on experts' assumptions. The EPBD guidelines point out as input documentation for the establishment of RBs, the work carried out within the IEE TABULA project, in which three methodologies [21] to classify RBs are defined:

I. Creation of an "*Example (Reference) Building*". This methodology is used when no statistical data are available, and it thus relies on the basis of experts' assumption and studies. Information from different sources but all based on experience and experts' inquiries are properly combined to provide a building that is the most probable of a group of buildings, within a selected location and age.

II. Selection of a "*Real (Reference) Building*". The RB is the most typical building in a certain category. It is a real existing building, with average characteristics based on statistical analysis. To define a Real Building it is therefore necessary to have a large amount of information on the building stock.

III. Creation of a "*Theoretical (Reference) Building*". This method processes statistical data in order to define a RB as a *statistical composite of the features found within a category of buildings in the stock* [22]. The building is therefore made of the most commonly used materials and systems.

Fig. 2 illustrates the methodologies described above. In particular the input data for the creation of an Example (Reference) Building model are derived from handbooks, design manuals, standards and codes, and appropriately selected on the basis of the experts' assumptions. This building is thus a fictional building.

On the contrary, the methodologies that refer to the building stock in order to derive a RB, are outlined in the bottom part of Fig. 2. First of all, it should be noted that only a sample of a national/regional building stock is known from surveys, energy certificates, etc. This is the reason why only a sample of the building stock can be used as the input data of a RB definition.

Generally, data on the building stock sample, are processed by statistical tools in order to have a synthetic representation of this sample (mean conditioned area, mean U-value of opaque components, etc.). These statistical results can be treated aggregately or separately. In the first case, it is possible to select from the building stock sample, the building that is the most close to the statistical results: this is a Real RB.

On the contrary, in the second case, the process of selection from the building stock sample is made for each of the building features the statistical analysis has been disaggregated into. The RB will be made in this case of a summation of various features of real buildings, but will not represent a real building itself. This

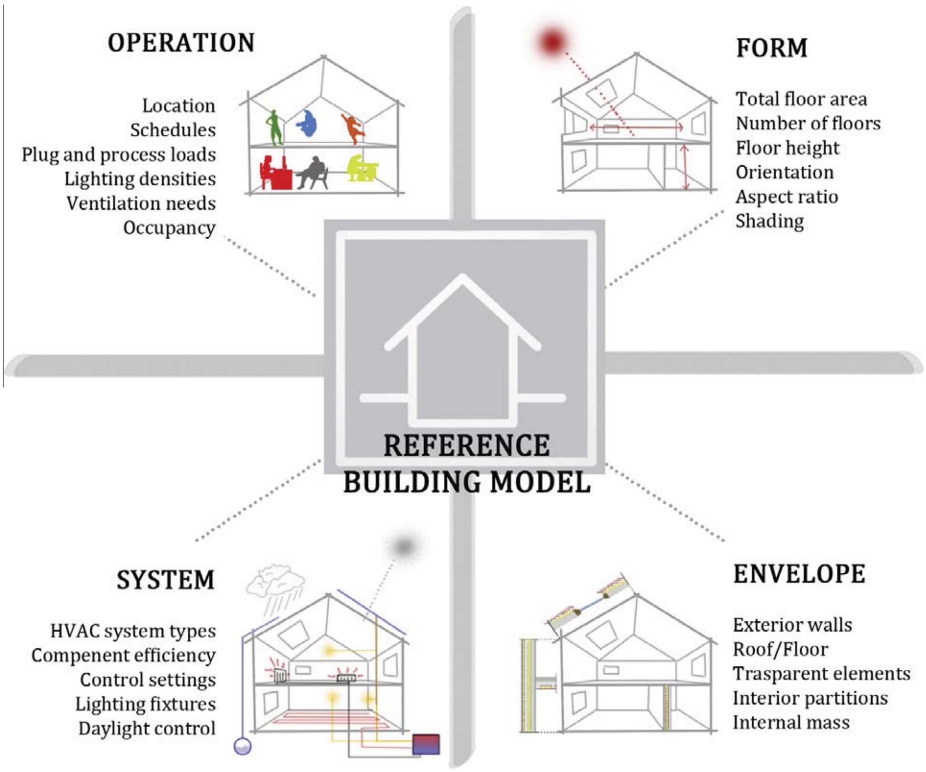

Fig. 1. Four sub-sets of features for defining reference building models according to DOE methodology [6].

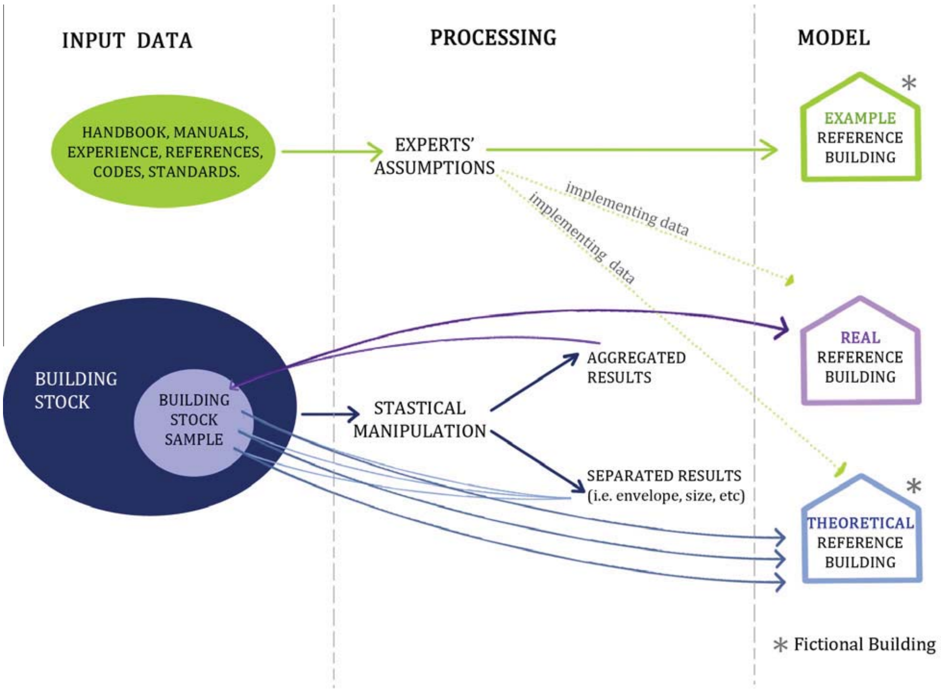

Fig. 2. General methodology for establishing reference building models.

process is similar, for example, to the creation process of a test reference year.

These methodologies can be applied to each of the four sub-sets mentioned previously. For instance it is possible to characterize the general geometry of a residential building as well as to indentify the main heating system as the most typical of that building category referring respectively to empirical data and to statistical analysis. Depending on the available data, it is possible to use just one of the above methodologies for all models (I, II and III) in a RB, or apply them differently to each model of the same RB. This is the reason why in Fig. 2, a dashed arrow goes from the experts' information to the Real and Theoretical RB models: in fact for some of the sub-set of features that made a complete RB model, the statistical data may not be available and other sources should be used. This is typically the case of the features of the operation sub-set (e.g. internal gains, occupancy, etc.), where reference to standards can avoid the uncertainty due to the real observations of the building stock or the lack of information.

It is important to note that the process to rely on when creating RBs is equal for all RBs as the "final product/result" is the same, although the input data used are not the same. The result will always be a RB model but with different quality of data.

Within the same category of RBs, it is notable to set the same boundary conditions and reference use patterns in order to make results to be compared.

Furthermore the methodology for the output presentation is another major issue to be taken into account. Once provided the results from MSs, it is necessary that the methodology to refer to has the same basis. For instance it is important to provide the same output variables in order to ensure comparisons between MSs are adequate. Due to the targets related to nZEB, the EPBD recast required MSs to calculate a primary energy indicator expressed in kWh/m^2 per year for RBs. Moreover a numerical indicator for the disaggregated delivered energy (heating, cooling, lighting, equipment, domestic hot water, ventilation), expressed in kWh/m^2 a is requested. Overall the indicators to be taken into account should be selected in order to define the performance level of a nZEB and should be used by all MSs.

2.3. US experience: DOE benchmark building models

The US Department of Energy (DOE) established strong targets in order to improve energy efficiency in existing and new building stock. Thereby a set of RB energy models [23] were defined for the most common commercial building categories in US, to be used as starting points for analysis related to energy research studies. They were created under the collaboration of the following DOE research laboratories: the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL) and Lawrence Berkeley National Laboratory (LBNL). Fifteen commercial building categories plus one multifamily residential building were gathered across sixteen locations (representative of US climate zones) and three construction periods (pre-1980, post-1980, new buildings). Not all commercial building categories were included into the database, those categories vary greatly and could not be defined into standard building models. Referred to as benchmark building models, they were created on the basis of the 2003 Commercial Buildings Energy Consumption Survey (CBECS) dataset (EIA 2005), especially with regard to the building geometry. Within the same categories, the building models have all the same form, area and operation schedules. Indeed they differ for insulation levels, lighting levels and HVAC equipment. These last parameters are thus defined to be in compliance with the minimum requirements of the energy standard selected in connection with the construction age of the building as listed below:

- ANSI/ASHRAE/IESNA Standard 90.1-2004 for benchmark building models for new construction.
- ANSI/ASHRAE/IESNA Standard 90.1-1989 for models related to a construction age subsequent 1980.
- Standard previous to Standard 90.1-1989 in conjunction with experts' assumptions for models preceding 1980.

Benchmark building models are published into a proper section dedicated to commercial building into DOE website. To be used with the energy simulation program EnergyPlus, 256 models into an idf format (input data file), were developed. Moreover spreadsheet scorecards provide a detailed building description regarding the model parameters and annual energy performance within the selected building category and climate zone.

Benchmark building models do not fit in a just one of the methodologies described above, as the sources used to extract data from are several. Beyond all doubts methodology I can be excluded as benchmark building models are not real buildings. Thereby they are based on data obtained according to methodologies II and III. They refer especially to the following sources:

- The *2003 Commercial Buildings Energy Consumption Survey (CBECS)* and *AIA Guidelines for Design and Construction* for the definition of program, form and fabric sections.
- ANSI/ASHRAE/IESNA Standard 90.1 for the definition of the program and fabric sections as well.
- Experts' studies were used for the equipment section in conjunction with the Standard 90.1.

Throughout the development of the RBs it is intended to assess the effect of energy efficiency technologies on commercial buildings. RBs can also be used to measure the progress of DOE energy efficiency goals for commercial buildings. They are not meant to represent a particular building as they are hypothetical building models with typical operation schedule and typical construction technologies. Moreover DOE's Building Energy Code Program and PNNL use these models for assessing the development of new versions of ASHRAE Standard 90.1.

2.4. National and European studies on RBs

At European level some studies have been carried on in connection to the theme of RBs.

In particular some RBs, mostly within the residential category, were developed and are listed below.

According to the EPBD recast, the Buildings Performance Institute Europe (BPIE) drew up a set of principles concerning the nZEB. Within its study, BPIE outlined the boundaries of the current nZEB definition and produce a set of possible improvements, referred as principles that can be applied to guarantee a better road towards the implementation of nZEB by MSs. In particular two RBs [18] were created across three representative European climates (Copenhagen, Stuggart and Madrid), in order to assess the principles defined. A single-family house was defined, from analysis [19], as the most typical single family building in the residential building stock at European level. Moreover a multi-storey office building was chosen attempting to cover non-residential categories. The building defined has thus very simple features in order to be used also as multi-family building. Both RBs can be considered example buildings for new construction as they were built on experts' assumption.

Additionally, concerning the residential stock within Italian territory, two IEE [Intelligent Energy Europe] projects can be quoted as also recommended in the Guidelines as input documentation about RBs to refer to. The two projects, TABULA and ASIEPI, previously described, are thus discussed into this paragraph as Italy participated as partner and provided some relevant results.

Within the collaboration of thirteen countries, TABULA dealt with the development of an harmonized structure for residential building typologies. Each participant country developed a set of typical buildings, representative of the residential building and gathered in terms of construction period of the country and of the building size. In particular Italy collected the buildings according to three independent variables: 3 climatic zones, 7 construction ages and 4 type of Italian residential buildings (single-family house, multi-family house, terraced house, apartment block). RBs are example and theorical buildings as defined in compliance with the methodology II and III illustrated above. Depending on the age and the level of investigation (building, system and operation) considered, each RB has different basis.

Furthermore ASIEPI gathered, as a subtask within its project, a set of possible RBs [24] to be used in pilot comparison studies. A variety of typical houses were defined for 12 European countries, including Italy. A single family house, varying from row house to detached house, was defined for each participant country. The single family house was chosen as a valuable RB mainly for two reasons. Firstly because, as stated above, it represents the most typical residential building in Europe and secondly small and simple houses were preferred to perform comparison studies in order to minimize the errors of a complex geometry. RBs were defined by all participant countries referring to the methodology II previously introduced. RBs, as supported by experts' estimations, are example buildings.

At European level others studies regarding the residential stock were developed. In particular a seven-step procedure to determine cost optimal and nZEB energy performance level [25] was applied to a Estonian detached house used as typical representative buildings of new construction. The RB was selected by some experts and can be considered a Real Building.

With specific regard to Italy, there are some studies regarding the office building category to be taken into account for their relevance on the topic. At the present time, concerning the office building the most important reference is a research study [26] carried out by ENEA[1] (Italian National Agency for New Technologies Energy and Sustainable Economic Expansion) and finalized to a quantitative and qualitative analysis of Italian commercial stock and in particular concerning office buildings. This research considered approximately 65,000 Italian office buildings and defines two main categories (a small office building and a medium office buildings) as the most representative. In particular within this research, two office RBs valuable for the existing stock were defined. They differ from each other in terms of size (total floor area and number of floors), construction age and percentage of openings. They both have a rectangular shape and a similar interior layout. The smaller one is representative of office buildings built until 1970, whereas the bigger one is representative of office buildings built from 1971 until now. Data concerning the building form builds on statistical basis as well as data about the building system. Whilst the definition of the building envelope was based on assumptions related to the construction age of the buildings and as a result of a telephone survey. The 2nd model defined consists of an office building of medium size, with a covered floor area of 2400 m^2 and 5 floors above ground. As presented in Fig. 3, the interior layout is characterized of cellular offices, a central core for the distributive elements (stairs and elevators) and service areas. The core zone has no openings and it is not subjected to direct solar radiation. Each office has two opening, with exception for the corner ones that have three windows. There is no solar radiation shading. The building construction is consistent with traditional Italian technologies (reinforced concrete structure, brick walls with insulation, flat roof and a double glazing with aluminum frame). Moreover a split DX (direct expansion) system and a gas boiler are respectively defined for cooling and for heating. The building uses natural gas to provide space heating and to serve the water heating system.

3. The cost optimal levels of minimum energy performance

Prior to the calculation of cost-optimal levels of energy performance, MSs are required to investigate valuable energy efficiency measures (based also on renewable energy sources) for each RB and to assess the primary energy demands related to each package

---

[1] A deeper research on the Italian office building stock was carried out, in 2009, by ENEA (Italian National Agency for New Tecnologies, Energy and Sustainable Economic Expansion) and finalized to the quantitative and qualitative analysis of Italian commercial stock, especially Office Building and Schools.

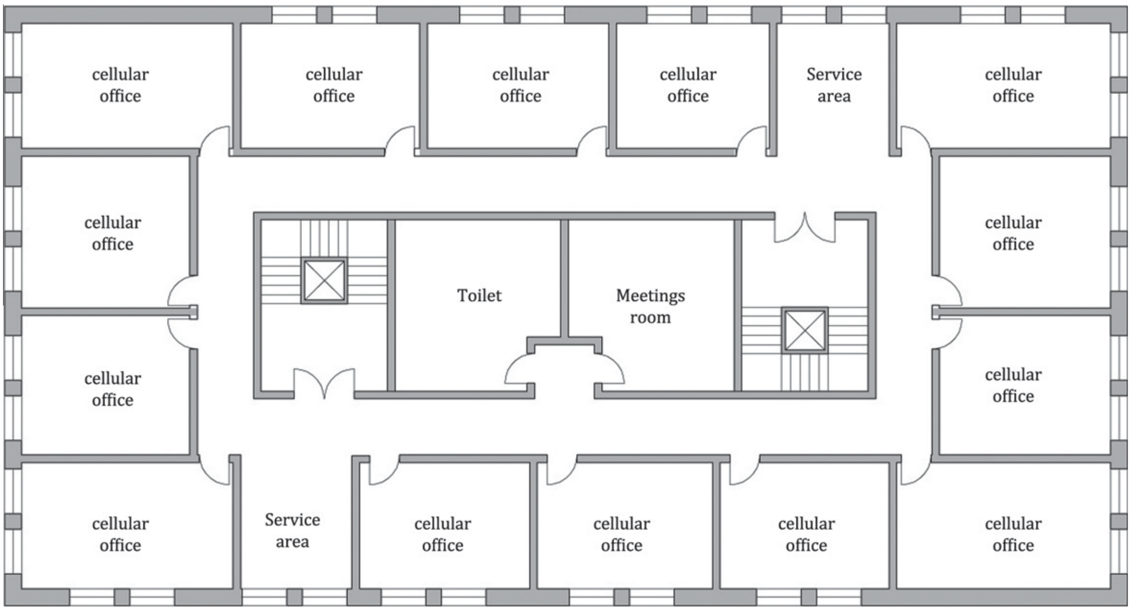

Fig. 3. Medium office building plan.

of measures within the same category of RB. Measures are combined into different packages/variants in order to reach better results energy performance in the RB models.

Subsequently the global cost of each measures/variants package can be calculated according to the classification defined in EPBD recast - Annex I and referring to Standard EN 15459. Usually in economic calculation, only the upfront investment [27] cost is considered, whilst according to the classification provided into the Guidelines initial investment cost, running cost, replacement costs and disposal costs must be included over the building lifecycle. Energy costs are also included as a sub-category in running costs. A full approach for new construction as well as for major refurbishment is demand to calculate the global costs, that must be market-based.

An important issue discussed during MSs meeting is the definition of the calculation period as part of the net present value approach. It was thus proposed to use a calculation period of 30 years for residential buildings and of 20 years for non-residential categories as it is quite difficult to predict prices for a time frame superior to 30 years.

In conclusion the optimal cost range is assessed by spotting the mean value of primary energy consumption and global cost both related to different packages of measures on each RB category. The combination of packages with the lowest cost defines the cost-optimal level of minimum energy performance requirements. When packages have very similar costs, the package with the lowest primary energy demand should be selected to define the cost-optimal level.

An exemplar report on the methodology to be followed was conducted by BPIE [28] defining also different possible packages of measures on a theoretical RB. The study analyzes the current energy policy and provides guidance and support to the methodology addressing mainly to policy makers. Moreover in the previous study quoted for the definition of an Estonian residential RB [25], a systematic and robust scientific procedure to determine cost optimal and nZEB energy performance levels was developed.

4. An Italian RB case study: an office building

In the following, the development of a RB for the office category [29], customized to the Italian territory, and its boundary conditions, are defined.

4.1. Definition of the model

The case study builds on two important references:

- The ENEA research over the office building category (paragraph 2.4) as a starting point to define RBs for existing and new construction.
- The methodology for establishing DOE benchmark building models (paragraph 2.3) as a model to refer to.

The methodology used within the case study, matches thus with the one described previously for establishing DOE benchmark buildings models and pictured into Fig. 2.

The quantitative and qualitative analysis carried on by ENEA defined two RBs for the existing stock, and gathered them depending on five different construction ages (pre-1920, 1920/1945, 1946/1971, 1972/1991, post-1992) and three main climate zones (North, Center, South and Islands). In particular, among the two ENEA models created, the larger building was selected for this study as considered more representative of the existing building stock, for its dimensions and technologies. As described in the previous paragraph, the office building has a rectangular plan with 5 floors above ground and a covered area of 2400 m^2, as pictured in Fig. 3. For its dimensions, it can be referred as a medium office building with traditional construction technologies. It is thus made of a reinforced concrete structure with brick walls, a flat roof and a double glazing with aluminum frame. The RBs defined for North, Central and South Italy differ from each other with regard to the dimensions of the transparent components on the façade. In particular RBs for Central and South Italy are characterized by an increase of the glazing surface.

With reference to the four sub-set of Fig. 1, ENEA survey provided a proper description of the RBs in terms of form, envelope and system.

Subsequently, an analysis over 50 projects of office buildings realized in Italy in the past 10 years was carried out in order to indentify the current design approach. All projects were gathered in terms of size (small, medium, large and very large office) and four office buildings with average values have been thus set out.

In conclusion, the ENEA model was used in conjunction to the analysis reported above to define four reference office building

Table 1
Geometrical data for reference buildings in the north of Italy.

	Value	Unit
Storeys	5	–
Building total height	14.5	m
Wall area	1296	m^2
Window area	588	m^2
Gross roof area	450	m^2
Gross total area	2400	m^2
Gross area of typical floor	540	m^2
Volume	34800	m^3
Floor height	2.9	m
Window-wall ratio	45	%

models, one for existing buildings and three for new constructions. All models were built on the ENEA medium office building as starting point, but they then differ from each other in terms of construction technologies, thermo-physical properties of the envelope and plan layout. The building shape as well as the gross area and system remain unchanged for all models. The geometrical data of the buildings, for the North of Italy, are reported in Table 1.

The four RBs defined are listed below:

- Type A. It is the medium office building defined in the ENEA research. As it was originated from an analysis over the existing building stock, the values of the construction component are not consistent with Italian current Standard. It can be considered a RB for the existing stock. It is a *Theorical building* based on statistical data for the form, envelope and system sub-set features, and an *Example building* for the definition of the operation sub-set features.
- Type A1. It is a reference building for new constructions. It is thus equal to Type A but with some alterations on the envelope. The thermal-physical properties of the construction components were hence modified due to make the model be in compliance with the current Italian energy standard for buildings (D.lgs 311/2006 [30], D.P.R. 59/2009 [31]). Like Type A, it is a *Theorical building* for the form and system sub-set features, whilst it is an *Example building* for the envelope and operation sub-set features.
- Type B. It is equal to Type A1 with alterations to the plan layout, from a cellular office to a mixed office (both cellular and landscape office) and alterations to the façade (from a traditional opaque envelope to a ventilated façade). It is an *Example building* for new constructions.
- Type C. In analogy with the previous model (Type B), it has a transparent façade instead of the ventilated one. It is an *Example building* for new constructions as well.

Table 2 lists the thermal trasmittance of the main envelope components in the RBs.

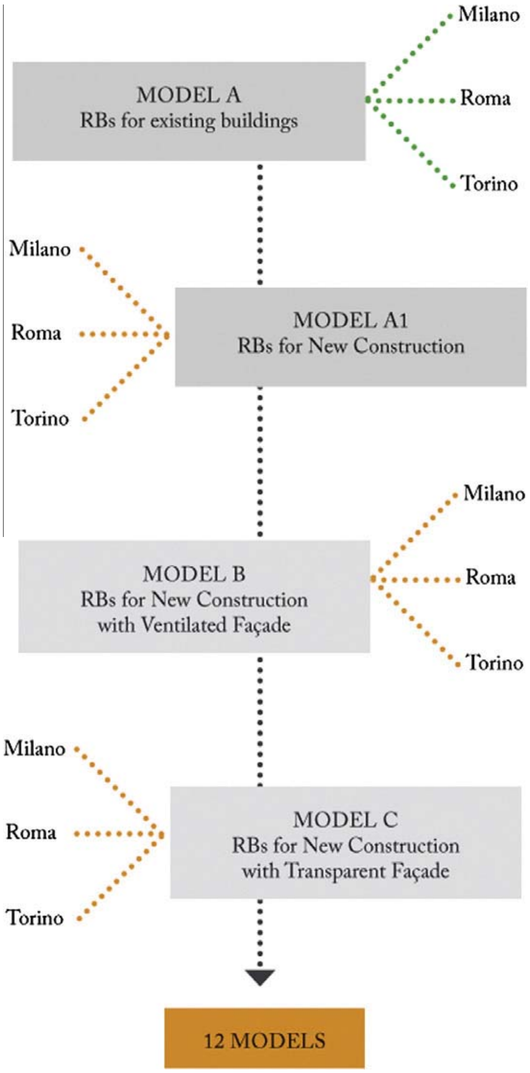

Fig. 4. Reference building scheme.

The HVAC components and the energy system remain unchanged for all the RBs. For heating and cooling, the primary systems are respectively a gas boiler and water-cooled chiller, and the terminals are four-pipe fan coil units with outside air.

Both the analysis previous mentioned did not provide any information about the use of the building, its occupancy and the internal gains to be considered for a full energy study of the building. Therefore, in order to fill in the operation sub-set features as

Table 2
U Values for all reference buildings in the north of Italy.

	Type A (W/m^2 K)	Type A1 (W/m^2 K)	Type B (W/m^2 K)	Type C (W/m^2 K)
Exterior wall				
Type A/A1 Plasterboard/brick/air/insulation/brick	0.76	–	–	–
Type B Plasterboard/brick/insulation/air/brick	–	0.34	0.29	–
Flat roof				
Plasterboard/slab/insulation/slab/concrete plaster	0.295	0.295	0.295	0.295
Window				
Double glazing with aluminum frame	3.2	1.87	1.87	
Type C- Glazing façade	–	–	–	1.87
Slab above ground				
Floor/concrete/insulation/slab/gravel	0.516	0.30	0.30	0.30

pictured in Fig. 2, some assumption were made based on design manuals and standard references. In particular indoor thermal comfort was set according to Italian national standard 10339 [32]. Occupancy, lighting and equipment schedules were defined with reference to European Standard EN 15232 [33] as considered representative of the daily usage of the building in Italy. In particular schedules from energy class C were selected, as representative of reference and basic values. For all models input data regarding the operation in the building model were set with the same values. As they were extracted from standards and design manuals, all models are Example buildings with specific regard to the operation sub-set features.

All four models belong to the same category of RBs, as the main activity is the office use. Therefore it is important to set the same boundary conditions (e.g. climate) and reference use patterns in order to compare the results from all four models. As stated before, ENEA models were defined for three main climatic zones. For this study, only the models referring to the North and Central Italy were considered as most of Italian office buildings are located in the Northern and Central part of Italy. The Statistical analysis included in ENEA survey highlighted in fact the great concentration of office buildings in the North of Italy, especially in the region Lombardia. Furthermore as Italian territory is divided into seven climatic zones, three location (Turin, Milan and Rome) were thus selected within these areas due to represent with more accuracy the different climatic conditions. Turin and Milan are located in the same climate area (zone E) which is representative of the 90% of office buildings in the North of Italy. As emerged from ENEA analysis, just into the District of Milan there are nearly 4800 office buildings, followed by Rome with 2600 and Turin and Rome with 2250 units. Zone E is characterized by a number of Degree Days (DD) that ranges from 2100 to 3000, whilst climatic zone D, where Rome is located, has a number of DD varying from 1440 to 2100.

All RBs were modeled within DesignBuilder, the graphical interface of EnergyPlus program. All data extracted from the analysis mentioned previously, from the design manuals and the standards were all gathered into the simulation program in order to perform an analysis over the models energy consumption.

Hourly weather data were taken from the International Weather for Energy Calculation database (IWEC files) developed by ASHRAE 2001. The weather files provided in .epw format, as to be read with the EnergyPlus program, correspond to a typical meteorological year respectively in Turin, Milan and Rome. Turin and Milan have a continental climate, with cold-dry winter and hot-humid

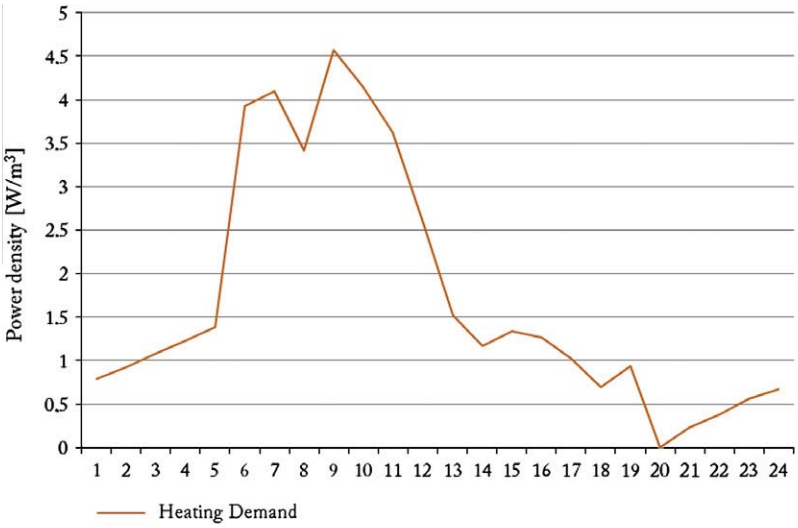

Fig. 5. Daily energy demand in winter-final use, Type A1, Milan.

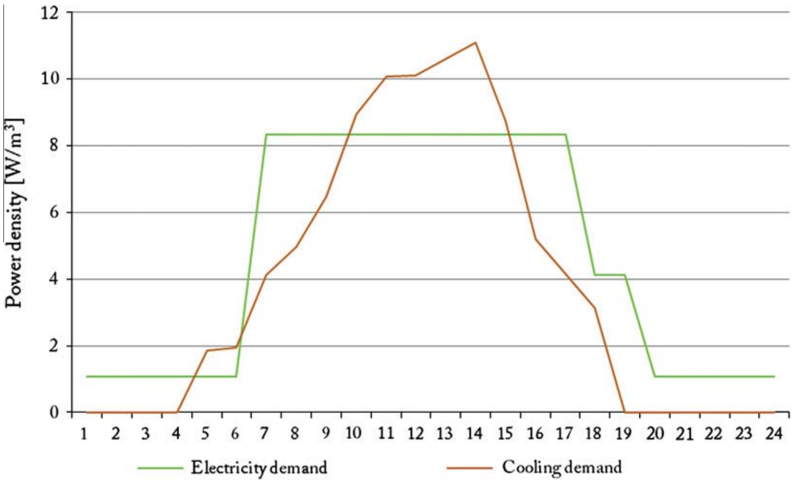

Fig. 6. Daily energy demand in summer-final use, Model A1, Milan.

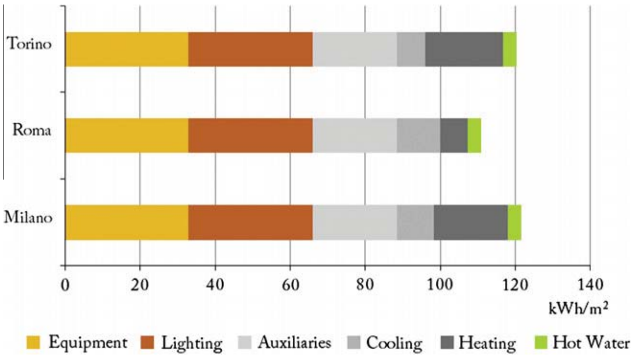

Fig. 7. Annual energy consumption, final use – Type A.

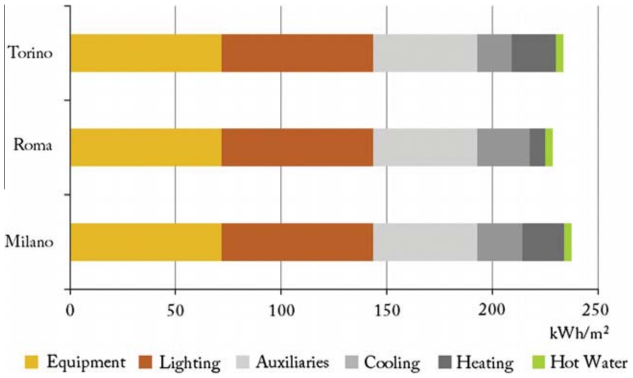

Fig. 8. Annual primary energy – Type A.

summer, while Rome has a Mediterranean climate, with milder winter and hot-dry summer.

The RBs models for Turin and Milan have identical characteristics both for the building envelope and geometry, whereas in the models for Rome some alterations concerning the envelope components were applied. All RBs were modeled into 5 conditioned thermal zones per storey (15 thermal zones in total): one core zone for distributive elements and services areas and 4 perimetric office areas that correspond to the North, South, West and East zones of the building. Furthermore, as mentioned previously, in the models for Central Italy (Rome), the area of opening elements was increased, in particular the area of a single window was increased from 3.1 to 3.5 m^2. The thermal proprieties of the envelope components were also modified as climatic zone D, in compliance with Italian Standard regulation, has different values for the thermal trasmittance (U value).

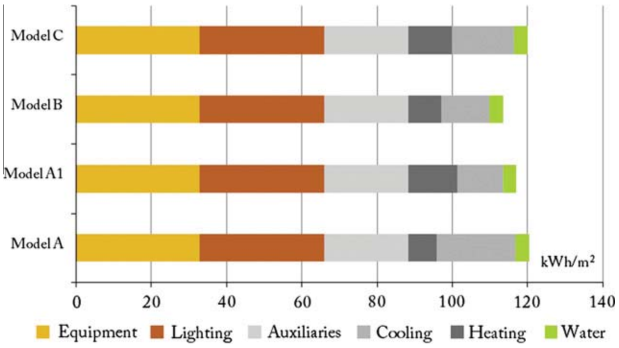

Fig. 10. Annual energy demand-final use, Milan.

In conclusion as all the four RBs models were simulated for three climatic zones, 12 models were defined (Fig. 4).

4.2. Results

Annual, monthly and daily simulations were performed for all models in order to compare the results between the two different locations and all four RBs. Moreover all simulation made possible to establish a benchmark energy consumption for a typical office building in Northern and Central territory in Italy. In particular the daily simulations regarded a typical winter design day in January and a typical summer design day in July and enabled to draw a daily curve of energy consumption for each model as pictured in Figs. 5 and 6. The methodology used for the representation compares results in a simple and comprehensive way. Figs. 7 and 8 refer to RB Type A and compare over the 3 locations respectively the final use energy demand and the primary energy demand. Milan and Turin are located in the same climate zone (Italian zone E) with a higher value of Degree Day (DD) and colder winter, compared to Rome (Italian zone D), characterized by a warmer climate. In Milan the energy demand reaches thus the highest values due to the high energy demand for heating and cooling, whereas Rome has the highest cooling demand due to the warm climate.

Fig. 9 draws the monthly energy demand over the whole year, disaggregated into heating, cooling and electricity in Rome. Heating and cooling are seasonal whereas electricity has constant value during the whole year, with light differences due to the different month length. Especially in August the electricity energy demand is lower because of summer holidays.

Afterwards in Fig. 10 the energy consumption of different models in the same location is emphasized: the maximum value of energy demand belongs to the Type A, the RB for existing buildings, as its construction elements do not respect the current standard

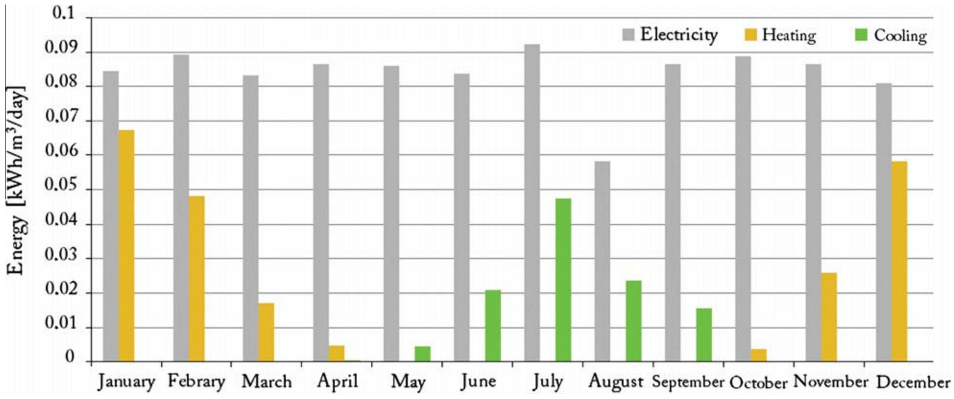

Fig. 9. Monthly energy consumption-final use – Type A, Rome.

