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Nearly Zero Energy Buildings: technical solutions for Mediterranean climate and influence of occupancy

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Abstract (English)

The European Union has identified construction, responsible for about 40% of global energy consumption, as the key sector for smart and sustainable growth, through the development of strategies and tools aimed at making buildings more energy efficient and comfortable. The 2010/31/EU Directive on the energy performance of buildings introduced the concept of nearly Zero Energy Building (nZEB). The nearly zero energy building is defined as "a building with very high energy performance, in which the very low or almost zero energy needs, should be significantly covered by energy from renewable sources, including energy from renewable sources produced on-site or nearby”. All new buildings must be “nearly zero energy” by 31st December 2020 and the deadline is 2018 for public buildings. The target is also extended to buildings undergoing renovation. The nZEB definition results in a set of requirements that the building has to meet in terms of characteristics of the envelope, efficiency of energy systems, and integration of renewable energy sources. The design strategies for the reduction of energy consumption vary according to the climatic conditions. Solutions typically used in cold climates, such as high thermal insulation and maximization of solar gains, may be inadequate in climates characterized by prevailing cooling requirements. Furthermore, international studies showed that the action of the occupants is crucial in the design and, even more, in the operation and maintenance of low energy buildings. In order to achieve optimal levels of comfort and energy efficiency, the dynamic interaction between the building and the users has to be considered. The present research aims to verify the feasibility of nearly Zero Energy Buildings in the Mediterranean climate, achieved through the use of advanced construction techniques and highlighting the role of thermal inertia. The study seeks to deepen the understanding of occupant behavior and the impact of occupancy modeling on the energy performance of buildings and on the actual attainment of the nZEB objective.

Abstract (Italian)

L’Unione Europea ha individuato nell’edilizia, responsabile di circa il 40% del consumo globale di energia, il settore chiave per la crescita intelligente e sostenibile, sviluppando strategie e strumenti finalizzati a rendere gli edifici energeticamente più efficienti e confortevoli. La Direttiva 2010/31/UE sulla prestazione energetica nell’edilizia ha introdotto il concetto di nearly Zero Energy Building (nZEB). L’edificio a energia quasi zero è definito come “edificio ad altissima prestazione energetica, il cui fabbisogno energetico, molto basso o quasi nullo, dovrebbe essere coperto in misura molto significativa da energia da fonti rinnovabili, compresa l’energia da fonti rinnovabili prodotta in loco o nelle vicinanze”. Entro il 31 dicembre 2020 tutti gli edifici di nuova costruzione dovranno essere a energia quasi zero e la scadenza è anticipata al 2018 per gli edifici pubblici. Il target interessa anche gli edifici sottoposti a interventi di ristrutturazione. La definizione di nZEB si traduce in una serie di requisiti che l’edificio deve rispettare in termini di caratteristiche dell’involucro, efficienza degli impianti energetici e integrazione di fonti energetiche rinnovabili. Le strategie progettuali per il contenimento dei consumi variano in funzione delle condizioni climatiche. Soluzioni tipicamente impiegate in climi freddi, come l’elevato isolamento termico e la massimizzazione degli apporti solari, possono risultare inadeguate in climi caratterizzati da prevalente fabbisogno di raffrescamento. Inoltre, studi a livello internazionale hanno evidenziato come nella progettazione e, ancor di più, nel funzionamento e mantenimento degli edifici a basso consumo energetico, sia cruciale l’azione degli occupanti. Per raggiungere livelli ottimali di comfort ed efficienza energetica è fondamentale considerare l’interazione dinamica tra la costruzione e gli utenti. Il presente lavoro di ricerca si propone di verificare la fattibilità di edifici ad energia quasi zero in clima Mediterraneo, realizzati mediante l’impiego di tecniche costruttive avanzate e mettendo in evidenza il ruolo dell’inerzia termica. Inoltre, lo studio mira ad approfondire la comprensione del comportamento degli occupanti e l’impatto della modellazione dell’occupazione sulla prestazione energetica degli edifici e sul concreto raggiungimento dell’obiettivo nZEB.

Table of contents

Introduction

The research context

Sustainable management and preservation of natural resources, together with the reduction of energy consumption and containment of emissions, are indispensable conditions to ensure the continuance of life on Earth. Global warming and the resultant dangerous climate changes have become a real threat to the survival of the human species. This issue has been highlighted for several years and governments from worldwide countries have tried to cope with its consequences by planning strategies and interventions to ensure development while protecting the environment. With this aim, at the Paris Climate Conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. The agreement set out a global action plan to limit global warming below 2°C.

The EU was the first major economy to submit its intended contribution to the new agreement in March 2015 and to undertake concrete actions including policies, legislation, and initiatives for:

- more efficient use of less polluting energy;
- cleaner and more balanced transport options;
- more environmental-friendly land-use and agriculture;
- more sustainable cities;
- more climate-resilient communities;
- fewer emissions from all sectors of the economy.

Energy production and use account for about 80% of the EU's greenhouse gas emissions. Therefore, to tackle climate change effectively, a largely “decarbonization” of energy systems by moving away from fossil fuels is required. The European Commission has published a Roadmap to a low-carbon economy which lays out the path to a competitive more climate-friendly and less energy consuming economy. In particular, the roadmap suggests that, by 2050, the EU should cut its emissions to 80% below 1990 levels through domestic reductions alone, i.e. rather than relying on international credits. All sectors need to contribute to the low-carbon transition according to their technological and economic potential. Action in all the main sectors responsible for Europe's emissions (power generation, industry, transport, buildings, construction, and agriculture) will be needed, but differences exist between sectors on the amount of reductions that can be expected, as illustrated in figure 1[1].

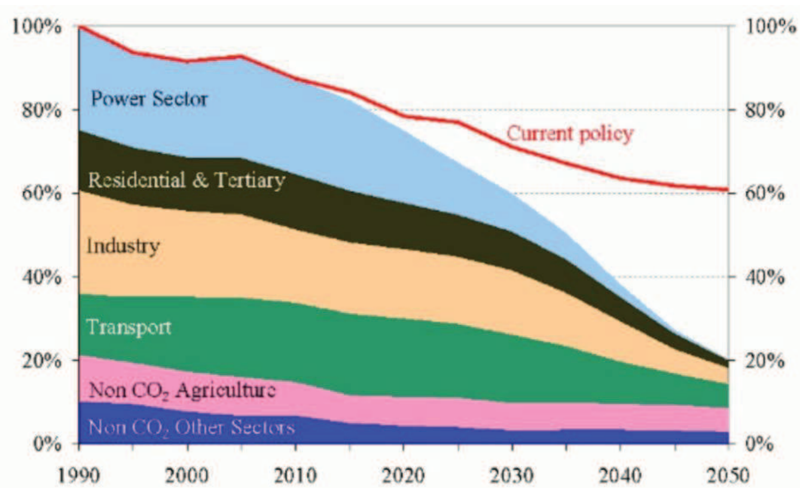

Figure 1 - Possible 80% cut in greenhouse gas emissions in the EU (100%=1990) [2].

The power sector has the biggest potential for cutting emissions and it can almost totally eliminate CO_2 emissions by 2050. Electricity could partially replace fossil fuels in transport and heating. Electricity will come from renewable sources such as wind, solar, water, and biomass or other low-emission sources like nuclear power plants or fossil fuel power stations equipped with carbon capture and storage technology. This will also require substantial investments in smart grids.

A significant contribution will also be given by the reduction of emissions in the building sector that are expected to be almost completely cut by around 90% in 2050. Energy performance will be improved by the implementation of measures such as:

- passive housing technology in new buildings
- refurbishing old buildings to improve energy efficiency
- substituting electricity and renewables for fossil fuels in heating, cooling, and cooking

In order to achieve the goals set in the agreement, buildings are increasingly being designed according to high energy performance standards, by applying bioclimatic principles and by using eco-friendly materials, able to ensure an adequate level of environmental sustainability [3]. Design criteria are addressed at obtaining buildings with "nearly zero" energy consumption [4] through the creation of high-performance building envelopes and the integration of high-efficiency heating/cooling systems powered by renewable sources [5].

Climatic context has a significant impact on the energy use of the building [6]. Different strategies are required according to the characteristics of climate which, as shown in figure 2, can vary considerably depending on the location.

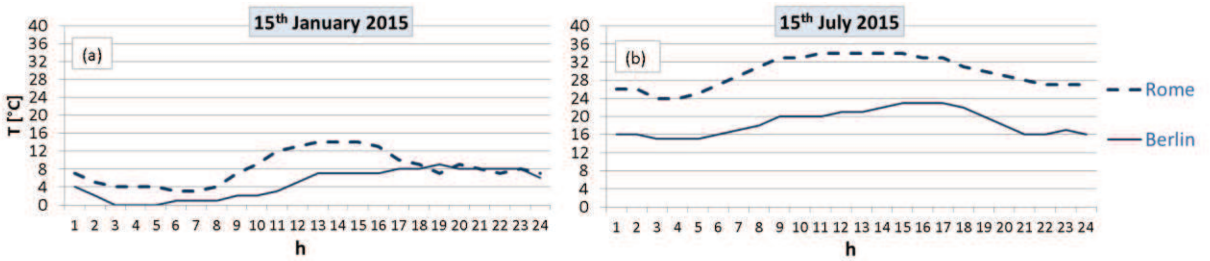

Figure 2 - Outside air temperature on a typical winter (a) and summer (b) day for two different European cities with Mediterranean (Rome) and continental (Berlin) climate [7].

Generally, in Mediterranean regions, the cooling energy demand is higher than heating requirements [8]. Therefore, typical solutions applied in low-energy buildings in cold climates consisting of the use of increased insulation thicknesses and large south-facing glazed surfaces can be unsuitable for buildings in a warm climate [9]. In fact, an excessive insulation of the envelope prevents heat transfer during summer and, moreover, transparent surfaces, although useful for the positive contribution to the heating balance in winter, can lead to an undesirable overheating in summer [10] [11]. Furthermore, the evolution of the construction market and the need to meet new requirements are leading to the overcoming of traditional construction techniques, stimulating innovation and the deployment of advanced systems, characterized by higher sustainability and able to better comply with the increasingly demanding scenario. Consequently, in place of traditional techniques consisting of masonry or reinforced concrete frames with hollow brick envelopes, innovative systems are being introduced, made of wood or steel structures and precast panels or box-structures to be completed on site. New technologies ensure faster construction times and lower construction costs. They also allow significant savings of water and energy during the building process, as well as a saving of raw materials, seeking to obtain the complete reuse of building components. However, with regard to the energy performance, the literature revealed that the application of these new construction systems has been mainly focused on buildings realized in climates with prevailing heating demand, integrating high thermal insulation thicknesses within the elements. By contrast, their application in warm climates is still quite unexplored and poses some issues since the high thermal insulation and the low thermal inertia can produce an increase in cooling demand and a thermal discomfort in summer. Thus, the use of specific strategies is required in order to make these technologies suitable for fulfilling energy requirements in a warm climate, such as the Mediterranean. As reported in the literature, different passive techniques such as natural ventilation, thermal mass, and nightly free-cooling are used to reduce summer energy needs [12]. Several authors studied the effect of various design features of massive external walls and thermal insulation on heating and cooling loads in residential and non-residential buildings [13].

Moreover, it is necessary to consider that for the actual achievement of the nearly zero energy building objective, optimization of the construction in terms of energy efficiency does not seem to be sufficient, since another crucial aspect needs to be evaluated, namely the way the building is used by its occupants. It is widely recognized, indeed, that energy consumption is not only affected by the physical properties of the building but also by the characteristics and behaviour of the users [14]. Recent studies have shown that by enhancing the energy efficiency of the building, the behaviour of the occupants tends to assume increasing importance in energy consumption [15] [16] [17] [18]. Variations in energy consumption in buildings with the same physical features are, in fact, attributable to different occupancy modes [19] [20] produced by lifestyle, personal attitudes, comfort perception, experience and household characteristics [21][22]. Factors such as age, income, education, and number of occupants have a significant impact on energy consumption [23]. Studies conducted in the U.S.A. and the Netherlands showed that physical characteristics account for only 40% to 54% of the variation in energy use [24] [25]. Nevertheless, the effect of socio-economic, cultural and demographic factors on energy use has not yet been clearly defined.

Objectives and methodology

The aim of the research is to analyse the feasibility of nearly Zero Energy Buildings in the Mediterranean area considering the active role of the occupants in the management of the house. In particular, the effectiveness and potential use of advanced technical solutions that fulfil the criteria of flexibility, adaptability, and sustainability are studied. In addition to the physical characterization of the building-plant system, the research intends to evaluate the influence of occupancy on energy consumption, through survey techniques and processing aimed at the development of occupancy profiles that can prefigure different use scenarios of the building. The research framework is schematized in figure 3.

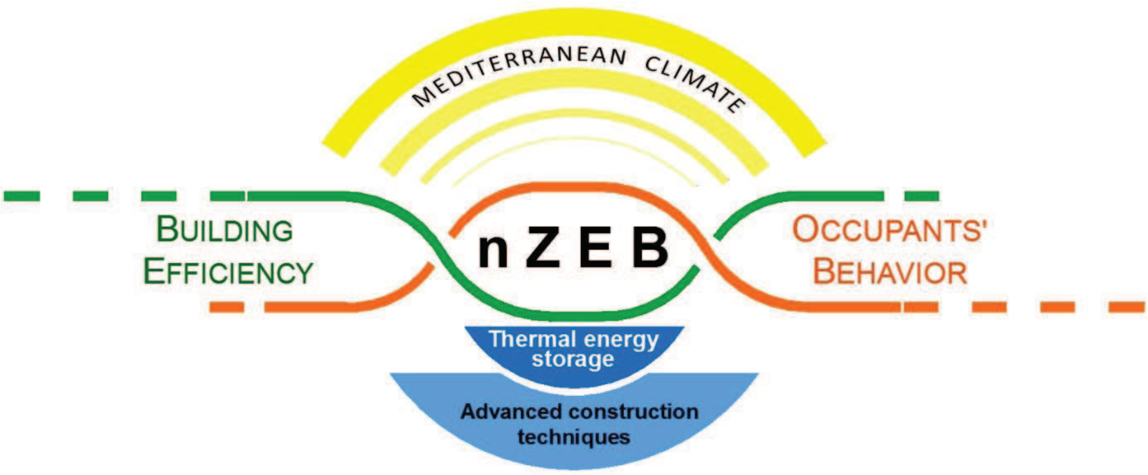

Figure 3 – Conceptual framework of the research.

The proposed issue will be addressed through the development of the following points:

- Examination of innovative and sustainable technologies for nZEBs construction;
- Modulation of shape-architecture-structure-materials to obtain nZEBs in warm climates
- Study of solutions to implement appropriate strategies able to make the building "nearly zero energy" even in the cooling season and to better exploit the thermal storage capacity of the fabric;
- Analysis of measures to improve the energy efficiency of existing buildings and cost-effectiveness evaluation;
- Investigation of the role played by occupants in the design and operation of nZEBs;
- Identification of specific characteristics of occupant behaviour in the research area;
- Description of use patterns that allow prediction of actual consumption and to avoid, or at least minimize, the differences between calculated and actual performances.

The research work requires a theoretical and practical study supported by simulation tools and experimental activities, and can be divided into the following phases:

- Investigation of the different approaches and indicators used for the definition of nZEB obtained from new constructions or from the renovation of existing buildings, and application in the national context;
- Testing of solutions combining passive and activities strategies, i.e. thermal mass and renewable energy sources, to bring the building's balance close to "zero";
- Data collection through monitoring in test sites;
- Assessment of the building energy performance by dynamic simulation;
- Implementation of optimization algorithms;
- Data collection through questionnaires and subsequent statistical processing aimed at identifying the social and behavioural characteristics of the occupants in the analysis area;
- Definition of occupancy profiles based on user preferences and habits.

Expected results

The research will allow evaluation of the effectiveness of innovative building systems for the construction of nearly zero energy buildings. Technical solutions suitable for the Mediterranean climate are expected to be identified and the validity of strategies aimed at limiting cooling requirements will be verified.

The research will also help in clarifying the influence of occupants in the variation of energy consumption and in defining occupancy models to be used in the design phase in order to achieve a better correspondence between simulated and real behaviour.

Thesis structure

The diagram in figure 4 summarizes the thesis structure. The work is divided into six chapters. The first chapter deals with the definition and concept of Zero Energy buildings at different levels. The second chapter focuses on constructive and technological solutions for newly built edifices and the strategic function of thermal inertia is deepened in chapter 4. Chapter 5 tackles the problem of building retrofitting and economic optimization. The impact of occupancy on building energy performance is faced in chapter 5 while chapter 6 concerns the definition of occupancy profiles. The main findings are summarized in the Conclusions.

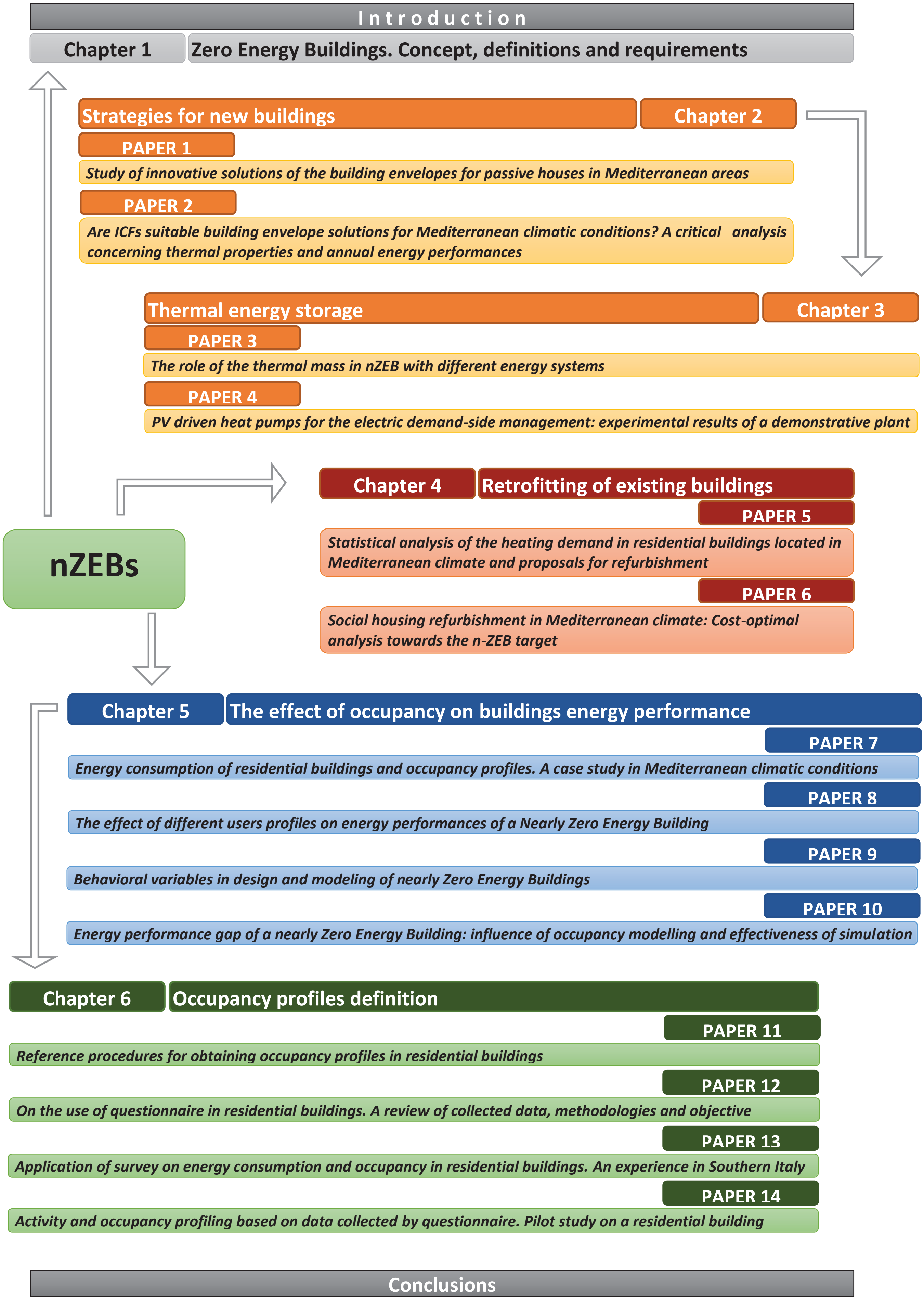

Figure 3 – Thesis structure.

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Chapter 1

Zero Energy Buildings: concept, definitions and requirements

The "low-energy" building concept has evolved over time. There are several standards that identify high energy efficiency buildings and the most recent definition concerns the "zero-energy" label. Although the idea that a zero energy building should use low energy is quite clear, when seeking to codify it into quantitative requirements the definition has raised numerous questions and it is still widely debated.