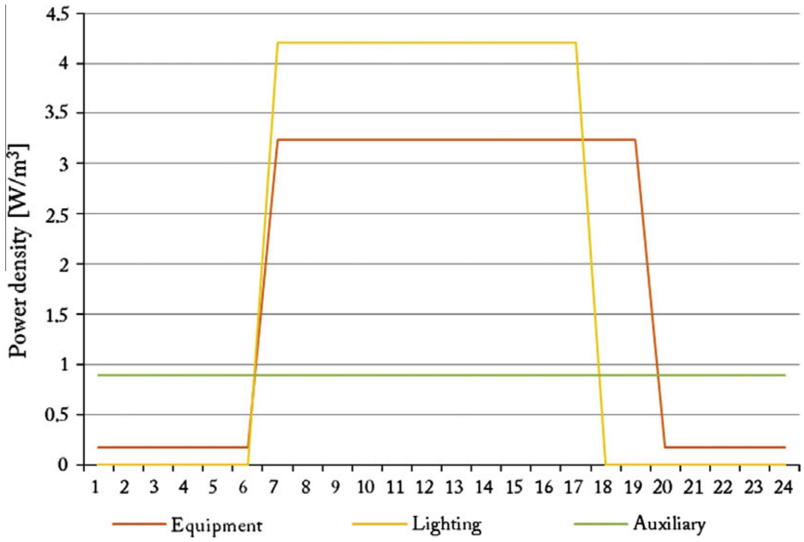

Fig. 11. Daily electricity demand-final use.

limit in thermal insulation. Between the other buildings, Type B has a better energy performance due to its ventilated façade whereas Type C, with a transparent façade has a higher energy consumption.

As also explained previously internal gains remain unchanged for all RB models. Standard prescription for lighting and equipment use and in general occupancy level as established by Standards, are constant for all models as the main activity is always the one of an office building. Daily energy consumptions related to internal gains are thus drawn in Fig. 11.

5. Conclusion

This paper builds on the EPBD recast and outlines the requirements of the same Directive concerning the implementation of nZEB. In particular the state of art with attention to the current energy policy within Europe, is described. Subsequently, with a clear reference to the Guidelines and a few European projects (e.g. TABULA, ASIEPI) a methodology to define RBs for cost-optimal calculation is provided. The methodology here recommended, describe what data are required and how to collect and gather them into different categories. Moreover a short review of previous and current studies related to RBs at European and national level is subsequently given. In conclusion with the case study reference models for office building categories are defined. The models created represent a first attempt to draw together a detailed picture of non-residential stock in Italy. The model for existing buildings has a solid foundation of data from statistical analysis, whilst the model for new model can be still be improved through the implementation of more documentation and references.

Cost-optimal analysis together with the definition of RBs represent a compulsory step to be taken to respect the EPBD requirements for the conversion towards nZEB by 2020 in Europe. Further developments from all MSs are thus expected to come with regard to the methodology used and the final product, the RBs that will be provided.

References

[1] EPBD recast. Directive 2010/31/EU of the European parliament and of council of 19 May 2010 on the energy performance of buildings (recast). official journal of the European union; 2010.

[2] Guidelines accompanying on supplementing directive 2010/31/EC of the European parliament and of the council on the EPBD (recast) by establishing a comparative methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements.

[3] Loga T, Diefenbach N, editors. Use of building typologies for energy performance assessment of national building stocks. Existent experiences in European countries and common approach. First TABULA synthesis report. Darmstadt; Institut Wohnen und Umwel; 2010. ISBN: 978-3-941140-14-1. <www.building-typology.eu>.

[4] Spiekman M, editor. Comparison of energy performance requirements levels: possibilities and impossibilities. Summary report. Report of ASIEPI; March 31, 2010. <http://www.asiepi.eu>.

[5] Tommerup H, Svendsen S. Energy savings in danish residential building stock. Energy Build 2006;38(6):618–26.

[6] Gaglia AG, Balaras CA, Mirasgedis S, Georgopoulou E, Sarafidis Y, Lalas DP. Empirical assessment of the hellenic non-residential building stock. Energy consumption, emissions and potential energy savings. Energy Convers Manage 2007;48(4):1160–75.

[7] Desideri U, Leonardi D, Arcioni L, Sdringola P. European project Educa-RUE: an example of energy efficiency paths in educational buildings. Appl Energy 2012:3–5. http://dx.doi.org/10.1016/j.apenergy.2012.02.00 [ISSN 0306-2619].

[8] Olofsson Thomas, Mahlia TMI. Modeling and simulation of the energy use in an occupied residential building in cold climate. Appl Energy 2012;91(1):432–8.

[9] Attia S, Evrard A, Gratia E. Development of benchmark models for the Egyptian residential buildings sector. Appl Energy 2012;94(6):270–84.

[10] Wan KSY, Yik FWH. Building design and energy end-use characteristics of high-rise residential buildings in Hong Kong. Appl Energy 2004;78(1):19–36.

[11] Hernandez P, Burke K, Lewis JO. Development of energy performance benchmarks and building energy ratings for non-domestic buildings: an example for Irish primary schools. Energy Build 2008;40(3):249–54.

[12] Gustavsson L, Joelsson A. Life cycle primary energy analysis of residential building. Energy Build 2010;42(2):210–20.

[13] Verbeeck G, Hens H. Life cycle inventory of buildings: a calculation method. Energy Build 2010;45(4):1037–41.

[14] CEN [European Committee for Standardization]. Energy performance of buildings – Economic evaluation procedure for energy systems in buildings. Standard EN 15459:2007, Brussels: CEN; 2007.

[15] Becchio C, Guglielmino D, Fabrizio E, Filippi M. Whole cost analysis of building envelope technologies according to the European Standard EN 15459. In: Proc of climamed '11 VI congreso mediterraneo de climatizacion, ATECYR, Madrid; 2–3 June 2011. pp. 291–306. [ISBN 978-84-95010-41-4].

[16] Jurnitski J. How to calculate cost optimal nZEB energy performance? REHVA Eur HVAC J 2011;48(5):36–41.

[17] Draft Working Document on supplementing Directive 2010/31/EC of the European Parliament and of the Council on the EPBD (recast) by establishing a comparative methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements.

[18] Atanasiu B, Boermans T, Hermelink A, Schimschar S, Grözinger J, Offermann M, et al. Principles for nearly zero energy buildings. Paving the way for effective implementation of policy requirements. Brussels: Building Perfomance Institute Europe (BPIE); 2011 [ISBN: 9789491143021].

[19] Economidou M, Atanasiu B, Despret C, Economidou M, Maio J, Nolte I, Rapf O, et al. Europe's building under the microscope. A country by country review of

the energy perfomance of buildings. Brussels: Building Perfomance Institute Europe (BPIE); 2011 [ISBN: 9789491143014].

[20] Deru M, Griffith B, Torcellini P. DOE commercial building benchmark models. In: Proceedings, ACEEE summer study on energy efficiency in buildings, Pacific Grove, CA. Golden, CO: Pacific Northwest National Laboratory; August, 2008.

[21] Ballarini I, Corgnati SP, Corrado V, Talà N. Building typology brochure – Italy [Fascicolo sulla tipologia edilizia italiana]. Italian TABULA, report; october 2011. <www.building-typology.eu>.

[22] ECBS. Stock aggregation, in "Annex 31-Energy related environmental impact of buildings", IEA-ECBCS (International Energy Agency-Energy Conservation in Buildgins and Community Systems); 2004.

[23] Deru M, Field K, Studer D, Benne K, Griffith B, Torcellini P, et al. Department of energy commercial reference building models of the national building stock. Technical, report NREL/TP-5500-46861; 2011.

[24] Spiekman M, Westerlaken N. Reference buildings for EP calculation studies. Report of ASIEPI WP2; 2009. <www.asiepi.eu>.

[25] Kurnitski J, Saari A, Kalamees T, Vuolle M, Niemela J, Tark T. Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation. Energy Build 2011;43(11):3279–88.

[26] Citterio M. Analisi statistica sul parco edilizio non residenziale e sviluppo di modelli di calcolo semplificati [Statistical analysis on the non residential building stock and development of simplified calculation tools] report RSE/2009/161, ENEA, Cresme Ricerche Spa e Ministero dello Sviluppo Economico; 2009 [in Italian].

[27] Dolmans D. Change is going to come. A new mandate: nearly zero energy buildings. Eur HVAC Rehva J 2011;48(6):34–7.

[28] BPIE [Building Perfomance Institute Europe]. Cost optimality. Discussing methodology and challenges within the recast energy perfomance of buildings directive. Report; 2010.

[29] Fabrizio E, Guglielmino D, Monetti V. Italian benchmark building models: the office building. In: Soebarto V, Bennetts H, Bannister P, Thomas PC, Leach D, editors. Driving better design through simulation, IBPSA Australia & AIRAH, Melbourne; 2011. p. 1981–88. [ISBN 978-0-646-56510-1].

[30] Decreto Legislativo n. 311 del 29 Dicembre 2006, Disposizioni correttive ed integrative al decreto legislativo 19 agosto 2005, n. 192, recante attuazione della direttiva 2002/91/CE, relativa al rendimento energetico nell'edilizia.

[31] Decreto del presidente della repubblica 2 aprile 2009, n. 59, Regolamento di attuazione dell'articolo 4, comma 1, lettere a) e b), del decreto legislativo 19 agosto 2005, n. 192, concernente attuazione della direttiva 2002/91/CE sul rendimento energetico in edilizia.

[32] UNI, Impianti aeraulici a fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura, Norma UNI 10339; 1995.

[33] CEN [European Committee for Standardization]. Energy performance of buildings. Impact of building automation, controls and building management.Standard EN 15232:2007, Brussels: CEN; 2007.

Paper II

C. Becchio, E. Fabrizio, V. Monetti, M. Filippi, *Cost optimal levels of energy requirements for nearly-ZEB: application to an Italian reference building for existing offices*, CLIMA 2013 11th REHVA World Congress “Energy efficient, smart and healthy buildings”, Prague, 16-19 June 2013 (ISBN 978-80-260-4001-9).

Cost optimal levels of energy requirements for nearly-ZEB: application to an Italian reference building for existing offices

Cristina Becchio[#1], Enrico Fabrizio[*2], Valentina Monetti[#3], Marco Filippi[#4]

[#] *Dipartimento Energia (DENERG), Politecnico di Torino*
Corso Duca degli Abruzzi 24, 10124, Torino, Italia
[1]cristina.becchio@polito.it
[3]valentina.monetti@polito.it
[4]marco.filippi@polito.it
[*] *DISAFA, Università degli Studi di Torino*
Via Leonardo da Vinci 44, 10095 Grugliasco (TO), Italia
[2]enrico.fabrizio@unito.it

Abstract

The recast of the Directive on the Energy Performance of Buildings has set out that Member States must ensure that minimum energy performance requirements are set with a view to achieve cost optimal levels for buildings, building units and buildings elements. A cost optimal level is defined as the energy performance level which leads to the lowest cost during the estimated economic lifecycle. It must be calculated in accordance with a comparative methodology framework that is based on the global cost method. This one considers, for each energy efficiency measure, the initial investment, the sum of the annual costs for every year (including energy costs) and the final value, all with reference to the starting year of the calculation period.

In this study, the global cost method is applied to a reference building for existing offices customized to the Italian context to assess the cost optimal levels. In detail, different packages of energy efficiency measures, which consist in the implementation of envelope thermal insulation and the improvement of systems efficiency, were considered. Moreover, the utilization of renewable energy sources was taken into account with the installation of PV system on the building roof. Then, the energy consumptions of the reference building and the impact of the improvement measures were assessed. Finally, the costs of the different packages were estimated, according to the European Standard EN 15459:2007, in order to establish which of them has the lowest global cost and, consequently, represents the cost optimal level.

Keywords – cost optimal analysis; cost optimal levels; retrofit measures; minimum energy performance; dynamic simulation

1. Introduction

It is widely recognized that the building sector is one of the key consumer of energy. Buildings account for 40% of the total energy consumption in the European Union [1]. The sector is expanding and this trend raises some environmental issues such as the exhaustion of energy resources, global warming, the depletion of the ozone layer and climatic changes. In order to reduce the growing energy expenditure, the European Directive imposes the adoption of measures to improve the energy efficiency in buildings. The recast of the Directive on the Energy Performance of Buildings (EPBD recast) defines all new buildings will be nearly zero-energy buildings by the end of 2020. However, the transformation of the EU's building stock will not be completed until well after 2020 and the 20 % target can only constitute an intermediate step. Indeed, the recent Commission roadmap for moving towards a competitive, low-carbon economy showed that greenhouse gas emissions in the building sector could be reduced by around 80 – 90 % by 2050. If the building sector is to deliver this important contribution by the middle of this century, defining minimum energy performance requirements for new and existing buildings represent a key element in European building codes.

Consequently, EPBD recast [2] has set out that Member States (MSs) ensure that minimum energy performance requirements are set with a view to achieve cost optimal levels for buildings, building units and buildings elements. A cost optimal level is defined as the energy performance level which leads to the lowest cost during the estimated economic lifecycle. It must be calculated in accordance with a comparative methodology framework that is based on the global cost method. The methodology is addressed to national authorities and the cost optimal level is not calculated for each case, but for developing generally applicable regulations at national level. To apply this methodology MSs are expected to define a series of Reference Buildings (RBs) as baseline and representative models of the national building stock. In the Guidelines of the EPBD recast [3] it is clearly stated that the establishment of RBs is the first step of the calculation procedure. In fact, the developed RBs can be exploited as a basis for analysing national building stock and the potential potential impacts of energy efficiency measures in order to select effective strategies for upgrading existing buildings [4]. Additionally, MSs must define energy efficiency measures (EEMs) to be applied to RBs; EEM can be a single measure or constitute a package of measures. Finally, once estimated the RBs energy consumptions and the impact of the different EEMs, the costs of the different packages are estimated in order to establish which of them has the lowest global cost and, consequently, represents the cost optimal level. The global cost method considers, for each EEM, the initial investment, the sum of the annual costs for every year (including energy costs) and the final value, all with reference to the starting year of the calculation period. A measure or package of measures is cost-effective when the cost of implementation is lower than the value of the benefits that result, taken over the expected life of the measure. The cost-optimal result represents that retrofit action or combination of actions that minimized the global cost. From the variety of specific results for the assessed packages, a cost curve can be derived. The lowest part of the curve represents the economic optimum for a combination of packages.

2. Scope of the work

In a country like Italy where the building stock consists mainly of existing buildings, the specification of energy performance requirements for existing buildings becomes a key element of national building sector policies. Therefore, in this paper the application of the cost optimal methodology, following the Guidelines of the EPBD recast [3], to a Reference Building for existing offices customized to the Italian context is presented. Specifically, different EEMs involving the improvement of the building envelope thermal performances and the systems efficiency were considered. Moreover, the utilization of renewable energy sources was taken into account with the installation of a PV system on the building roof. Then, the energy consumptions of the Reference Building and the impact of the improvement measures were assessed with a dynamic simulation software tool. Finally, the costs of the different packages were estimated, according to the European Standard EN 15459:2007 [5], in order to establish which of them has the lowest global cost and, consequently, represents the cost optimal level.

Among the various studies that are being developed at each national level on this topic, this work is characterized by the use of dynamic simulation in order to accurately estimate the energy demand for heating, cooling, electric lighting, electricity from renewable sources, and especially the trade-off between heating energy and cooling energy, that is particularly important in an office building. Given the use of dynamic simulation and the inherent calculation times, a study based on a limited amount of technically feasible packages of energy efficiency measures, rather than a parametric study, was conducted.

3. The Reference Building

The main purpose of a Reference Building is to represent the typical and average building stock in a certain MS, since it is impossible to calculate the cost optimal situation for every individual building [6]. Hence, it must be chosen to reflect as accurately as possible the present national building stock so that the methodology can deliver representative calculation results.

The case study hereby analyzed is a theoretical Reference Building (for the significance of a theoretical RB see [6]) that is a fictional building composed of disaggregated statistical data related to the main building features gathered together to create a typical Italian office building. It is the results of a national survey [7] carried out by ENEA (Italian National Agency for New Technologies Energy and Sustainable Economic

Expansion) and finalized to a quantitative and qualitative analysis of the Italian office building stock. The RB is representative of office buildings located in the North of Italy and built since 1970 until today.

The RB is a five-storey 2760 m^2 office building with an unconditioned basement and it is located in Turin. It is characterized by a total net conditioned area of 2300 m^2. The gross area of a typical floor is equal to 480 m^2, while its gross height is equal to 3.5 m.

The building has a rectangular plan (16 m x 30 m), with an interior layout characterized by cellular offices on the perimeter areas and a central core for the services areas. It is oriented N-S on its cross-section. It has an aspect ratio of 0.33 m^{-1}, it is thus a quite compact building. The ratio of the transparent area to the opaque envelope is 38%.

It consists of a reinforced concrete structure, brick walls with insulation, plane insulated roof and double glazing windows with aluminum frame with thermal break and with internal blinds.

The primary system is constituted by a condensing boiler and a chiller with cooling tower; the terminals of heating and cooling system are four-pipe fan coil units.

4. Energy Efficiency Measures

In accordance with the EPBD Guidelines [3], Member States must define energy efficiency measures to be applied to the established RBs. The EEMs can regard the building envelope, passive techniques, building systems as well as the use of renewable energy sources. It is therefore recommended that measures be combined in packages of measures and/or variants, since meaningful combinations of measures can create synergy effects that lead to better results (regarding costs and energy performance) than single measures.

The definition of the EEMs, that are all technically feasible, was carried out on two stages. The EEMs were aimed first to the improvement of the building envelope performances and then to the improvement of systems efficiency and to the exploitation of renewable energy sources. The latter measures were applied to some of the previous models, and in particular, to the RB, which is the solution with the lowest global cost, and to the model which reported the lowest primary energy consumption.

The first set of 12 EEMs consists in an improvement of the thermal insulation of the building envelope. Since the RB is assumed to be located in Turin (climate zone E), the considered U-values correspond to the requirements established by the new regulations on energy performance of buildings in Piedmont Region [8]. Furthermore the EEMs concerning the retrofitting of the building envelope were also distinguished into “homogenous measures” that regarded all the building envelope or “not homogeneous measures” that concerned just selected building components. Three homogenous EEMs were defined. The U-values applied for the EEM1 are the U-value limits set by the Piedmont Region regulation [8]; the U-values applied for the EEM2 are the optional U-value targets set by the Piedmont Regional regulation [8]; the U-values applied for the EEM3 are the optional U-value targets set by the Turin city regulation [9].

Table 1. Thermal features of the Reference Building and of the homogenous Energy Efficiency Measures involving the improvement of the building envelope thermal insulation

EEM		U-value [W/m^{2}K]	EEM		U-value [W/m^{2}K]
RB	Walls	0.75	EEM2	Walls	0.24
	Windows	3.19		Windows	1.5
	Roof	0.81		Roof	0.22
	Ground slab	1.45		Ground slab	0.26
EEM1	Walls	0.33	EEM3	Walls	0.14
	Windows	2		Windows	1.2
	Roof	0.29		Roof	0.15
	Ground slab	0.30		Ground slab	0.16

Table 2. Thermal features of the not homogenous Energy Efficiency Measures involving the improvement of the building envelope thermal insulation

EEM		U-value [W/m^{2}K]	EEM		U-value [W/m^{2}K]
EEM4	Walls	0.75	EEM9	Walls	0.24
	Windows	2		Windows	1.5
	Roof	0.81		Roof	0.81
	Ground slab	1.45		Ground slab	1.45
EEM5	Walls	0.75	EEM10	Walls	0.75
	Windows	3.19		Windows	1.2
	Roof	0.29		Roof	0.81
	Ground slab	0.30		Ground slab	1.45
EEM6	Walls	0.33	EEM11	Walls	0.75
	Windows	2		Windows	3.19
	Roof	0.81		Roof	0.15
	Ground slab	1.45		Ground slab	0.16
EEM7	Walls	0.75	EEM12	Walls	0.14
	Windows	1.5		Windows	1.2
	Roof	0.81		Roof	0.81
	Ground slab	1.45		Ground slab	1.45
EEM8	Walls	0.75			
	Windows	3.19			
	Roof	0.22			
	Ground slab	0.26			

Measures from EEM4 to EEM12 are indeed not homogeneous. Tables 1 and 2 list the U-values achieved with each EEM.

The EEMs considered within the second stage consisted in the introduction of an artificial lighting control (alc) and in the installation of PV panels on the plane roof. In this case, three different configurations were studied:

- covering of the entire roof with PV panels (power: 38 kW_p);
- covering of one half of the roof with PV panels (power: 21 kW_p);
- covering of one fourth of the roof with PV panels (power: 11 kW_p).

In table 3 the packages from EEM13 to EEM24 are summarized.

Table 3. Description of Energy Efficiency Measures affecting the lighting system efficiency and the exploitation of renewable energy sources

EEMs Description		1st stage EEM considered	ID
Package 1	alc	RB	EEM13
		EEM3	EEM14
		EEM8	EEM15
Package 2	PV: 100% roof	RB	EEM16
Package 3	PV: 50% roof	RB	EEM17
Package 4	PV: 25% roof	RB	EEM18
Package 5	alc PV: 100% roof	RB	EEM19
		EEM3	EEM20
Package 6	alc PV: 50% roof	RB	EEM21
		EEM3	EEM22
Package 7	alc PV: 25% roof	RB	EEM23
		EEM3	EEM24

5. Energy evaluation

The objective of the energy evaluation was to determine the annual overall energy use in term of delivered energy (divided by sources) and primary energy, which includes energy use for heating, cooling, lighting and equipment. In this study, the annual primary energy consumption for hot water (that is equal to 4.4 kWh/m^2) was neglected.

The Reference Building was modeled and simulated by the energy simulation software EnergyPlus (version 6.0).

The typical weather conditions of the Turin location refers to the IGDG Weather for Energy Calculation database of climatic data.

Each floor of the building office was divided into 5 thermal zones, one large core and four perimeter zones (Fig. 1). In total the model is composed of 25 thermal zones plus the unconditioned basement. The interior partitions of the cellular offices were defined as internal mass.

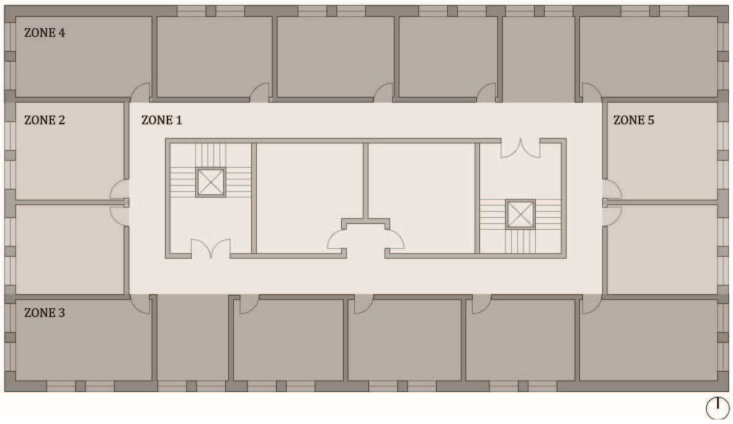

Fig. 1. Reference Building plan with the subdivision in thermal zones

The operational parameters were set to be consistent with the building typology. For the office areas, people per zone floor area were fixed to 0.06 pers/m^2[10]. Lighting and appliances power densities were respectively defined to 13 W/m^2 and 10 W/m^2 for the office areas and 7 W/m^2 and 2.9 W/m^2 for the central core [11]. These densities were linked to the activities schedules carried out in the building during the weekdays and the weekends. A specific occupancy schedule [11] and a schedule related to the use of the lighting system [12] and of the appliances have been defined.

The control of the solar shading is done on the basis of the total solar radiation incident on each window (above 300 W/m^2 internal blinds are shut). The control of the artificial lighting is done on the basis of the daylighting illuminance levels in each zone with a continuous/off regulation type.

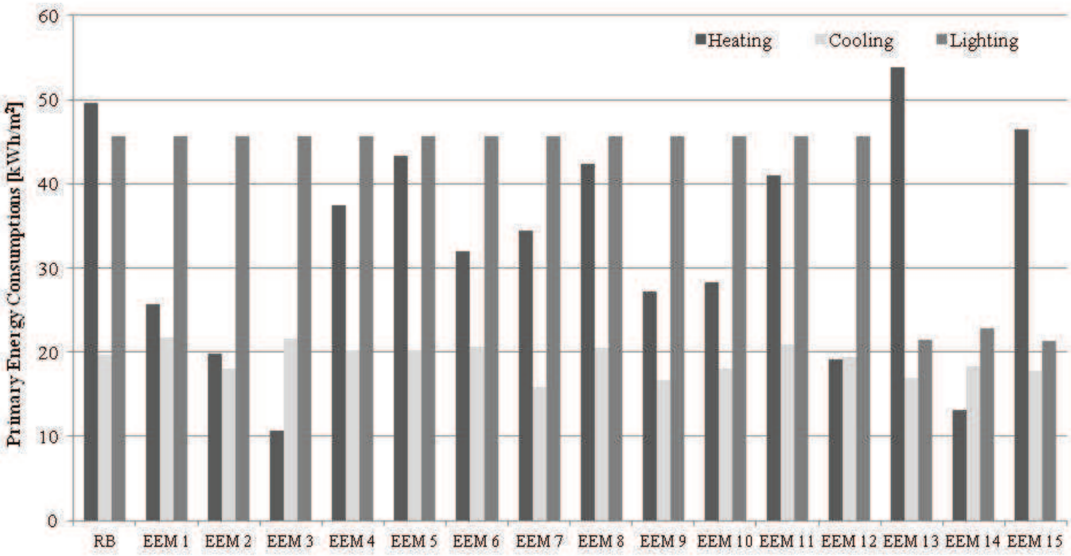

Fig. 2. Annual primary energy consuptions for space heating, cooling and lighting

The heating system has been assumed to be active from the 15th of October to the 15th of April in compliance to the Italian regulations for the climatic zone E. The cooling system has been set to operate during the remaining period due to the high presence of internal gains. During weekdays, the heating and cooling setpoints were set respectively to 21,5 °C and 26 °C from 5 a.m. to 7 p.m.

During weekdays, the outdoor air flow rate is set at 11 l/s per person operating from 5 a.m. to 7 p.m.

In Figure 2 primary energy consumption of RB and EEMs are reported.

6. Economic evaluation

In accordance with the EPBD, global cost calculations result in a net present value of costs incurred during a defined calculation period, taking into account the residual values of components with longer lifetimes. Following the procedure described in the European Standard EN 15459, global cost is directly linked to the duration of the calculation period τ and it can be written as:

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

where C_G (τ) 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). The discount rate R_d is used to refer the costs to the starting year; it is expressed in real terms, hence excluding inflation, and it depends from the real interest rate.

In this research, the calculation period was set as equal to 30 years. According to the Guidelines [3] the real interest rate was fixed equal to 4%. The investment costs of EEMs were evaluated by referring to the price list of the Piedmont Region of 2012 [13].

With regard to periodic cost of replacement of building envelope components, it was assumed to replace only the windows, for which it has been considered an average lifespan of 25 years. In the case of the Reference Building, however, since it is an existing building, it was assumed to replace them after 13 years. With regard to the data on the duration of the system components reference was made to Appendix A of EN 15459:2007. This Appendix reports also the annual maintenance costs of systems components (expressed as a percentage of the cost of the component) that were used in this analysis.

For RB and for each EEM the costs related to energy consumption for space heating (natural gas), for space cooling, for the auxiliary of heating and cooling system, for lighting and for appliances (electricity) were considered. In detail:

- natural gas cost: 0.083 €/ kWh;
- electricity cost: 0.16 €/ kWh;
- electricity tax: 100 €/kW.

About the PV system, the following assumptions were made:

- feed-in tariff: 0.171 €/kWh (11 kW_p) or 0.157 €/kWh (21 and 38 kW_p) taken for 20 years [14];
- incentive for the electricity consumed on site: 0.089 €/kWh (11 kW_p) or 0.075 €/kWh (21 and 38 kW_p) taken for 20 years [14];
- feed-in tariff from the 21st to the 30th year: 0.03 €/kWh.

7. Cost optimal levels of energy consumptions

The primary energy use versus the global cost is reported in Figure 3 for the various EEMs. It should be noted that the primary energy consumption includes also the energy for lighting and equipment.

In the graph, in correspondence to the RB a vertical line that represents the maximum primary energy consumption was drawn.

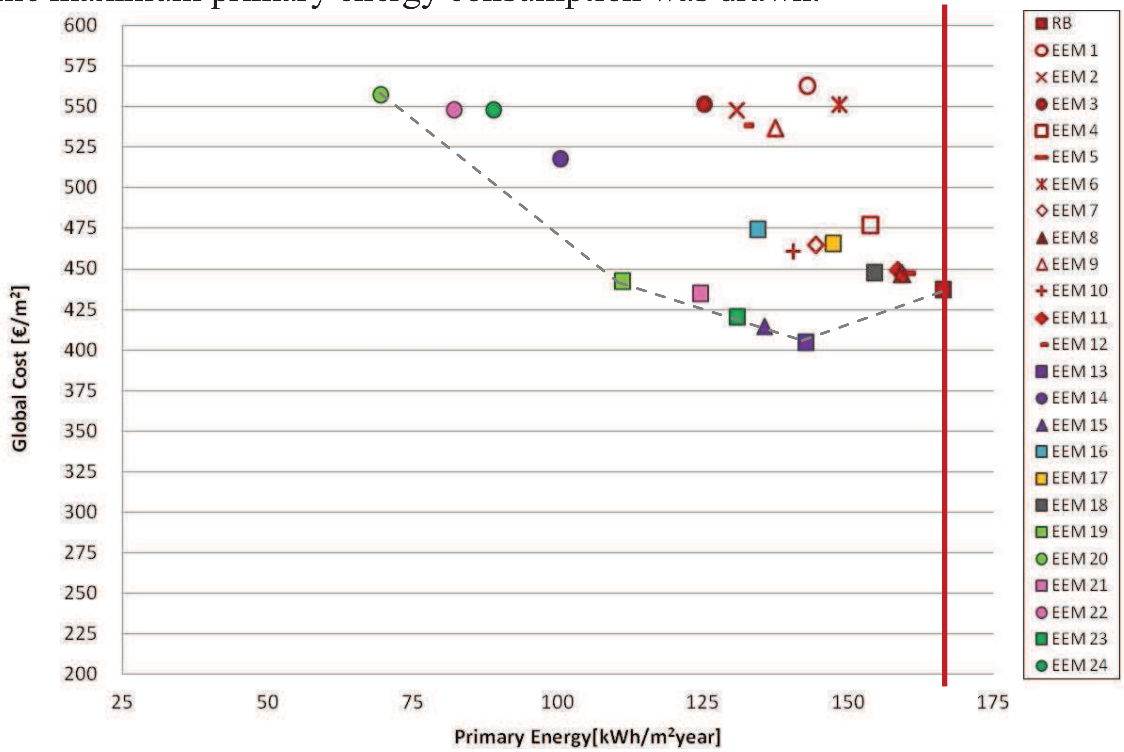

Fig. 4. Global costs of the Reference Building and of the different Energy Efficiency Measures

The energy efficiency measures allow savings from 6 to 97 kWh/m^2y (primary energy) in absolute terms; in percentage terms, the savings are between 4 and 58%. The minimum value of consumption is achieved with the EEM20, which combines all the measures and has the maximum levels of thermal insulation and PV.

The graph underlines that EEMs have both lower and higher global cost values compared to the RB. Global cost values higher than RB tend to be the ones of the envelope EEMs, because the investment costs for the different efficiency measures cannot be repaid by the economic savings associated with energy savings obtained.

Global costs lower than the cost of the RB tend to be associated with systems EEMs.

The EEM with the lowest global costs is EEM 13 and has a primary energy indicator of 143 kWh/m^{2}y. It does not improve the thermal insulation of the building envelope but considers only the introduction of lighting controls.

Further studies are needed to simulate different EEMs which combine various levels of thermal insulation for the envelope components (windows, walls, roof, slab).

References

[1] BPIE (Buildings Performance Institute Europe). *Cost Optimality. Discussing methodology and challenges within the recast Energy Performance of Buildings Directive.* 2010. BPIE.

[2] EPBD recast (2010). Directive 2010/31/EU of the European Parliament and of Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union.

[3] Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements.

[4] Becchio C., Corgnati S.P., Ballarini I., Corrado V. *Energy saving potentialities by retrofitting the European residential sector*. In «Rehva Journal», pp. 34-38, December 2012. Rehva.

[5] CEN [European Committee for Standardization]. Energy performance of buildings - Economic evaluation procedure for energy systems in buildings. Standard EN 15459:2007, Brussels, 2007. CEN.

[6] Corgnati S.P., Fabrizio E., Filippi M., Monetti V. *Reference buildings for cost optimal analysis: Method of definition and application.* In «Applied Energy», pp. 983-993, February 2013.

[7] Citterio M. *Analisi statistica sul parco edilizio non residenziale e sviluppo di modelli di calcolo semplificati, Report RSE/2009/161*, Enea, Cresme Ricerche Spa e Ministero dello Sviluppo Economico, Maggio 2009.

[8] Deliberazione della Giunta Regionale 4 agosto 2009, n. 46-11968. Aggiornamento del Piano regionale per il risanamento e la tutela della qualità dell'aria - Stralcio di piano per il riscaldamento ambientale e il condizionamento e disposizioni attuative in materia di rendimento energetico nell'edilizia ai sensi dell'articolo 21, comma 1, lettere a) b) e q) della legge regionale 28 maggio 2007, n. 13 "Disposizioni in materia di rendimento energetico nell'edilizia". Agosto 2009. Regione Piemonte.

[9] Agenzia Energia e Ambiente di Torino. *Allegato energetico – ambientale al regolamento edilizio della città di Torino. Allegato alla deliberazione n. 2010-08963/38.* Agosto 2009. Regione Piemonte.

[10] UNI 10339:1995. Impianti aeraulici a fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura. 1995. UNI.

[11] EN 15232:2012. Energy performance of buildings – Impact of Building Automation, Controls and Building Management.

[12] Reinhart C. F. Lightswitch-2002: a model for manual and automated control of electric lighting and blinds. In «Solar Energy», pp. 15-28, 2004. Elsevier.

[13] Prezzi di riferimento per opere e lavori pubblici nella Regione Piemonte, 2012, Regione Piemonte.

[14] Gestore Servizi Energetici, http://www.gse.it/it.

Paper III

P. Dabbene, C. Becchio, E. Fabrizio, V. Monetti, M. Filippi, *Cost optimality assessment of a single-family house: building and technical systems solutions for the nZEB target*, Energy and Buildings, Volume 90, March 2015, pages 173-187, doi:10.1016/j.enbuild.2014.12.050.

Energy and Buildings 90 (2015) 173–187

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Cost optimality assessment of a single family house: Building and technical systems solutions for the nZEB target

Cristina Becchio[a], Paolo Dabbene[a], Enrico Fabrizio[b], Valentina Monetti[a,*], Marco Filippi[a]

[a] DENERG, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] DISAFA, Università degli Studi di Torino, Largo Paolo Braccini 2, 10095 Grugliasco (TO), Italy

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 5 November 2014
Accepted 29 December 2014
Available online 6 January 2015

Keywords:
EPBD recast
Nearly zero energy buildings (nZEB)
Cost optimal
Dynamic simulation
Energy efficiency measures
Systems
Residential building

ABSTRACT

Europe has set a clear path to guide Member States into the accomplishment of the nearly zero energy buildings (nZEBs) target. To this regard, within EPBD recast directive, a cost optimality procedure has been defined. This study presents different cost optimal solutions of building and technical systems for nZEBs in Italy. In total 40 economically and technically feasible energy efficiency measures for a high performing single family house were analyzed. Special attention was devoted to the study of the building technical systems. Achieving a net zero balance required a high efficient system combined with high insulation and a large PV system, which plays a key role in the nearly and net zero building energy balance. Three net zero energy balance solutions, based on all electric systems, were presented. Net ZEB solutions allowed also the building carbon footprint to be reduced by 40% compared to the reference case study. Without proper financial subsides, net ZEB solutions are still far for being economic feasible, having a global cost 212–313 €/m^2 higher than cost optimal solutions. In conclusion, this paper aims to present guidelines for designing reference building envelope and technical systems solution for residential nZEB.

1. Introduction

1.1. Cost optimality and nZEB studies review

In Europe the building sector is responsible for about 40% of the final energy demand [1] and for about 36% of CO$_2$ gas emissions [2]. European Directive EPBD recast 2010 [1] represents a strong commitment for reducing the energy consumptions and improving the energy efficiency of the building stock. The Directive set minimum requirements of energy performance for buildings and building components and furthermore established clearly nearly zero energy buildings (nZEBs) as political target. Due to criticalities aroused around the cost efficiency of nZEBs, EPBD also attempted to go one strong step further forward 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. Even though nZEB target is technically effective for low rise developments (e.g. many examples of existing nZEBs can be listed), nZEBs reveal to be still not cost efficient yet in terms of cost optimality. Cost optimal levels can be seen as a first step towards the achievement of the nZEB target. They refer to the energy performance in terms of primary energy leading to the minimum life cycle cost.

Before the EBPD cost optimal approach, studies were mostly focused on the energy saving accomplishments, investigating also the assessment of life cost analysis [3,4] or the total net present value in a defined building life cycle [5]; moreover, generally in economic calculation, only the upfront investment cost was considered [6], whilst according to the EPBD Guidelines [7] initial investment cost, running costs, replacement costs and disposal costs must be included over the building lifecycle.

Since the launch of the EPBD recast, several researches focused on the cost optimal approach, together with the study of zero energy solutions for new and existing buildings. Two exemplar reports on the cost optimal methodology by BPIE identified strengths and weakness of the cost optimal approach [8] and provided results from case studies in three different countries (Austria, Germany and Poland) [9]. The first report [8] analyzed the current energy policy and provided guidance and support to the methodology addressing mainly to policy makers. In particular different gaps for each country [9] were investigated in the cost-optimal energy performance levels, due to different national requirements (e.g. prescribed building envelope *U*-values).

Different approaches for the application of the cost optimal methodology were used; from a simulation-based approach to the

---

* Corresponding author. Tel.: +39 011 4341778.
E-mail addresses: valentina.monetti@polito.it, valentina.monetti@hotmail.it (V. Monetti).

http://dx.doi.org/10.1016/j.enbuild.2014.12.050
0378-7788/

use of simplified models. Kurnitski et al. presented a systematic and robust scientific procedure to determine cost optimal and nZEB energy performance levels, by means of building simulation, of an Estonian residential reference building [10] and of an office building [11]. A multi-stage methodology was studied for finding cost optimal and nZEB solutions for a single family house in Finland [12]. Corrado et al. [13] studied a new procedure for the optimization of the cost optimal levels of an Italian residential reference building, based on a sequential search technique that considers a number of discrete options. Ferrara et al. used a simulation-based optimization method to study cost optimal solutions for a real high-performing family house, with a view of achieving nZEB performances [14]. Ganiç et al. [15] implemented the cost optimal methodology in Turkey and investigated the validity of the procedure under national market conditions.

Due to the high pressure generated by energy policies and by the international agreement in climate change, a worldwide interest has recently aroused around nZEBs [16–20], making them a permanent item in the international agenda. The concept of nZEB has in fact been widely studied both in cold [21] and warm climates [22,23]. Furthermore, analysis on the design of nZEBs solutions with a view of cost-optimality in compliance with EPBD requirements has also been published. BPIE [16] has analyzed a single family house and a multi-family building, across three different European climates (Copenhagen, Stuttgart and Madrid), revealing nZEB to be more financially convenient in southern Europe. However in order to achieve the nZEB target, it was observed from literature a common agreement [12–18] about the need of subsidy or incentive schemes for the installation of systems for onsite energy production from renewable sources.

1.2. Aim of the study

This study focused on the definition of cost optimal and nZEB solutions for a new single family house in Italy. The comparative methodology framework of the EBPD Directive was followed and different combinations of Energy Efficiency Measures (EEMs) were defined. In order to provide exemplar cost optimal building systems to be applied to new residential buildings, the study was especially devoted to the investigation of new system configurations in a view of achieving nZEB performances.

Energy assessment was performed by means of the dynamic energy simulation software EnergyPlus. A detail modeling, within the EnergyPlus program, of technical energy systems was carried out. The implementation of systems for the production of energy from renewable sources was crucial and necessary for the study of the whole building system configurations.

In order to identify the measure with the lowest global cost, economic calculations based on the global cost method from EN 15459 [24] were performed. A calculation period of 50 years was selected since the study referred to a new construction. A detailed economic assessment for each EEM was carried out. Cost optimal levels of energy performance for the single family house studied were assessed.

Three system configurations for a single family house, with a net zero energy balance, were proposed. Onsite production of energy from renewable sources revealed to be a key element for achieving nZEB levels. In conclusion this paper aimed to provide some reference optimal solutions, especially for technical systems, for the design of nearly and net zero residential buildings.

2. Methodology

2.1. The reference building

As explained previously, this study aims to supply guidelines for the design of nZEB residential buildings, achieving results that may be generalized across the Italian residential building stock. With this purpose, a real reference building (RB), defined as an existing building with average characteristics based on statistical analysis [25], was selected to be representative of Italian residential dwellings. In particular a detached house was selected as case study and a building energy model was created by the authors. In Italy single family houses represent thus the second most diffuse building typology across the national area, as reported into the national buildings stock census [26] and into related studies [27,28].

The selected RB is a two-storey house with a conditioned net floor area of 174 m^2, a net floor height of 2.7 m and a conditioned net volume of 581 m^3. The aspect ratio is 0.78 m^{-1}, while the window-to-wall ratio is 28%. Technical drawings and an isometric view of the building are provided in Fig. 1.

Since the building is located in Turin (North Italy), the RB *U*-values are set in compliance with the minimum values required by regional regulation [29,30]; this minimum level of thermal insulation is denominated EI0. Table 1 lists the *U*-value [W/m^2 K] of each main building envelope component and the average *U*-value of the whole building.

In order to prevent summer overheating, windows are equipped with horizontal overhangs and interior blinds, respectively, on the South and on the East and West façade; this shading measure is denominated SO0.

RB primary system is denominated Building Technical System 0 (BTS 0). As showed in Fig. 2 and Table 2, space heating is provided by a gas condensing boiler combined with solar collectors (SC). Heating terminals are radiant floors in all areas, except for bathrooms that are equipped with radiators. Space cooling is supplied by a multi-split air conditioner with direct-expansion units. Domestic hot water (DHW) is provided by a solar water heater with auxiliary gas condensing boiler. Three flat plate solar collectors (SC DHW80%) are installed on the roof, for a total area of 5.9 m^2, designed to cover 80% of the DHW net energy need, as presented on the 2nd column of Table 3. Four additional solar collectors (SC heating), with a total area of 9.1 m^2, as listed in Table 3, provide hot water only for space heating. Moreover, in order to comply with national regulations [31] on the minimum total power output for PV systems, based on the building floor area, 9 crystalline silicon panels (11.9 m^2) are installed on the roof, with a total power of 1.6 kW_p (see PV 1.6 in Table 3).

2.2. Energy Efficiency Measures

As in compliance with EPBD Guidelines [7], a set of EEMs were defined and applied to the RB. Several measures were investigated but major efforts were spent to develop different system configurations. Moreover due to the high time required for modeling, simulating and carrying on the economic analysis, not each and every EEM could be assessed, but a set of EEMs was thus selected from a wider group of possible ones. In total the number of EEMS to be investigated was limited to 40.

In order to reduce the building space heating and cooling energy needs, building envelope EEMs could not be excluded from the study and were also investigated. Three different packages of EEMs for improving the building insulation (EI1, EI2 and EI3) and four EEMs for shading (SO1, SO2, SO3 and SO4) were proposed. Higher insulation levels of the envelope components were obtained by increasing the insulation thickness. EI1 and EI2 *U*-values are the optional values set, respectively, by the regional regulation [29] and by the Turin city regulation [30]. *U*-values applied to EI3 are similar to those used in passive houses. Table 1 lists the main *U*-value of the building envelope components for each EEM. Different shading solutions, both between-glass-systems (SO1/2) and both external systems (SO3/4), with blinds or shades, were implemented for reducing cooling loads and energy consumption.

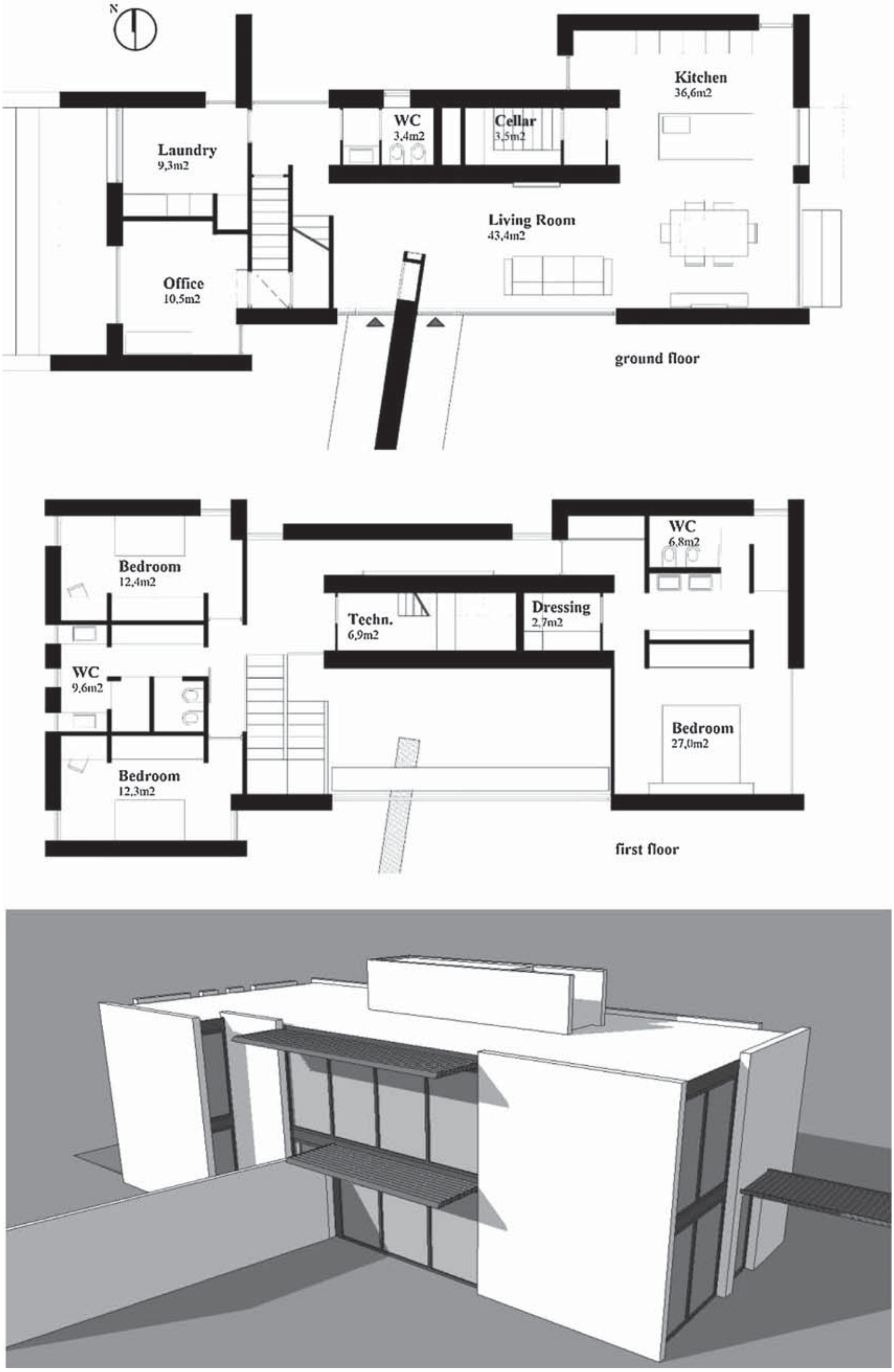

Fig. 1. Technical drawings and isometric view of the case study.

Table 1
Thermal features of the RB and of the building envelope EEM.

Envelope thermal insulation (EI)	Construction layers			
	EI 0	EI 1	EI 2	EI 3
External wall	U 0.33 W/m^2 K	U 0.23 W/m^2 K	U 0.15 W/m^2 K	U 0.11 W/m^2 K
Roof	U 0.28 W/m^2 K	U 0.21 W/m^2 K	U 0.15 W/m^2 K	U 0.11 W/m^2 K
Ground floor	U 0.29 W/m^2 K	U 0.21 W/m^2 K	U 0.15 W/m^2 K	U 0.11 W/m^2 K
Windows	$U_g/U_f/U_w$ 1.76/2.00/1.94 W/m^2 K SHGC 0.57	$U_g/U_f/U_w$ 1.48/1.00/1.49 W/m^2 K SHGC 0.57	$U_g/U_f/U_w$ 1.06/1.00/1.19 W/m^2 K SHGC 0.43	$U_g/U_f/U_w$ 0.83/1.00/0.99 W/m^2 K SHGC 0.43
Envelope medium U-value	U 0.55 W/m^2 K	U 0.41 W/m^2 K	U 0.30 W/m^2 K	U 0.25 W/m^2 K

Table 2
EEMs for building technical systems (BTS).

Denomination	BTS 0	BTS 1	BTS 2	BTS 3
Heating	Gas condensing boiler with solar integration. Terminals: radiant heating floor and water radiators	Gas condensing boiler/air-to-water heat pump. Terminals: radiant heating floor and water radiators	Ground-to-water heat pump. Terminals: radiant heating floor and electric radiators	Air-to-water heat pump. Terminals: mechanical ventilation inlets and electric radiators
Cooling	Multi-split air conditioner	Air-to-water reversible cycle heat pump with radiant cooling floor	Ground- to-water reversible cycle heat pump with radiant cooling floor	Multi-split air conditioner
Domestic hot water (DHW)	Solar water heater with auxiliary gas condensing boiler	Solar water heater with auxiliary gas condensing boiler	Solar water heater with auxiliary electric resistance	Solar water heater with auxiliary electric resistance
Ventilation	–	Mechanical ventilation unit with heat recovery	Mechanical ventilation unit with heat recovery	Mechanical ventilation unit with heat recovery

In a second stage, after reducing space heating and cooling needs by improving the efficiency of the building envelope, three different solutions for the building primary system, together with three options for the solar system, were investigated. Alternative and more efficient system solutions, than the one adopted for the RB (BTS0) were applied as EEMs; BTS1/2/3 are the alternative systems, as showed in Table 2. The most significant measure in terms of impact, within the system solutions, is the mechanical ventilation unit with heat recovery, provided with a rotary heat exchanger with 90% efficiency.

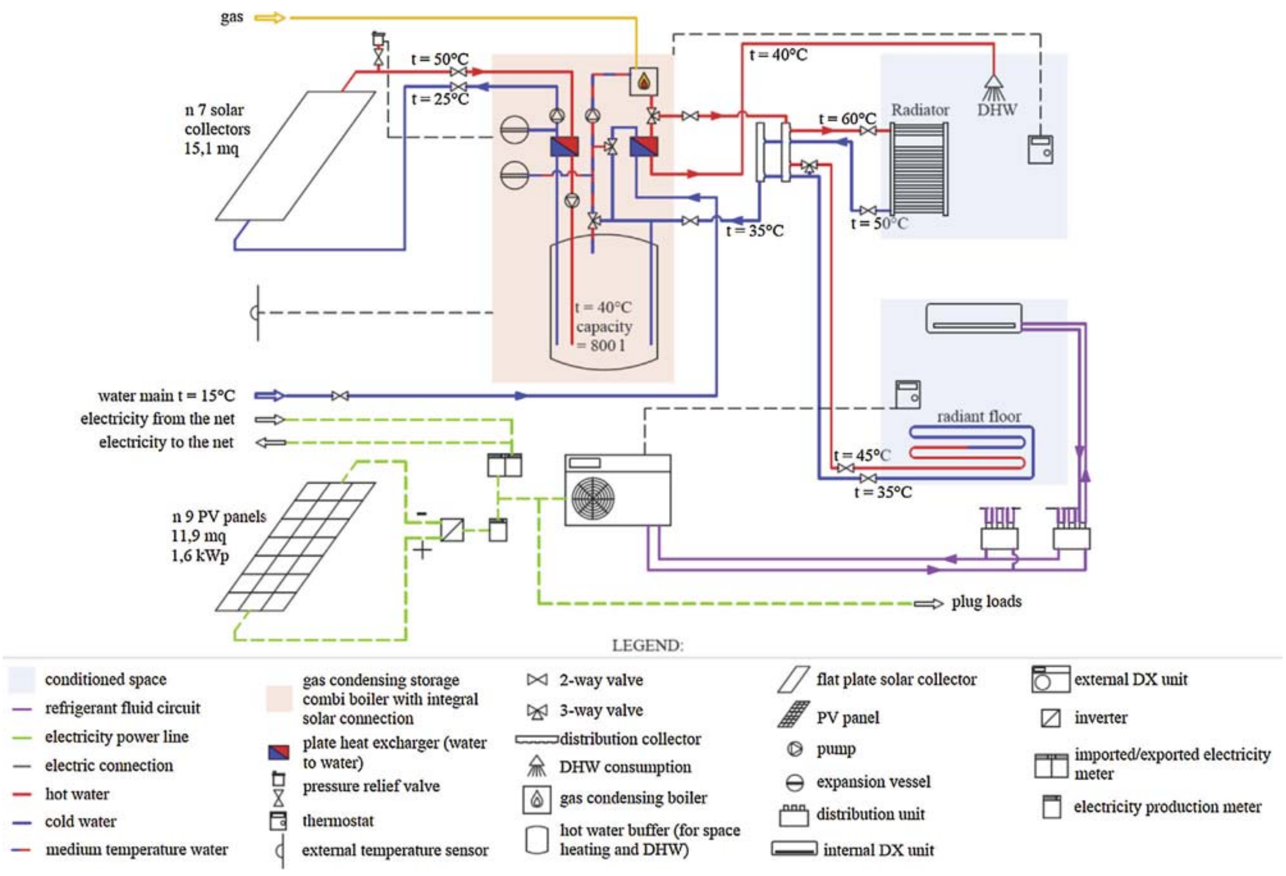

Fig. 2. Layout of the building technical system 0 (BTS0).

Table 3
Solar energy production-based EEMs.

Denomination	SC DHW80%	SC heating	PV1.6	PV3.2	PV6.3
Features	No. 3 flat plate solar collectors (SC) covering 80% of DHW net energy need	No. 4 flat plate solar collectors for space heating	No. 9/18/36 crystalline silicon panels with a 13.3% module efficiency and a total power 1.6/3.2/6.3 kW_p		

No geometric data were defined for the heat exchanger in the EnergyPlus model. Since the case study is a RB, standard and basic operating conditions for defining the heat exchanger performance, as provided within the EnergyPlus software, were set. In particular they were based on the sensible and latent effectiveness at 75% and 100% of the nominal rated supply air flow rate in heating and cooling conditions. In order to control the inlet air temperature, the ventilation unit integrates a heating coil (electric coil for BTS1/2, water coil for BTS3) and a direct-expansion cooling coil. BTS1 system (Fig. 3) uses the same heating terminals as BTS0. It is a hybrid system combining a gas condensing boiler with an air-to-water heat pump, which covers a part of the total heating load. The cooling plant consists of an air-to-water reversible cycle heat pump with radiant cooling floor, while DHW is produced by a condensing gas boiler, as in BTS0. BTS2 and 3 the gas boiler is substituted by a heat pump. BTS2 uses a ground-to-water reversible heat pump for space heating and cooling. The terminals are radiant heating and cooling floors and electric radiators in the bathrooms. DHW is produced by a solar water heater with an auxiliary electric resistance.

BTS3 (Fig. 4), was designed to be used in an highly insulated building (EI2/3) since the entire heating load is covered by the mechanical ventilation unit, which integrates an air-to-water heat pump for space heating. As in BTS2, electric radiators are placed in the bathrooms. The cooling system consists of a multi-split air conditioner with direct-expansion units. The DHW production is accomplished as in BTS2.

EEMs based on the energy production from renewable sources, as described previously in Section 2.1, are listed in Table 3. The number of PV panels on the roof increases from a minimum of 9 panels (PV1.6 and 11.9 m^2) up to 18 (PV3.2 and 23.8 m^2) and 36 (PV6.3 and 47.6 m^2); 36 is the maximum number of PV panels that can actually be placed on the roof.

External shading options, such as SO3/4, were used only with high levels of envelope insulation (EI2/3) because of the higher demand for space cooling energy. Technical systems with gas boilers, such as BTS0/1, were associated only with medium/low levels of thermal insulation EI0/1, while buildings with better insulation (EI2/3) were entirely based on heat pumps systems (BTS2/3).

EEMs from 1 to 29 were selected to assess the influence of insulation, shading options and building systems on the global cost. EEMs from 30 to 40 were defined to evaluate PV systems, combined with different heating and cooling system. EEMs 38–39–40, are equal

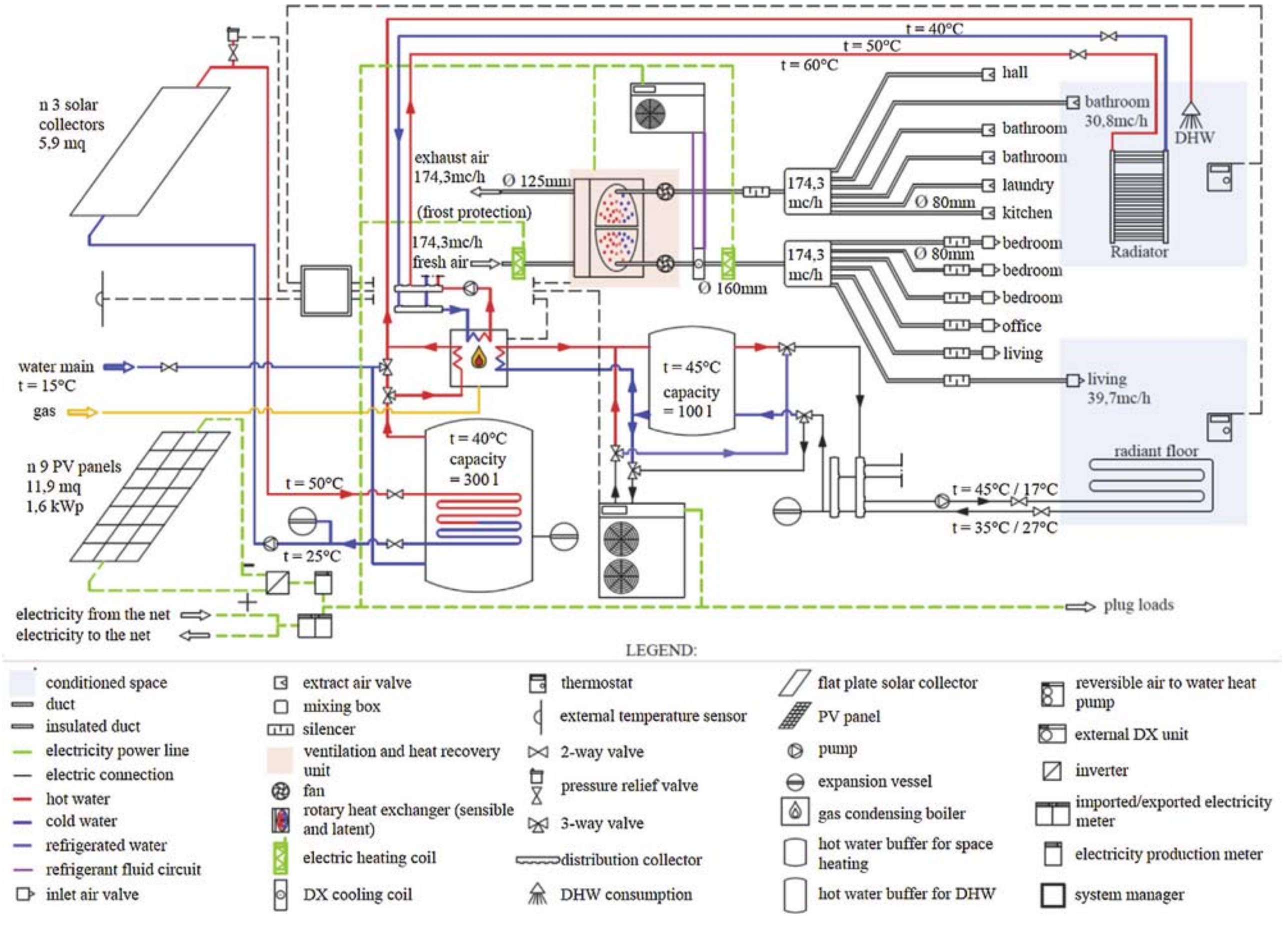

Fig. 3. Layout of the building technical system 1 (BTS1).

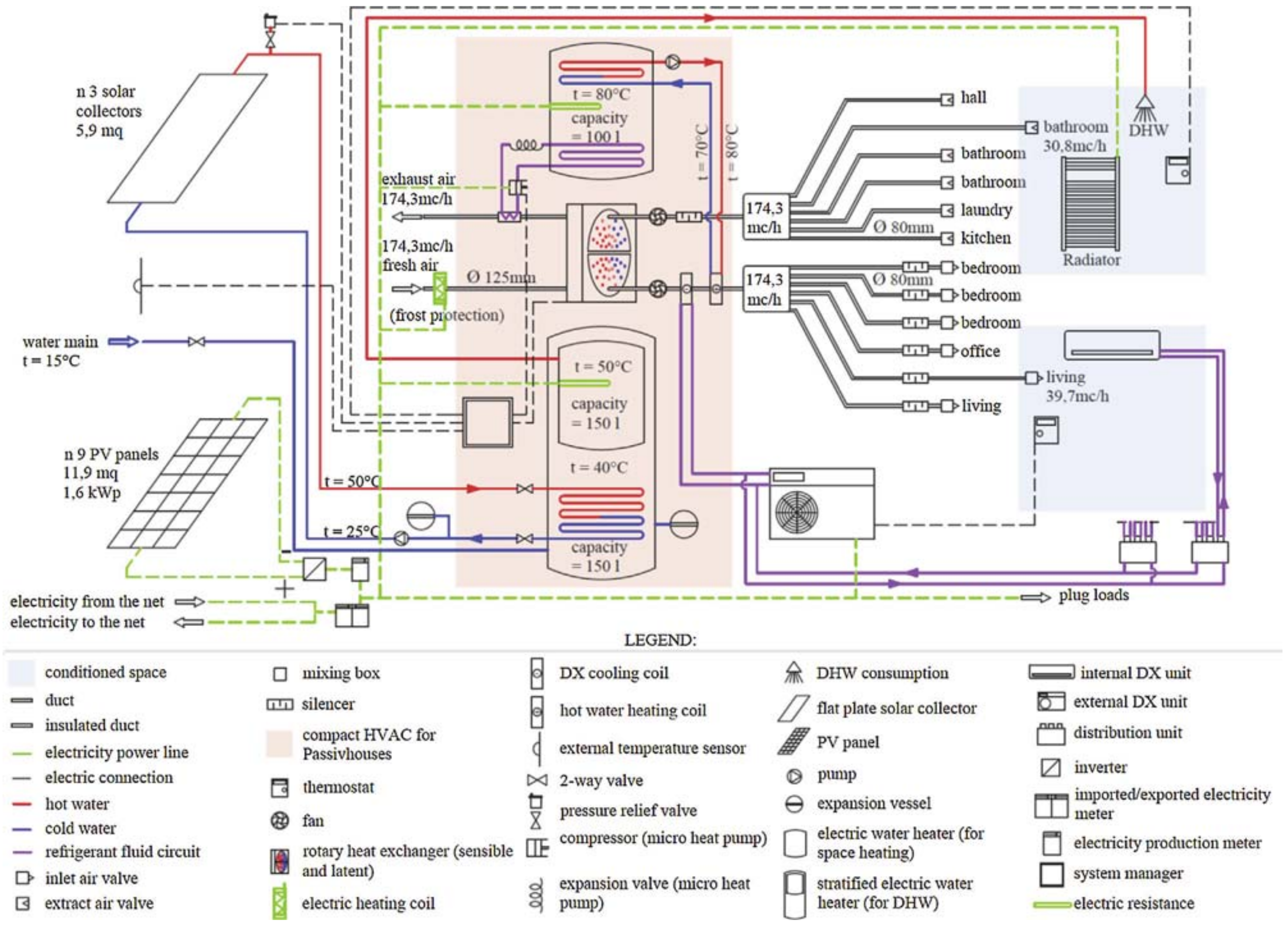

Fig. 4. Layout of the building technical system 3 (BTS3).

to EEMs 19–24–28 (characterized by a low energy demand) but equipped with a total roof PV system (PV6.3) in order to achieve a Net Zero Energy balance.

2.3. Energy model

The energy assessment of the building was conducted by means of dynamic simulation through the EnergyPlus program (version 7.0) [32]. EnergyPlus is a modular building energy analysis and thermal load simulation program, developed by the research laboratories of the U.S. Department of Energy since 2001. It has been chosen for the aim of this study for being an open-source free software, well-known and widely used all over the world, in both academic and commercial contexts, for building and HVAC system design and dynamic simulation. Among all simulation tools, EnergyPlus is not an user-friendly software, but it is so far one of the most used for being one of the most mature ones in terms of capabilities [33]. EnergyPlus application is in fact quite wide and ranges from the study of building envelope façade [34] to the study of ventilation strategies [35] or of specific building systems [36], from the assessment of reference buildings [37] and of test building [38] to the energy assessment of different building types, like agricultural greenhouses [39].

The building thermal zone calculation method of EnergyPlus is an air heat balance solution method, based on the assumptions that, by default, the temperature of the air in the thermal zone and of each surface are uniform, the long and short-wave irradiation is uniform, the surface irradiation is diffusive and the heat conduction through the surface is one-dimensional. The calculation of the air heat balance, neglecting the heat transfer due to infiltration and to inter-zone air mixing, can be carried out as follows:

$$C_z\frac{d\theta_z}{d\tau}=\sum_{i=1}^{N}\dot{Q}_{i,c}+\sum_{i=1}^{N_{\mathrm{surfaces}}}h_iA_i\left(\theta_{s,i}-\theta_z\right)+m_vC_p\left(\theta_\infty-\theta_z\right)+Q_{\mathrm{sys}}$$

where N is the number of convective internal loads, $\dot{Q}_{i,c}$; $h_iA_i\left(\theta_{s,i}-\theta_z\right)$ is the convective heat transfer from zone surfaces at temperature $\theta_{s,i}$; $m_vC_p\left(\theta_\infty-\theta_z\right)$ is the heat transfer due to ventilation with the outside air; $\theta_{s,i}$ is the system output; C_z is the capacitance that takes into account the contribution of the zone air as well as that of thermal masses which are assumed to be in equilibrium with the zone air.

The convection between the air and the surrounding surfaces of the enclosure is computed by means of time dependent coefficient. The conduction heat transfer through the envelope components is treated by means of conduction transfer function coefficients (CTFs) method and takes into account both the thermal resistance and capacity of each envelope component. The time step of calculation was set to 6 times per hour.

The energy modeling was carried out into two different stages. In particular the RB was first modeled within the free-add on “Legacy OpenStudio Plug-in” for the SketchUp program. The model was then exported into the EnergyPlus software (.idf format) in order to define the building envelope, the operation settings and the system.

The building was divided into 11 thermal zones, two of them were not conditioned (cellar and technical room).

A detailed sub-hourly simulation was conducted for each EEM, using the reference IWEC (International Weather for Energy

Calculations) weather file for Turin retrieved from the EnergyPlus weather data files database [40]. A reference weather file, referred as Typical Meteorological Year (TMY), is a synthetic typical year composed of 12 typical months selected from a multi-year series (at least 20 years of records) [41]. In detail a TMY is composed of 8760 hourly records of various climatic parameters such as dry-bulb and wet-bulb temperature, dew point, wind direction and speed, barometric pressure, relative humidity, could cover and type, total horizontal and direct normal solar radiation data [42]. The method used for generating this type of weather files is also part of the ISO Standard 15927-4 [43].

Once completed the geometry, the thermal features of the building envelope materials were then specified in order to define the layers of each building envelope component. The *U*-value of the building envelope were defined complying, for the RB, with the minimum values required by the regional regulation [29] and, for the EEMs, with the optional values of the Turin city regulation [30], as presented previously in Table 1.

In compliance with Italian regulations [44], for climatic zone E, the one which Turin belongs to, heating season ranges from 15th October to 15th April. Cooling season starts on 1st May and ends on 30th September. Temperature set points were set, respectively, to 21 °C from 7 a.m. to 8 p.m. (18 °C during the remaining hours) for heating, and to 26 °C from 7 a.m. to 5 p.m. (28 °C during the remaining hours) for cooling.

Occupancy was fixed to 0.04 pers/m^{-2} [45] and lighting and equipment power densities were, respectively, defined as 4.5 and 3 W/m^2; these unitary values were associated to the relative activities schedules [46]. The outdoor air flow rate is constantly set to 0.3 ACH. Shading systems are active only during the cooling season and when incident solar radiation is greater than 100 W/m^2.

All technical systems and components were modeled using EnergyPlus. The condensing gas boiler for BTS0/1 was modeled using normalized efficiency curves, while the boiler nominal thermal efficiency was set to 0.9. In BTS1, the gas boiler was associated with an air source heat pump water heater, with a nominal 4.2 COP, that turns off when the outside temperature falls below 5 °C. Under those conditions it is the gas boiler that operates and provides heating energy to the building. The performance of the ground-to-water heat pump of BTS2, was evaluated with the equation-fit model in EnergyPlus, using curves fitted from the catalog data. It has a nominal COP of 4.9 in heating mode, and a nominal EER of 4.3 in cooling mode. The vertical ground heat exchanger consist of 2 × 76 m depth boreholes. In BTS3, the micro-heat pump was modeled as an air source heat pump for water heating with a nominal 4.2 COP. The multi-split air conditioner was modeled as a packaged terminal air conditioner, with a single speed DX cooling coil with a rated efficiency of 3.

The mechanical ventilation system was modeled with a rotary heat exchanger with 90% nominal effectiveness. For BTS1-2, the ventilation unit uses variable speed fans with a total nominal flow rate of 175 m^3/h. For BTS3 design flow rate is based on building heating loads, since no water terminals are used to control the temperature inside the building.

The DHW need was calculated in compliance with UNI/TS 11300-2 [47] and estimated as 85 m^3/yr. For BTS0/1, DHW water heater was modeled as a mixed water buffer with a separate instantaneous gas boiler (23 kW). For BTS2-3, a stratified water heater with an electric resistance (2 kW) was modeled.

Three flat plate solar collectors were modeled in conjunction with water heaters, providing approximately 80% of the DHW net energy need for each EEMs (SC DHW80%). Four additional solar collectors (SC heating) are coupled only with BTS0, providing hot water for space heating during the heating season (they are not used during summer). Variable speed pumps are associated with solar systems. Thermal and optical performance parameters for the single flat plate solar collectors systems (SC DHW80% and SC heating) set into the building energy model, are provided in Table 4.

Table 4
Solar collectors thermal and optical performance parameters.

Denomination	SC DHW80%	SC heating
Number of panels	3	4
Gross area for single SC [m^2]	1.98	2.2775
Single panel dimensions [mm]	1021 × 1946 × 83	1204 × 1889 × 101
Test fluid	Water	Water
Test flow rate [m^3/s]	0.0000372	0.0000447
Coefficient 1 of Efficiency equation [−]	0.753	0.0779
Coefficient 2 of Efficiency equation [W/m^2 K]	−5.2917	−4.2847
Coefficient 3 of Efficiency equation [W/m^2 K^2]	0.00638	−0.00483
Coefficient 2 of incident angle modifier [−]	0.1429	−0.2947
Coefficient 3 of incident angle modifier [−]	−0.2362	−0.0119

PV panels were modeled using the “Equivalent One-Diode” option, using empirical relationships to predict PV operating performance based on many environmental variables such as cell temperature. A simple ideal inverter, with a nominal efficiency of 0.95, is connected with the PV panels. The performance characteristics for the crystalline silicon PV systems are provided in Table 5. The PV panel type is the same for all the three system configuration but the number of panels varies from 9 to 18 to 36.

2.4. Global cost method

Global cost and net present value were calculated following the procedure of the European Standard EN 15459 [24]. Global cost formula can be written as

$$C_G(\tau) = C_G + \sum_{J}\left[\sum_{i=1}^{\tau}\left(C_{a,1} \times R_d(i) - V_{f,\tau}(j)\right)\right]$$

where C_G (τ) corresponds to 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 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.

Table 5
Performance characteristics of the photovoltaic (PV) modules.