1.1. Zero Energy Buildings: a review of definitions around the world

As reported by [1], different examples of definitions of zero carbon or zero energy buildings can be found in literature (Table 1) and understanding what they mean on a measurable level is often a complex and challenging task.

Table 1. Summary of net zero and zero-energy building definitions from literature.

Source	Definition
[2]	A **zero-energy house (ZEH)** is considered to be self-sufficient in space heating and hot water supply during normal climate conditions in Denmark.
[3]	A **ZEH** is defined as a house where no fossil fuels are consumed, and annual electricity consumption equals annual electricity production. Unlike the autarkic situation, the electricity grid acts as a virtual buffer with annually balanced delivers and returns.
[4]	A **ZEH** is one that optimally combines commercially available renewable energy technology with the state-of-the-art energy efficiency construction techniques. In a zero energy home no fossil fuels are consumed and its annual electricity consumption equals annual electricity production. A zero energy home may or may not be grid-connected. In a zero-energy home annual energy consumption is equal to the annual energy production using one or more of the available renewable energy resources.
[5]	Homes that utilise solar thermal and solar photovoltaic (PV) technologies to generate as much energy as their yearly load are referred to as net zero energy solar homes (**ZESH**).
[6]	A **zero energy building (ZEB)** is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable energy technology.
[7]	A **net-zero energy (NZE)** commercial building is a high-performance commercial building designed, constructed and operated: (1) to require a greatly reduced quantity of energy to operate; (2) to meet the balance of energy needs from sources of energy that do not produce greenhouse gases; (3) to act in a manner that will result in no net emissions of greenhouse gases; and (4) to be economically viable.
[8]	A **net-zero energy home** is a home that, over the course of a year, generates the same amount of energy it consumes. A net-zero energy home could generate energy through PV panels, a wind turbine or a biogas generator.
[9]	A **ZEH** produces as much energy as it consumes in a year
[10]	**Zero net energy buildings** are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grid. Seen in these terms, they do not need any fossil fuel for heating, cooling, lighting or other energy uses, although they sometimes draw energy from the grid.
[11]	**Net zero-energy buildings (nZEB)** are those producing as much energy on an annual basis as it consumes on-site, usually with renewable energy sources such as PV or small-scale wind turbines

[12]	The **nearly zero** or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.
[13]	The **nZEB** concept can be defined as a building that over a year is neutral meaning that it delivers as much energy to the supply grid as it uses from the grid.
[14]	The understanding of an **nZEB** is primarily based on the annual balance between energy demand and energy generation on the building site. An **nZEB** operates in connection with an energy infrastructure such as the power grid.
[15]	A **life cycle zero-energy building (LC-ZEB**) is one where the primary energy used in the building in operation plus the energy embodied within its constituent materials and systems, including energy generating ones, over the life of the building is equal to or less than the energy produced by its renewable energy systems within the building over their lifetime.
[16]	A **nZEB** can be succinctly described as a grid-connected building that generates as much energy as it uses over a year. The 'net zero' balance is attained by applying energy conservation and efficiency measures and by incorporating renewable energy systems.
[17]	A **nZEB** is a building with greatly reduced energy demand that can be balanced by an equivalent on-site generation of electricity, or other energy carriers, from renewable sources.
[18]	A **ZEB** combine shighly energy-efficient building designs, technical systems and equipment to minimise the heating and electricity demand withon-site renewable energy generation typically including a solar hot water production system and a roof top PV system. A ZEB can be off or on-grid.

The definitions can be summarised in the following equations [1]. The period of balance or comparison can be a month, a year or a different time span. If the balance in an energy equation is higher than zero, a net positive energy building is obtained.

(1) Net zero site energy:

$$r_s - m \geq 0$$

Where *m* is the consumption measured by the utility metre and r_s is the measured renewable energy produced on site.

(2) Net zero-source energy

$$r_s - (m+g) \geq 0 \quad \text{or} \quad r_s - p \geq 0$$

Where $p = (m + g)$ is primary energy and *g* is the energy losses in the utility system due to energy conversion and transmission.

(3) Near zero energy

$$r_{sn} - p \approx 0$$

Where r_{sn} is the renewable energy produced on-site or nearby by the building owner.

(4) Net zero cost (i.e. the financial value of the energy produced equals that of the required energy. This though does not mean the two balance in energy or carbon units, as they may be from different sources, for example production of electricity but use of natural gas. Being a financial balance, the approach might be naturally attractive to building owners.):

$$\$r_{sn} - \$m \geq 0$$

Where $\$m$ is the cost of purchased grid-based energy and $\$r_{sn}$ is the income from the renewable energy produced on-site or nearby by the building owner.

(5) Net zero exergy

$$\sum \epsilon_{ex} - \sum \epsilon_{im} \geq 0$$

Where $\Sigma\epsilon_{ex}$ is the exergy exported to the grid and $\Sigma\epsilon_{im}$ is the exergy imported from the grid.

(6) Net-zero carbon

$$CO_2r - CO_2m \geq 0$$

Where CO_2m is the $MtCO_2$ emitted from grid-based energy sources and CO_2r is the $MtCO_2$ avoided by carbon neutral energy sources provided by building owner or utility.

(7) Net zero total energy

$$r - (p + e) \geq 0$$

Where e is the embodied energy of building components amortised on an assumed lifetime.

(8) Net zero energy location (net zero total energy plus transportation)

$$r - (p + t) \geq 0 \quad \text{or} \quad r - (p + t + e) \geq 0$$

Where r is the renewable energy provided by the building owner or purchased from a utility and t is the commuting energy of building users/occupants.

[6] proposed four definitions for zero energy buildings:

• **Net Zero Site Energy (site ZEB)**: the building produces at least as much energy as it uses in a year, when accounted for at the site.

• **Net Zero Source Energy (source ZEB)**: the building produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion factors.

• **Net Zero Energy Costs (cost ZEB)**: the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.

• **Net Zero Energy Emissions (Emissions ZEB)**: the building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

Each zero energy definition affects how buildings are designed to achieve the goal. It can emphasize energy efficiency, supply-side strategies, purchased energy sources, utility rate structures, or whether fuel-switching and conversion accounting can help meet the goal. Table 3 highlights benefits and drawbacks of each definition.

Table 3. Zero Energy Buildings definitions summary according to [6].

Definition	Advantages	Disadvantages	Other issues
Site ZEB	– Easy to implement. – Verifiable through on-site measurements. – Conservative approach to achieving ZEB. – No externalities affect performance, can track success over time. – Easy for the building community to understand and communicate. – Encourages energy-efficient building	– Requires more PV export to offset natural gas. – Does not consider all utility costs (can have a low load factor). – Not able to equate fuel types. – Does not account for nonenergy differences between fuel types (supply availability, pollution).	
Source ZEB	– Able to equate energy value of fuel types used at the site. – Better model for impact on national energy system. – Easier ZEB to reach.	– Does not account for nonenergy differences between fuel types (supply availability, pollution). – Source calculations too broad (do not account for regional or daily variations in electricity generation heat rates). – Source energy use accounting and fuel switching can have a larger impact than efficiency technologies. – Does not consider all energy costs (can have a low load factor).	– Need to develop site-to-source conversion factors, which require significant amounts of information to define.
Cost ZEB	– Easy to implement and measure. – Market forces result in a good balance between fuel types. – Allows for demand-responsive control. – Verifiable from utility bills.	– May not reflect impact to national grid for demand, as extra PV generation can be more valuable for reducing demand with on-site storage than exporting to the grid. – Requires net-metering agreements such that exported electricity can offset energy and nonenergy charges. – Highly volatile energy rates make for difficult tracking over time.	– Offsetting monthly service and infrastructure charges require going beyond ZEB. – Net metering is not well established, often with capacity limits and at buyback rates lower than retail rates.
Emissions ZEB	– Better model for green power. – Accounts for nonenergy differences between fuel types (pollution, greenhouse gases). – Easier ZEB to reach.		– Need appropriate emission factors.

A source ZEB definition can emphasize gas end uses with respect to the electric use to take advantage of fuel switching and source accounting to reach a source ZEB goal. Conversely, a site ZEB can emphasize electric heat pumps for heating end uses over the gas counterpart. For a cost ZEB, demand management and on-site energy storage are important design considerations, combined with selecting a favorable utility rate structure with net metering. An emissions ZEB is highly dependent on the utility electric generation source.

The International Energy Agency discussed and proposed definitions of Zero Energy Buildings within the IEA SHC Task 40/ECBCS Annex 52: *Towards Net Zero Energy Solar Buildings*, involving almost 20 countries [19]. The project aimed at studying current net-zero, near net-zero and very low energy buildings and to develop a common understanding of a harmonized international definitions framework, tools, innovative solutions and industry guidelines. Substantial and meaningful documentation has been produced as part of different subtasks, comprising:

- ZEBs definitions and large scale implications
- Design process tools
- Advanced building design, Technologies and engineering

The knowledge disseminated by the project, including books, design tools and publications (available at [20]), represents a key reference for the research in this sector.

In particular, regarding ZEB definition, as stated by [21], the most important issues that should be considered for developing a consistent ZEB definition are: (1) the metric of the balance, (2) the period of balance, (3) the type of energy use included in the balance, (4) the type of energy balance, (5) the accepted renewable energy supply options, (6) the connection to the energy infrastructure and (7) the requirements for the energy efficiency, the indoor climate and in case of grid-connected ZEB for the building–grid interaction. Moreover, the role of Net Zero Energy Buildings on future energy systems is discussed in [22], by considering the interplay between on-site generation and the building loads, often called **load matching**, and the resulting import/export interaction with the surrounding electricity grid, commonly named **grid interaction**. Net ZEBs play the dual role of being producers and consumers of heat and electricity (“prosumers”) and can be assumed as distributed energy resources in the system. Quantitative indicators describing load matching and grid interaction are defined in this study and five case studies (three monitored and two simulated buildings) representing different building typologies, renewable energy technologies and climatic zones, were considered for a more in-depth analysis.

According to the definition provided by [17], the Net ZEB balance is a condition that is satisfied when weighted supply meets or exceeds weighted demand over a period of time, nominally a year (figure 2). The **weighted demand** is the sum of all delivered energy (or load), obtained summing all energy carriers each multiplied by its respective weighting factor. The **weighted supply** is the sum of all exported energy (or generation), obtained summing all energy carriers each multiplied by its respective weighting factor.