Denomination	SC DHW80%
PV circuit	Equivalent one-diode
Number of cells in series [−]	72
Active area [m^2]	1.125
Transmittance absorptance product [−]	0.95
Semiconductor bandgap [eV]	−4.2847
Short circuit current [A]	−0.00483
Open circuit voltage [V]	−0.2947
Reference temperature [°C]	−0.0119
Reference insolation [W/m^2]	1000
Module current at max. power [A]	4.95
Module voltage at max. power [V]	35.4
Temperature coeff. of short circuit current [A/K]	0.0008
Temperature coeff. of open circuit voltage [V/K]	−0.145
Nominal operating cell temperature test ambient temperature [°C]	20
Nominal operating cell temperature test cell temperature [°C]	45.35
Nominal operating cell temperature test insolation [W/m^2 K]	800
Module heat loss coefficient [W/m^2 K]	30
Total heat capacity [J/m^2 K]	50,000

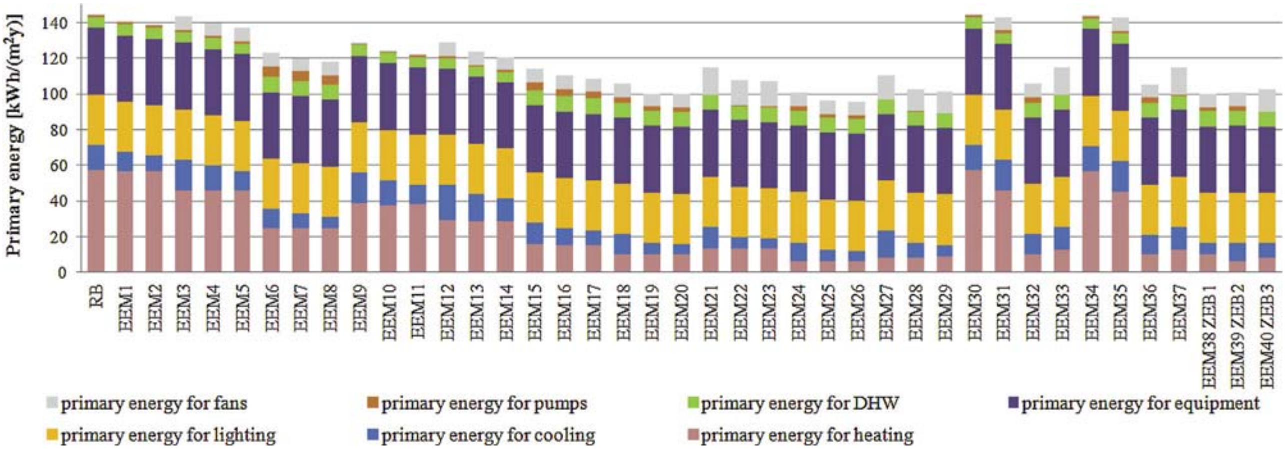

Fig. 5. End use primary energy consumptions.

Since calculation refers to a new construction, the calculation period was set to 50 years. The inflation rate was set to 2.15%, while the market interest rate is equal to 2.67%. They were both calculated as mean value over the last 10 years (from 2003 to 2013), in the Euro area.

The EEMs investment costs were calculated referring to the price list of the Piedmont Region in 2013 [48]. Replacement costs of the building constructions were considered for windows (25 years lifespan), for roof waterproof coat (30 years lifespan) and for all shading systems (25 years lifespan). Replacement costs of the building technical systems were considered according to the components lifespan defined in Appendix A of EN 15459 [24]. Maintenance costs were considered for technical systems components, as a percentage of the initial investment cost. Energy costs were considered for space heating and domestic hot water (natural gas or electricity), and for space cooling, lighting, equipment, ventilation and auxiliary (electricity).

The current Italian prices used for calculations, are listed in detail:

- 0.889 €/m^3 for natural gas [49];
- 0.190 €/kW h for electricity [49];
- 0.039 €/kW h feed-in tariff for PV electricity [50].

Subsidies related to renewable sources were accounted; a financial subsidy for flat plate solar collectors of 170 €/m^2 was taken into account for the first two years [51].

3. Results

3.1. Primary energy for end use and PV on-site use

The annual overall energy use was assessed in terms of delivered primary energy, including energy use for heating, cooling, domestic hot water, lighting, equipment and ventilation. Primary energy values were calculated using Italian primary energy factors (e.g. 1.092 for natural gas and 2.174 for electricity).

Fig. 5 shows the energy consumption in terms of primary energy for each end use (including solar collectors contribution for DHW and space heating). As can be seen, energy consumption for lighting and equipment are constant in all EEMs as no energy efficiency measure for the lighting and equipment systems was studied.

Important reductions were achieved for the heating demand, resulting in primary energy reduction from 58 to 7 kW h/m^2 y. Cooling consumption does not have great impacts on total energy consumptions due to the building heavy constructions and it is not subjected to large variations. However, with a high level of envelope insulation (EI3), external shading devices are needed in order to prevent overheating. Primary energy consumptions for cooling range from 19 to 6 kW h/m^2 y.

DHW consumption tends to remain quite constant (9 to 6 kW h/m^2 y of primary energy) since all EEMs are provided with the same number of solar collectors. Depending on the energy vector used (gas or electricity) and consequently on the system type, a difference in the energy consumption is observed.

Table 6 summarizes the various performance parameters of the PV system and of the energy exchange with the utility grid for the RB and some EEMs. The on-site consumption was computed from the hourly values of PV production and electricity use. It can be seen that the last EEMs (EEM34, 38, 39 and 40) present a PV production greater than the electricity use (Ratio total PV production/total electricity use >1) but the on-site use does not go beyond 40%. Instead, when the PV production is lower, greater on-site use ratios can be obtained (RB and EEM30).

From simulations, the available solar radiation at the location, on horizontal surface, amounts to 1283 kW h/m^2 y, while the solar radiation on the PV surface (tilt angle 22°) amounts to 1462 kW h/m^2 y. From PV production, the electricity used on site, for example for the RB with 9 panels in total, is 2080 kW h.

3.2. Economic evaluations of EEMs

Economic calculation was performed in compliance with the global cost method, as previously described.

Initial investment cost (IC) is, for all EEMs, the most relevant cost as can be seen in Fig. 6.

Fig. 7 only reports IC for all the considered EEMs. As can be seen, a similar increment in EEMs, both for the envelope components and both for the systems, is recorded. The highest increment regards EEMs that consider EI2,3 and BTS2,3. For example, in Fig. 8, the influence of each cost category, for the RB and EEM40, is highlighted. EEM40 has EI3 as insulation level, BTS3 for system package and a full PV roof (PV 6.3). IC increases from 47% (RB) to 49% (EEM40), amounting, respectively, to 1193 €/m^2 and 1414 €/m^2. The increment of IC is far from being considered negligible, as it accounts for about 19% on the total global cost. It is mainly caused by the investment on high insulation, external shading devices and PV systems.

Maintenance costs influence on the global cost is generally limited (from 5 to 10%); systems with mechanical ventilation, such as BTS1/2/3, tend to have higher maintenance costs. Replacement costs are quite relevant as being the RB a new construction, calculation period was set to 50 years. Due to that, most of the building

Table 6
Renewable energy from PV panels for some selected EEM and the RB.

	RB	EEM30	EEM34	EEM38	EEM39	EEM40
Electricity end use [kW h]	6503	6499	6491	8024	8064	8197
PV production [kW h]	2080	4140	8191	8191	8191	8191
PV electricity used on-site [kW h]	1698	2462	2951	2824	3153	3171
Net electricity coming from utility [kW h]	4805	4038	3541	5200	4911	5025
Surplus electricity going to utility [kW h]	382	1678	5240	5367	5038	5019
Ratio on-site use/total PV production [–]	0.82	0.59	0.36	0.34	0.38	0.39
Ratio surplus exported/total PV production [–]	0.18	0.41	0.64	0.66	0.62	0.61
Ratio on-site PV use/total electricity use [–]	0.26	0.38	0.45	0.35	0.39	0.39
Ratio total PV production/total electricity use [–]	0.32	0.64	1.26	1.02	1.02	1.00

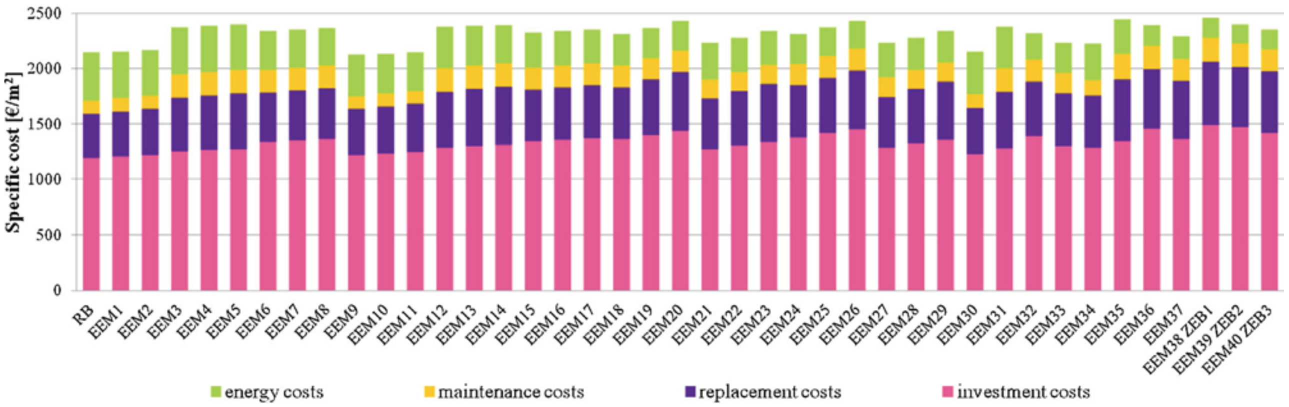

Fig. 6. Costs breakdown analysis.

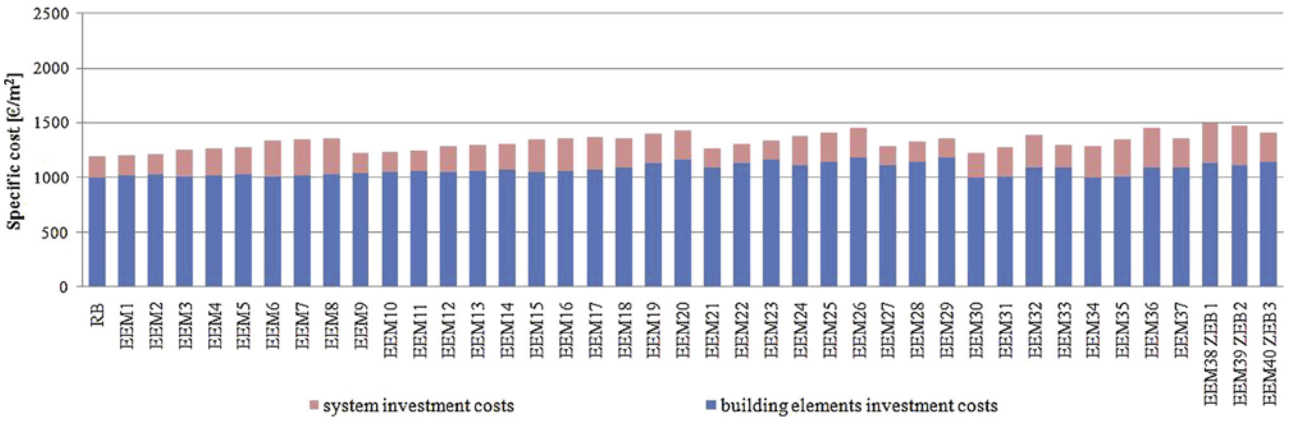

Fig. 7. Investment costs breakdown analysis for building envelope and systems.

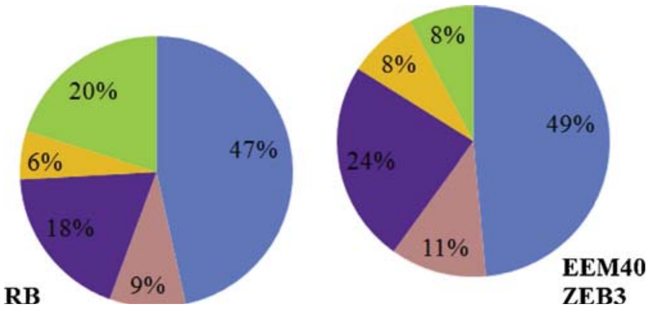

Fig. 8. Influence percentage of each type of costs for case studies RB an EEM40.

technical components were replaced two times during calculation (e.g. components with 20 years lifespan as boilers, heat pumps, ventilation units, pumps and solar collectors). Energy cost, related to energy consumptions, as reported in the previous paragraph, range from 20 to 7% over the total global cost.

3.3. Cost optimal solutions

The results, in terms of energy consumption (kW h/m^2 y) versus global cost (€/m^2), are reported for the RB and all EEMs in Fig. 9. A vertical line identifies the position of the Reference Building (RB) which represents the maximum net primary energy consumption (118 kW h/m^2 y). The minimum net primary energy consumption is achieved by EEMs 38/39/40 which represent net zero energy buildings (0 kW h/m^2 y). EEMs allow energy savings from 2 to 118 kW h/m^2 y (net primary energy) in absolute terms, and from 2 to 100% in percentage terms. Global cost ranges from 2128 €/m^2 of EEM9, which is the cost-optimal solution, to 2457 €/m^2 of EEM38 ZEB1 which is a highly efficient net zero energy building. EEMs with the lowest costs, which also correspond to the cost optimal levels, are EEM9 and EEM10 with a global cost reduction of 17 and 9 €/m^2 compared to RB. With a net primary energy consumption decrease from 118 kW h/m^2 y (RB) to 103/98 kW h/m^2 y (EEM9,10) cost optimal solutions are quite close to actual minimum requirements. However the

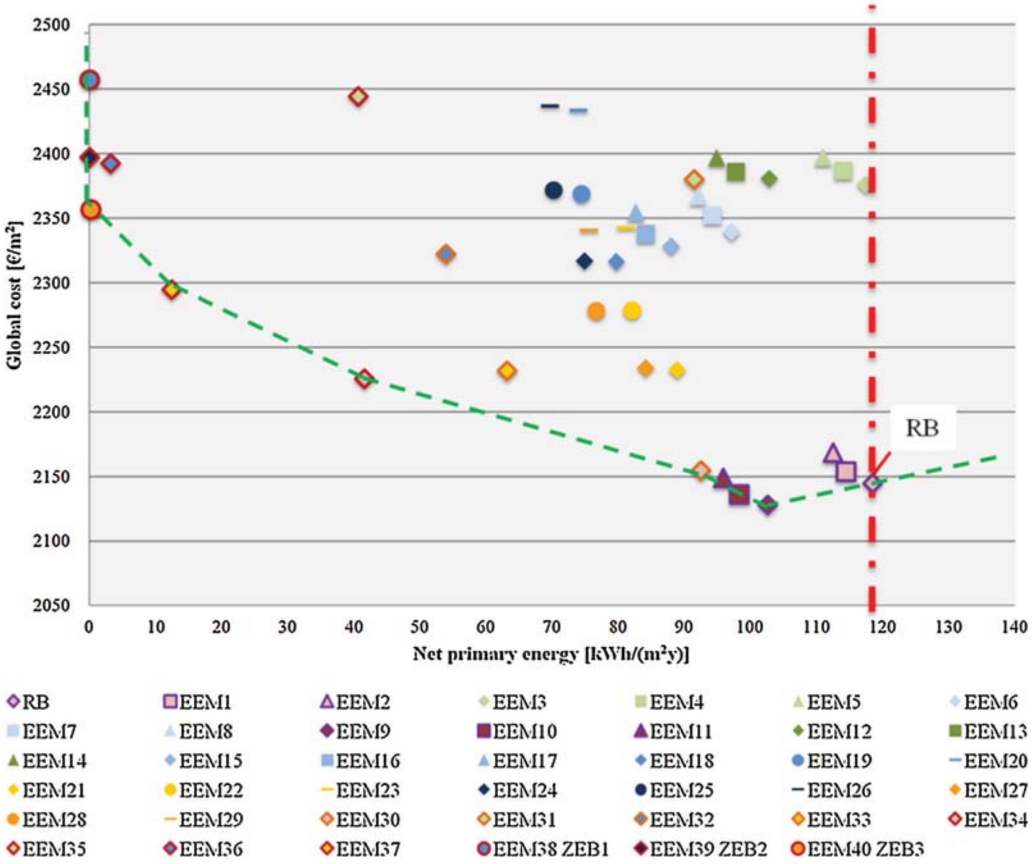

Fig. 9. Global costs versus net primary energy of RB and of the other EEMs.

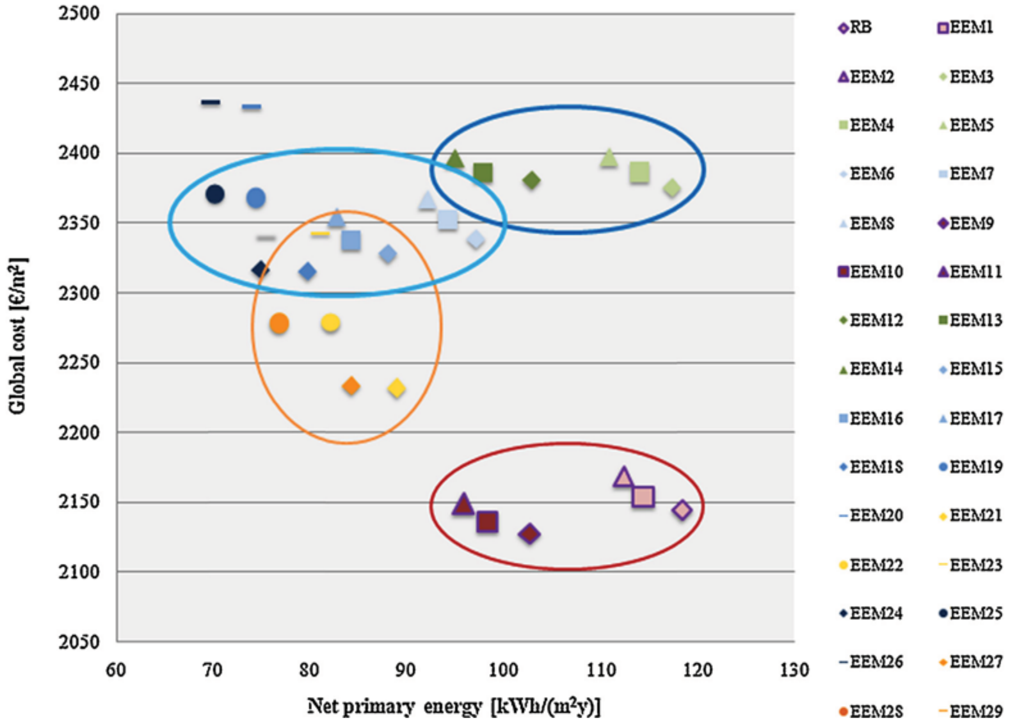

Fig. 10. The effect of different systems solutions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

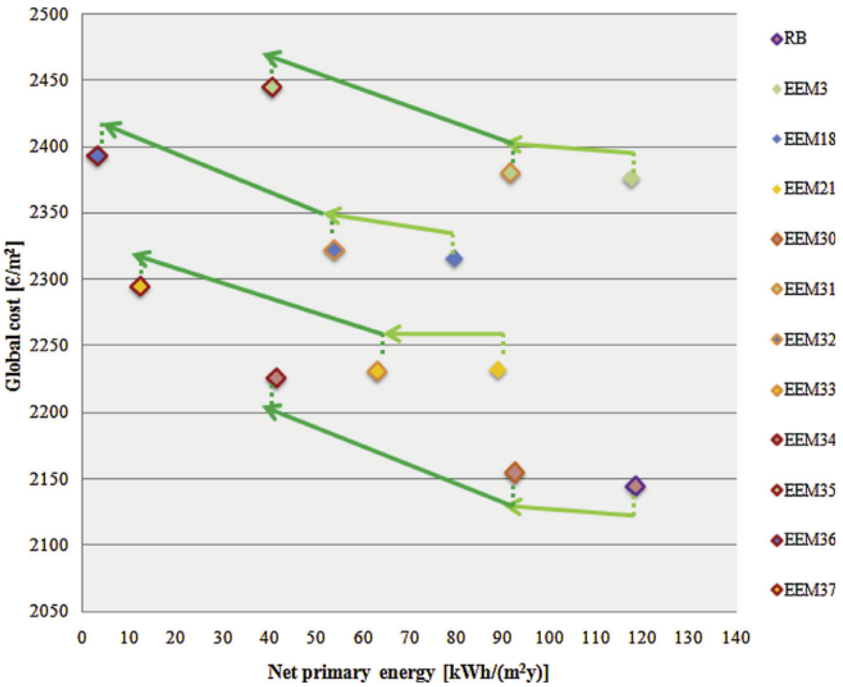

Fig. 11. The effect of increasing PV.

reduction in terms of primary energy consumption is still relevant (15–20%).

This study showed that cost optimal levels of energy performance (EEM9,10) are reached with a level of thermal insulation (EI1) higher than minimum requirements, combined with internal or between-glass shading systems (SO0/1), conventional building technical systems (BTS0) (condensing gas boiler with water terminals integrated by solar collectors, and direct expansion cooling) and a small amount of photovoltaic panels (PV1.6).

The graph also shows that net zero energy balance can be reached by different EEMs, but the difference between these solutions, in terms of global cost, can be very relevant (>100 €/m²).

Fig. 10 reports the effect of different system solution in terms of primary energy and global cost. The worst performing EEMs, in terms of primary energy consumptions, are the ones included into

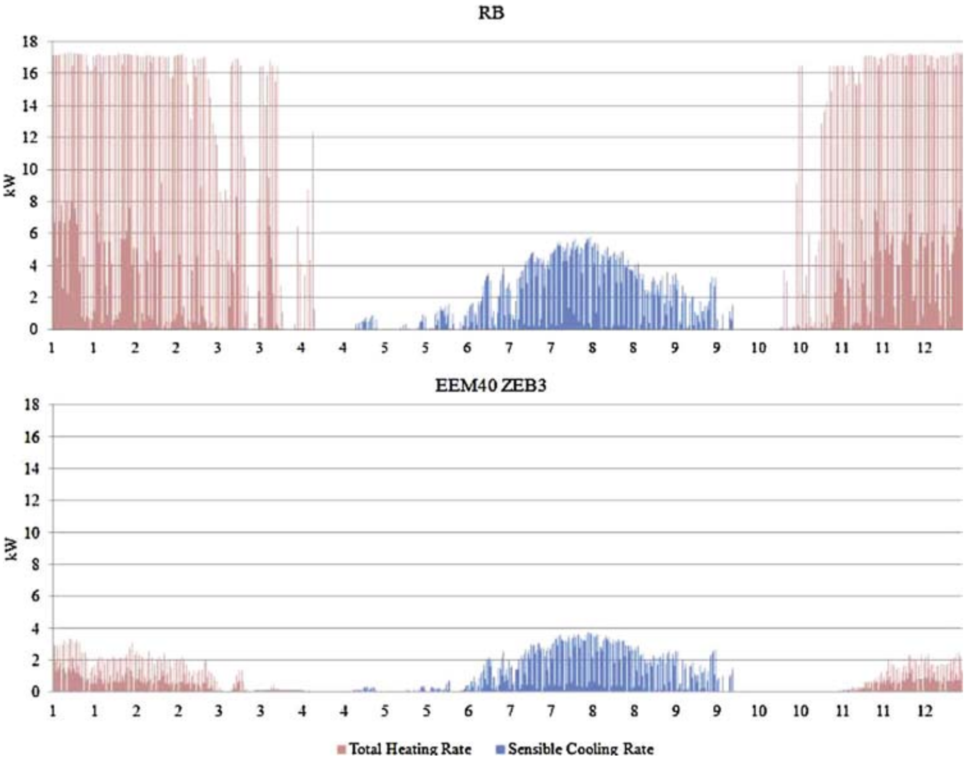

Fig. 12. Annual heating and cooling rate of the RB and of EEM40.

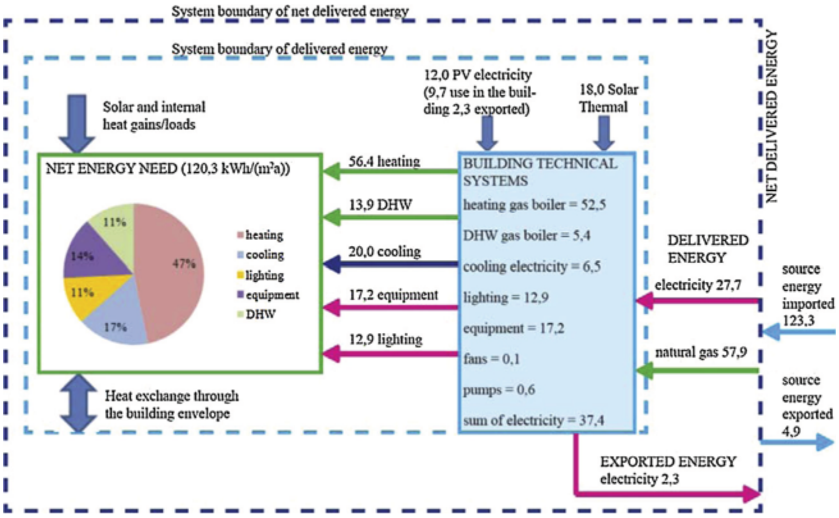

Fig. 13. Energy flows [kW h/m^2 y] and system boundary of RB.

the red (BTS0) and dark blue (BTS1) clouds. They are similar on the energy consumptions but differ on the global cost values. In fact, conventional building technical systems, as BTS0, have lower global costs because of small costs of investment, maintenance and replacement; on the other hand, BTS1 solutions, which combine a gas boiler with a heat pump for heating, show highest values of global cost. In this case hybrid heating generation seems not to pay off the initial investment for both boiler and heat pump. The more performing EEMs, for the energy side, are the ones into light blue (SO2) and yellow (SO3) clouds, which however have the highest values of global cost. System BTS2, which involves the use of a ground source heat pump, has very low energy costs and maintenance costs, but the initial investment cost is quite relevant. System BTS3 can be a valid alternative to conventional systems, since the initial investment cost is limited (involving only the ventilation system and not water terminals) together with the ones of maintenance and replacement. Energy costs are also very small;

Fig. 11 points out the effect, on the global cost and on the primary energy consumption, of the increasing of PV, into all four building technical systems measures. Since increasing PV panels leads to a higher amount of electricity exported in the net, and the feed-in tariff for PV electricity is quite small (<0.04 €), global cost increases when large PV arrays are installed. However, increasing the installed PV from 1.6 kW$_p$ to 3.2 kW$_p$ produces a relatively small increase in the global cost, since most of the electricity generated by PV is still consumed on site by the building, and a relatively small amount of energy is exported in the grid.

The increment of PV panels tends to generate higher global costs, however larger photovoltaic systems are more economically convenient for building designed with mechanical ventilation and electric boilers or heat pumps. Since electricity demand is increased, these systems allow a better matching between energy generation and consumption.

Moreover the use of all electric systems consent to reduce the building carbon print. CO_2 emissions of the RB amount approximately 19 kg CO_2/m^2 per year, whereas with only electric systems, compensated by the PV energy production, CO^2 emissions are reduced of approximately 40%, ranging from 11 to 11.8 kg CO_2/m^2 per year (EEM 38, 39 and 40).

3.4. Net ZEB solutions

The main aim of this study was to provide guidelines for the design of cost optimal solutions for net ZEB single family houses. Due to that, among the EEMs proposed, EEM38, 39 and 40 succeeded to reach net zero performances. They have high levels

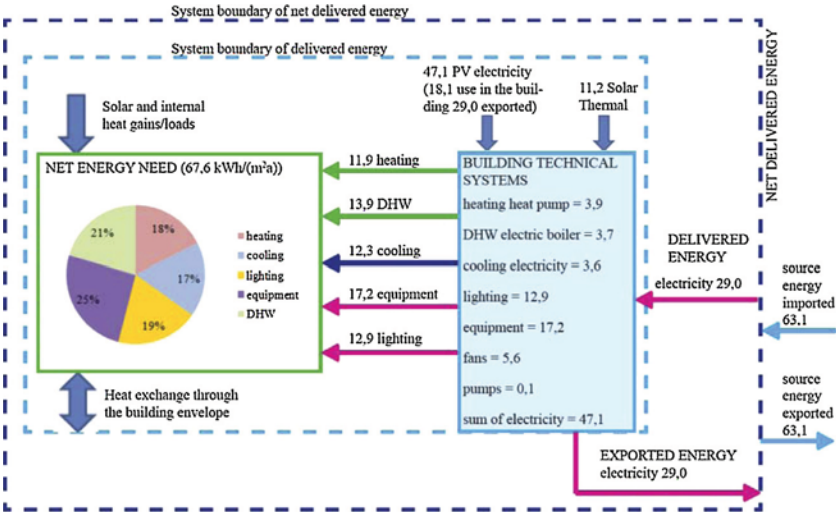

Fig. 14. Energy flows [kW h/m^2 y] and system boundary of EEM40 ZEB3.

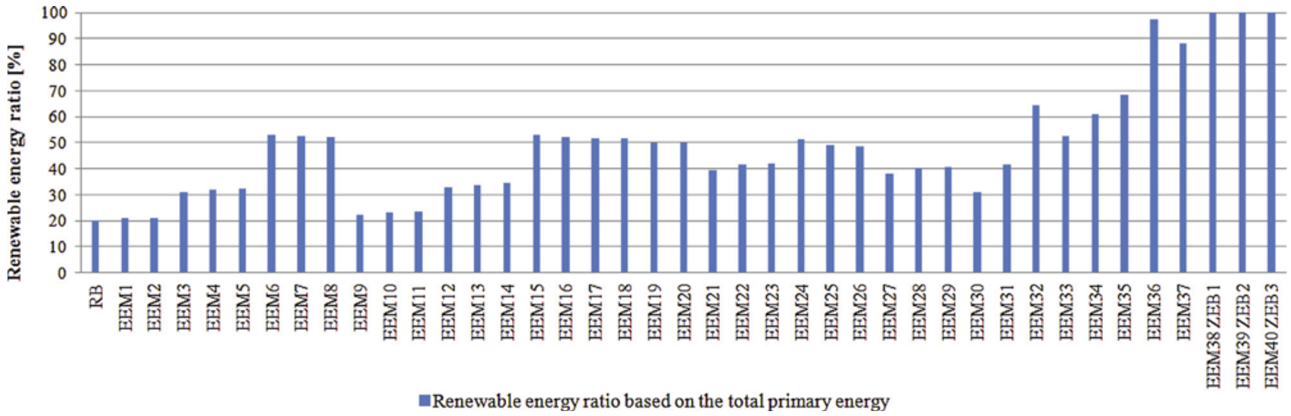

Fig. 15. Renewable energy ratio based on the total primary energy.

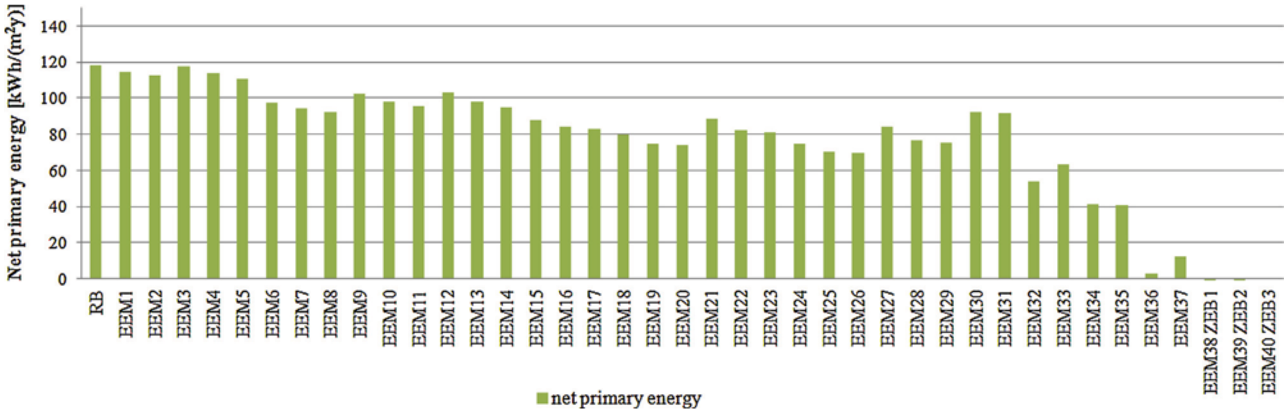

Fig. 16. Net primary energy consumptions.

of thermal insulation (EI2/3) combined with internal or external blinds (SO0/3), technical systems entirely based on heat pumps with mechanical ventilation and heat recovery (BTS2/3), and the maximum level of PV installed (PV 6.3).

Fig. 12 spots the difference into the heating and cooling energy rate for the RB (on the left side) and EEM40 (on the right side). As can be observed, larger reduction and low energy demand are obtained especially for heating rate, due the highly insulated building envelope (EI3).

As can been observed from Fig. 9, the most cost efficient zero energy solution is EEM40, with the lowest global cost between the three ZEB EEMs, accounting for about 2350 €/m^2.

In order to provide a clear comparison with the RB, the energy flows, in kW h/m^2 y, for the RB and EEM40 ZEB3 are presented in Figs. 13 and 14. The system boundaries and energy flows are consistent with the REHVA definition [52,53]. For the RB (Fig. 13) the main consumption is associated with space heating, while in EEM40 with electric equipment due to a higher thermal insulation (Fig. 14).

Renewable energy ratio, based on REHVA technical definition [54], was calculated in terms of total primary energy, for all energy uses, assuming that exported energy compensates delivered energy. Net imported electricity was assumed to be 100% non renewable. As can also be observed in Fig. 15, the minimum renewable energy ratio is reached by RB (20%), while for net zero energy buildings a 100% renewable energy ratio is achieved.

Fig. 16 shows for each EEM the net primary energy consumption, that is equal to the primary energy imported minus the primary energy exported. Both electricity from PV consumed on site, and electricity exported on the net, are accounted in this graph. This means that the nZEB cases (EEM 38, 39 and 40) can be considered zero-energy buildings only if the net exchange between the utility grid is taken into account and if the surplus exported energy is weighted (in terms of primary energy) equally to the electricity coming from the utility.

4. Conclusions

Cost optimal levels for a single family house in Northern Italy were investigated. Different cost optimal solutions of HVAC systems were studied and proposed for nearly zero energy houses. Three systems configurations achieved a net zero energy balance. A well-defined procedure, based on the comparative methodology framework of the EPBD guidelines, was followed to define technically and economically feasible EEMs. Great attention was paid to the study of cost optimal and net zero balance solutions for the building system, but the building envelope EEMs were not neglected and were studied in the first stage of the procedure. It was thus necessary to minimize the space heating and cooling need of the reference case study in order to start designing the building system with a good building envelope performance and consequently optimize the system configuration.

This study showed that nearly zero energy levels can be reached both with conventional technical systems (e.g. condensing gas boiler with water terminals) with an average level of insulation, adding a large number of PV panels (e.g. 35 W_p/m^2), and with advanced technical systems [55] (e.g. all air ventilation systems with heat pumps) with high levels of insulation and again a large number of PV panels. However, in order to reach net zero balance solutions, high levels of thermal insulation (EI2/3) combined with more energy efficient technical systems entirely based on heat pumps with mechanical ventilation and heat recovery (BTS2/3), and the maximum level of PV installed (PV6,3), are required.

Cost optimal solutions tend to have a small renewable energy ratio (20–30%) since they are mainly based on gas boiler systems, while nearly zero energy solutions have higher values of renewable energy ratio (60–90%). These high values can be reached increasing on-site electricity production by means of PV systems, associated with advanced heat pump systems but also with conventional gas boiler systems (in this case the maximum renewable ratio achievable is around 65–70%).

The economic calculations performed within this study, according to the micro-economic approach of the EPBD guidelines, investigated the investors' perspective towards nZEB target. It was observed, with regard to the feasibility of nZEBs solutions, that the results obtained are consistent with the state of the art. In fact, as anticipated in the introduction, net zero energy building are still quite far in terms of cost optimality from matching optimal solutions.Net ZEB solutions, hereby presented, were selected to be technically feasible, but as from results they cannot considered also economical practicable. As mentioned previously (Fig. 12) net zero energy balance are reached into EEMs 38, 39 and 40, but the difference between these solutions and the other EEMs studied, in terms of global cost, can be very relevant (>212–313 €/m^2 than cost optimal EEMs). The gap from RB (minimum law requirements) to EEM40 ZEB3 (which is the most convenient solution for ZEBs) is about 212 €/m^2 (10% increase of global cost) while the increase in initial investment cost is about 221 €/m^2 (18% increase of investment cost). In order to make nZEB real and support the design of nZEB as required by EBPD, a system of incentives has to be provided at national or regional levels.