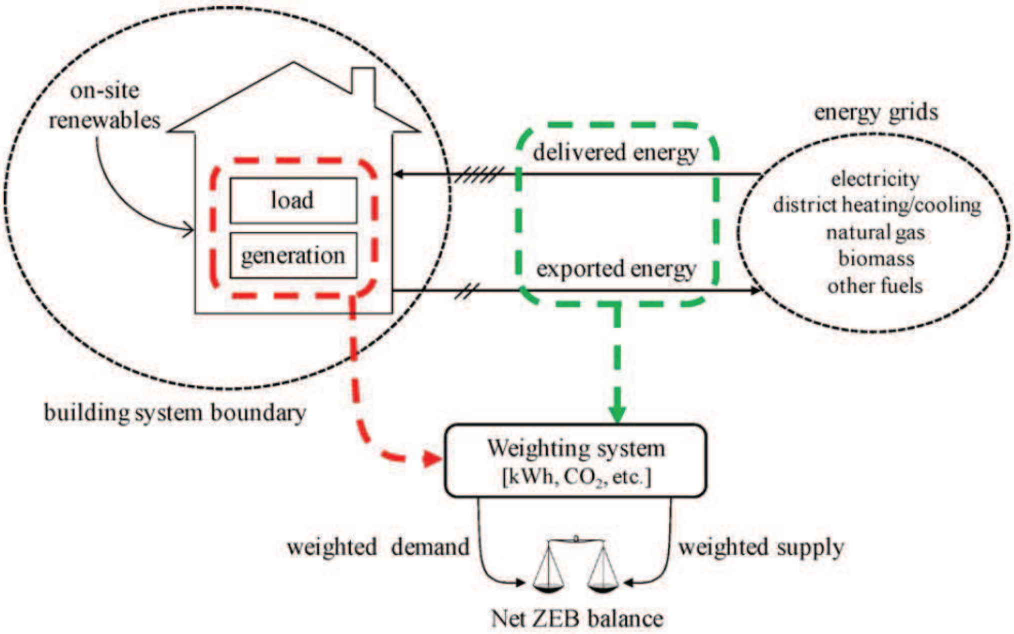

Figure 2 – Connection between building and energy grid and Net ZEB balance calculation [17].

The net zero energy balance can be determined either from the balance between delivered and exported energy or between load and generation. The former choice is named **import/export balance** while the latter **load/generation balance**. A third option is possible, using monthly net values of load and generation and it is named **monthly net balance**. The Net ZEB balance is calculated based on the equation (1):

$$\text{Net ZEB balance: } |\text{weighted supply}| - |\text{weighted demand}| = 0 \qquad (1)$$

Where absolute values are used to avoid confusion on whether supply or demand is considered as positive. The Net ZEB balance can be represented graphically as in figure 3, plotting the weighted demand on the x-axis and the weighted supply on the y-axis.

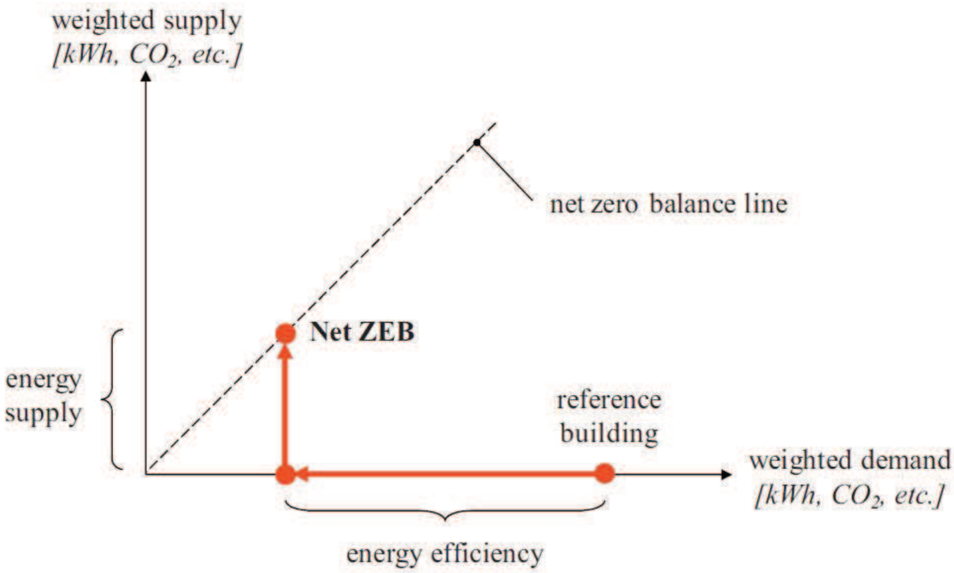

Figure 3 – Graph representing the net ZEB balance concept [17].

The reference building may represent the performance of a new building built according to the minimum requirements of the national building code or the performance of an existing building prior to renovation work. Starting from the reference case, the pathway to a Net ZEB is given by the balance of two actions:

(1) reduce energy demand (x-axis) by means of energy efficiency measures;

(2) generate electricity as well as thermal energy carriers by means of energy supply options to get enough credits (y-axis) to achieve the balance.

During the design phase, it is possible to prefigure different scenarios that can satisfy the Net ZEB Objective. Simulation and optimization tools are crucial in this perspective. As pointed out in [23] building performance simulation tools can be used as a method of informing the design decision of Zero Energy Buildings. [24] highlighted how building performance optimization should be extended in common industry practice trying to overcome the detected existing limitations due to the difficulty of implementation, lack of time and expertise, model uncertainty.

1.2. Overview of application of the nearly Zero-Energy Building (nZEB) definition across Europe

Regarding the definition provided the by European Union, as reported by the 2010/31 EU Directive (EPBD recast) [12], a "**nearly zero-energy building**" is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced either on-site or nearby. The detailed application in practice of nZEBs has been entrusted to each individual Member State. Therefore, the general definition provided by the European directive was successively declined into the different local contexts reflecting national or regional conditions and each country introduced various methods and different parameters to be considered for the achievement of the nZEB target. However, the main aspects that need to be properly defined in the nZEB definition are displayed in figure 4.

Generally, a numerical indicator of primary energy use expressed in $kWh/m^2 \cdot year$ is established as the main requirement, but other indicators can also be considered, such as CO_2 emissions, envelope performance, overheating index, performance of technical systems. Moreover, the share of renewable energy, when indicated, can be expressed in a qualitative or quantitative way.

Furthermore, energy uses considered in the calculation of energy performance can vary between Member States. As reported in table 4, all countries include heating, domestic hot water, ventilation and air conditioning within energy uses, both for residential and non-residential buildings.

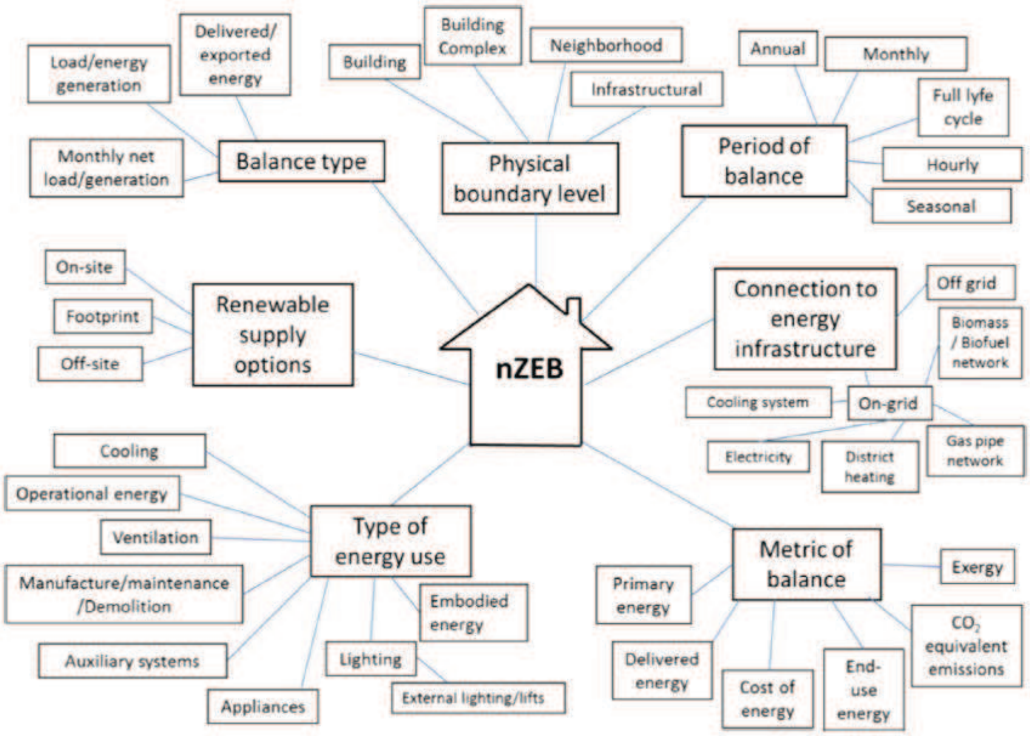

Figure 4 – Main nZEBs topics to be clarified in definitions [25].

Table 4. Energy uses included in nZEBs Member State definitions (✓= considered, not considered = X, not defined = - , / = possible to add) [25].

	Heating DHW	Ventilation, cooling, air conditioning	Auxiliary energy	Lighting	Plug loads, appliances	Central services	Electric vehicles	Embodied energy
Austria	V	V	V	V	V	X	X	X
Belgium	V	V	V	V	X	-	X	X
Bulgaria	V	V	V	V	V	V	X	X
Cyprus	V	V	X	V	X	X	X	X
Czech R.	V	V	V	V	X	X	X	X
Germany	V	V	V	V	X	X	X	X
Denmark	V	V	V	V	-	-	-	-
Estonia	V	V	V	V	V	V	-	-
Finland	V	V	V	V	V	\	-	-
France	V	V	V	V	X	X	X	X
Croatia	V	V	V	V	X	V	X	X
Hungary	V	V	V	V	\			
Ireland	V	V	V	V	X	X	X	X
Italy	V	V	V	V	X	V	X	X
Lithuania	V	V	V	V	V	V	V	V
Luxembourg	V	V	V	V	X	V	X	X
Latvia	V	V	V	V	V	X	X	X
Malta	V	V	V	V	X	V	X	X
Netherlands	V	V	V	V	V	V	V	-
Poland	V	V	V	X	-	-	-	-
Portugal	V	V	-	V	-	-	-	-
Sweden	V	V	V	V	-	-	-	X
Slovakia	V	V	V	V	X	V	X	X
UK	V	V	V	V	X	X	V	X

2016/1318 EU Recommendation [26], containing guidelines for the promotion of nearly zero-energy buildings, provides numeric benchmarks in terms of primary energy need, established as the reference level of ambition for obtaining nearly zero energy buildings in various climatic zones of Europe, as illustrated in table 5.