Criticalities about the values of economic factors to be used for the economic evaluation of the global cost should be taken into account. For instance the value of the interest rate or the inflation rate were set in the study as a mean of the last 10 years in Euro area, but as the energy prices, they are subjected to evolution during the applied calculation period is also an important issue. For this reason further cost optimal studies should concentrate on sensitivity analyses on the economic assumptions. Analysis on the possible evolution of the energy costs and on the inflation rate to be used in the global cost calculation would be for example an important asset in order to achieve the nZEB target.

Furthermore, the comparison between the optimal solutions in terms of achievable energy savings, and the economic cost optimal ones, represents also an interesting topic. It would be thus challenging, in further studies, to analyze the differences between them and try to reduce the gap between energy and economic optimal solutions, in order to have an unicum optimal solution.

Besides, it would be useful trying to bridge the gap between cost optimal solutions and nZEBs ones. From the results it is clear that nZEB and net ZEB solutions could still not be considered cost effective.

Finally, the range of EEMs to be investigated may be enlarged. The use of automated optimization methodologies, such as those performed by Corrado et al. [13] coupled with quasi-steady state models and Ferrara et al. [14] coupled to dynamic building energy simulation, would allow to consider a wider set of solutions.

Acknowledgments

The authors would like to thank the owner of the single family house, engineer Stefano Corgnati, and the architecture firm "GOODFOR" with the architect Marco Luciano for providing the technical plans and construction data of the case study.

References

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Off. J. Eur.Union (2010).
[2] BPIE (Building Performance Institute Europe), Europe's buildings under the microscope, in: A Country-by-Country Review of the Energy Performance of Buildings, BPIE, October 2011.
[3] L. Gustavsson, A. Joelsson, Life cycle primary energy analysis of residential building, Energy Build. 42 (2010) 210–220.
[4] R. Azari, Integrated energy and environmental life-cycle assessment of office building envelopes, Energy Build. 82 (2014) 156–162.
[5] G. Verbeeck, H. Hens, Life cycle inventory of buildings: a calculation method, Build. Energy 45 (2010) 1037–1041.
[6] D. Dolmans, A change is going to come. A New Mandate: nearly zero energy buildings, Eur. HVAC REHVA J. 48 (2011) 34–37, No. 6.
[7] Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council, Off. J. Eur.Union (2012).
[8] BPIE (Buildings Performance Institute Europe), Cost optimality, in: Discussing Methodology and Challenges within the Recast Energy Performance of Buildings Directive, BPIE, 2010.
[9] BPIE (Building Performance Institute Europe), Implementing the cost-optimal methodology in EU Countries, in: Lessons Learned from Three Case Studies, BPIE, March 2013.
[10] K. Kurnitski, A. Saari, T. Kalamees, M. Vuolle, J. Niemela, T. Tark, Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation, Energy Build. 43 (2011) 3279–3288.
[11] E. Pikas, M. Thalfeldt, J. Kurnitski, Cost optimal and nearly zero energy building solutions for office buildings, Energy Build. 74 (2014) 30–42.
[12] A.M. Hamdy, A. Hasan, K. Siren, Multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010, Energy Build. 56 (2013) 189–203.
[13] I. Ballarini, V. Corrado, S. Paduos, Assessment of cost-optimal energy performance requirements for the Italian residential building stock, Energy Procedia 45 (2014) 443–452.
[14] M. Ferrara, E. Fabrizio, J. Virgone, M. Filippi, A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings, Energy Build. 83 (2014) 442–457.
[15] N. Ganiç, A.Z. Yilmaz, Adaptation of the cost optimal level calculation method of Directive 2010/31/EU considering the influence of Turkish national factors, Appl. Energy 143 (2014) 94–107.
[16] BPIE (Building Performance Institute Europe), Paving the way for effective implementation of policy requirements, in: Principles for Nearly Zero Energy Buildings, BPIE, November, 2011.
[17] M. Bojic, N. Nikolic, D. Nikolic, J. Skerlic, I. Miletic, Toward a positive-net-energy residential building in Serbian conditions, Appl. Energy 88 (2011) 2407–2419.
[18] K.F. Fong, C.K. Lee, Towards net zero energy design for low-rise residential buildings in subtropical Hong Kong, Appl. Energy 93 (2012) 686–694.
[19] N. Aste, R. Adhikari, M. Buzzetti, Beyond the EPBD: the low energy residential settlement Borgo Solare, Appl. Energy 87 (2010) 629–642.
[20] A. Mohameda, A. Hasanb, K. Sirén, Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives, Appl. Energy 114 (2014) 385–399.
[21] A.J. Marszal, P. Heiselberg, R. Lund Jensen, J. Nørgaard, On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark, Renew. Energy 44 (2012) 154–165.
[22] M. Cellura, F. Guarino, S. Longo, M. Mistretta, Energy life-cycle approach in net zero energy buildings balance: operation and embodied energy of an Italian case study, Energy Build. 72 (2014) 371–381.
[23] M.J.N. Oliveira Panão, M.P. Rebelo, S.M.L. Camelo, How low should be the energy required by a nearly zero-energy building? The load/generation energy balance of Mediterranean housing, Energy Build. 61 (2013) 161–171.
[24] EN-15459, Energy performance of buildings, in: Economic Evaluation Procedure for Energy Systems in Buildings, 2007.
[25] S.P. Corgnati, E. Fabrizio, M. Filippi, V. Monetti, Reference buildings for cost optimal analysis: method of definition and application, Appl. Energy 102 (2013) 983–993.
[26] ISTAT, 14° Censimento generale della popolazione e delle abitazioni (14th National Census of Italian Population and Building Stock), ISTAT, Rome, 2001.
[27] V. Bianco, F. Scarpa, L.A. Tagliafico, Analysis and future outlook of natural gas consumption in the Italian residential sector, Energy Convers. Manage. 87 (2014) 754–764.
[28] AA.VV, Main results of the TABULA project, in: Typology Approach for Building Stock Energy Assessment, Institut Wohnen und Umwelt, Darmstadt, 2012 (Final Project Report: Appendix Volume).
[29] Deliberazione della Giunta Regionale 4 agosto 2009, n. 46-11968 Aggiornamento del Piano regionale per il risanamento e la tutela della qualità dell'aria–Stralcio di piano per il riscaldamento ambientale e il condizionamento e disposizioni attuative in materia di rendimento energetico nell'edilizia ai sensi dell'articolo 21, comma 1, lettere a) b) e q) della legge regionale 28 maggio 2007, n. 13 Disposizioni in materia di rendimento energetico nell'edilizia, Agosto 2009, Regione Piemonte.

[30] Agenzia Energia e Ambiente di Torino, Allegato energetico–ambientale al regolamento edilizio della città di Torino, in: Allegato alla deliberazione n. 2010-08963/38, Agenzia Energia e Ambiente di Torino, Regione Piemonte, Agosto 2009.

[31] Italian Government, Legislative decree 3 March 2011, no. 28 implementing the European Union Renewable Energy Directive 2009/28/CE.

[32] D.B. Crawley, L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, R.K. Strand, R.J. Liesen, D.E. Fisher, M.J. Witte, J. Glazer, EnergyPlus: creating a new-generation building energy simulation program, Energy Build. 33 (2001) 319–331.

[33] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, Build. Environ. 43 (2008) 661–673.

[34] F. Goia, M. Haase, M. Perino, Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective, Appl. Energy 108 (2013) 515–527.

[35] R. Zhang, K.P. Lam, S. S. Yao, Y. Zhang, Coupled EnergyPlus and computational fluid dynamics simulation for natural ventilation, Build. Environ. 68 (2013) 100–113.

[36] Y.P. Zhou, J.Y. Wu, R.Z. Wang, S. Shiochi, Y.M. Li, Simulation and experimental validation of the variable-refrigerant-volume (VRV) air-conditioning system in EnergyPlus, Energy Build. 40 (2010) 1041–1047.

[37] N. Fumo, P. Mago, R. Luck, Methodology to estimate building energy consumption using EnergyPlus Benchmark Models, Energy Build. 42 (2010) 2331–2337.

[38] N.M. Mateus, A. Pinto, G. Carrilho da Grac, Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell, Energy Build. 75 (2014) 511–522.

[39] E. Fabrizio, Energy reduction measures in agricultural greenhouses heating: envelope, systems and solar energy collection, Energy Build. 53 (2012) 57–63.

[40] EnergyPlus Energy Simulation Software, Weather Data for Simulation, ⟨http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_simulation.cfm⟩.

[41] G. Pernigotto, A. Prada, B. Costola, A. Gasparella, J.L.M. Hensen, Multi-year and reference year weather data for building energy labelling in north Italy climates, Energy Build. 72 (2014) 62–72.

[42] D.B. Crawley, Which weather data should you use for energy simulations of commercial buildings? ASHRAE Trans. 104 (1998) 498–515.

[43] ISO, Hourly data for assessing the annual energy use for heating and cooling, in: ISO 15927-4, ISO, 2005.

[44] Italian Government, Complying the European Directive 2002/91/EC on the energy performance of buildings, in: Decree of the President of the Italian Republic, 1993, 26 August (No. 412) (D.P.R. 412/1993).

[45] UNI, Impianti aeraulici a fini di benessere – Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura – Generalità, classificazione e requisiti, in: UNI 10339:1995, UNI, 1995.

[46] National Renewable Energy Laboratory (NREL), U.S. Department of Energy, commercial reference building models of the National Building Stock, in: Technical Report NREL/TP-5500-46861, National Renewable Energy Laboratory (NREL), February 2011.

[47] UNI/TS, Prestazioni energetiche degli edifici—Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale e per la produzione di acqua calda sanitaria, in: UNI/TS 11300-2, UNI/TS, 2008.

[48] Prezzi di riferimento per opere e lavori pubblici nella Regione Piemonte, 2013, Regione Piemonte.

[49] Autorità per l'energia elettrica e il gas: ⟨http://www.autorita.energia.it/it/index.html⟩.

[50] Autorità per l'energia elettrica e il gas: ⟨www.autorita.energia.it/it/comunicati/14/140130.html⟩.

[51] Italian Regulation, Ministerial decree 28 December 2012 implementing art.28 of Legislative decree No.28/2011 on the Incentive for the production of thermal energy by renewable sources and small energy efficiency activities.

[52] J. Kurnitski, F. Allard, D. Braham, G. Goeders, P. Heiselberg, L. Jagemar, R. Kosonen, J. Lebrun, L. Mazzarella, J. Railio, O. Seppänen, M. Schmidt, M. Virta, How to define nearly net zero energy buildings nZEB–REHVA proposal for uniformed national implementation of EPBD recast, REHVA Eur. HVAC J. 48 (2011) 6–12.

[53] J. Kurnitski (Ed.), F. Allard, D. Braham, D. van Dijk, C. Feldmann J. Fox, J. Graslund, P. Heiselberg, F. Hovorka, R. Kosonen, J. Lebrun, Z. Magyar, L. Mazzarella, I. Martinac, V. Novakovic, J. Railio, O. Seppanen, I. Sartori, J. Zirngibl, M. Schmidt, M. Virta, K. Voss, A. Wahlstrom, REHVA nZEB technical definition and system boundaries for nearly zero energy buildings, 2013 revision for uniformed national implementation of EPBD recast prepared in cooperation with European standardization organization CEN, REHVA Report No. 4, REHVA, Brussels, 2014.

[54] J. Kurnitski, Technical definition for nearly zero energy buildings, REHVA Eur. HVAC J. 3 (2013) 22–28.

[55] E. Fabrizio, F. Seguro, M. Filippi, Integrated HVAC and DHW production systems for zero energy buildings, Renew. Sustainable Energy Rev. 40 (2014) 515–541.

Paper IV

Fabrizio, V. Monetti, M. Filippi, *Impact of low investment strategies for space heating control: application of thermostatic radiators valves to an old residential building*, Energy and Buildings, Volume 95, 2015, pages 202-210, 10.1016/j.enbuild.2015.01.001.

Energy and Buildings 95 (2015) 202–210

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Impact of low investment strategies for space heating control: Application of thermostatic radiators valves to an old residential building

Valentina Monetti[a], Enrico Fabrizio[b,*], Marco Filippi[a]

[a] DENERG, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[b] DISAFA, Università degli Studi di Torino, Largo Paolo Braccini 2, 10095 Grugliasco (TO), Italy

ARTICLE INFO

Article history:
Available online 10 January 2015

Keywords:
Building energy retrofit
Calibration
Building simulation
Residential
Thermostatic radiator valves
District heating

ABSTRACT

With an old mean construction age, Italian buildings are considered as long-lasting goods; 75% and 17% of Italian live respectively in buildings built before 1990 and before 1950. The potential energy savings that can be achieved from the refurbishment of existing dwellings are clearly high. To this regard, the European Directive EPBD recast defines a comparative framework to improve buildings energy performance aiming to the nearly zero energy target by 2020. It is thus important to point out energy retrofit actions to be widely applied to the whole existing buildings stock and to be cost optimal.

This paper analyzes the application of space heating control devices such as thermostatic radiators valves (TRVs) on an old existing multi-family building in Turin by means of the EnergyPlus dynamic simulation code. Measured data of the energy supplied by the district heating network were used for calibrating the model. In order to evaluate the impact of the TRVs, simulations were performed with and without TRVs. The application of the dynamic energy simulation to different patterns of TRVs use was proved to bring back significant energy savings from a minimum of 2% up to a maximum of 10%.

1. Introduction

1.1. The retrofit of existing residential buildings

In Europe the building sector contributes largely to the total energy consumption with a 40% influence on the total assessed energy uses [1]. To this regard, many energy efficiency targeted policies and projects have been launched. In particular, the EPBD recast Directive promotes nearly zero energy buildings for the public and the private sectors as a mandatory regulation within 2020 [1]. Nonetheless, by the time this “energy efficient” approach will become the standard best practice for buildings design, energy consumptions will increase even more. Furthermore, concerns about the state of the existing dwelling should be taken seriously. Most of the energy consumptions are attributable to the existing stock because of the buildings age, the construction technologies and the low efficiency of the energy systems that supply the buildings. Moreover, the low replacement rate of old dwellings by new ones amounts to 1–3% per year [2], and especially in Italy residential buildings are often seen as long-term assets. Approximately 75% and 17% of Italians live respectively in buildings built before 1990 and before 1950 [3], confirming the European trend about the old mean building construction age. The amount of energy consumed by the existing dwellings has not been quantified but it is beyond any doubt that great energy savings can be achieved [4]. Moreover, the energy savings that can be obtained with the energy retrofitting of existing dwellings are greater than the ones that can be obtained with the construction of a relatively small proportion of new dwellings. Therefore, the refurbishment of the existing building stock has to be planned and applied in order to have a timely energy reduction.

There again the major focus is nowadays on the design of new buildings with low energy consumptions. Discussions about the choice of demolishing old building and replacing them with new and more efficient ones have raised without any real agreements [5]. Some countries resort frequently and openly to building demolition and re-construction. Indeed other countries like Italy usually avoid demolition due to the cultural heritage of its proper existing building stock. For them, to preserve and to renovate existing buildings is thus the most common and acceptable solution. Due to that, a great amount of Italian energy refurbishment projects, approximately 40% on the overall, regarded buildings built before 1960

---

[*] Corresponding author. Tel.: +39 011 6705525; fax: +39 0116705516.
E-mail address: enrico.fabrizio@unito.it (E. Fabrizio).

http://dx.doi.org/10.1016/j.enbuild.2015.01.001

and characterized by low energy performance and without any thermal insulation layer [6]. Moreover, among historical buildings (all buildings built in a different period from the present), approximately 1.8% belong to the Italian Cultural Heritage [7] and are thus subjected to protection by Ministerial Authorities. This means that any retrofit intervention on such buildings should be aimed to the preservation of the materials and goods, as well as to the protection of the buildings cultural values [4].

Nowadays the number of energy retrofit technologies has been increasing in size. Energy efficiency measures (EEMs) can range from actions on the envelope to the system, and on building operation and control. According to a survey on the 2011 Italian 65% tax reduction on existing building energy efficiency projects [6], the most common retrofit measures are windows replacement (59%), replacement of the heating system with a more efficient one (28%) and installation of solar thermal collectors (11%). The improvement of thermal insulation in the building envelope, in both vertical and horizontal components, regards only 3% [6] of the retrofit applications sent for tax reduction. In fact, even if the improvement of the building envelope performance could bring to higher mean energy savings, the mean investment cost is higher than other market available measures. To this regard, the decision on which type of refurbishment should be applied to the building depends on various factors and between them, the most influencing one relapses on the investment profit [2]. It is not an easy task to decide if an energy measure to undertake is worth the investment. Due to that, ad hoc cost optimal levels of energy performance need to be defined for the considered energy efficiency measures in compliance with the EPBD recast requirements [1]. To this regard, analysis on the cost optimal methodology [8], applied to reference building case studies [9] can guide and help in the selection of the most profitable measures.

Moreover, the type of energy efficiency measures that can be selected is quite small for buildings that are considered historical and protected as cultural heritage. It is thus important to point out energy retrofit actions to be widely applied to the whole building stock and to be cost optimal. Thermostatic radiator valves (TRVs) represent a quite common refurbishment measure, which is to be reinforced by law by 2016 in the city of Turin. They have been widely studied, ranging from the study of their adjustment characteristics to their control effectives [10]. Additionally, past studies have demonstrated that TRVs bring an average energy saving from 10% [11] to 50% if considered together with the increase of the envelope thermal insulation [12,13].

1.2. Objective of the study

This study aims, by means of dynamic simulation, to investigate the control effectiveness of TRVs. Additionally cost optimal calculations are used to analyze the feasibility and application of TRVs on an existing building as a low cost energy efficiency measure. The selected case study is an existing multifamily building located in Turin (North Italy). The building, built at the beginning of XIX century, belongs to that category of refined aristocratic buildings characterized by obsolete mechanical systems and without thermally insulated building envelopes, requiring thus heavy retrofit interventions. However, due to its construction age and to its belonging to the cultural heritage patrimony, TRVs represented one of the most eligible EEMs for reducing the energy consumptions. Other kinds of EEMs, which may have higher energy savings, such as those concerning the building envelope could not be taken into consideration for their impact on the building façade, subjected to protection and thus to architectural restraints for its cultural heritage. The energy assessment of the case study was carried out by means of dynamic energy simulation with the EnergyPlus code. Measured data of about two months operation during the winter season, were used for calibrating the energy model. The calibration procedure was carried out based on the total heating energy rate delivered at the building district heating sub-station. The case study was simulated with and without TRVs. The application of TRVs was proved to bring back significant energy savings, around 10% in compliance with results found in literature [11]. A comparison with measured data was also performed. In particular, the results of the present study were also compared to the utility energy bills of another residential existing multi-family building, subjected to the application of TRVs in the last years. The comparison with the utility bills, before and after the application of TRVs, of the other case study brought back results similar to the simulated ones presented within this study.

2. The case study

The case study hereby presented is a multi-family residential building located in the city of Turin, in North Italy. It is an existing historical building (Fig. 1) built at the beginning of XIX century.

The architectural protections and restraints for Cultural Heritage issues, shrinks quite a lot the kind of retrofit measures to be applied to the buildings. Most of them are thus not allowed, even if high energy savings, for their major impact on the building façade (e.g. external increase of thermal insulation cannot be pursued in order to preserve the original historical façade). For this reason, the type of building envelope retrofit measures that could be applied to it, are quite few, including the hereby studied application of TRVs for the space heating control.

Data collection of the building geometry and construction features came from the buildings energy certificate and technical drawings. However, for a full and correct building characterization, additional information were obtained from in situ inspections. In particular, as there were no attic plans, the in situ inspections were strictly necessary and they revealed the attic restoration, following to the issue of the building energy certificate.

The case study is a four-storey building with a total gross volume of 7820 m^3 and a 4 m floor-to-ceiling height. The typical building plan, with a gross floor area of approximately 500 m^2 is composed of three apartments, with an overall number of 12 apartments. The attic does not follow the apartment layout, but is divided into 11 small apartments/studio. The building also has a basement where the district sub-station and the respective apartments cellars are located. Except for the staircase and the basement, all areas are conditioned. Table 1 lists the main geometrical information about the case study.

With regard to the envelope, the building reflects the traditional architecture of its construction age. It is thus composed of bearing brick walls with no insulation and a pitched roof. The transparent elements are single glazing windows with a wood frame. Except for the attic interiors, the building envelope was not refurbished. Consequently, the building does not fulfill with the current Italian regulation, in terms of thermal insulation and energy conservation. As no measured data for the building envelope characterization were available, data from national manuals and standards were adopted [14,15]. In particular the U-values of the building envelope main components were defined based on the building construction age, and also modified taking into consideration the envelope decay until the current analysis.

Table 2 lists the main building envelope components U-values.

With regard to the heating system, as well as a great part of the urban dwellings in Turin, the case study is served by the district heating network. As mentioned previously, the district heating building sub-station (Fig. 2) is located in the basement and has a heating capacity of 250 kW. The supply side is composed of vertical columns and the terminal units are iron-cast radiators; some

Fig. 1. Case study photo and second floor plan.

of them still maintain the original size, others were replaced and integrated with additional components. To this regard, the on-spot investigations allowed to size correctly the apartments radiators. TRVs, which as heating control strategies will be compulsory by law from September 2016, were not present but were simulated within this study.

3. Data monitoring

Measured data of the energy supplied to building were available at the district heating sub-station of the case study and they were used for calibrating the building model. Data were available only for half heating season from January to March. The data, available in a quite short time step (6 min), were harmonized in order to fill in the possible gap in the measurements. The measured data were detailed in: total water flow rate (m^3/h), delivered heating rate (W), primary loop inlet temperature (°C), primary loop outlet temperature (°C) and outdoor dry-bulb temperature (°C). The outdoor dry-bulb temperatures were used for creating the real weather file to be used to simulate the building energy model. Maximum water flow rate and delivered heating rate were used to validate the sizing of the building system. As it is depicted in Fig. 3, the heating system operates from 5 a.m. to 9 p.m. with a 2 h stop from the 9 a.m. to 12 a.m. The highest point in power delivering is recorded in the early morning, around 6 a.m., and after the stop at mid-day.

Fig. 4 shows the trend of the measured primary and secondary loop inlet temperatures. The mean outlet temperatures were approximately 110 °C for the primary loop and 65 °C (until the end of February) for the secondary loop. Lower temperatures were recorded in the outlet secondary loop toward the end of the heating period (e.g. 50 °C in April). From the 6th until the 14th February the

Fig. 2. Case study district heating sub-station.

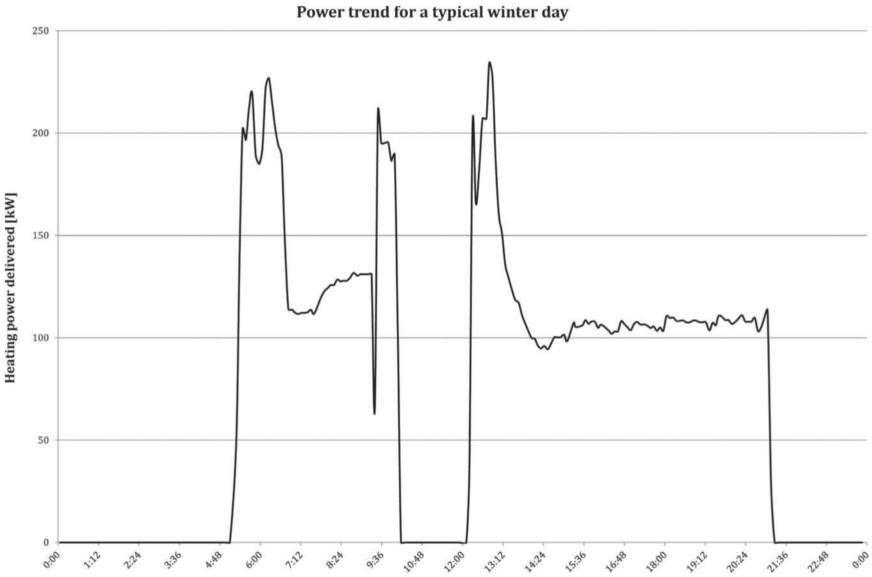

Fig. 3. Building power delivered in a typical winter day.

heating system operated continually due to atypical and extremely cold weather conditions.

4. Energy modeling

4.1. Simulation assumptions

The building energy assessment was carried out by means of dynamic simulation through a data driven approach. The building model was created within the EnergyPlus program. In particular the Openstudio plug-in for the 3d program Google Sketch-up was used to define the building geometry following imported in EnergyPlus, where the energy model was completed. The building was simulated in climatic zone E (Northern Italy). In order to evaluate the effect of each single TRV, as a common rule for the modeling, each room with a radiator, and consequently with a TRV, was defined as a thermal zone. Considering that the dwelling was a multi-family building, the building model proved to be quite detailed and complex. The thermal zoning was indeed defined depending on the day use (e.g. living room, kitchen) and night use of the rooms (e.g. bedrooms). Each apartment was divided into five main thermal zones. In order to make the model lighter, when it was possible, some rooms with the same type use, were merged into a unique thermal zone (e.g. two bedroom composed a unique thermal zone). Overall 55 conditioned thermal zones and 5 unconditioned ones were defined. Internal mass was also defined to represent the dividing ceiling/floor of the unconditioned staircases thermal zone.

Furthermore, the influence of the surrounding urban context was taken into account with the definition of shading surfaces (each one with its own reflectance proprieties), for each neighboring building, as depicted in Fig. 5.

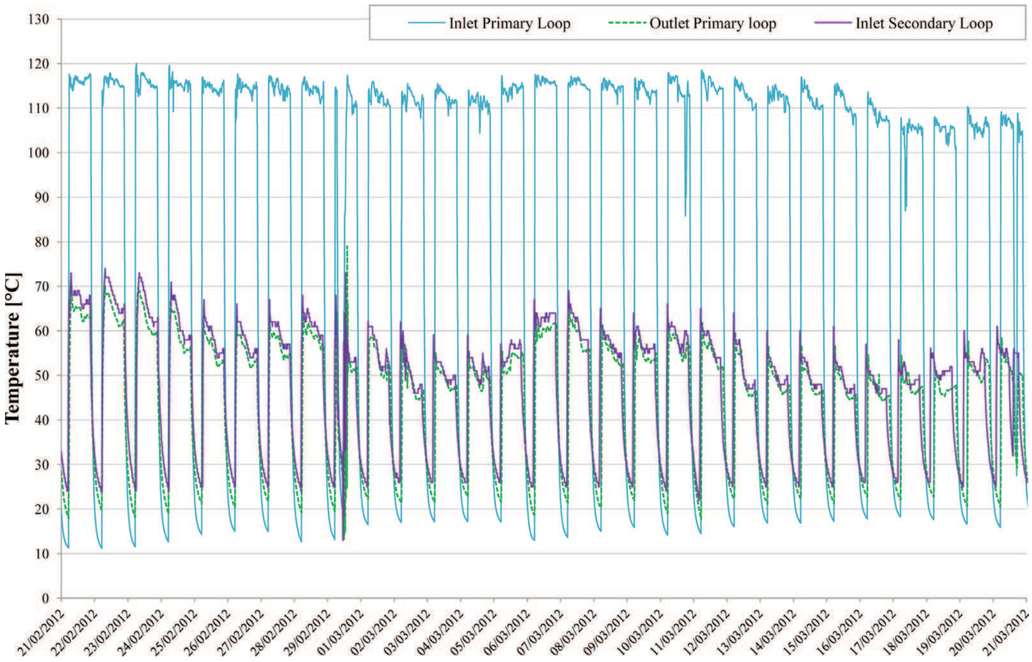

Fig. 4. Inlet temperature of primary and secondary loop trend and outlet temperature of the primary loop trend during one-month period.

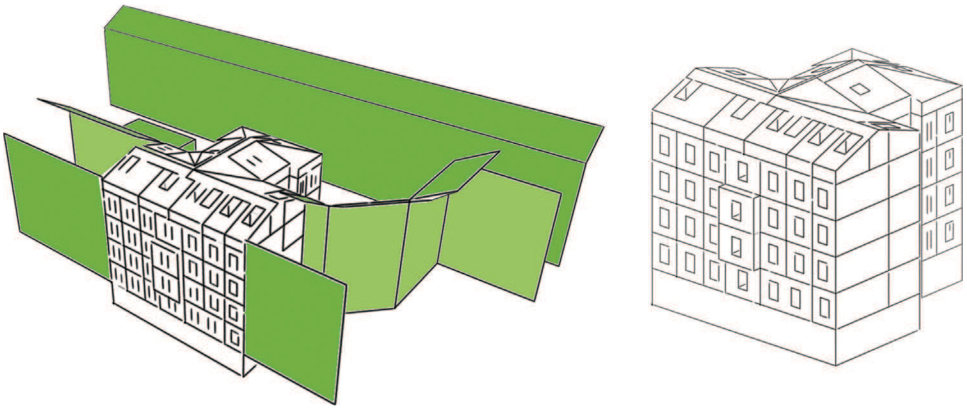

Fig. 5. View of the building model with the surrounding context.

Table 1
Case study main geometrical data.

Number of storeys	4
Number of apartments	12
Conditioned gross floor area	2114 m^2
Total gross volume	7820 m^2
Typical storey gross floor area	498 m^2
Floor-to-ceiling height	4 m
North façade	
Opaque building envelope	322 m^2
Transparent building façade	76 m^2
South façade	
Opaque building envelope	412 m^2
Transparent building façade	65 m^2
East façade	
Opaque building envelope	208 m^2
Transparent building façade	35 m^2
West façade	
Opaque building envelope	275 m^2
Transparent building façade	34 m^2

Typical Meteorological Year (TMY) data of Turin was used in first simulation runs. Secondly, for the building model calibration, a real weather file was then used.

The internal gains of the building were defined on the basis of the reference commercial building models database (which includes residential and non-residential buildings) created by the United States Department of Energy laboratories [16]. Schedules for occupancy, lighting and equipment were distinguished depending on the zone daily or night use. Lighting and appliances power densities were set respectively to 3.88 W/m^2 and 5.38 W/m^2. According to Italian regulation the occupancy rate was fixed to 0.04 pers/m^2 [17].

Natural ventilation and infiltration air flow rate was set to 0.5 ACH for dimensioning the radiator units.

The heating thermostat was set according to calibration assumptions, as reported in the next paragraph. Temperature set point are not constant during the whole day but they are set to make the heating system operates from 5 a.m. to 9 p.m., with a 2 h stop, from the 9 a.m. to 12 a.m.

Table 2
Case study envelope main components *U*-value.

Building envelope component	*U*-value [W/m^2 K]
Exterior walls	1.9
Roof	2.17
Ground slab	2.1
Attic slab	2.15
Window	4.9

4.2. Calibration assumptions

In order to compare the simulate building energy performance with measured data, the building energy model was adjusted through a calibration methodology until the simulated heating demand of the whole building matched with the monitored one.

As measured data were available for a limited period (from the end of January until the end of March), the calibration process regarded only half of the heating season. A real weather data file was created for calibrating the model. Assumptions, based on monitored data, were made in order to tune realistically the model and obtain valuable results.

A first simulation for sizing the radiator heating rate was run. From monitoring, there were no data about the heating rate portion for each radiator; only the total building heating rate was noted. Due to that, in order to proceed with the radiators sizing, on-spot investigation on a typical apartment allowed radiators typology and dimensions to be clarified. The simplified procedure of Italian Standard [18] that regards the allocation of heating and domestic hot water consumptions in multi-family buildings with central heating systems, was also used to support the correct radiators sizing. In particular the procedure allows to estimate the nominal thermal power affecting each radiator unit, depending on typology and dimensions of the terminal units.

Then, the building model was simulated without TRVs, before their installation. As already mentioned, no monitored data about the real occupants' habits were available, so the heating thermostat was defined on an expected users' behavior as pictured in Fig. 6.

The ground floor, due to its commercial use (e.g. professional bureau), has a lower heating temperature set point, set at 20.5 °C, than the higher ones, approximately 21.5–22 °C, of the upper residential floors. For the middle storey, an intermediate temperature at 21 °C was set for thermostat. During the short monitoring period, from January to March, that is less than half heating season, the total building heating energy consumption, at the district heating sub-station, amounted approximately to 59 kWh/m^2 while from calibrated simulations they were 52 kWh/m^2.

After this first simulation, during the monitored period, a complete simulation, for the whole heating season, from October 15th to April 15th, was run to assess the total building heating energy consumption with the standard TRY of the Torino location. Fig. 7 outlines the step of the procedure followed within this study.

4.3. TRVs application

The aim of the study was to simulate the obtainable effect of the application of the TRVs on a multi-family building. A scheme of the

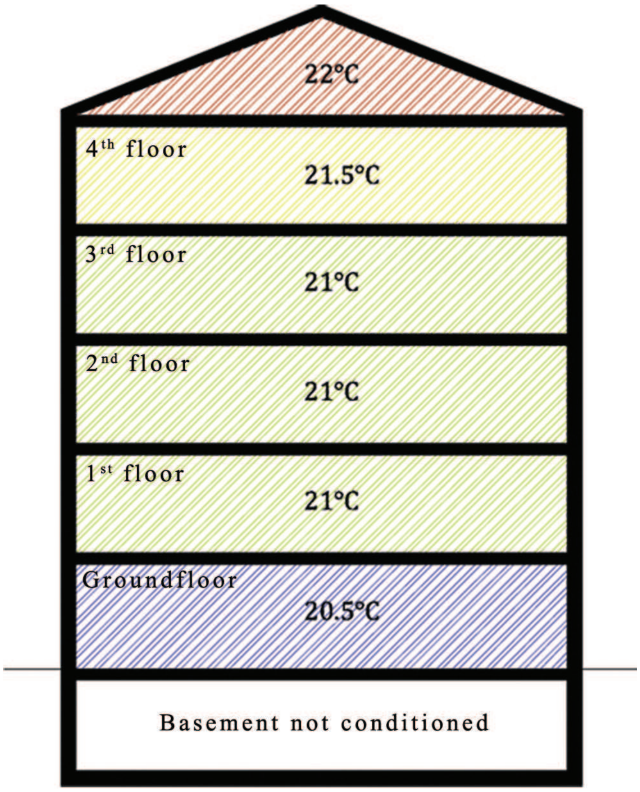

Fig. 6. Calibration heating temperature thermostat.

application of TRVs on a classical system configuration of central heating system connected to a district heating plant is pictured in Fig. 8.

No measured data about the real occupants' habits (e.g. heating temperature set point) were available. For simulating the use of the TRVs by the occupants' opening of the TRVs, different temperature set points, and thus different thermostats were defined. They were set on the basis of the occupants' habits with the TRVs setting. In literature the use of a similar approach to simulate the effect of TRVs in residential buildings through different temperature set point was also adopted [19].

Within this study, three sets of thermostat were created and applied to the building model in order to simulate different scenarios. For each scenario three different thermostats were defined. Within each scenario, a 0.50 °C gradient difference was set for every thermostat. Overall nine different solutions were tested on the model. In particular, the first solution (Scenario 1) defined a constant thermostat for all flat in all storey; three temperature set points of 20.5 °C (Scenario 1A), 21 °C (Scenario 1B), and 21.5 °C (Scenario 1C), were applied once at time as considered the most frequently set point used by the occupants. The second solution (Scenario 2) considered a different thermostat for the ground, middle and top storey, due to different boundary conditions (e.g. intermediate storey tend thus are affected by lower energy losses). For instance, the thermostat of Scenario 2A applied a 19.5 °C set point to ground floor, 20 °C set point to middle floor and 20.5 °C to the top storey. The third scenario (Scenario 3), that can be considered the most realistic one, distinguished the heating temperature set point depending on the room typology (living or sleeping area), but only in the middle storey. The thermostat in Scenario 3 C was set to 19.5 °C in the bedrooms, 20.5° in the entrance area and 21.5° in the living rooms. Ground and upper storey temperature were set in compliance with the second scenario.

5. Results

5.1. Energy assessment

Fig. 9 outlines the main results obtained from the application of the TRV of the building models through different thermostat. Nine scenarios were simulated. The blue bar represents the heating energy consumptions attributable to the calibrated building model without the thermostatic radiator valves, amounting to 115.4 kWh/m^2. The greater energy saving achieved is recorded in Scenario 3A, that with 103.4 kWh/m^2 brought to a reduction of 10% on the building heating energy consumptions. The lower reduction is indeed encountered within Scenario 1C, that achieved a 2% reduction on the energy consumptions. In general scenarios "A" (1A, 2A and 3A), which bring to greater energy savings, have lower temperature set points.

Fig. 10 draws the typical daily trend of the power delivered to the heating sub-station. The curves sketched within the graph, represent the trend attributable to Scenario 1 (1A, 1B and 1c) as well as the trend of the building before the TRVs application. The curve hereby pictured is defined from measured data. The power delivered to the building is thus reduced due to the TRVs.

A similar range of energy savings, from a minimum of 5% to a maximum of 20%, was encountered within the application of

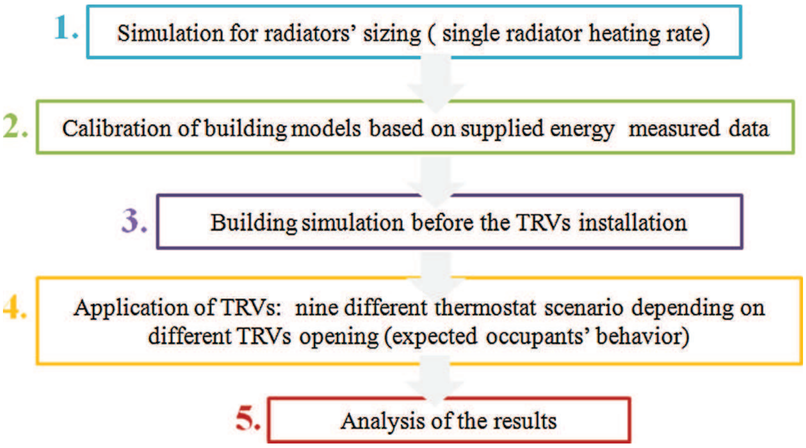

Fig. 7. Flow diagram of the methodology approach followed within the study.

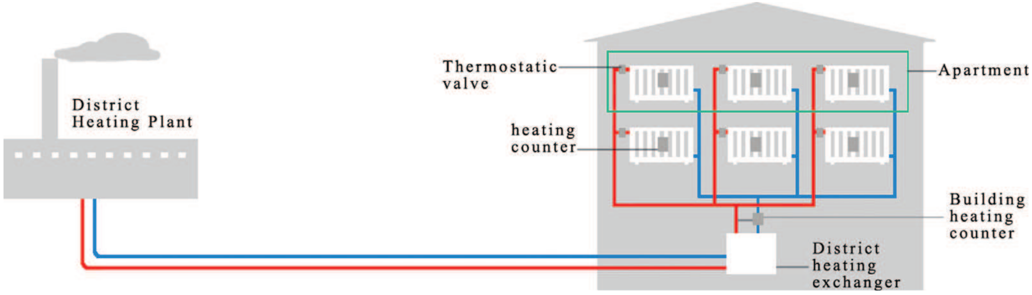

Fig. 8. System configuration: district heating plant connection with the building system.

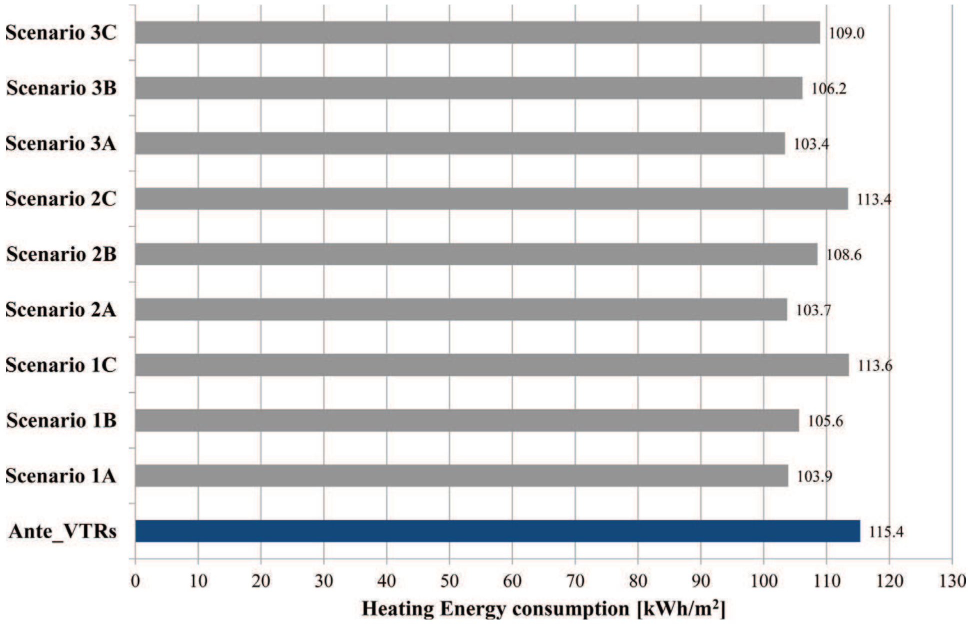

Fig. 9. Heating energy consumption of the nine different simulation scenario.

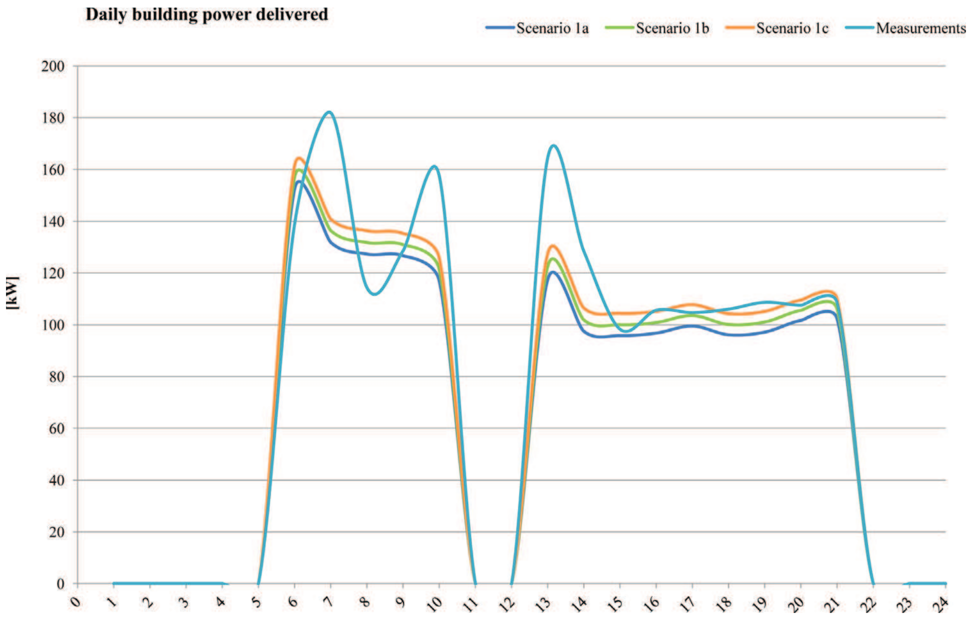

Fig. 10. Comparison of the delivered power to building within Scenario 1.

this same methodology to another multi-family building already equipped with TRVs (confidential information). Historical energy consumptions of the years previous the TRVs installation were noted in addition to the measurements coming from the district heating building sub-station. Real historical annual gas consumptions from the bills were normalized to the standard Heating Degree Days of the Turin location and aggregated into a mean value before the installation of the TRVs and a mean value after the installation of the TRVs. The percentage reduction between the values after and before TRVs was between 10% and 15% and confirmed the results of the simulations.

Table 3
Investment cost for the TRVs installation.

TRVs package per radiator	Unitary cost [€]	Total cost [€]
Valve with lockshield (supply included)	27.92	2345.28
Radiator control (supply included)	23.25	1953.00
Radiator radio heating counter (supply included)	30	2520.00
Assembly (removing of old valves and installation of new TRVs)	5.19	435.96
Energy measures at the building level		
System pump with variable flow rate	3200	6400.00
System scrubbing for removing contaminants	1830	1830.00
Total cost	15,484.24	

5.2. Economical assessment

An economical analysis was carried out in order to investigate the economical feasibility of TRVs as low investment energy efficiency measures. The cost optimal approach, required by the European Directive EPBD recast [1], is now commonly used for assessing the whole-cycle financial feasibility of EEMs in the residential sector [20,21] and was applied to the case study. The global cost, calculated for the installation of the TRVs on the case study corresponds to the net present value of costs occurred during a defined calculation period of 30 years, taking into account the residual values of the TRVs replacements. As in compliance with the European Standard EN 15459, global cost is directly linked to the duration of the calculation period τ and it can be written as:

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

where C_G (τ) 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).

The discount rate R_d is used to refer the costs to the starting year; it is expressed in real terms, hence excluding inflation, and it depends from the real interest rate, set to 4.5%. The investment costs of the TRVs were calculated with reference to the 2013 Piedmont Region price list [17] and to some technical specifications. The economical assessment considered not only the installation of the TRVs but also others measures (e.g. variable flow rate pump installation, etc.) at the building level for the implementation of TRVs. Table 3 summarizes briefly the main item considered in the economical assessment (investment cost).

With regard to the periodic cost of replacement, it was assumed that TRVs, together with the heating energy counter, should be changed after 20 years. The annual maintenance cost of the TRVs package was set to 1.5%, in compliance with the Appendix A of EN 15,459 [22]. The district heating energy tariff was set to 0.12 €/kWh with reference to the residential buildings energy rate of the main district energy company in Turin. Only the costs related to energy consumption for space were considered.

The investment cost of the TRV installation on each radiator amounts to 84 €, excluding the investment cost attributable to the whole building systems (e.g. implementation of variable flow rate pumps). Table 4 lists the disaggregated global cost components for the building without TRVs and the Scenario 1B, with TRVs.

Overall the total investment cost can be considered affordable, accounts for approximately 7.3 €/m^2. Due to a reduction on the running cost, also a lower global cost is achieved. Looking at the “Scenario 3” a mean energy savings of 9.11 kWh/m^2 was achieved. It means that in less than 7 years the overall investment cost (15,484 €) can be overcome. Considering the building is served by the district heating network, approximately 2300 €/year may be saved. If not served by the district heating grid, higher savings, around 14,000 €, may be reached.

In a view of retrofitting the existing building stock, among a wide range of EEMs, from the building envelope interventions to the improvement of the building systems, TRVs can thus be considered one of the lowest investment cost measures, that can be easily applied to a large portion of the existing dwellings, including the historical buildings. Previous studies with a view of cost optimality, investigated different packages of EEMs on a multi-family residential building, assessing much higher global cost compared to the ones presented within this study [23]. For example building envelope EEMs could thus bring to global cost values, from 650 to 680 €/m^2 while the global cost values of EEMs for the building envelope together to the building system and the integration of renewable sources, range from a minimum of 560 to 770 €/m^2.

Table 4
Global cost components for “Scenario 3”.

	Energy consumptions [kWh/m^2 year]	Investment cost [€/m^2]	Replacement cost [€/m^2]	Running cost [€/m^2]	Final value [€/m^2]	Total global cost [€/m^2]
ANTE TRV	115	0.00	0.71	303.03	−0.45	303.3
S 3A	103	7.3	2.19	275.8	−0.93	284.4
S 3B	105	7.3	2.19	283.1	−0.93	291.7
S 3C	108	7.3	2.19	290.5	−0.93	299.1

6. Conclusions

The case study was calibrated based on monitored data and then simulations were run with and without TRVs in order to evaluate their effect as a reduction on the building heating energy consumptions. The results showed that the use of TRVs can bring to a reduction on the total heating energy consumption, during a complete heating season up to a maximum of 10% for the presented case study. They also confirmed the application of TRVs to a multi-family building as low investment retrofit measure that can be easily applied also to historical buildings.

TRVs were simulated only on the basis of theoretical assumptions and expected occupants' behavior. In order to have a more accurate calibration a higher quantity and variety of monitored data is necessary. For instance, the temperature set point imposed by the occupants could improve the calibration process, helping to understand the real occupants' behavior and their comfort requirements. This information would thus have allow defining a more realistic thermostat for the TRVs regulation. Nevertheless, the calibration methodology gave back reliable results that are consistent with other studies concerning the TRVs [12].

Further studies could regard the application of a more consistent calibration methodology to the case study hereby presented; a sensitivity and uncertainty analysis-based calibration could be carried for defining the most influencing parameters for the building model calibration. Once defined them, the model could proceed to be tuned.

References

[1] European Parliament, EPBD Recast, Directive 2010/31/EU of the European Parliament and of Council of 19 May 2010 on the Energy Performance of Buildings (Recast), Official Journal of the European Union, 2010, pp. 13–25.

[2] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: methodology and state-of-the-art, Energy Build. 55 (2012) (2012) 889–902.

[3] ISTAT, L'abitazione delle famiglie residenti in Italia: Anno 2008. Statistiche in breve: famiglia e società, Italian National Institute of Statistics, 2010.

[4] M. Filippi, Remarks on the green retrofitting of historic buildings in Italy, in: Proceeding of Historical and Existing Buildings: Designing the Retrofit, Rome, 26–28th February, 2014.

[5] K. Gram-Hanssen, Existing buildings – users, renovations and energy policy, Renew. Energy 61 (2014) 136–140.

[6] M. Nocera, Le detrazioni fiscali del 55% per la riqualificazione energetica del pa-trimonio edilizio esistente 2011 published by ENEA (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile), 2013.

[7] D. Lgs. 22/01/2004, n. 42 Codice dei Beni Culturali e del Paesaggio.

[8] C. Becchio, Assessment of Energy and Cost Effectiveness in Retrofitting Existing Buildings (Ph.D. thesis), Politecnico di Torino, Italy, 2013.

[9] S.P. Corgnati, E. Fabrizio, M. Filippi, V. Monetti, Reference buildings for cost optimal analysis: method of definition and application, Appl. Energy 102 (2013) 983–993.

[10] B. Xua, A. Huangb, L. Fua, H. Dia, Simulation and analysis on control effectiveness of TRVs in district heating systems, Energy Build. 43 (2011) 1169–1174.

[11] B. Xu, L. Fu, H. Di, Dynamic simulation of space heating systems with radiators controller by TRVs in buildings, Energy Build. 40 (2008) 1755–1764.

[12] F. Tahersima, J. Stoustrup, J. Rasmussen, An analytical solution for stability-performance dilemma of hydronic radiators, Energy Build. 64 (2011) 439–446.

[13] S. Svendsen, H.M. Tommerup, M. Beck Hansen, Energy Project Villa, Technical University of Denmark, Department of Civil Engineering/Rock-wool, Denmark, 2005.

[14] I. Ballarini, S.P. Corgnati, V. Corrado, N. Talà, Building Typology Brochure – Italy, Italian TABULA Report, 2011, October, www.building-typology.eu

[15] UNI, UNI/TS 11300-1 Standard. Energy Performance of Buildings – Part 1: Evaluation of Energy Need for Space Heating and Cooling, 2011.

[16] NREL, PNNL, LBNL, U.S Department of Energy Commercial Reference Building Models of the National Building Stock, Technical Report NREL/TP-5500-46861, National Renewable Energy Laboratory, 2011.

[17] UNI, UNI 10339 Standard. Air-conditioning Systems for Thermal Comfort in Buildings. General, Classification and Requirements. Offer, Order and Supply Specifications, Italian National Body for Standard (UNI), Milan, 1995.

[18] UNI, UNI 10200 Standard. Centralized Heating Systems – Heating Costs Sharing, Italian National Body for Standard (UNI), Milan, 2005.

[19] V. Fabi, R. Andersen, S.P. Corgnati, Influence of occupant's heating set-point preferences on indoor environmental quality and heating demand in residential buildings, HVAC&R Res. 19 (2013) 635–645.

[20] M. Ferrara, E. Fabrizio, J. Virgone, M. Filippi, A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings, Energy Build. 84 (2014) 442–457.

[21] V.M. Barthelmes, C. Becchio, M.C. Bottero, S.P. Corgnati, The influence of energy targets and economic concerns in design strategies for a Residential Nearly-Zero Energy Building, Buildings 4 (2014) 937–962.

[22] EN-15459, Energy Performance of Buildings, Economic Evaluation Procedure for Energy Systems in Buildings, 2007.

[23] C. Becchio, V. Fabrizio, V. Monetti, Livelli di prestazione energetica ottimali per edifici a Energia quasi zero: il caso di un edificio multifamiliare, in: Proceeding of 67° Congresso Nazionale ATI, Trieste, 11–14 Settembre, 2012.

Paper V

E. Fabrizio, V. Monetti, *Methodologies and advancements on the calibration of building energy models*, Energies, Volume 8, Issue 4, April 2015, 2548-2574, 10.3390/en8042548.

Energies **2015**, *8*, 2548-2574; doi:10.3390/en8042548

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Review

Methodologies and Advancements in the Calibration of Building Energy Models

Enrico Fabrizio [1],†,* and Valentina Monetti [2],†

[1] DISAFA, Università degli Studi di Torino, Largo Paolo Braccini 2, 10095 Grugliasco (TO), Italy

[2] DENERG, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy;
E-Mail: valentina.monetti@polito.it

† These authors contributed equally to this work.

* Author to whom correspondence should be addressed; E-Mail: enrico.fabrizio@unito.it;
Tel.: +39-011-670-5525; Fax: +39-011-670-5516.

Academic Editor: Enrico Sciubba

Received: 16 December 2014 / Accepted: 24 March 2015 / Published: 31 March 2015

Abstract: Buildings do not usually perform during operation as well as predicted during the design stage. Disagreement between simulated and metered energy consumption represents a common issue in building simulation. For this reason, the calibration of building simulation models is of growing interest. Sensitivity and uncertainty analyses play an important role in building model accuracy. They can be used to identify the building model parameters most influent on the energy consumption. Given this, these analyses should be integrated within calibration methodologies and applications for tuning the parameters. This paper aims at providing a picture of the state of the art of calibration methodologies in the domain of building energy performance assessment. First, the most common methodologies for calibration are presented, emphasizing criticalities and gaps that can be faced. In particular the main issues to be addressed, when carrying out calibrated simulation, are discussed. The standard statistical criteria for considering the building models calibrated and for evaluating their goodness-of-fit are also presented. Second, the commonly used techniques for investigating uncertainties in building models are reviewed. Third, a review of the latest main studies in the calibrated simulation domain is presented. Criticalities and recommendations for new studies are finally provided.

Keywords: calibration methodologies; building performance simulation; sensitivity analysis; uncertainty analysis; existing buildings

---

1. Introduction

Since the mid-1970s, building simulation (BS) has emerged as an attempt to emulate reality [1] and improve on traditional manual methods to study and optimize the energy performance of buildings and systems. At first, BS was used throughout the design process, from the early stages to detailed construction phases. As Clarke pointed out [1], simulation may be used at any design stage to address relevant questions when assisting the building design practice. So far, the BS domain has grown and continuous improvements are being made to software features and, above all, to the building models robustness [2]. In response to current high and ambitious sustainability goals, building design has been recently subjected to changes, involving BS directly. As the main focus is still to reduce the energy demand of the building and optimize its energy performance, BS, as a clear response, is of growing importance. However, its potential is not fully exploited and even acknowledging the upward slope of its productivity for the last two decades, its uptake is still restricted [2]. It is much more common to see BS applications in construction or advanced design phases rather than in early phases (e.g., concept design). Despite this, a recent boost has been given to BS by its application in post-construction stages [3]. Buildings do not perform as well as predicted. Several studies have thus highlighted great discrepancies between simulated building energy performance and measured performance [3–5]. Due to this, an extensive interest in building real-monitoring and operation diagnostic has been aroused and the disagreement between measured and simulated data has thus become a primary issue in the BS domain. In order to make BS a more reliable tool for the design process, improvements towards a better match of the simulated and monitored building energy performance have emerged as an imminent need.

This particular application of building simulation is customarily called calibrated simulation (CS). It corresponds to the process of fine-tuning or of “calibrating” the simulation inputs so that the observed energy consumptions closely match those predicted by the simulation program [6]. The use of CS is growing in importance and many activities [3], mostly related to the commissioning or the assessment of the energy retrofit scenario of existing buildings, in fact require a calibration-based study. In particular, on-going and post-construction commissioning of new and existing buildings requires the use of calibrated simulation for operational optimization of control strategies or for diagnostic purposes for further prediction of energy savings [7–9].

Additionally, CS has been officially endorsed by the International Performance Measurements and Verification protocol (IPMVP) [10]. Within IPMVP two main approaches for energy savings projects are listed; retrofit isolation options (Option A and B) and whole facility options (Option C and D) [10]. Option D is a simulation-based approach that requires models to be calibrated based on measured monthly or hourly data. CS, within Option D, is the suggested procedure for performance and usage verification of the whole building or specific building components. The IMPVP approach is also applied in the Federal Energy Management Program (FEMP) Measurements and Verification (M&V) guidelines [11].

However, although many improvements have been made in BS and the use of CS is growing fast, many issues and criticalities still characterize the calibration process. When performing CS, it is important to distinguish different levels of calibration. First, depending on the monitored data available, calibration can be performed hourly, or monthly. Second, the type of in-depth analysis on the building model can regard only the building system or the whole building, also described within M&V guidelines [10].

Several studies based on calibration have been carried out [6,12–17] but as yet no universal consensus guidelines have been presented. There are thus standard criteria for validating a calibrated model but the lack of a formal and recognized methodology still makes CS a process highly dependent on the user's skills and judgments.

This paper aims at providing a review of the state of the art in the domain of calibrated simulation. In particular it reviews the current techniques used for calibrating a building model, focusing on gaps and criticalities related to CS. The paper is organized as follows: the scope and applications of CS is given in the introduction; Section 2 briefly outlines the main issues faced when calibrating a building model; Section 3 presents the statistical criteria used for judging the goodness-of-fit of the calibrated models; Section 4 reviews the most used calibration techniques in building simulation domain; Section 5 focuses on the reliability of building models and presents the techniques for investigating uncertainties; Sections 6 and 7, respectively, provide a brief description of the main CS applications and point out criticalities and gaps in CS.

2. Typical Calibration Issues

Building energy models are complex and composed of a large number of input data. When modeling a building within a simulation program, the accuracy especially relies on the ability of the user to input the parameters (input data) that results in a good model of the actual building energy use [3]. Given the large number of parameters involved, the process of calibrating a detailed energy model is a highly undetermined problem that brings to a non-unique solution [15,18].

It is quite common to use a "trial and error" method to calibrate a building model. This kind of approach, driven by experience assumptions, may bring inexperienced users to time consuming and unsolved problems. Usually building energy models are complex. Many assumptions on the building characterization, with a direct impact on the simulation results, have to be made. Moreover the process of modeling acquires higher degree of difficulty during calibration. Therefore, in order to handle properly the model complexity during calibration, the tuning process of the model parameters requires domain experts' knowledge.

It is essential to define the level of calibration to work on and, more importantly, to verify if the data collected are adequate for carrying out the calibration. To this regard, in order to compare predicted consumption with measured consumption, utility bills data are necessary; they represent the minimum requirement for CS, in terms of measurements and history data about the building. Additionally, depending on the input data available, different levels of calibration can be listed [17,18], as reported in Table 1. Utility bills are necessary for all the calibration levels. The period of availability of measured data or utility bills should be at least one-year-long in order to provide reliable results. Level 1 is a first calibration based on incomplete and split information due to the availability of nothing but as-built data.

It is thus the weakest calibration level as the information about the building definition and operation is not detailed and cannot be cross-checked with on-site visits. In Level 2 site visits or inspections allow verifying as-built data and collect more information. In Level 3, which is based on detailed audit of the case study, on-spot measurement of the building operation and energy consumption are collected. Level 4 and 5, based, respectively, on short-term and long-term monitoring, are the most detailed levels of calibration. At this level data loggers are thus installed in the building to collect all the required missing information.

Table 1. Calibration levels based on the building information available [17,18].

Calibration Levels	**Building Input Data Available**					
	Utility Bills	**As-Built Data**	**Site Visit or Inspection**	**Detailed Audit**	**Short-Term Monitoring**	**Long-Term Monitoring**
Level 1	X	X				
Level 2	X	X	X			
Level 3	X	X	X	X		
Level 4	X	X	X	X	X	
Level 5	X	X	X	X	X	X

CS is a complex process, which is usually based on the users' experience. Many issues can be faced when dealing with calibration. Previous studies [6,17–20] investigated CS application focusing on the main issues that characterize CS. In particular a very detailed review was carried out recently by Coakley *et al.* [19], about the state of the art, in the CS domain, gathering the most recent applications of CS depending on the type of building model and on the approach used (manual or automated). The review hereby presented intents to start from the background provided within [19] and integrate it with the more recent applications and findings in the CS domain. In particular, a detailed review of the current sensitivity and uncertainty analyses used for calibration is also presented aiming at underpin it as crucial and essential part of the process of calibration.

The list of the issues affecting calibration proposed by [19], revised and integrated by the authors of this paper is hereinafter provided as follows:

- Standardization. Statistical criteria are used for assessing whether or not a building model can be considered calibrated. They do not provide a method about how calibrating a building model. Therefore, so far, there is no formal and recognized standard methodology or guidelines for CS, which is usually carried out based on users' judgment and experience.
- Calibration costs. The modeling process does not represent an easy task, even for building simulation that does not require calibration. Calibrated models are far more complicated and require higher expenses than "uncalibrated" models. Calibration, as no automated procedure has been defined yet, is highly time-consuming indeed. Furthermore time and expense for collecting sub-metered data, contribute to CS costs.
- Model complexity. Depending on the type of energy model created and on the model complexity, the number of input data considered may vary. Normative quasi-steady models are simpler than transient energy models, created within energy simulation program (e.g., EnergyPlus, TRNSYS (Transient System Simulation Tool), *etc.*). The degree of simplification of the building model

concerns directly the input data, as the more complex the models is, the larger amount of input data are required.

- Model input data. Large quantity of input data are always involved in the building modeling process. However, the quantity may vary depending on the level of detail pursued in the model definition and on the data availability (e.g., problems of data quality). Measured data are sometime used for providing the model with further information (e.g., building occupancy, temperature set point, *etc.*) during validation of the calibrated model based on statistical indices.
- Uncertainty in building models. When manual calibration is carried out, a deterministic approach is usually adopted. However as not all input data affect the investigated energy consumption in the same ways, it is important to identify, throughout a screening analysis, the parameters that influence the most the building model, and define their level of uncertainty.
- Discrepancies identification. Issues concerning the reason of discrepancies between simulated consumption and measured consumption is often encountered during CS. Experienced users may be able to detect the underlying causes of the mismatch due to their building simulation skills and knowledge. These disagreements may be linked to a chain of causes or imputation errors in building model definition or also to measurements errors.
- Automation. So far, no approved automated methodology for calibration has been presented. Various CS application, based on users' experience and manual approach, can be listed. An automated methodology will so far reduce expenses and also attempt to wider the knowledge of calibration to other professionals.
- User's experience. Another issue that should be taken into consideration is the user's experience. Reddy *et al.* [17] claims that "calibration is highly dependent on the personal judgment of the analyst doing the calibration". Since from the first stages of simulation, the user's experience can affect calibration results. Even with a systematic and automated procedure, users are still responsible of CS and a more than basic knowledge of the building simulation domain is required for applying the procedure. A deep sensibility towards the modeling process may in fact reduce calibration expenses, in terms of timing and avoiding mistakes.

3. Criteria for the Model Goodness-of-Fit

So far statistical indices are the most used criteria for evaluating the accuracy of calibration and whether or not a model should be considered calibrated. These criteria determine how well simulated energy consumption matches the measured utility data at the selected time interval. They do not constitute a methodology for calibrating buildings models, but rather a measure of the goodness-of-fit of the building energy model.

After calibration has been endorsed as a methodology for the energy savings estimation, statistical indices have become the international reference criteria for the validation of calibrated models. They have been recommended by three main international bodies in the following documents:

- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guidelines 14 [21];
- International Performance Measurements and Verification protocol (IPMVP) [19]; and
- M&V guidelines for FEMP [11].

During calibration two main sets of data are needed: the simulation data set, from the building model created, and the metered data set, from the real building monitoring. The building model data set is composed of large quantity of data, among which, the most influencing parameters have to be selected in order to find a matching between simulated and measured energy consumption. Commonly the Mean Bias Error (*MBE*) and the Coefficient of variation of the Root Mean Square Error (*Cv(RMSE)*) are the two statistical indices used. The consideration of both indices allows preventing any calibration error due to errors compensation. MBE measures how closely simulated data corresponds to monitored data. It is an overall measure of how biased the data are. MBE is calculated, as reported in Equation (1), as the total sum of the difference between measured and simulated energy consumption at the calculation time intervals (e.g., month) of the considered period. The difference is then divided by the sum of the measured energy consumption.

$$MBE\ (\%) = \frac{\sum_{Period}(S-M)_{Interval}}{\sum_{Period} M_{Interval}} \times 100\% \tag{1}$$

where

- *M* is the measured energy data point during the time interval; and
- *S* is the simulated energy data point during the same time interval.

Due to a compensation effect (positive and negative values contribute to reduce *MBE* final value), *MBE* usually is not a "stand-alone" index, but it is assessed together with the *Cv(RMSE).* The Root Mean Squared Error (RMSE) is a measure of the sample deviation of the differences between the measured values and the values predicted by the model. The *Cv(RMSE)* is the Coefficient of Variation of RMSE and is calculated as the RMSD normalized to the mean of the observed values. *Cv(RMSE)* is either a normalized measure of the variability between measured and simulated data and a measure of the goodness-of-fit of the model. It specifies the overall uncertainty in the prediction of the building energy consumption, reflecting the errors size and the amount of scatter. It is always positive. Lower *Cv(RMSE)* values bring to better calibration. It is calculated as follows in Equations (2)–(4):

$$Cv(RMSE_{Period}) = \frac{RMSE_{Period}}{A_{Period}} \times 100 \tag{2}$$

$$RMSE_{Period} = \sqrt{\frac{\sum(S-M)^2_{Interval}}{N_{Interval}}} \tag{3}$$

$$A_{Period} = \frac{\sum_{Period} M_{Interval}}{N_{Interval}} \tag{4}$$

where $N_{Interval}$ is the number of time intervals considered for the monitored period.

In addition, Reddy *et al.* [6] have proposed an aggregated index that considers all three main types of the building energy uses (electricity in kWh, demand in kW, gas use in m^3). It is a weighted mean of *MBE* and *Cv* that takes into account the weight of each energy quantity on the total annual energy cost.

In order to consider a model calibrated, a threshold limit of the *MBE* and the *Cv(RMSE)* must be respected. Depending on the time interval for the calibration (monthly or hourly) and in compliance with the requirements of the Standard/Protocol considered, the limit threshold is subjected to slight differences, as reported in Table 2.

Table 2. Threshold limits of statistical criteria for calibration in compliance with [10,11,21].

Statistical Indices	Monthly Calibration			Hourly Calibration		
	St. 14	IPMVP	FEMP	St. 14	IPMVP	FEMP
MBE [%]	±5	±20	±5	±10	±5	±10
Cv(RMSE) [%]	15	-	15	30	20	30

If a model is calibrated in compliance with these limits, "it is sufficiently close to the physical reality that it is intended to simulate" [16]. However, these thresholds represent a first guidance for the building calibration and should not be taken as definite values. The presented statistical indices are related only to the predicted building energy consumption. The compliance with the thresholds can also be achieved with different models, as the solution is not unique and may not guarantee that all the model input data are correctly tuned. As stated before, calibration is an underdetermined problem.

Moreover it is important to note that this validation approach does not take into account uncertainties in the model and takes no notice of other influent parameters, such as indoor condition, temperature trend and occupancy.

4. Calibration Methodologies for Building Simulation Models

Clarke *et al.* [22] have proposed four main categories of calibration methodologies, revised also by Reddy *et al.* [16]:

(1) manual calibration methods based on an iterative approach;
(2) graphical-based calibration methods;
(3) calibration based on special tests and analysis procedures; and
(4) automated techniques for calibration, based on analytical and mathematical approaches.

Different methods, from the four main categories above, can be used during the same calibration process. For example, both graphical and mathematical/statistical methods can be used in synergy to improve the calibration of a building model. Moreover, both manual and automated calibration can be based on analytical procedures.

4.1. Manual Calibration

This first category includes all CS applications without a systematic or an automated procedure. It is based on users' experience and judgment and it is also the most commonly used in simulation applications [12,23,24]. It includes "trial and error" approaches, which are based on an iterative manual tuning of the model input parameters. Input data are altered based on the users' experience and knowledge about the building. Manual calibration corresponds thus to subjective and *ad-hoc* approaches.

4.2. Graphical Techniques

Within the manual calibration methodologies, techniques based on graphical representations and comparative displays of the results are included. They generally consist of time-series and scatter plots. Apart from classical and time-series plots [23–25] still used for calibration purposes, innovative methods have been also employed to this regard; two main techniques can be listed for their wide application:

- 3D comparative plots; and
- calibration and Characteristic signature.

4.2.1. 3D Comparative Plots

A 3D plot approach has been developed to analyze hourly differences, during the whole simulation period, between simulated and measured data [26]. This method is used for calibrating time-dependent parameters, such as schedule loads. Hourly values are computed and compared in the plot. The originality of this method relies on the increased ease of identifying even small differences in the measured and simulation data comparison. An example 3D plot, created by the authors and pictured in Figure 1 shows on a daily basis three different D graphical plots, representing measured data, simulated data and the difference between simulated and measured data, respectively. This type of representation has also been used with statistical indices (MBE and *Cv(RMSE)*) for analyzing the goodness-of-fit of the building model.

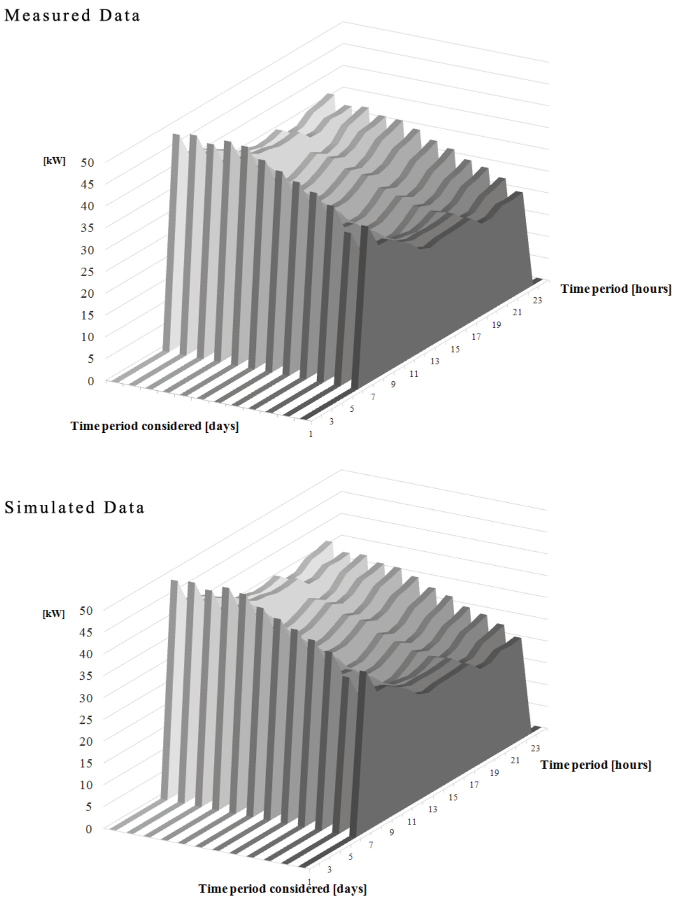

Figure 1. *Cont.*

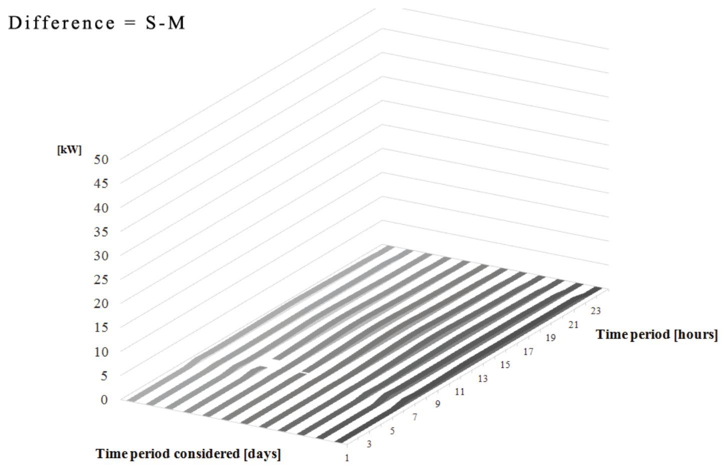

Figure 1. Example of 3D comparative plots.