Table 5. nZEB primary energy use reference benchmarks for a new single family house in different EU climatic zones [26].

EU Climatic zone	Primary energy use [kWh/m²·y]	On-site renewable sources [kWh/m²·y]	Net Primary energy use [kWh/m²·y]
Mediterranean	50 - 65	50	**0 - 15**
Oceanic	50 - 65	35	**15 - 30**
Continental	50 - 70	30	**20 - 40**
Nordic	65 - 90	25	**40 - 65**

A technical definition for nearly zero energy buildings was proposed by REHVA in order to help experts in the Member States in defining nearly zero energy buildings according to a uniform methodology. Energy calculation framework and system boundaries associated with the definition were provided to specify which energy flows in which way are taken into account in the energy performance assessment. The nearly net zero energy building definition shall be based on delivered and exported energy based on EPBD recast [12] and EN 15603:2008 [27]. The net delivered energy, calculated using equation (2), is given by the difference between delivered and exported energy per energy carrier.

$$E = \sum_i (E_{del,i} - E_{exp,i}) f_i$$

Where $E_{del,i}$ and $E_{exp,i}$ are the delivered and the exported energy, respectively, accounted separately for each energy carrier i, and f_i is the primary energy factor for the considered energy carrier.

System boundaries assumed in the nZEB definition, connecting the building to energy networks are detailed in figure 4. The net energy need is obtained by the difference between the energy needs of the building for different uses (heating, cooling, ventilation, domestic hot water, lighting and appliances, if appliances are included in the system boundary) and the contribution of solar and internal gains. The net energy requirement is supplied by technical systems that usually exhibit some system losses, which involve the shifting from net energy need to the delivered energy provided by the grid. Furthermore, part of the energy demand can be met by local generation, and if the energy produced onsite exceeds the building requirements, the surplus is fed into the grid. Finally, primary energy can be attained by applying the conversion factors for each energy carrier.

Therefore, the minimisation of the net energy needs is an essential pre-condition to obtain nearly zero energy buildings, because energy needs are the starting point for the calculation of primary energy. Besides, very low energy needs are also a precondition to achieve a significant share of energy from renewable energy sources and nearly zero primary energy.

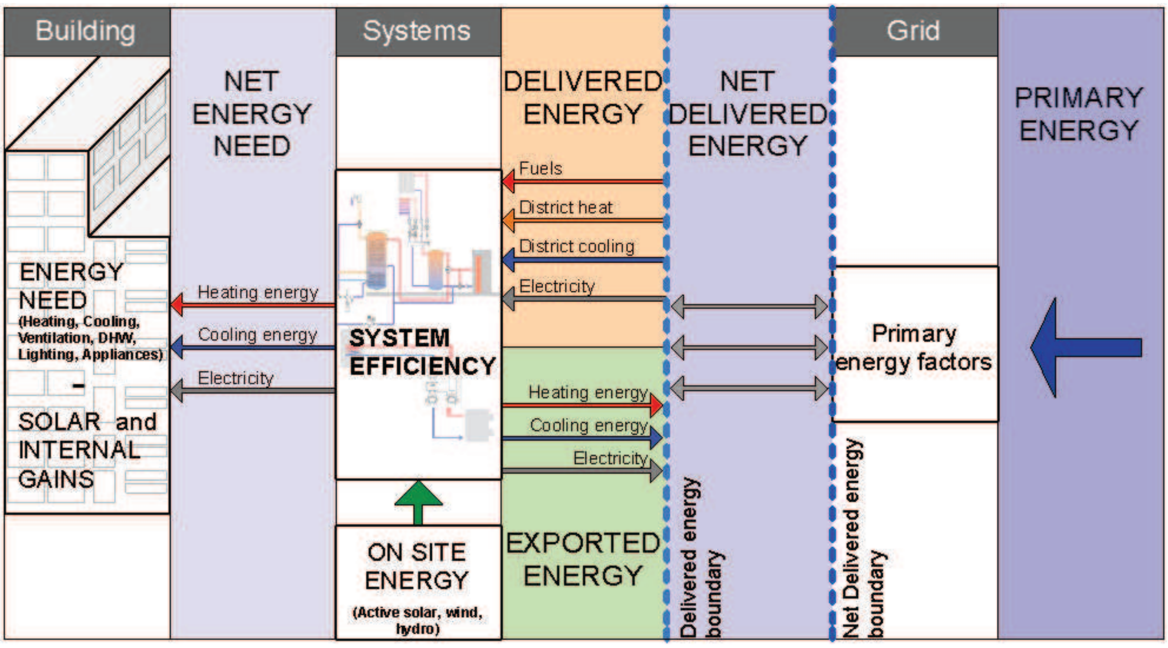

Figure 4 – Building energy requirements from net energy need to primary energy demand and system boundaries.

1.3. Implementation of nZEBs at national level

A new methodological framework for calculating energy performance of buildings was introduced in Italy with D.M. 26 June 2015 [28] in which the definition of nZEB was also clarified. In particular, a list of requirements was specified in order to label the building as nearly zero energy, concerning characteristics of the building envelope, efficiency of the systems and mandatory shares of renewable energy sources. In particular, the Italian nZEB standard provides for the compliance with further minimum requirements in addition to the overall limit on primary energy consumption: net energy performance indexes to be compared with the limit values of the reference building, average heat transfer coefficient, "equivalent summer solar area" referred to glazed surfaces and protection from solar radiation, efficiency of air conditioning and DHW systems, limits on the thermal transmittance of the dispersing elements. A National nZEB Observatory was established in 2017 in order to obtain statistics and information on policies, public and private initiatives of information/education and the status of the research in this field. From an initial assessment, according to data provided in the Energy Efficiency Report 2017 [29], the number of nZEBs in Italy ranges from 650 to 850 and 93% are residential buildings. Figure 5 shows the diffusion of nZEBs in different Italian Regions.

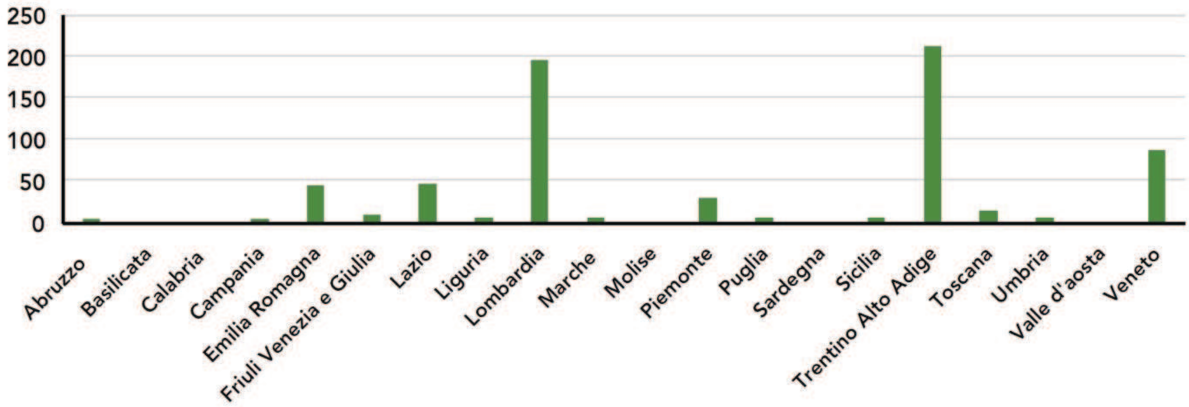

Figure 5 – Diffusion of nZEBs in Italy [29].

The graph also includes buildings that have obtained or are in the process of obtaining environmental sustainability certifications (CasaClima, Passivhaus and LEED), only for the highest ranking, attesting energy performance levels in line with the requirements fixed for NZEB classification. The poor diffusion is due to the currently unacceptable payback of the extra costs incurred to achieve nZEB level. Nevertheless, despite the still limited number, a rapid increase in nZEBs between one year and the next has been recorded [30].

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Chapter 2
Strategies for new buildings

Due to the significant changes undergone in the construction, maintenance and operation of buildings, demanding lower energy consumption, low CO_2 emissions, higher duration and lasting quality, the construction industry is today called upon to provide innovative solutions based on new methods and construction technologies. Advances in material sciences, building components production and assembly technologies allow the implementation of more efficient building systems which are less expensive in term of resources, time and energy. Consequently, the focus on sustainable design is increasingly shifting towards the promotion of opportunities that arise from the use of new and emerging products and construction methods. Many of these technologies are already developed, but little known or scarcely adopted by a wider audience of designers. Moreover, the spread and success of these systems are often linked to their applicability with respect to the combination of international standards and local understanding. Since each context is different, customized solutions engineered to meet design requirements are needed in order to achieve effective results. The present chapter includes two studies on the use of non-traditional construction systems, i.e. dry technology and Insulated Concrete Forms (ICFs), for newly built low-energy buildings. Considerable advantages are provided by both analysed technologies:

- compliance with the constraints provided by the seismic regulations
- possibility of organizing internal space freely
- easy assembly and reduced construction time
- Flexibility and structure modularity

Regarding thermal behaviour, the effectiveness of these systems has been widely studied for cold climates. However, the use in a warm climate requires some improvement to reduce cooling energy needs. Therefore, the paper in Section 2.1 deals with strategies to adapt dry technology to the Mediterranean area. The increase of thermal inertia of the building envelope together with an appropriate design of insulation thickness can lead to satisfactory results. For example, it is shown that thermal exchange towards the ground is advantageous during the summer season. So, the insulation layer in the ground slab should be designed so that it can provide sufficient thermal insulation during the heating season, without completely preventing losses during the cooling season (figure 1).

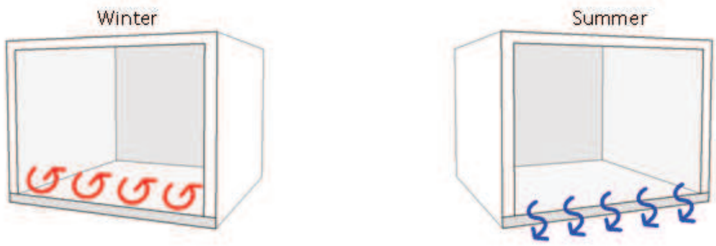

Figure 1. Ground floor slab: trade-off between thermal insulation in winter and thermal losses in summer.

Furthermore, the coupling with advanced technology systems such as the heat pump combined with renewable systems, alongside with night-time free-cooling and appropriate solar shadings seem to be valid strategies to make the dry technique also applicable in a warm climate. Regarding ICFs constructions, these have the noticeable advantage of being already equipped with a high thermal mass. However, it cannot be fully exploited as it is contained within two insulating layers limiting heat exchange. For this reason, in the paper presented in Section 2.2, the effectiveness of an innovative solution, consisting of the replacement of the inner layer of the framework with a more conductive material, is studied. The proposed new layering facilitates the activation of the thermal mass embodied in the building envelope.