4.2.2. Calibration Signature

The term signature is used to refer to a graphical representation of the difference between the simulated and the measured energy performance of a particular case study [27]. It corresponds to a normalized plot of the differences between the predicted and simulated energy consumption, as a function of the outdoor air temperature.

$$Residual = S - M \tag{5}$$

$$Calibration\ signature\ = \frac{-\ Residual}{M_{maximum}} \times 100\% \tag{6}$$

For each temperature, the difference between measured and simulated energy values, divided by the maximum measured energy value and multiplied by 100%, is plotted *versus* the temperature, to draw the trend of the signature. For a model perfectly calibrated the signature should be a flat line. An example calibration signature is depicted in Figure 2.

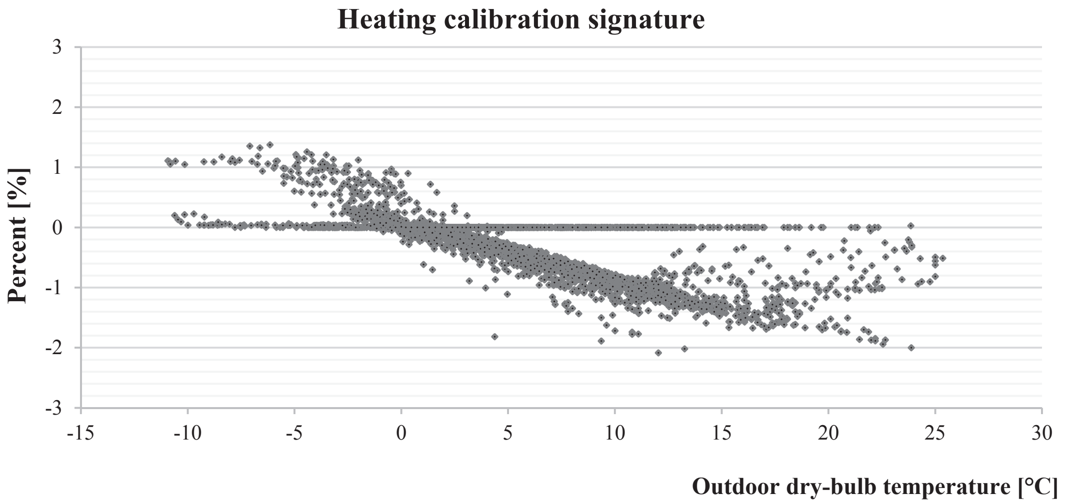

Figure 2. Example of calibration signature.

Another signature, referred as characteristic signature, should be defined for comparing values from two distinguished simulations, instead of values from measured and simulated data. The characteristic signature should be taken as reference or baseline for the measured values. Characteristic signatures are generally calculated based on a daily average basis and are denoted by a characteristic shape due to the climate and the system type considered.

$$Characteristic\ signature = \frac{Change\ in\ energy\ consumption}{M_{maximum}} \times 100\% \tag{7}$$

When assessing both characteristic and calibration signatures, the differences between the two curves help users detect errors in the simulation inputs for calibrating the model. It is thus possible to study the effect of the input parameters variation in the building models looking at the calculated signature.

A proposed methodology based on the use of the calibration and characteristic signatures is presented in [27] as a fast procedure. Assessed for both heating and cooling consumption, usually the calibration signature is compared to the characteristic signature of the investigated system configuration or studied climate, to verify if, varying one or more parameters, the signatures are similar, and an acceptable value of the combined error, $ERROR_{TOT}$, is reached. This error is calculated as follows:

$$ERROR_{TOT} = \left[\left(RMSE_{CLG}^2 + RMSE_{HTG}^2\right) + \left(MBE_{CLG}^2 + MBE_{HTG}^2\right)\right] \tag{8}$$

where

subscripts $_{HTG}$ and $_{CLG}$ refer, respectively, to the heating and cooling time intervals considered;
RSME is the Root Mean Squared Error calculated as in Equation (3); and
MBE is the Mean Bias Error calculated as in compliance with Equation (1).

When the minimum of $ERROR_{TOT}$ is achieved, then the calibration can be considered concluded.

Several applications of this methodology can be found in research and academic US studies [28–30]. In particular, it has been presented within Sub-Task D2 of the International Energy Agency ECBCS Annex 40 "Commissioning of Buildings and HVAC Systems for Improved Energy Performance" [31].

4.3. Calibration Based on Analytical Procedures

This category is based on analytical and test procedures, such as short or long-term monitoring periods. It can be distinguished from the automated methodologies as it does not employ mathematical or statistical procedure for the calibration process.

Among the special tests that can be used for calibrating the building models, measurement tests (such as blower door tests or wall thermal transmittance measures) are considered. As they are quite invasive, especially when buildings are constantly occupied, they cannot always be performed.

Short-term monitoring and *in situ* inspections can also assist the calibration process. For example, the PSTAR (Primary and Secondary Term Analysis and Renormalization) method [32] is a unified method of hourly simulations of a building and analysis of performance data, based on the use of short-term monitoring data.

The building energy balance is assessed as sum of the heat flows calculated after the audit inspection. Heat flows are assessed based on macro-dynamic calculations. Each heat flow term is then classified as primary or secondary depending on its magnitude. Primary terms are then renormalized (calibrated) based on monitored data.

Within this category, calibrations that are assisted by audit reports are also included. This builds on building verification from the audit information and technical specifications.

4.4. Automated Techniques for Calibration Based on Analytical and Mathematical Approaches

Automated techniques include all approaches that cannot be considered user driven and are built on sort of automated procedures [19]. They can be based on mathematical procedures (e.g., Bayesian calibration) or analytical approaches.

4.4.1. Bayesian Calibration

Bayesian analysis is a statistical method that employs probability theory to compute a posterior distribution for unknown parameters (θ) given the observed data (*y*). It is used for calibration purposes for incorporating directly uncertainties in the process [33,34]. Traditionally, the Bayesian technique was used for the model predictions in other domains (such as geochemistry [35] or geology [36,37]) rather than in building physics simulation. However, recently different studies [38–40] have focused on the application of this technique to the building simulation domain.

Based on the Bayesian theory [41], a set of values of the uncertain parameters θ of the energy model is formulated in order to find a matching between the simulation outcomes and the measured data *y*. Three different sources of uncertainty are investigated: parameter uncertainty in the energy model; discrepancy $\delta(x)$ between the energy model and the real building behavior; observation error $\varepsilon(x)$. A prior probability density function is assigned to each calibration uncertain parameter based on users' judgment and experience.

The formulation adopted for denoting the observation $y(x)$ is the following:

$$y(x) = \eta(x, \theta) + \delta(x) + \varepsilon(x) \tag{9}$$

Observations (*y*) are calculated as a results of simulation outcomes from the model ($\eta(x, \theta)$) having known parameters (*x*), unknown parameters (θ), observation errors ($\varepsilon(x)$) and discrepancies $\delta(x)$. A Gaussian process, based on a multivariate normal vector is adopted to denote $\eta(x,\theta)$ and $\delta(x)$. The energy model outputs are thus denoted as normal distribution. In order to solve the multivariate distribution the Markov Chain Monte Carlo algorithm is used to compute the probability density function of the calibration parameters considered. Finally a posterior distributions function of each uncertain parameter is assessed.

4.4.2. Meta-Modeling

According to Van Gelder *et al.* [42], a meta-model is a mathematical function which coefficients are determined based on a limited number of input/output combinations. Different meta-models techniques can be found in literature [42]: polynomial regression (PR), multivariate adaptive regression splines (MARS), kriging (KR), radial basis function networks (RBF), and sigmoidal neural networks (NN).

A meta-model can be defined as a "model of a model" [43] or a surrogate model that is usually used for reducing the model complexity. It is thus a simpler and computationally faster version of the model.

For instance, meta-models created within building simulation programs are based on an essential characterization of the building. This type of building energy models is defined by varying all of the input parameters of the original and more complex model within a certain range, around its baseline design. Usually for creating an *n* sample of the *p* inputs, sampling techniques, like in the Monte Carlo Analysis as further described in the paper, are used.

Once the meta-model is derived from the full original model, an optimization algorithm is applied. One of the main benefits of meta-modeling is the reduced simulation time that allow different optimization scenarios to be performed. Meta-modeling is also employed as sensitivity analysis for the assessment of the building energy performance.

4.4.3. Optimization-Based Methods

The term optimization is used in building simulation to refer to an automated approach based on numerical simulation and mathematical optimization [44,45]. Optimization-based methods are usually built on the coupling between a building simulation software (e.g., EnergyPlus, TRNSYS, *etc.*) and an optimization program (e.g., GenOpt), which employs optimization algorithms [45–47]. Simulation-based optimization has recently been used for various applications in building simulation [48–50], and also for the calibration of building models [43,51]. In order to perform the optimization, an objective function has to be set within the optimization program. Usually in calibration application the objective function is defined as a function of the difference between measured and simulated data. The optimization is thus based on the matching between a set of measured data and simulated data.

5. Model Uncertainties

Uncertainty and sensitivity analyses represent an integral part of the modeling process, especially for calibrated simulation. Saltelli *et al.* [52] claimed the relevance of sensitivity analyses in the modeling process models when dealing with uncertainties, treating the choice of the model as one of the sources of uncertainty. Recently uncertainty and sensitivity analyses have found applications in various engineering fields and especially in the building physics domain [18,33,39,53–64]. They can help overcoming gaps in the building knowledge, identifying and ranking the sources of uncertainties. As Campolongo *et al.* [54] stated, “uncertainty and sensitivity analyses study how the uncertainties in the model inputs ($X_1, X_2, \ldots, X_k$) affect the model response Y”. The uncertainty analysis (UA) aims to quantify the output variability. On the other hand, as claimed by Saltelli *et al.* [41] “sensitivity analysis (SA) is the study of how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input”.

Notwithstanding uncertainties are often overlooked in calibration studies and not included in calibration methodologies. They are referred as procedural techniques [19] that can be used to assist improving the calibration process. Nevertheless, considering that calibration is a highly under-determined problem, it is important to account for uncertainties in the model during CS. Uncertainties can thus hold a great potential for the design practice. Their identification can have a great impact on the model reliability. Uncertainty analyses may assist calibration for better probabilistic predictions, especially when analyzing different retrofit scenario or during commissioning. In fact even when the building model is created upon the “best plausible estimates”, in terms of input parameters values and building system and operation definition, disagreements between simulated and measured energy consumption may be encountered. Such discrepancies may be attributed to an incomplete knowledge of the building; the building model may thus not reflect correctly the real behavior of the building intended to be simulated.

In the building physics domain, uncertainties may result from different sources. Heo [34] identified four main categories of uncertainty sources in building models, when carrying out studies on energy retrofit analyses. Table 3 lists them.

Table 3. Source of uncertainty in building energy models [34].

Category	Factors
Scenario uncertainty	Outdoor weather conditions Building usage/occupancy schedule
Building physical/operational uncertainty	Building envelope properties Internal gains HVAC systems Operation and control settings
Model inadequacy	Modeling assumptions Simplification in the model algorithm Ignored phenomena in the algorithm
Observation error	Metered data accuracy

All four categories refer to uncertainties in the physical domain of the building. The first category "Scenario uncertainty" concerns the external environment (e.g., outdoor weather conditions) and the building use. Usually, real weather data are used for creating real weather file to be employed in simulation instead of TMY weather data. Incomplete and fragmented data can determine uncertainties in the data collection and consequently in the definition of the real weather data. Similarly, uncertainties can affect the definition of the building use, which is set by means of schedules expressing the building occupancy and operation. The second category refers to uncertainties in the building modeling, with special regard to the building envelope thermo-physical properties, the building internal gains (people, appliances, lightings, *etc.*), the HVAC definition and its operational and control settings. The third category refers to uncertainties in the building model as physical representation of the real phenomena. Each building model is thus an approximation of a real building, created on the basis of assumptions and simplifications. The last category refers to observation errors in the measured data. The data quality of measurement used for calibrating the model can affect the accuracy of the results. Therefore uncertainties in measured data have thus to be taken into account.

From literature, different methods for SA and UA can be applied. First, it is essential to distinguish two main approaches: external and internal methods [55]. Within internal methods fall all those approaches where, the mathematics equations, which the simulation models are built on, are not subjected to review. Internal methods won't be described within the present paper, as the focus of this section will be on uncertainties coming from outside the system. The deterministic approach used for defining and simulating the building models is not discussed. Indeed, external methods include all methods aiming to alter the simulation model parameters and measure the effect of their variation on the outputs. Under the umbrella of the external methods two different categories can be identified [54]: local and global approaches. The first category includes both screening methods and local methods. They are both considered One At a Time (OAT) method as one parameter (input data) is varied at time while all the others are maintained constant. Uncertainties in one parameter are thus calculated for studying how the variations affect the model output. Interactions between different model inputs are therefore overlooked. Global sensitivity methods are, on the other hands, based on varying more parameters simultaneously. They study thus the influence of uncertain input on the whole space.

5.1. Screening-Based Method

Screening analyses are local sensitivity analyses usually aimed at identifying the most important or influent parameters to be considered in further global SA.

5.1.1. Sensitivity Index

It is an OAT method and one of the simplest methods for screening the most important parameters over the investigated output in a model. Standard values and two extreme values on the standard one (minimum and maximum values) are defined for the studied model parameters. To evaluate the sensitivity of each parameter a specific measure, the sensitivity index (SI) is calculated. It corresponds to the output difference, in %, for the extreme values of the parameter considered. It is calculated for each parameter once at time. It is formulated as follows [57]:

$$SI = \frac{E_{max} - E_{min}}{E_{max}} \times 100\% \tag{10}$$

When the parameter SI changes considerably, the parameter can be considered sensitive, thus influent.

5.1.2. Differential Sensitivity Analysis

Another simple method used for carrying out a sensitivity analysis is the Differential Sensitivity Analysis method (DSA) [64]. Each parameter is varied once at a time. The measure used for assessing the variation of the input on the studied output is the influence coefficient (IC). It is a non-dimensional measure calculated as follows:

$$IC = \frac{\frac{\Delta OP}{OP_{bc}}}{\frac{\Delta IP}{IP_{bc}}} \tag{11}$$

where

OP is the output data value;
IP is the input data value; and
the subscript $_{bc}$ indicates the values referring to the baseline model.

Usually DSA is employed in compliance with other screening techniques, like the Morris method [18,64].

5.1.3. Elementary Effects

The most common screening technique is the Morris method, also known as method of the “Elementary Effects” (EE) [54,65]. It is an OAT method as well. It is one of the most effective local SA methods due to its global approach. For this reason it also considered a global SA method rather than a local one. The model sensitivity to the parameter analyzed is investigated through two measures: the mean value and standard deviation of the computed EE for each factor investigated. They are both used to rank the parameters for their influence on the output considered. For this reason this method is also referred as the EE method. The EE of a given parameter X_i at a given point is formulated as follows [54,56]:

$$EE_i = \frac{Y(x_1, x_{i-1}, x_i + \Delta_{i+1}, \dots, x_k) - Y(x_1, \dots, x_k)}{\Delta_i} \tag{12}$$

where

Y is the system output evaluated before and after the variation of the i_{th} parameter; and
Δ is an incremental effect that is a multiple of $1/(p - 1)$.

As different trajectories are defined each time a new parameter is changed, the baseline value is every time different.

For each factor k, r different elementary effects, as r different trajectories, are sampled. The mean values μ_i of the sample of r value of EE_i, as measure of the overall effect of the input X_i on the output Y, is then assessed. Moreover, the standard deviation σ_i of each of the k distributions of values of EE_i, as an expression of the interactions effects, is also computed. The formulation for μ_i and σ_i are, respectively, presented in Equations (12) and (13):

$$\mu_i = \frac{\sum_{j=1}^{r} EE_i(X^j)}{r} \tag{13}$$

$$\sigma_i = \sqrt{\frac{\sum_{j=1}^{r} [EE_i(X^j) - \mu_i]^2}{r}} \tag{14}$$

The results are usually plotted in the typical two-dimensional graph proposed by Morris [65]. Mean values μ for each parameter (on the X-axe) are compared to the corresponding standard deviation σ (on the Y-axe). The points with the highest values of both the measures are the most critical for calibration. The parameters with high standard deviations but low mean have also to be considered influential for calibration, as the lower values of μ can be attributed to compensation errors (negative and positive values).

A revised version of the Morris method has been developed by Saltelli *et al.* [18,54,56]. Instead of the mean value calculation, this version is based on the absolute value of the mean, $\mu_i^{\square}$, in order to avoid cancellation errors.

$$\mu_i^* = \frac{\sum_{j=1}^{r} \left| EE_i\ (X^j) \right|_i ()}{r} \tag{15}$$

The EE method does not allow UA as it does not take into account the shape of probability density function of the parameters. It cannot be considered a quantitative analysis as it does not quantify the parameters influence. However this method can be used to isolate the very few influent parameters and rank them among a large number of studied parameters. For this reason it has been widely employed in building energy analyses and in the first stages of calibrated simulation [38,64,66,67].

5.2. Regression Analysis

Regression analysis are used both in the early design stages, for considering different design scenarios and their impact on the building energy consumption, and in post-construction stages, for assisting the calibration of building models. Regression equations are thus employed for carrying out global sensitivity analysis to identify the most influencing parameters in the energy consumptions of the building model to be calibrated [41]. It is a method commonly used to reduce the computational costs. As statistical method, it aims to estimate the relationships between different variables in a model, investigating how a dependent variable changes based on the variation of an independent variable. Specifically it aims to estimate the regression function, which is the function of the independent variable. In particular standardized regression coefficients are used in SA for applying sensitivity rankings to the input parameters [41]. They represent a mean of the parameter influence on the model. Based on the relative magnitude of the regression coefficients, a sensitivity ranking is assessed.

Applications of similar mathematical models to the domain of building simulation can be found in literature [62,63,68,69].

5.3. Variance-Based Method

Variance-based methods aim to decompose the uncertainty of the outputs over the input variables. Usually two main sensitivity measures are assessed within this type of technique:

- first-order index, S_i, which represents the effect of the input parameter X_i on output variation y;
- total order index, S_{Ti}, that measures the effect of the parameter alone and the sensitivity of the interaction of the parameter with all other parameters, as described in Equation (16).

$$S_{Ti} = S_i + S_{ij} + S_{ik} + \cdots + S_{ijk} + \cdots \tag{16}$$

The variance-based method can cope with non-linear and non-monotonic models and appreciate the interaction effects among input factors.

5.3.1. ANOVA

The Analysis Of Variance (ANOVA) technique is a variance-based method used for global sensitivity analysis purpose [70,71]. This is a statistical technique where the output variance is divided over the input variables. The variance is a measure of the output dispersion, used to assess the relevance of each input design variable. This technique is based on the decomposition of the model variance into first-order index, second-order or higher-order indices and the total effect index.

5.3.2. FAST

The Fourier amplitude sensitivity test (FAST) was first introduced by Cukier *et al.* [72] in the 1970s and used for carrying out global SA of mathematical models. The classical FAST method [72] was used to compute only the first order sensitivity index S_i, while an extended version has been later proposed by Saltelli *et al.* [73] for the simultaneous estimation of the first and total sensitivity index, respectively, S_i and S_{Ti}, for a given factor X_i [41].

The FAST method is considered superior to other local SA methods as it allows apportioning the output variance to the variance in the input parameters [73]. It computes the individual contribution of each input factor, referred as "main effect" in Statistics, to the output variance [41,73].

Sobol [41,73] has developed a global SA method, which is considered a natural and more general extension of the FAST approach. In this case, the main effect, S_i, and the interaction terms, S_{ij}, are calculated together with higher-order terms computed by means of MCA. Both FAST and Sobol's method allow the evaluation of each parameter contribution to the variance caused by the main effect, however FAST is computationally faster than Sobol's that decomposes all the output variance indeed.

5.4. Monte Carlo Method

Monte Carlo analysis (MCA) is one of the most commonly used techniques for carrying out global sensitivity and uncertainty analysis [43,59,67,74–78]. It is based on a repeated number of simulations with a random sampling of the models input. Each uncertain model input is defined through a probability distribution. All input parameters are then varied simultaneously. MCA assesses an estimate of the overall uncertainty in the model predictions based on the uncertainties in the input parameters.

Different techniques may be used for sampling the data: random, stratified sampling and Latin Hypercube Sampling [79]. In the first case the input values are a random sample from the probability distribution. Stratified sampling is an improvement of the random technique that, based on the subdivision of the probability distribution of the input factor into different strata of equal probability, force the sample to conform to the whole distribution studied [80]. Latin Hypercube sampling is a stratified sampling where the values generated for each input factor come from a different stratum.

MCA is based on a matrix that contains, for N model runs, the randomly generated sample values of each of the input parameters under examination. MCA allows a better coverage of the sample space of the input parameters [77] as, for example with a Latin Hypercube Sampling, N, then evaluated N times, once for each row of the sample, creating an input-output map within the parameters.

6. Calibrated Simulation Applications

A list of the main and most recent applications of CS is reported in Table 4. All studies are classified according to some criteria characterizing the calibration process:

- the calibration methodology adopted;
- the calibration level pursued;
- the model complexity;
- the simulation tool used; and
- the integration of SA/UA in the calibration process.

Reddy *et al.* [6] presented a four-step general methodology for calibrating building models, which is accompanied by a detailed review of calibration techniques [17] and applied to three case studies [16]. The methodology proposed does not aim to find a unique and best calibrated solution but it rather aims to find a small set of most plausible solutions indeed. Although tested with the DOE-2, in the ASHRAE research project 1051-RP, the methodology can be applied to any simulation program. It was developed as a robust but flexible methodology for calibrating building models. The core of the methodology is represented by the sensitivity analysis for identifying the parameters that influence the most the model outputs during calibration. First a set of influential parameters are defined with their best-guess value; secondly Monte Carlo simulations are run to filter and to identify the more sensitive parameters to be tuned for calibration. The case studies were investigated for the calibration level 4. After sensitivity analysis is performed, a set of the most plausible solutions for the parameters tuning is defined to make the measured consumption match the predicted ones from the simulation program. The methodology has also been applied to other case studies [81] and used for research activities [82].

Bertagnolio *et al.* [18] developed an evidence-based calibration methodology intended to be manual but systematic [83] and applied it to a real office building. The application of the developed methodology is quite detailed, and ranges from the calibration level 1 to level 4 (see Table 1 for further specifications). The methodology builds mainly on an intensive use of a sensitivity analysis (Morris method) and (non-intrusive) measurements. The case study was modeled, based on the available measured energy use data, as a simplified building energy model. The accuracy of the building model was verified for each calibration level fulfilling the MBE and *Cv(RMSE)* statistical indices.

Eisenhower *et al.* [13] developed a systematic and automated approach for calibrating building energy models. The methodology identifies critical and influential parameters and automatically tunes them to calibrate the building model. In particular, after a first sampling of all the model parameters (2063), a sensitivity analysis was run for ranking the parameters, in terms of their impact on the output results. A quasi-Monte Carlo approach was used as SA. From 2063 input data sampled, a set of top 10 parameters was defined for the calibration stage. In order to reduce the calibration computation time a meta-model of the case study was created within the EnergyPlus program.

Heo *et al.* [34,38] applied a Bayesian calibration of normative energy models for accounting uncertainties during the retrofitting of existing buildings. Calibration was carried out to assess a set of energy retrofit measures to apply to the case study. The normative energy model of the case study was also compared with a detailed transient model created in EnergyPlus. CS is assisted by the Morris method, to screen and reduce the number of parameters to calibrate. From the results, it emerged that the calibrated normative model predicts as accurately as the calibrated transient model, but requires much lower computation time.

Raftery *et al.* [84] presented an evidence-based method for CS and applied it to a real monitored building [85]. The method aims to improve the reliability of calibrated models classifying the changes made to the building model depending on a hierarchy of sources. This hierarchy impacts on the source reliability that brings to changes in the model. These changes are stored by a control program that allows the users to review the building model and the changes made to its. After the modeling is completed, an iterative calibration is carried out until the model can be considered calibrated and its accuracy verified.

Taheri *et al.* [51] carried out an optimization-aided model calibration method and applied it to an existing university building for a five-month calibration period. Based on first monitored data, occupancy schedules were created and implemented in the EnergyPlus building model. An objective function, based on the difference between the measured and simulated zone mean air temperature was defined to calibrate the building model. The calibration process was divided into four steps in order to investigate and tune the most influent parameters, in the building model; starting from a number of eight parameters in the first calibration, the number of parameters investigated was reduced to two in the second and third calibrations, and to one in the fourth and fifth calibrations. The same method was also applied to other case studies [86–88].

Maile *et al.* [20] developed a method, named Energy Performance Comparison Methodology (EPCM), for providing feedback in the building design and operation, and especially for investigating the buildings performance problems based on a comparison of measured and simulated energy performance data. The EPCM is a three-step method: preparation, matching, and evaluation steps.

Another interesting two-step methodology was proposed by Palomo del Barrio *et al.* [89], with specific regard to the validation of empirical models. Based on the analysis of the model parameters space, the methodology first checks the model validity to detect significant disagreements between measurements and simulations in the model performance (sensitivity analysis), and then investigates the differences between model simulations and measurements (optimization of model parameters).

7. Conclusions

Due to recent interest both in studies concerning the disagreement between measured building energy consumption and predicted energy consumption by building energy simulation programs and in the assessment of the occupant behavior, the application of calibration has expanded. Assessment of occupant behavior also involves sensitivity and uncertainty analyses, since the occupancy related to the building usage is one of the main sources of uncertainty in the building simulation models. However, despite the increasing importance and use of CS, the lack of a harmonized and officially recognized procedure for performing calibration of building energy models still remains a major issue.

This study reviews the most used calibration methodologies in the domain of building simulation, aiming to highlight the pros and cons of the calibration and pointing out criticalities and gaps of such methodologies. With regard to the model complexity, automated models, based on mathematical and statistical techniques, tend to use simplified models, rather than more detailed ones, in order to reduce computational time. Manual and graphical methods may also avoid the use of highly complex models. Complex models are in fact hard to handle and to tune when using both manual methods and automated procedures. Additionally, automated methods may bring a reduction on the computational time of the calibration process. Of course even if automated methods can provide guidance to "non-properly" experienced users towards calibration, they may represent procedures, which are too complex, bringing users to a confusing and unorganized process. User's skills and knowledge constitute an essential and primary element for performing calibration; they thus directly impact on the calibration running time, regardless of the calibration method applied and the accuracy of the building models achieved.

Among the methods presented some are emerging more than others, being applied in many studies. The current trend, based on the literature review hereby presented, is the search for and use of automated methods, based on the implementation of sensitivity and uncertainty analysis, to fine-tune the models and improve thus their accuracy. This is particularly true for complex dynamic models of buildings that are used by professionals. In many cases, it is possible to have large sets of measured data, however, due to the high number of parameters of a dynamic model and the computational time necessary, the process of calibrating the model is done merely with a trial error approach. Application in the design professionals' community is the challenge that calibrated simulation will face in the next future.

Table 4. List of the most recent published application CS in the domain of building simulation.

Author	Title	Year	Journal/ Conference	Ref.	Calibration Characterization							
					Model type		**Calibration level**	**Calibration Method**		**SA/UA**	**Monitoring period**	**Simulation tool or Standard**
Palomo del Barrio, E.; Guyon, G.	Application of parameters space analysis tools for empirical model validation	2004	Energy and Buildings, 36, 23-33	[89]	-	whole building model	-	-	Optmization	SA	-	CLIM2000
Liu, S.; Henze, G.P.	Calibration of building models for supervisory control of commercial building	2005	9th International Building Simulation Association (IBPSA) Conference 2005	[48]	Detailed	whole building model	-	Automated	Optmization	-	-	EnergyPlus, GenOpt
Pan, Y.; Huang, Z.; Wu, G.	Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai	2007	Energy and Buildings, 39, 651-657	[12]	Detailed	whole building model	Level 3	Manual	Iterative	-	-	DOE-2
Reddy, T.A.; Maor, I.; Panjapornpon, C.	Calibrating Detailed Building Energy Simulation Programs with Measured Data–Part II: Application to Three Case Study Office Buildings (RP-1051)	2007	HVAC and Research, 13, 221-241	[16]	Detailed	whole building model	Level 4	Mathematical	-	Montecarlo	N.A.	DOE-2
Hassan, M.A.; Shebl, S.S.; Ibrahim, E.A.; Aglan, H.A.	Modeling and validation of the thermal performance of an affordable, energy efficient, healthy dwelling unit	2011	Journal of Building Simulation 4, 255-262	[24]	Detailed	whole building model	Level 4-5	Manual	Iterative	-	Short-term	Visual DOE-4
Liu, G.; Liu, M.	A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems	2011	Building and Environment 46, 409-420	[28]	-	whole building model	Level 4	Graphical	Calibration Signature	NA	Short-term	-
Raftery, P.; Keane, M.; Costa, A.	Calibrating whole building energy models: Detailed case study using hourly measured data	2011	Energy and Buildings 2011, 43, 3666-3679	[85]	Detailed	whole building model	Level 4	Manual	Iterative	-	Long-term	EnergyPlus
Bertagnolio, S.; Randaxhe, F.; Lemort, V.	Evidence-based calibration of a building energy simulation model: Application to an office building in Belgium	2012	12th International Conference for Enhanced Building Operations, Manchester, UK	[83]	Normative (quasi-steady)	whole building model	Level 1 to 4	-	evidence-based	Morris Method	Short-term	ISO 13790
Heo, Y.; Choudhary, R.; Augenbroe, G.A.	Calibration of building energy models for retrofit analysis under uncertainty	2012	Energy and Buildings 47, 550-560	[38]	Normative (quasi-steady)	whole building model	-	Mathematical	Bayesian	Morris Method	-	ISO 13790
Fontanella,G.; Basciotti, D.; Dubisch, F.; Judex, F.; Preisler, A.; Hettfleisch, C.; Vukovic, V.; Selke, T.	Calibration and validation of a solar thermal system model in Modelica	2012	Journal of Building Simulation 5, 293-300	[25]	Detailed	Solar System	Level 4	-	Optmization	-	Short-term	Modelica (Dymola), GenOpt

Table 4. *Cont.*

Author	Title	Year	Journal/ Conference	Ref.	Calibration Characterization							
					Model type		Calibration level	Calibration Method		SA/UA	Monitoring period	Simulation tool or Standard
Maile, T.; Bazjanac, T.; Fischer, M.	A method to compare simulated and measured data to assess building energy performance	2012	Building and Environment 56, 241-251	[90]	Detailed	whole building model	N.A.	Manual	Iterative	-	Long-term	Not specified
Parker, J.; Cropper, P.; Shao, L.	A calibrated whole building simulation approach to assessing retrofit options for Birmingham airport	2012	IBPSA-England, 1st Building Simulation and Optimization Conference, Loughborough, UK	[91]	Detailed	whole building model	Level 2	Manual (Raftery *et al.*)	Iterative	-	Long-term	IES
Kim, Y.; Yoon, S.; Park, C.	Stochastic comparison between simplified energy calculation and dynamic simulation	2013	Energy and Buildings 64, 332-342	[59]	Simplified (A), detailed (B)	whole building model	-	Matematical	Bayesian	SA-Morris Method	-	ISO 13790 (A), EnergyPlus (B)
Manfren, M.; Aste, N.; Moshksar, R.	Calibration and uncertainty analysis for computer models– A meta-model based approach for integrated building energy simulation	2013	Applied Energy 103, 627-641	[39]	Simplified and detailed	whole building model	Level 4	Mathematical	Bayesian, Meta-modelling	with Bayesian calibration	Short-term	-
O’Neill, Z.; Eisenhower, B.	Leveraging the analysis of parametric uncertainty for building energy model calibration	2013	Journal of Building Simulation 5, 365-377	[13]	meta-model	whole building model	Levels 4-5	Automated	Optmization	quasi-Montecarlo approach	Long-term	EnergyPlus, Design-Builder
Taheri, M.; Tahmasebi, F.; Mahdavi, A.	A case study of optimization-aided thermal building performance simulation calibration	2013	13th Conference of IBPSA Chambéry, France	[51]	Dynamic	whole building model	Level 4	Automated	Optmization	-	Short-term	EnergyPlus, GenOpt
Mihai, A.; Zmeureanu, R.	Calibration of an energy model of a new research center building	2014	13th Conference of IBPSA Chambéry, France	[92]	Dynamic	whole building model	Level 4	Manual	evidence-based	-	Short-term	eQuest
Mustafaraj, G.; Marini, D.; Costa, A.; Keane, M.	Model calibration for building energy efficiency simulation	2014	Applied Energy 130, 72-85	[93]	Dynamic	whole building model	Level 3-4	Manual	Iterative (based on Bertagnolio and Raftery methods)	SA	Short-term	Design-Builder, EnergyPlus
Penna, P.; Gasparella, A.; Cappelletti, F.; Tahmasebi, F.; Mahdavi A.	Optimization-based calibration of a school building based on short-term monitoring data	2014	10th European Conference on Product and Process Modeling	[88]	Detailed	whole building model	Level 3-4	Automated	Optmization	-	Short-term	TRNSYS, GenOPt

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Clarke, J.A. *Energy Simulation in Building Design*, 2nd ed.; Butterworth Heinemann: Oxford, UK, 2001.
2. Hensen, J.L.M.; Lamberts, R. Introduction to building performance simulation. In *Building Performance Simulation for Design and Operation*, 1st ed.; Hensen, J.L.M., Lamberts, R., Eds.; Spon Press: Oxfordshire, UK, 2011.
3. Claridge, D.E. Building simulation for practical operational optmization. In *Building Performance Simulation for Design and Operation*, 1st ed.; Hensen, J.L.M., Lamberts, R., Eds.; Spon Press: Oxfordshire, UK, 2011.
4. Emily, M.; Ryan, E.M.; Sanquist, T.F. Validation of building energy modeling tools under idealized and realistic conditions. *Energy Build.* **2012**, *47*, 375–382.
5. Dall'O', G.; Sarto, L.; Sanna, N.; Martucci, A. Comparison between predicted and actual energy performance for summer cooling in high-performance residential buildings in the Lombardy region (Italy). *Energy Build.* **2012**, *54*, 234–242.
6. Reddy, T.A.; Maor, I.; Panjapornpon, C. Calibrating detailed building energy simulation programs with measured data—Part I: General methodology (RP-1051). *HVAC&R Res.* **2007**, *13*, 221–241.
7. Claridge, D.E. Using simulation models for building commissioning. In Proceedings of the Fourth International Conference for Enhanced Building Operations, Paris, France, 18–19 October 2004.
8. Tian, Z.; Love, J.A. Energy performance optimization of radiant slab cooling using building simulation and field measurements. *Energy Build.* **2009**, *41*, 320–330.
9. Morrison, L.; Azebergi, R.; Walker, A. Energy modeling for measurement and verification, In Proceedings of the SimBuild 2008—Third National conference of IBPSA-USA, Berkley, CA, USA, 30 July–1 August 2008.
10. IPMVP New Construction Subcommittee. *International Performance Measurement & Verification Protocol: Concepts and Option for Determining Energy Savings in New Construction, Volume III*; Efficiency Valuation Organization (EVO): Washington, DC, USA, 2003.
11. FEMP. *Federal Energy Management Program, M&V Guidelines: Measurement and Verification for Federal Energy Projects Version 3.0*; U.S. Department of Energy Federal Energy Management Program: Washington, DC, USA, 2008.
12. Pan, Y.; Huang, Z.; Wu, G. Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai. *Energy Build.* **2007**, *39*, 651–657.
13. O'Neill, Z.; Eisenhower, B. Leveraging the analysis of parametric uncertainty for building energy model calibration. *Build. Simul.* **2013**, *6*, 365–377.
14. Tian, W. A review of sensitivity analysis methods in building energy analysis. *Renew. Sustain. Energy Rev.* **2013**, *20*, 411–419.
15. Carroll, W.L.; Hitchcock, R.J. Tuning simulate building description to match actual utility data: Methods and implementation. *ASHRAE Trans.* **1993**, *99*, 982–993.

16. Reddy, T.A.; Maor, I.; Panjapornpon, C. Calibrating detailed building energy simulation programs with measured data—Part II: Application to three case study office buildings (RP-1051). *HVAC&R Res.* **2007**, *13*, 221–241.
17. Reddy, T.A. Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty and tools. *ASHRAE Trans.* **2006**, *112*, 226–240.
18. Bertagnolio, S. Evidence-based model calibration for efficient building energy services. Ph.D. Thesis, University of Liège, Liège, Belgium, June 2012.
19. Coakley, D.; Raftery, P.; Keane, M. A review of methods to match building energy simulation models to measured data. *Renew. Sustain. Energy Rev.* **2014**, *37*, 123–141.
20. Maile, T. Comparing measured and simulated building energy performance data. Ph.D. Thesis, Stanford University, Stanford, CA, USA, August 2010.
21. ASHRAE. *ASHRAE Guideline 14-2002: Measurement of Energy Demand and Savings*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2002.
22. Clarke, J.A.; Strachan, P.; Pernot, C. An approach to the calibration of building energy simulation models. *ASHRAE Trans.* **1993**, *99*, 917–927.
23. Pedrini, A.; Westphal, F.S.; Lamberts, R. A methodology for building energy modelling and calibration. *Build. Environ.* **2002**, *37*, 903–912.
24. Hassan, M.A.; Shebl, S.S.; Ibrahim, E.A.; Aglan, H.A. Modeling and validation of the thermal performance of an affordable, energy efficient, healthy dwelling unit. *J. Build. Simul.* **2011**, *4*, 255–262.
25. Fontanella, G.; Basciotti, D.; Dubisch, F.; Judex, F.; Preisler, A.; Hettfleisch, C.; Vukovic, V.; Selke, T. Calibration and validation of a solar thermal system model in Modelica. *J. Build. Simul.* **2012**, *5*, 293–300.
26. Haberl, J.S.J.; Bou-Saada, T.E. Procedures for calibrating hourly simulation models to measured building energy and environmental data. *J. Sol. Energy Eng.* **1998**, *120*, 193–204.
27. Liu, M.; Claridge, D.E.; Bensouda, N.; Heinemeier, K.; Uk Lee, S.; Wei, G. *High Performance Commercial Building Systems: Manual of Procedures for Calibrating Simulations of Building Systems*; Lawrence Berkeley National Laboratory, 2003. Available online: http://buildings.lbl.gov/cec/pubs/E5P23T2b.pdf (accessed on 23 March 2015).
28. Liu, G.; Liu, M. A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems. *Build. Environ.* **2011**, *46*, 409–420.
29. Bensouda, N. Extending and formalizing the energy signature method for calibrating simulation and illustrating with application for three California climates. Master's Thesis, Texas A&M University, College Station, TX, USA, August 2004.
30. Kandil, A.; Love, J.A. Signature analysis calibration of a school energy model using hourly data. *J. Build. Perform. Simul.* **2014**, *7*, 326–345.
31. Claridge, D.E. *Using Whole Building Simulation Models in Commissioning. IEA Annex 40 Working Paper.* Available online: http://www.commissioning-hvac.org/files/doc/A40-D2-M4-US-TAMU-02.pdf (accessed on 23 March 2015).
32. Subbarao, K. *PSTAR—Primary and Secondary Terms Analysis and Renormalization. A Unified Approach to Building Energy Simulations and Short-Term Monitoring*; SERI/TR-254-3175; Solar Energy Research Institute: Golden, CO, USA, 1988.

33. Booth, A.T.; Choudhary, R.; Spiegelhalter, D.J. Handling uncertainty in housing stock models. *Build. Environ.* **2012**, *48*, 35–47.
34. Heo, Y. Bayesian calibration of building energy models for energy retrofit decision-making under uncertainty. Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, USA, December 2011.
35. Tierney, J.E.; Tingley, M.P. A Bayesian, spatially-varying calibration model for the TEX86 proxy. *Geochim. Cosmochim. Acta* **2014**, *127*, 83–106.
36. Zhang, W.; Arhonditsis, G.B. Predicting the Frequency of Water Quality Standard Violations Using Bayesian Calibration of Eutrophication Models. *J. Gt. Lakes Res.* **2008**, *34*, 698–720.
37. Rahn, K.; Butterbach-Bahl, K.; Werner, C. Selection of likelihood parameters for complex models determines the effectiveness of Bayesian calibration. *Ecol. Inform.* **2011**, *6*, 333–340.
38. Heo, Y.; Choudhary, R.; Augenbroe, G.A. Calibration of building energy models for retrofit analysis under uncertainty. *Energy Build.* **2012**, *47*, 550–560.
39. Manfren, M.; Aste, N.; Moshksar, R. Calibration and uncertainty analysis for computer models—A meta-model based approach for integrated building energy simulation. *Appl. Energy* **2013**, *103*, 627–641.
40. Pavlak, G.S.; Florita, A.R.; Henze, G.P.; Rajagopalan, B. Comparison of Traditional and Bayesian Calibration Techniques for Gray-Box Modeling. *J. Arch. Eng.* **2014**, *20*; doi:10.1061/(ASCE)AE.1943-5568.0000145.
41. Saltelli, A.; Tarantola, S.; Campolongo, F.; Ratto, M. *Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models*, 1st ed.; John Wiley & Sons Ltd.: Chichester, UK, 2004.
42. Van Gelder, L.; Das, P.; Janssen, H.; Roels, S. Comparative study of metamodelling techniques in building energy simulation: Guidelines for practitioners. *Simul. Model. Pract. Theory* **2014**, *49*, 245–257.
43. Eisenhower, B.; O'Neill, Z.; Narayanan, S.; Fonoberov, V.A.; Mezic, I. A methodology for meta-model based optimization in building energy models. *Energy Build.* **2012**, *47*, 292–301.
44. Nguyen, A.; Reiter, S.; Rigo, P. A review on simulation-based optimization methods applied to building performance analysis. *Appl. Energy* **2014**, *113*, 1043–1058.
45. Evins, R. A review of computational optimization methods applied to sustainable building design. *Renew. Sustain. Energy Rev.* **2013**, *22*, 230–245.
46. Attia, S. Computational optimization zero energy building design: Interviews with 28 international experts. *International Energy Agency (IEA) Task 40: Towards Net Zero Energy Buildings Subtask, B*; Université Catholique de Louvain: Louvain la Neuve, Belgium, 2012.
47. Machairasetal, V.; Tsangrassoulis, A.; Axarli, K. Algorithms for optimization of building design: A review. *Renew. Sustain. Energy Rev.* **2014**, *31*, 101–112.
48. Liu, S.; Henze, G.P. Calibration of building models for supervisory control of commercial building. In Proceedings of the Ninth International IBPSA Conference 2005, Montréal, QC, Canada, 15–18 August 2005.
49. Hani, A.; Koiv, T. Optimization of office building façades in a warm summer continental climate. *Smart Grid Renew. Energy* **2012**, *3*, 222–230.
50. Ferrara, M.; Fabrizio, E.; Virgone, J.; Filippi, M. A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings. *Energy Build.* **2014**, *84*, 442–457.

51. Taheri, M.; Tahmasebi, F.; Mahdavi, A. A case study of optimization-aided thermal building performance simulation calibration. In Proceedings of the 13th Conference of International Building Performance Simulation Association, Chambéry, France, 25–28 August 2013.
52. Saltelli, A.; Tarantola, S.; Campolongo, F. Sensitivity analysis as an ingredient of modeling. *Stat. Sci.* **2000**, *15*, 377–395.
53. Spitz, C. Analyse de la Fiabilité des Outils de Simulation et des Incertitudes de Métrologue Appliquée à L'efficacité Energétique des Bâtiments. Master's Thesis, Universitè de Grenoble, Grenoble, France, March 2012.
54. Campolongo, F.; Saltelli, A.; Cariboni, J. From screening to quantitative analysis. A unified approach. *Comput. Phys. Commun.* **2011**, *182*, 978–988.
55. Macdonald, I.A. Quantifying the Effects of Uncertainty in Building Simulation. Ph.D. Thesis, Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK, 2002.
56. Campolongo, F.; Cariboni, J.; Saltelli, A. An effective screening design for sensitivity analysis of large models. *Environ. Model. Softw.* **2007**, *22*, 1509–1518.
57. Saltelli, A.; Ratto, M.; Andres, T.F.; Campolongo, J.; Cariboni, D.; Gatelli, M.; Saisana, M.; Tarantola, S. *Global Sensitivity Analysis: The Primer*; John Wiley & Sons Ltd.: Chichester, UK, 2008.
58. Hopfe, C.J. Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization. Ph.D. Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, 2009.
59. Kim, Y.-J.; Yoon, S.-H.; Park, C.-S. Stochastic comparison between simplified energy calculation and dynamic simulation. *Energy Build.* **2013**, *64*, 332–342.
60. De Wit, S.; Augenbroe, G. Analysis of uncertainty in building design evaluations and its implications. *Energy Build.* **2002**, *34*, 951–958.
61. Saltelli, A.; Tarantola, S.; Chan, K. A quantitative, model independent method for global sensitivity analysis of model output. *Technometrics* **1999**, *41*, 39–56.
62. Wang, M.; Wright, J.; Buswell, R.; Brownlee, A. A comparison of approaches to stepwise regression for global sensitivity analysis used with evolutionary optimization. In Proceedings of the BS2013, 13th Conference of International Building Performance Simulation Association, Chambéry, France, 26–28 August 2013.
63. Dedovic, N.; Igic, S.; Janic, T.; Matic-Kekic, S.; Ponjican, O.; Tomic, M.; Savin, L. Efficiency of small scale manually fed boilers—mathematical models. *Energies* **2012**, *5*, 1470–1489.
64. Heiselberg, P.; Brohus, H.; Hesselholt, A.; Rasmussen, H.; Seinre, E.; Thomas, S. Application of sensitivity analysis in design of sustainable buildings. *Renew. Energy* **2009**, *34*, 2030–2036.
65. Morris, M.D. Factorial sampling plans for preliminary computational experiments. *Technometrics* **1991**, *33*, 161–174.
66. Corrado, V.; Mechri, H.E. Uncertainty and sensitivity analysis for building energy rating. *J. Build. Phys.* **2009**, *33*, 125–156.
67. Sanchez, D.G.; Lacarrièrea, B.; Musy, M.; Bourgesa, B. Application of sensitivity analysis in building energy simulations: Combining first- and second-order elementary effects methods. *Energy Build.* **2014**, *68*, 741–750.

68. Calleja Rodríguez, G.; Carrillo Andrés, A.; Domínguez Muñoz, F.; Cejudo López, J.M.; Zhang, Y. Uncertainties and sensitivity analysis in building energy simulation using macroparameters. *Energy Build.* **2013**, *67*, 79–87.
69. Domínguez-Muñoz, F.; Cejudo-López, J.M.; Carrillo-Andrés, A. Uncertainty in peak cooling load calculations. *Energy Build.* **2010**, *42*, 1010–1018.
70. Encinas, F.; de Herde, A. Sensitivity analysis in building performance simulation for summer comfort assessment of apartments from the real estate market. *Energy Build.* **2013**, *65*, 55–65.
71. Archer, G.; Saltelli, A.; Sobol, I. Sensitivity measures, ANOVA-like techniques and the use of bootstrap. *J. Stat. Comput. Simul.* **1997**, *58*, 99–120.
72. Cukier, R.I.; Levine, H.B.; Schuler, K.E. Nonlinear sensitivity analysis of multiparameter model systems. *J. Comput. Phys.* **1978**, *26*, 1–42.
73. Saltelli, A.; Bolado, R. An alternative way to compute Fourier amplitude sensitivity test (FAST). *Comput. Stat. Data Anal.* **1998**, *26*, 445–460.
74. Janssen, H. Monte-Carlo based uncertainty analysis: Sampling efficiency and sampling convergence. *Reliab. Eng. Syst. Saf.* **2013**, *109*, 123–132.
75. Sun, Y.; Gu, L.; Wu, C.F.W.; Augenbroe, G. Exploring HVAC system sizing under uncertainty. *Energy Build.* **2014**, *81*, 243–252.
76. Spitz, C.; Mora, L.; Wurtz, E.; Jay, A. Practical application of uncertainty analysis and sensitivity analysis on an experimental house. *Energy Build.* **2014**, *55*, 459–470.
77. Lomas, K.J.; Eppel, H. Sensitivity analysis techniques for building thermal simulation programs. *Energy Build.* **1992**, *19*, 21–44.
78. Macdonald, I.A. Comparison of sampling techniques on the performance of Monte-Carlo based sensitivity analysis. In Proceedings of the 9th Conference of International Building Performance Simulation Association, Glasgow, UK, 27–30 July 2009.
79. Sun, J.; Reddy, T.A. Calibration of building energy simulation programs using the analytic optimization approach (RP-1051). *HVAC&R Res.* **2006**, *12*, doi:10.1080/10789669.2006.10391173.
80. McKay, M.D.; BeckMan, R.L.; Conover, W.J. A comparison of three methods for selecting values of input variables in the analysis of output from computer code. *Technometrics* **2000**, *42*, 55–61.
81. Gestwick, M.J.; Love, J.A. Trial application of ASHRAE 1051-RP: Calibration method for building energy simulation. *J. Build. Perform. Simul.* **2014**, *7*, 346–359.
82. Collis, J.; Robertson, J.; Polly, B. *Evaluation of Automated Model Calibration Techniques for Residential Building Energy Simulation*; Technical Report NREL/TP-5500-60127; National Renewable Energy Laboratory: Golden, CO, USA, 2013.
83. Bertagnolio, S.; Randaxhe, F.; Lemort, V. Evidence-based calibration of a building energy simulation model: Application to an office building in Belgium. In Proceedings of the Twelfth International Conference for Enhanced Building Operations, Manchester, UK, 23–26 October 2012.
84. Raftery, P.; Keane, M.; O'Donnell, J. Calibrating whole building energy models: An evidence-based methodology. *Energy Build.* **2011**, *43*, 2356–2364.
85. Raftery, P.; Keane, M.; Costa, A. Calibrating whole building energy models: Detailed case study using hourly measured data. *Energy Build.* **2011**, *43*, 3666–3679.

86. Tahmasebi, F.; Mahdavi, A. A two-staged simulation model calibration approach to virtual sensors for building performance data. In Proceedings of the 13th Conference of International Building Performance Simulation Association, Chambéry, France, 25–28 August 2013.
87. Tahmasebi, F.; Mahdavi, A. An optimization-based approach to recurrent calibration of building performance simulation models. In Proceedings of the ECPPM2012 eWork and eBusiness in Architecture, Engineering and Construction, Vienna, Austria, 17–19 September 2014.
88. Penna, P.; Gasparella, A.; Cappelletti, F.; Tahmasebi, F.; Mahdavi, A. Optimization-based calibration of a school building based on short-term monitoring data. In Proceedings of the eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2014, Vienna, Austria, 17–19 September 2014.
89. Palomo del Barrio, E.; Guyon, G. Application of parameters space analysis tools for empirical model validation. *Energy Build.* **2004**, *36*, 23–33
90. Maile, T.; Bazjanac, T.; Fischer, M. A method to compare simulated and measured data to assess building energy performance. *Build. Environ.* **2012**, *56*, 241–251.
91. Parker, J.; Cropper, P.; Shao, L. A calibrated whole building simulation approach to assessing retrofit options for Birmingham airport. In Proceedings of the IBPSA—England 2012, First Building Simulation and Optimization Conference, Loughborough, UK, 10–11 September 2012.
92. Mihai, A.; Zmeureanu, R. Calibration of an energy model of a new research center building. In Proceedings of the 13th Conference of International Building Performance Simulation Association, Chambéry, France, 25–28 August 2013.
93. Mustafaraj, G.; Marini, D.; Costa, A.; Keane, M. Model calibration for building energy efficiency simulation. *Appl. Energy* **2014**, *130*, 72–85.

Paper VI

V. Monetti, E. Davin, E. Fabrizio, P. André, M. Filippi, *Calibration of building energy simulation models based on optimization: a case study*, 6th International Building Physics Conference, Turin, 14-147 June 2015 (Paper accepted 15/05/2015).

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2015) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

6th International Building Physics Conference, IBPC 2015

Calibration of building energy simulation models based on optimization: a case study

Valentina Monetti [1], Elisabeth Davin [2], Enrico Fabrizio [3], Philippe André [2], Marco Filippi[1]

[1]Department of Energy, Politecnico di Torino, Torino, Italy
[2]Building Energy Monitoring and Simulation, Université de Liege, Arlon, Belgium
[3]DISAFA, Università degli studi di Torino, Torino, Italy

Abstract

This study applies an optimization-based approach for calibrating building energy models using monitored data. The calibration was carried out on a test building coupling the EnergyPlus energy simulation tool with the GenOpt optimization tool. The objective function was set to minimize the difference between simulated and monitored energy consumption. For evaluating the model accuracy, the Mean Bias Error (MBE) and the Coefficient of Variation of the RMSE (Cv (RMSE)) were calculated and found consistent with ASHRAE guideline 14 limits for a model to be considered calibrated.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL.

Keywords: Calibration; Building simulation; Optimization-aided calibration; validation; Monitoring.

---

1. Introduction

So far disagreement between simulated and monitored building energy consumption has become a common research issue. To this regard today building simulation concerns not only building design but also building operation, diagnosis and commissioning [1]. In particular, an extensive interest into building monitoring and operation diagnostic led to more frequent applications of building models calibration for the energy assessment. In order to have accurate results and make simulation predictions match closely real consumptions, calibration has become an essential process to be carried out for building simulation.

Usually, when data from monitoring are not available, building models are developed based on rules-of-thumb and on designers' experience. Indeed for calibrating a building model, the definition and the process of tuning the building input data has high relevance. Among all input data, it is especially important to accurately define, by means of sensitivity and uncertainty analysis, those data having a major impact on the building energy consumption.

This study presents a methodology for calibrating building energy models based on monitored data. An optimization-based approach was chosen and carried out based on the coupling of the EnergyPlus simulation software with the GenOpt optimization program. A test building located in a Belgian university campus was selected

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL.

as case study for testing the methodology. A short monitoring period of one month, during the winter season, was investigated for calibration on an hourly basis.

2. Methodology

The aim of this study is to present a simplified methodology to be used by professionals as well as by researchers, for the calibration of dynamic building energy models. The methodology described and applied within this paper was defined referring to a detailed literature review on the most recent approaches used for calibration [2] and in particular to Tahmasebi [3]. An optimization-based calibration methodology, builds on a four-steps methodology, was studied and applied to a test building. In general, the process of optimization, as applied nowadays to building simulation, consists into finding the parameters optimal values for a better building energy performance. As applied to calibration, optimization regards the parameters tuning for a better matching with the building measured data.

In Step 1 the building energy assessment is carried out by means of a dynamic energy simulation tool. The model defined at this stage is uncalibrated and based on the design data and standard boundary conditions.

From Step 2 to Step 4, the process of calibration, divided into three sub-stages (Pre-processing, Optimization and Post-processing and Validation) is performed. Depending on the input data availability, 4 different calibration levels can be distinguished as defined by Reddy in [4], from a first one based on as-built data and a more detailed one based on audit information, inspection and monitoring. The calibration conducted within this study fulfills with calibration level 4. Step 2 “Pre-processing” represents the very first stage of calibration, regarding the collection of data to use for tuning At first, an analysis on the metered data and on the building model input data was carried out. Metered meteorological data (e.g. outdoor dry bulb air, relative humidity, etc) are used for creating a real weather file for the simulations and other data from monitoring (e.g. indoor ambient temperature, heating energy consumption) are also processed. When calibrating a building model, the presence of different sources of uncertainty [5] should be considered by means of sensitivity and uncertainty analyses. Within this study, due to the large computational time related to the use of a dynamic energy simulation tool, sensitivity and uncertainty analyses are not conducted but, based on a detailed literature review [2], a set of parameters, referred as the most influencing the building energy consumption, is defined. Each influencing parameter is constrained in a range between a lower and an upper bound, representing the relative uncertainty domain. The selected parameters are gathered into four categories (site, building envelope, operation, building system).

For calibration, the optimization objective function is set on the building heating energy consumption. Four different files to be used in the optimization phase (where EnergyPlus is coupled with GenOpt) are prepared; the initialization file specifies the files location; the configuration file sets the configuration of the simulation program; the simulation input template file as a copy of the energy model where the values of each parameter, to be altered during optimization, are replaced by its variable name; the command file specifies all the parameters to be altered in the energy model, their variation constraints and the algorithm selected to perform the optimization.

During Step 3, the optimization-based calibration is performed: the building model parameters are altered, based on constraints, until the optimization problem is solved. The optimization is defined, within the initialization file, through a specific error-minimizing objective function aimed at reducing the difference between measured and simulated data. The optimization process stops when the minimum difference is found, that means that simulated heating energy consumption of the case study matches closely the monitored data. Different optimization runs are performed to find the “best estimates” for calibration, varying within each run, different parameters in the energy model (e.g. internal gains, building envelope features, etc).

Finally, Step 4 post-processes the optimization outputs for validating the calibrated building model based on its accuracy. The Mean Bias Error (MBE), the Root Mean Square Error (RMSE) and the Coefficient of Variation of the RMSE (Cv(RMSE)) are calculated and verified to be consistent with the ASHRAE guideline 14 limits [6], respectively ±10% and 30% on hourly basis.

3. Case study

3.1. Building characteristics

The case study is the two-storey test building “Jacques Geleen”, located in the Ulg environmental campus, in Arlon, Southern Belgium. The building was chosen first for the availability of monitored data and second, considering the small and manageable dimensions (total gross floor area of 162 m^2), for the affordable time estimation either for the modelling and the simulation process. Being a test building, it is built around a climatic room, surrounded by a buffer area. At each side of the climatic room two main zones can be identified: a two storeys office area on the north-east side of the building, including a small service area on the ground floor, and a technical room on the south-east side. The climatic room ceiling faces the unconditioned attic. A schematic 3d-skecth of the ground floor is pictured in Fig.1. The building has an all wooden structure and envelope. Windows are equipped with exterior wooden blinds that were shut during monitoring.

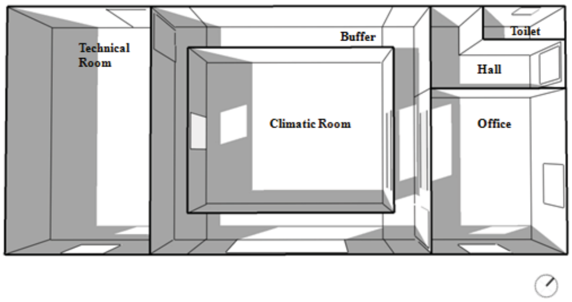

Fig. 1. Schematic 3d view of the ground floor.

3.2. Energy model

An energy model of the case study was created in EnergyPlus (version 7.0). The modeling was carried out in compliance with Step 1 of the methodology. Given the small dimensions, the modeling was quite detailed. A thermal zone was defined for each room (seven thermal zones in total); four conditioned zones (climatic room, office, buffer and upper-floor office) and three not conditioned (technical room, attic, toilet). The building envelope constructions, which U-value are reported in Table 1, were characterized in compliance with as-built technical documentation. Subsequently, during calibration, the thermal features of the building envelope material were altered. Except for the window in the upper-floor office, a wooden vertical venetian was modeled and applied to all exterior windows. Moreover, for higher accuracy in the simulations, the neighboring and buildings facing the case study were modeled as shading surfaces with their own reflectance properties.

Table 1. Thermal features of the main building envelope components of the case study.

Envelope component	Exterior wall	Roof	Ground slab	Window	Interior wall	Ceiling
U-value [Wm^2/K]	0.235	0.241	0.316	1.1	0.396	0.161

As the building is only used for experimental activities, occupancy was not considered. The definition of internal gains was limited to appliances (two computers in the office and a server in the attic) and other unlikely rated gains in the technical room. The two computers installed power was initially set to 230W based on a literature review. Based on on-spot-investigations, the server installed power was fixed to 120W. The natural ventilation and infiltration air flow rate was set to 0.43 ACH on the basis of blower door test investigations in some zones and to 0.5 ACH on the other zones. The office areas, the climatic room and the buffer were conditioned by means of electric resistances with a 20°C constant heating set point. Some resistances were equipped with PID controller and others with an on/off controller. A fan was set next to each electric resistance for diffusing the heating in the ambient air. The heating set point temperature was set as scheduled in function of the measured ambient air temperature. The monitoring period extends from the 8th of February to the 5th of March. Table 2 reports the heating energy consumption of the first “uncalibrated” energy model simulation. Even is at the whole building level simulation results are close to measured data, great discrepancies were noted between measured and simulated energy consumption in the single zones. Moreover, given the building small extent, a thermal zone calibration was chosen to be performed rather than a calibration at the whole building level.

Table 2. Measured and simulated (before calibration) heating energy consumption of the case study.

Energy consumption	Climatic Room	Buffer	Office	Office (1st floor)	Whole building
Measured [kWh/m^2]	1.0	18.9	5.9	11.4	37.2
Simulated [kWh/m^2]	4.6	16.7	4.7	10.6	36.6

3.3. Calibration

According to step 2 “Pre-processing”, metered meteorological data from the university campus weather station were processed for creating the real weather file. Other data from monitoring (e.g. indoor ambient temperature, heating energy consumption) were retrieved from ambient sensors located in the case study rooms. A set of the parameters considered as the most influent on the building energy consumption, was defined based on a detailed literature review [2]. For each parameter, a constraint, with a lower and an upper bound, was set based on spot-investigations. For the material properties parameters, the variation constraints (lower and upper bounds) were always set to 25%, while for the material thickness was limited to a 10%. An extract of the equipment internal gains parameters altered during optimization is reported in Table 3. For instance, the installed power in the attic room was set to 120W based on to on-spot measurements, while the computers power was set to 140W as initial value, with a lower bound of 80W and an upper bound of 230W, based on a literature review.

Table 3. Extract of the equipment related parameters altered during optimization.

Equipment: Power [W]	Starting value	Min	Max	Step	Variation range
Technical room	100	75	125	5	25%
Office	140	80	230	5	based on literature review
Attic	120	120	120.00	-	constant
Equipment: Radiative fraction [-]	**Starting value**	**Min**	**Max**	**Step**	**Variation range**
Technical room	0.5	0.375	0.625	5	25%
Office	0.5	0.375	0.625	5	25%
Attic	0.5	0.375	0.625	5	25%

As described in the methodology, during stage 3, the calibration was performed based on the optimization function. GenOpt was run, coupled with EnergyPlus, for optimizing the influencing parameters to make the simulated heating energy consumption match the measured one. A hybrid generalized pattern search with particle swarm optimization algorithm was used as generally recommended algorithm for problems where the cost function cannot be simply and explicitly stated, but can be approximated numerically by a thermal building simulation program. The optimization process stopped when the minimum absolute difference was found, that means that simulated heating energy consumption of the case study matched closely the monitored one. Two main sets of optimization runs were performed. First, a series of runs (from Calibration 1 to 6) was performed varying time dependent parameters (equipment, infiltration and ground temperature). Second, from Calibration 7 to 11, building envelope related parameters (thickness, density, conductivity and specific heat) were included in the optimization process. During stage 4 data from the calibration process were post-processed. For evaluating the model accuracy, the MBE and the Cv(RMSE) were calculated.

4. Results

Generally, one iteration should be sufficient to calibrate the building model. However as the process of calibration is a highly undetermined problem that leads to a non-unique solution [7], eleven calibration runs were performed. For each run, GenOpt recalled the EnergyPlus program and reached the objective function minimum after approximately 1500-1600 EnergyPlus simulations. Table 3 reports the list of the parameters involved in the GenOpt optimization process: the initial value (uncalibrated model), the defined constraints (lower and upper bound) and the final (calibrated) value for Calibration run 11 of each parameter.

Table 3. Thermal features of the case study building envelope main components for Calibration run 11.

	Initial value	**Lower bound**	**Upper bound**	**Final value**
Ground temperature				
Core	6.96	8.050	14.90	8.65
Perimeter	7.38	8.510	15.21	9.04
Internal gains				
Technical room: Power [W]	100	75	125	75
Technical Room: Radiative fraction [-]	0.5	0.25	0.75	0.35
Office: Power [W]	140	80	230	80
Office: Radiative fraction [-]	0.5	0.25	0.75	0.65
Attic: Radiative fraction [-]	0.5	0.25	0.75	0.75
Ventilation				
Office: infiltration [ACH]	0.43	0.1	1	0.3
Technical Room: infiltration [ACH]	0.5	0.1	1	0.9
Climatic Room: infiltration [ACH]	0.43	0.1	0.75	0.1
Buffer: infiltration [ACH]	0.43	0.1	0.75	0.75
Attic: infiltration [ACH]	0.5	0.1	1	0.2
Office 1st fllor: infiltration [ACH]	0.43	0.1	1	0.46
Entrance: infiltration [ACH]	0.43	0.1	1	1
Building envelope*				
OSB Panel 12mm				
Thickness [m]	0.012	0.009	0.015	0.011
Conductivity [W/ mK]	0.13	0.097	0.162	0.162
Density [kg/ m^3]	650	487	812	812
Specific Heat [J/kgK]	1880	1410	2350	2162
Rockwool 89mm				
Thickness [m]	0.089	0.07	0.11	0.08
Conductivity [W/ mK]	0.04	0.030	0.050	0.05
Density [kg/ m^3]	100	75	125	120
Specific Heat [J/kgK]	920	630	1050	874

* Only a selection of the materials parameters is reported.

MBE and CV(RMSE) were calculated and verified for each conditioned zone based on the heating building energy consumption. Table 4 reports the results of Step 4 of the calibration process (validation) related to the calibration run 5 (1st stage) and to the run 11 (second stage). MBE is always consistent with the ±10% threshold limit recommended by the ASHRAE guidelines 14 for hourly calibration, while Cv (RMSE) significantly improved during the second set of runs (run 11). In fact, in calibration run 5 MBE is consistent to the constraint limit due to compensation errors but except for the Climatic Room, the other zones are beyond the 30% limit. Initial calibration runs didn't achieve good results (MBE and Cv(RMSE) always out of threshold limits). The inclusion of non-time dependent variables, such as material proprieties, allowed considering the decaying of the building envelope and light "disagreements" between design and as-built construction, and achieving a better model performance.

Table 4. Validation results: values of MBE and Cv(RMSE) in calibration run 5 and 11.

	Heating energy consumption [kWh/m^2]			**MBE [%]**			**Cv(RMSE) [%]**		
	Measured data	run 5	run 11	Uncalibrated model	run 5	run 11	Uncalibrated model	run 5	run 11
Climatic Room	1.0	1.0	1.0	352	0.58	0.83	8696	14.34	20.40
Office	5.9	6.0	5.9	-20	2.14	-0.14	490	53.01	3.51
Office (1st floor)	11.4	11.7	11.4	-7	3.00	0.06	177	74.94	1.54
Buffer	18.9	18.5	18.9	-11	-2.22	-0.01	286	0.01	0.19

With regard to the variation of the parameters values during the calibration runs, in general the most stable parameters are those related to the building envelope, whose final values have light deviations from the respective initial values. On the contrary, the most unstable parameters are those related to the internal gains and ventilation rates. Fig.1 depicts the tuning results of some parameters. As it can be observed, for the installed power of the office computers and the infiltration rate of technical room, the tuning final value significantly varies during the calibration runs.

In particular, while computer power achieved the same final value from run 8 to 11, the infiltration rate still assumed different values. On the other hand, the variation of the materials thermal properties is milder, that means they hold a smaller influence on the optimization process.

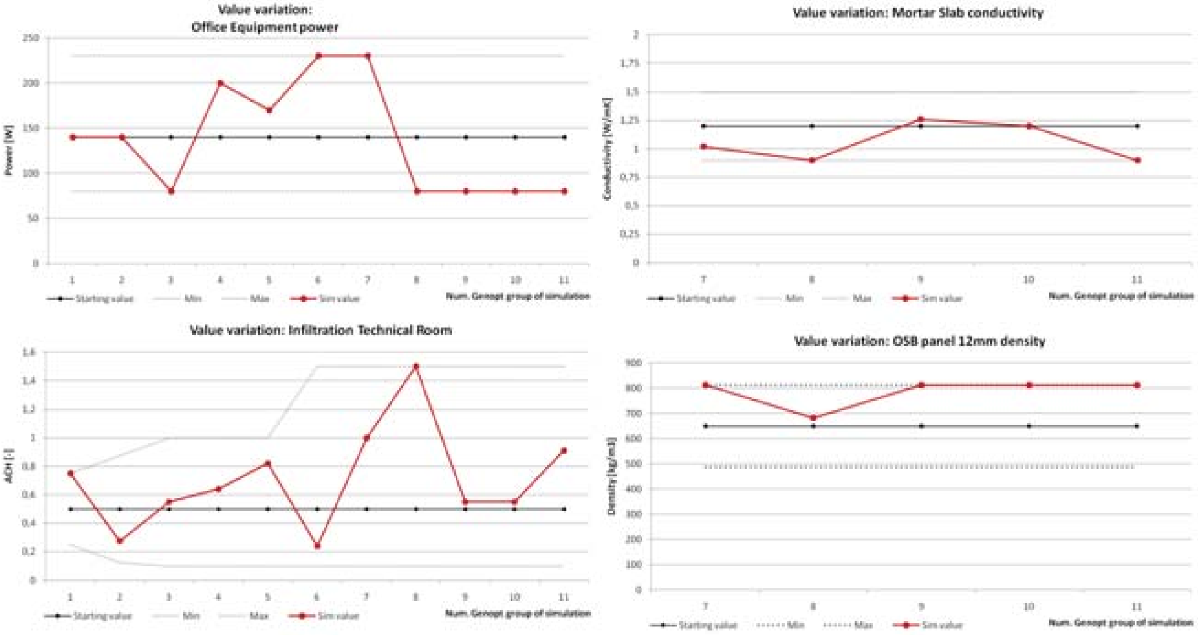

Fig. 1. Value variation of the office equipment parameters during the various calibration runs.

5. Conclusion

An optimization-based calibration was conducted on a test building for a short-term monitoring period. This automated approach was preferred to a manual approach for the possibility of including a higher number of parameters and changing simultaneously more than one parameters. The validation of the building model was based on the hourly threshold limits of the MBE and Cv(RMSE) statistical indices. Undoubtedly, further improvements can be made to refine the calibration process: statistical indices may be integrated in the optimization objective function and additional variables such as the indoor ambient temperature can be employed for calibration beyond the building energy consumption. The methodology should also be tested on more complex buildings and for a longer monitoring period.

References

[1] Claridge DE, Building simulation for practical operational optimization. In: Hensen, JLM, Lamberts R. Building performance simulation for design and operation, 1st ed. Routledge: Spon Press; 2011.

[2] Fabrizio E, Monetti E, Methodologies and advancements in the calibration of building energy models, Energies 2015, 8 (4), 2548-2574;

[3] Tahmasebi F, Mahdavi A, A two-staged simulation model calibration approach to virtual sensors for building performance data. In: Proceeding of 13th Conference of International Building Performance Simulation Association, Chambéry, France, 2013.

[4] Reddy TA, Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty and tools. ASHRAE Transactions 2006, 112, 226–240.

[5] Heo Y, Bayesian calibration of building energy models for energy retrofit decision-making under uncertainty. PhD Thesis. Georgia Institute of Technology. December 2011.

[6] ASHRAE, ASHRAE Guideline 14-2002: Measurement of Energy Demand and Savings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2002.

[7] Carroll WL, Hitchcock RJ, Tuning simulate building description to match actual utility data: Methods and implementation. ASHRAE Transactions 99, 982-34.

Ph.D candidate:

Valentina Monetti
Politecnico di Torino, Italy
Department of Energy
TEBE (Technology Energy Building Environment) research group
valentina.monetti@polito.it

University:

Politecnico di Torino, Italy
Department of Energy
Tebe Research Group

Ph.D course

Technological Innovation for the Built Environment – XXVII° cycle

Project period

12-01-2012 - 31-12-2014

Supervisors:

Marco Filippi
Full professor,
Department of Energy, Politecnico di Torino

Enrico Fabrizio
Ph.D., Assistant professor,
DISAFA, Università degli Studi di Torino