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2.1 Study of innovative solutions of the building envelope for passive houses in Mediterranean areas

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Contribution of the candidate: the candidate designed and analysed the dry assembled stratigraphies of external walls, roof, and floor. She designed and modeled the case study on DesignBuilder software and performed the simulations. She wrote the sections 1,2,3, and 5 of the paper.

Abstract

In Mediterranean climate, passive houses have to be designed to contrast overheating, considering the dynamic behaviour of the opaque envelope, the effect of shading devices and free-cooling. These aspects prevail on the use of elevated insulation thickness and large windowed surfaces toward South. Innovative technical solutions involving dry assembled opaque walls with natural materials and the role of thermal inertia combined with free-cooling, are investigated. A reference building with thermal energy requirements lower than 15 kWh/m², both in winter and in summer, was identified analysing the thermal bridges in the structural nodes and the rational exploitation of solar heat gains.

Keywords: dry assembled walls, envelope dynamic behavior, structural nodes, simulations, thermal energy demands

Nomenclature

f_a	Attenuation factor [-]
$g_{\perp}$	Normal solar transmittance [-]
g_{gl+sh}	Normal solar transmittance with shading device [-]
κ_M	Thermal capacity per unit area [J· K^{-1}·m^{-2}];
M_S	Surface mass [kg·m^{-2}]
S	Time shift [h]
U	Thermal transmittances of opaque and transparent walls [W·m^{-2}·K^{-1}]
Y_{IE}	Periodic thermal transmittance of opaque walls [W·m^{-2}·K^{-1}]

1. Introduction

The theme of sustainability in new buildings has reached considerable importance due to the difficult to attain two apparent conflicting targets: the reduction of the impact on the outdoor environment and the achievement of indoor thermal comfort condition [1]. The environmental impact of a building involves not only its management, but also the construction, the supply of the raw materials, their transportation and the eventual disposal of the same building [2]. The exploitation of particular materials associated to adequate sizing procedures and the employment of renewable sources to supply the air-conditioning plants, allow for the achievement of sustainable buildings [3]. Compared to traditional constructions, in continental climatic contexts passive houses are designed to attain limited energy consumption in heating applications, because the latter are predominant on cooling demands [4]. For this reason, building walls are equipped with high insulation thickness, to reduce transmission thermal losses, and large glazed surfaces facing South to maximize solar gains. However, if the same approach in warmer climatic context is used, the energy performances of the building are strongly penalized in summer [5]. In Mediterranean areas, in fact, thermal comfort conditions are compromised by indoor air overheating, also in winter. Therefore, building envelopes have to be equipped with suitable technical solutions to favour the nightly natural ventilation and the control of the solar radiation transmitted through glazed surfaces and opaque walls [6]. In the latter case, reduced value of the periodic thermal transmittance are recommended, because adequate time shifts and attenuation factors of the transmitted thermal wave allow for summer thermal loads removal by exploiting the nocturnal free-cooling. Additionally, the envelope sustainability can be improved by reducing the quantity of materials required for its realization, employing natural resources available in proximity of the construction site with the possibility to recover them during the building disposal [7]. In this paper, feasible building opaque envelopes for passive houses located in Mediterranean area and based on the employment of dry assembled walls, have been investigated. The general aim of the present work is the definition of a new housing model contextualized to the Mediterranean climate, which is more responsive to the current needs of the housing market and, at the same time, which addresses the major challenges imposed by the sustainability themes. Dry assembled walls allow for an easy building assembly, whereas an appropriate arrangement of layers with different properties can provide lightweight and robustness building envelope with high thermal inertia [8]. Dry assembled horizontal and vertical walls, with suitable layering systems, are able to realize flexible envelopes and to reduce the construction time. Moreover, the same walls can be built directly on site according to established sizes, in order to minimize the material wastage, and assembling them on appropriate frames, allow for the respect of the local anti-seismic legislation favouring the attainment of aesthetic and functional requirements. In order to validate the actual performances of the best technical solution individuated among the several examined cases, energy evaluations of a reference passive house optimized for the Mediterranean context, have been carried out by dynamic simulations in DesignBuilder® environment [9].

2. Technological criteria adopted for opaque walls

The proposed technological solutions concern a building structure frame made by steel beams, on which dry assembled walls can be easily mounted. The steel frame is required to respect the current seismic standards without compromising the choice of the internal environment subdivision. Moreover, the same frame structure allows a quick installation of ground and ceiling precast floors. Conversely, a steel frame could highlight the presence of thermal bridges, therefore appropriate correction actions have to be analysed adequately. The investigated wall layering systems consider traditional and innovative components to reduce the delivered thermal fluxes, both in winter and in summer, guaranteeing insulation properties and a suitable thermal inertia; the latter is required to rationalize the role of solar heat gains in the building. In winter, these are stored in the inner side and re-used during the night, whereas in summer solar gains are stored into the walls to avoid the indoor air overheating, and successively transferred towards outdoor by exploiting nightly free-cooling. For this reason, massive layers located on the inner surface of the opaque walls were considered, in particular the employment of a low cost and abundant material available in the construction site as the dry sand. In the following section, the investigated layering solutions for horizontal and vertical walls, are described.

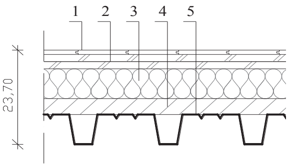
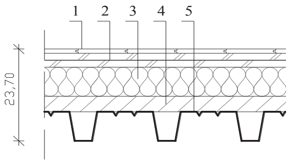
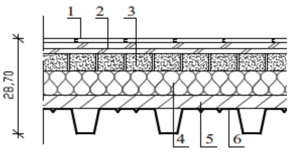
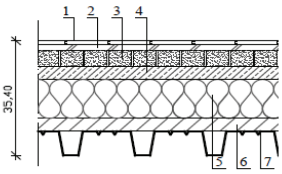
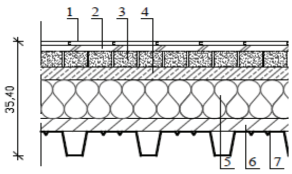
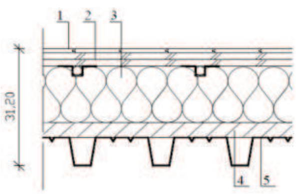
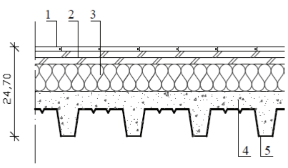
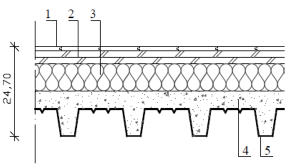
2.1 Ground floor layering

Ground floors transfer noticeable thermal energy towards the soil, therefore they assume a great importance for the energy performance of buildings located in warm climates [10]. These structures have to be sized in appropriate manner, because they have to reduce the winter thermal losses, but they must exploit the same losses as more as possible during summer. Moreover, due to the great available surface, they can be exploited as energy storage systems, therefore the surface mass represents a significant thermal property, as well as the thermal transmittance. Different solutions have been investigated, however in every analysed layering a steel corrugated sheet acts as supporting layer and guarantees the connection with the building frame, whereas wood is the natural material used to realize the internal covering. This typology of ground floor is an example of "uncooperative" system, where the steel corrugated sheet constitutes the floor deck without the employment of concrete binder. In some basement configurations, dry sand contained in honeycomb cardboard, or employed as filler material in the corrugated sheet, has been considered to increase the thermal capacity. Other layers, such as composite panels in concrete-wood, OSB panels and layers of gypsum fibres have been involved to increase the structure robustness. Regarding the insulation layer, different materials were investigated: cork panels, wood fibre panels, mineralized wood wool panels, mineral wool. In order to make a comparison with traditional insulation materials, a ground floor configuration equipped with expanded polystyrene, was also considered. In Tab. 1 the main thermal parameters of the layers employed for vertical and horizontal walls, deduced from EN ISO 10456 standard, are listed [8]. In Tab. 2, the layers constituting the investigated solutions of the ground floor, are described and shown. The insulation material represents the difference between B.1 and B.2 solutions, because in the latter mineral wool replaces the layer of mineralized wood wool. Compared to the B.1 solution, the B.3 system presents an additional dry sand layer to increase the thermal mass. Solutions B.4 and B.5 employ different insulation layers (composite panel, wood fibre and cork), while B.6 is equipped with a traditional layer of expanded polystyrene. Finally, a mineralized wood wool panel is contemplated in B.7 with thermal mass growth obtained by dry sand filled in the corrugated sheet; in B.8, an insulation layer of wood fibre panel replaces the wood wool.

Table 1. Thermo-physical characteristics of the involved materials.

Material	ρ[kg· m^{-3}]	c_p [J·kg^{-1}·K^{-1}]	Ms [kg·m^{-2}]	λ [W·m^{-1}·K^{-1}]
Wooden floor	817	1600	9	0.145
Wooden coating	500	1600	12	0.130
Gypsum fibre sheet	1222	1000	22	0.380
Gypsum	1600	1000	16	0.800
OSB panel	650	1700	26	0.130
Reinforced concrete panel	1150	1000	14	0.350
Wood fibre panel	140	2100	11	0.038
Mineralized wood wool	347	1810	26	0.065
Plywood panel	600	1600	9	0.440
Cork panel	150	1674	6	0.041
Concrete-wood comp. panel	1350	1880	54	0.260
Dry sand	1700	910	85	0.083
Steel corrugated sheet	7800	450	8	50.00
Waterproofing	900	1000	2.7	0.200
Waterproofing skim coat	1700	1200	5.1	0.560
Breathable membrane	343	1700	0.19	0.220
Expanded polystyrene	20	1450	3	0.035
Expanded polyurethane	38	1400	1.9	0.024

Table 2. Layering of the investigated basement floors.

B.1		1. Wooden floor	1.1 cm
		2. Gypsum fibre layer	3.6 cm
		3. Mineralized wood wool	7.5 cm
		4. OSB panel	4.0 cm
		5. Steel corrugated sheet	0.1 cm (7.5 gross)
B.2		1. Wooden floor	1.1 cm
		2. Gypsum fibre layer	3.6 cm
		3. Mineral wool	7.5 cm
		4. OSB panel	4.0 cm
		5. Steel corrugated sheet	0.1 cm (7.5 gross)
B.3		1. Wooden floor	1.1 cm
		2. Gypsum fibre layer	3.6 cm
		3. Dry sand	5.0 cm
		4. Mineralized wood wool	7.5 cm
		5. OSB panel	4.0 cm
		6. Steel corrugated sheet	0.1 cm (7.5 gross)
B.4		1. Wooden floor	1.1 cm
		2. Gypsum fibre layer	1.8 cm
		3. Dry sand	5.0 cm
		4. Concrete-wood composite panel	4.0 cm
		5. Wood fibre panel	12.0 cm
		6. OSB panel	4.0 cm
		7. Steel corrugated sheet	0.1 cm (7.5 gross)
B.5		1. Wooden floor	1.1 cm
		2. Gypsum fibre layer	1.8 cm
		3. Dry sand	5.0 cm
		4. Cork panel	4.0 cm
		5. Wood fibre panel	12.0 cm
		6. OSB panel	4.0 cm
		7. Steel corrugated sheet	0.1 cm (7.5 gross)
B.6		1. Wooden floor	1.1 cm
		2. Gypsum fibre layer	3.6 cm
		3. Expanded polystyrene	15.0 cm
		4. OSB panel	4.0 cm
		5. Steel corrugated sheet	0.1 cm (7.5 gross)
B.7		1. Wooden	1.1 cm
		2. Gypsum fibre layer	3.6 cm
		3. Mineralized wood wool	7.5 cm
		4. Dry sand	5.0 cm
		5. Steel corrugated sheet	0.1 cm (7.5 gross)
B.8		1. Wooden floor	1.1 cm
		2. Gypsum fibre layer	3.6 cm
		3. Wood fibre panel	7.5 cm
		4. Dry sand	5.0 cm
		5. Steel corrugated sheet	0.1 cm (7.5 gross)

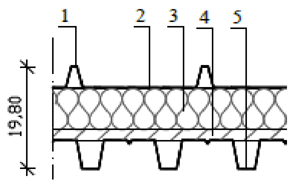
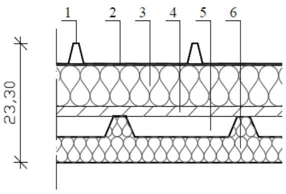
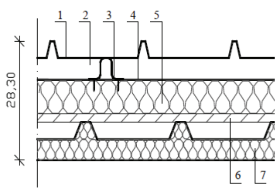
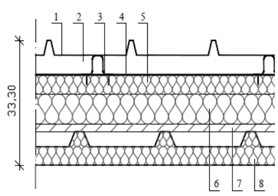
The role of the dry sand concerns not only the increment of the thermal mass, but represents a good solution as acoustic absorber and a suitable layer where technical plants can be placed. OSB panels are particularly suitable for support functions, widely used for flooring, roofing and cladding of walls, but also in other applications where they are used as functional structural elements. Gypsum fibre sheets are usually employed as dry levelling slab instead of traditional light-concrete slabs. Concrete-wood composite panels combine good insulation and structural properties. The considered materials, opportunely assembled, are able to realize building envelopes with several positive properties:

- reduce the construction time;
- improve the thermal and acoustic characteristics;
- are fire-resistant;
- allow for an easy structure inspection;
- realize light-weight structures with acceptable thermal capacity;
- facilitate the technical plant installation;
- can be recovered during the building demolition.

2.2 Ceiling floor layering

Ceiling floors have to guarantee high thermal inertia and impermeability to rainfall. The role of the thermal inertia of horizontal or pitched roofs is more evident in summer, because higher solar paths allow for remarkable thermal loads transferred through the structure. Therefore, materials with higher thermal capacity and waterproof coatings have been involved; in some solutions, the layers layout allows for a natural ventilation of the ceiling to reduce the effects of the absorbed solar radiation. The supporting structure is constituted by one or more steel corrugated sheets, by exploiting materials already described for the ground floor. The Tab. 3 lists the examined configurations.

Table 3. Layering of the investigated ceiling floors.

C.1		1. Steel corrugated sheet 2. Waterproofing 3. Wood fibre panel 4. OSB panel 5. Steel corrugated sheet	0.1 cm (4 cm gross) 0.3 cm 8.0 cm 2.0 cm 0.1 cm (5.5 cm gross)
C.2		1. Steel corrugated sheet 2. Waterproofing 3. Mineral wool wood 4. OSB panel 5. Air-gap 6. Steel corrugated sheet	0.1 cm (4 cm gross) 0.3 cm 8.0 cm 2.0 cm 5.0 cm 0.1 cm (4 cm gross)
C.3		1. Steel corrugated sheet 2. Air-gap 3. Metallic support 4. Breathable membrane 5. Mineral wool 6. OSB panel 7. Air-gap and steel corrugated sheet	0.1 cm (4 cm gross) 5.0 cm - cm 0.3 cm 8.0 cm 2.0 cm 0.1 cm (9 cm gross)
C.4		1. Steel corrugated sheet 2. Air-gap 3. Metallic support 4. Breathable membrane 5. Concrete-wood composite panel 6. Wood fibre panel 7. OSB panel 8. Air-gap and steel corrugated sheet	0.1 cm (4 cm gross) 5.0 cm - cm 0.3 cm 5.0 cm 8.0 cm 2.0 cm 0.1 cm (9 cm gross)

Compared to the C.1 solution, C.2 is equipped with an additional insulation layer of mineral wool, an internal air-gap and a different displacement of the lower corrugated sheet. C.3 layering involves a ventilated air gap on the external side, whereas wood fibre panel and an additional composite panel as insulation material, are employed in the C.4 solution (with ventilated air gap). Contrarily to the first solution, ceiling configurations C.2, C.3 and C.4 employ insulated corrugated steel sheet panels.

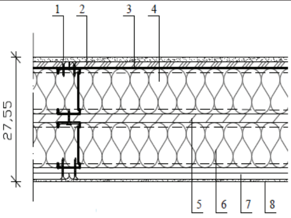
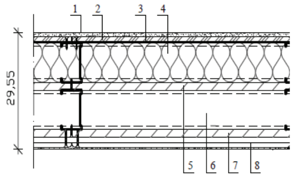
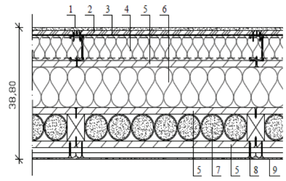
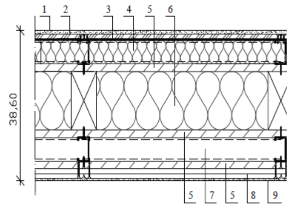
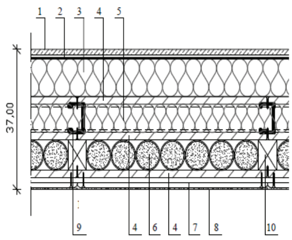
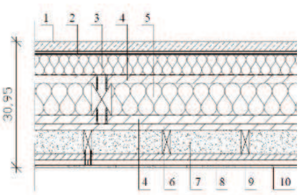
2.3 Vertical walls layering

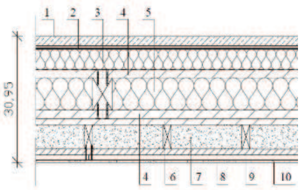
The employment of precise layers sequences has to ensure in a unique element the properties of thermal and acoustic insulation, the structural load transmission towards the ground, the internal space partition and the fire-resistance. These features can be reached especially assembling appropriate panels that allow:

- quick building fabric assembling;
- possibility to modify the panels in appropriate size by engraving and cutting techniques;
- panel connection to the structure frame by self-supporting screws;
- high impact strength and wind resistance;
- stability to the thermal stress due to the night-day temperature cycles;
- absence of crumbling or swelling effects due to moisture absorption.

For every investigated solution, the achievement of suitable values of steady and periodic thermal transmittances, are required [11]. In order to reinforce the vertical wall, an internal metallic frame realized with standardized profiles, is adopted. The several layering are described in Tab. 4, starting from the external to the internal side. The W.1 system uses wood fibre panels as insulation material, and reinforced concrete panel to give rigidity to the structure. Contrarily, the W.2 solution employs the same materials, but the insulation layer and an additional air gap on the internal side were added. In order to facilitate the wall assembly, W.3 system is equipped with pipes to dislocate loose sand, and an additional insulation layer (wood fibre panel). The W.4 solution is constituted by encapsulated dry sand located in the air gap (inside appropriate bags) on the internal side, whereas tubes containing dry sand, a higher insulation thickness and other elements that confer major robustness to the wall, constitute the W.5 vertical wall. A precast and reinforced system, composed by plywood panels containing dry sand, and a layer of expanded polyurethane, are employed in the W.6 solution. Finally, the W.7 configuration uses wood fibre panels as insulating layer to replace the expanded polyurethane. Conservatively, thermal properties of dry loose sand do not consider the encapsulating material properties and the additional thermal resistances due to the creation of air gaps.

Table 4. Layering of the investigated vertical walls.

W.1		1. Gypsum	0.5 cm
		2. Reinforced concrete panel	10.0 cm
		3. Waterproofing	0.3 cm
		4. Wood fibre panel	2.0 cm
		5. OSB panel	2.0 cm
		6. Woos fibre panel	10.0 cm
		7. Two gypsum sheets	2.2 cm
		8. Gypsum	0.5 cm
W.2		1. Gypsum	0.5 cm
		2. Reinforced concrete panel	10.0 cm
		3. Waterproofing	0.3 cm
		4. Wood fibre panel	7.0 cm
		5. OSB panel	2.0 cm
		6. Air gap	7.0 cm
		7. Two gypsum sheets	2.2 cm
		8. Gypsum	0.5 cm
W.3		1. Gypsum	0.5 cm
		2. Reinforced concrete panel	10.0 cm
		3. Breathable membrane	0.3 cm
		4. Wood fibre panel	4.0 cm
		5. OSB panel	2.0 cm
		6. Wood fibre panel	12.0 cm
		7. Dry sand encapsulated in pipes	7.0 cm
		8. Two gypsum sheets	2.5 cm
		9. Gypsum	0.5 cm
W.4		1. Gypsum	0.5 cm
		2. Reinforced concrete panel	10.0 cm
		3. Waterproofing	0.3 cm
		4. Wood fibre panel	4.0 cm
		5. OSB panel	2.0 cm
		6. Wood fibre panel	12.0 cm
		7. Air gap	6.8 cm
		8. Two gypsum sheets	2.5 cm
		9. Gypsum	0.5 cm
W.5		1. Wood coating	1.5 cm
		2. Waterproofing + air gap	2.3 cm
		3. Wood fibre panel	12.0 cm
		4. OSB panel	2.0 cm
		5. Wood fibre panel	5.5 cm
		6. Dry sand encapsulated in pipes	7.0 cm
		7. Two gypsum sheets	2.2 cm
		8. Gypsum	0.5 cm
		9. Metallic support	5.5 cm
		10. Wooden studs	7.0 cm
W.6		1. Wood coating	3.3 cm
		2. Waterproofing + air gap	1.3 cm
		3. Expanded polyurethane	4.5 cm
		4. OSB panel	2.0 cm
		5. Expanded polyurethane	9.0 cm
		6. Plywood panel	1.5 cm
		7. Encapsulated dry sand	6.8 cm
		8. Plywood panel	1.0 cm
		9. Gypsum sheet	1.0 cm
		10. Gypsum	0.5 cm

W.7		1. Wood coating 2. Waterproofing + air gap 3. Wood fibre panel 4. OSB panel 5. Wood fibre panel 6. Plywood panel 7. Encapsulated dry sand 8. Plywood panel 9. Gypsum sheet 10. Gypsum	3.3 cm 1.3 cm 4.5 cm 2.0 cm 9.0 cm 1.5 cm 6.8 cm 1.0 cm 1.0 cm 0.5 cm

3. Thermal characterization of the proposed opaque walls

By means of the data reported in Tab. 1, the following thermal parameters for vertical walls and ceiling floors have been calculated, and the correspondent results listed in Tab. 5:

- thermal transmittance;
- periodic thermal transmittance;
- surface mass;
- thermal capacity per unit area;
- time shift of the thermal wave;
- attenuation factor of the thermal wave;

Regarding the ceiling floors, the solution C.1 offers an acceptable value of the thermal transmittance, but the structure provides a high periodic transmittance value (higher than the limit value set by the current Italian legislation in the field of building energy performances), therefore dynamic parameters can be further improved [12].

In the solution C.2, the natural ventilation in the air-gap is activated exclusively in summer to favor the removal of the absorbed solar radiation, while the insulation layer is represented by mineral wool and corrugated steel sheet. This configuration allows for an evident improvement of the thermal transmittance and of the dynamic parameters. Moving the air-gap on the external side (solution C.3), thermal transmittance and periodic transmittance assume better values, with S=5.9 hours and f_a lower than 0.43. If wood fiber and concrete-wood panels are adopted as insulation layers (solution C.4), the thermal performances are further improved by reaching a thermal transmittance lower than 0.200 $W \cdot m^{-2} \cdot K^{-1}$, with S=12.9 hours and f_a= 0.152.

Regarding vertical opaque walls, OSB panels and a double insulation layer of wood fiber panel (solution W.1), provide good performances, but the structure is too light-weight. Replacing the wood fiber panel with encapsulated sand (W.2), the specific mass is considerably increased, with performances indexes slightly variable. If loose dry sand is dislocated into pipes (W.3), by adding a supplementary insulation layer on the external side, optimal performances in terms of thermal losses and dynamic behavior, are detected. A double insulation layer of wood fibre panels, without encapsulated dry sand on the inner side (W.4), provides good performances, but the total wall thickness is greater than the prior analyzed solutions. A further improvement can be achieved by filling the air-gap with loose sand, but this solution could provide structural problems with possible panel buckling.The solution W.5 employs newly dry sand in metallic pipes, but the external side is made by wood coating to form a reduced ventilated air-gap. Good thermal transmittance values have been determined, as well as dynamic parameters, but the displacement of the loose sand in the pipes lead to a non-homogenous massive layer. A combination of expanded polyurethane and precast massive layers (W.6), the latter realized with loose sand contained between plywood panels reinforced by wood studs, provides good results, but the structure is too lightweight also in this case. Finally, in the

W.7 solution, wood fibre panels replace the expanded polyurethane, providing better dynamic parameters but an increment of the thermal losses through the wall.

Regarding the ground floor, thermal transmittances varying between 0.206 $W \cdot m^{-2} \cdot K^{-1}$ (B.6) and 0.618 $W \cdot m^{-2} \cdot K^{-1}$ (B.7), were detected. These solutions produce lightweight ground floor, while the configuration B.5 seems to be the best compromise between thermal transmittance (0.248 $W \cdot m^{-2} \cdot K^{-1}$) and surface mass (220 $kg \cdot m^{-2}$). In Tab.5, the best considered thermal properties are highlighted in bold; regarding the ceiling, the C.4 system presents the best performance indexes, except the thermal capacity per unit of area. With reference to vertical walls, W.3 provides good results in terms of periodic transmittance and surface mass, while W.4 offers the greatest time shift and W.6 is preferable to reduce thermal losses and to store solar gains. However, dynamic simulations carried out on a reference building with actual climatic data will identify the optimal solution in order to detect the layering system that better conciliates the winter and the summer conflicting needs, in terms of minimal annual thermal energy requirements.

Table 5. Main thermal properties of the vertical walls and ceiling floors.

Solution	U [$W \cdot m^{-2} \cdot K^{-1}$]	Y_{IE} [$W \cdot m^{-2} \cdot K^{-1}$]	M_S [$kg \cdot m^{-2}$]	κ_M [$J \cdot K^{-1} \cdot m^{-2}$]	S [h]	f_a [-]
C.1	0.414	0.353	42.5	**25610**	3.9	0.916
C.2	0.195	0.080	17.1	8565	5.9	0.426
C.3	0.195	0.081	32.9	8731	5.9	0.427
C.4	**0.185**	**0.027**	**109.2**	8731	**12.9**	**0.152**
W.1	0.176	0.022	100.0	22000	14.7	0.130
W.2	0.292	0.033	267.1	121450	13.2	0.118
W.3	0.168	**0.004**	**275.6**	124201	20.9	**0.024**
W.4	0.158	**0.004**	229.7	121450	**21.4**	0.026
W.5	0.173	0.005	255.0	124201	19.6	0.030
W.6	**0.136**	0.013	177.8	**133581**	14.0	0.098
W.7	0.216	0.023	188.6	**133581**	15.8	0.105

4. Structural nodes and thermal bridges

Referring to the proposed structures, several critical points have to be analysed to evaluate suitable solutions able to contrast the thermal bridge effect:

- the coupling between vertical walls and steel pillars;
- the intersection between the ground floor and the perimeter walls;
- the intersection between ceiling floor and the perimeter walls;
- the coupling between the windowed system and the correspondent wall;

In the first case, the complete integration of the vertical walls with the discontinuous points represented by the steel pillars, is required. Therefore, the homogeneous insulation system on the external side of the vertical wall common to the examined solutions, is appropriate. In order to facilitate the wall assembly, see Fig. 1, a steel plate (a) settled on the HE 200 pillar sides is required. By supposing the employment of the W.7 solution, the external OSB panel and the external wood fibre panels assure the continuity of the insulation layer on the external perimeter of the building envelope.

Regarding the second structural node, the steel corrugated sheet of the ground floor has to be joined with the steel frame; at the same time, the internal part of the vertical wall W.7 (layers n. 5, 6 and 7) has to be installed before the floor insulating layer. Successively, the precast panel containing the loose sand can be installed on the ground floor, by employing a stiffening beam to prevent insulation crushing of the floor, putting in place also the massive layer of the same ground floor (see

Figure 2 where the exploitation of the B.5 system is supposed). This method allows for a continuity of the insulating layer between the horizontal and the vertical walls, forming a continuous insulation skin around the building envelope.

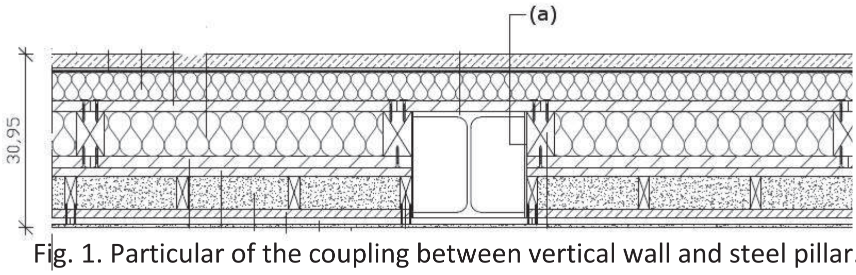


Fig. 1. Particular of the coupling between vertical wall and steel pillar.

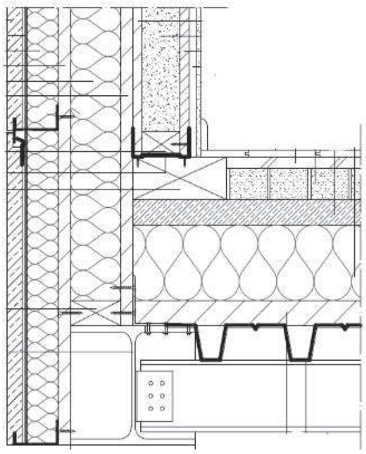


Fig. 2. Particular of the lowest vertical/horizontal wall junction.

In order to join the ceiling floor and the vertical wall, only the external side of the vertical wall continues until the highest part of the envelope, in order to realize the ceiling insulation layer hooking and to guarantee the insulation continuity. The latter has to be installed successively the vertical wall, and it has to be assembled layer after layer to ensure the pillars connection and the uniformity of the insulation layer on the external side of the building envelope (see Fig. 3 where a connection between C.4 and W.7 systems is shown).

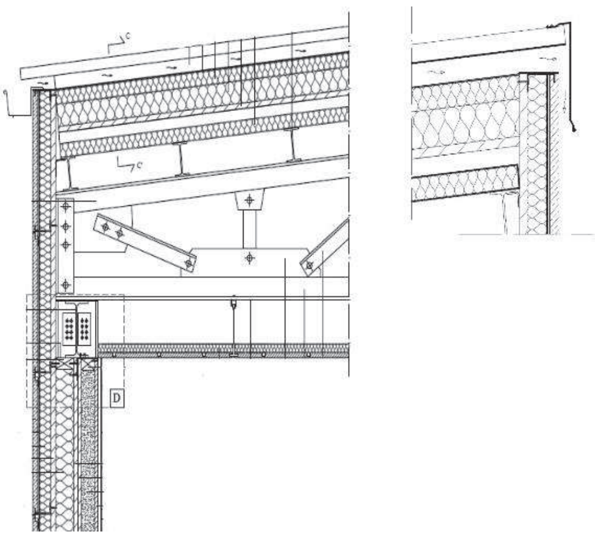


Fig. 3. Particular of the highest vertical/horizontal wall junction.

For the window-wall connection, three wood beams on the sides and the upper part of the wall hole, sized to support the vertical massive layer, are required. The thermal bridge linked to the sill presence is attenuated by rigid foam of EPS, while the external insulation layer continues on the inner side of the wall hole until the window frame.

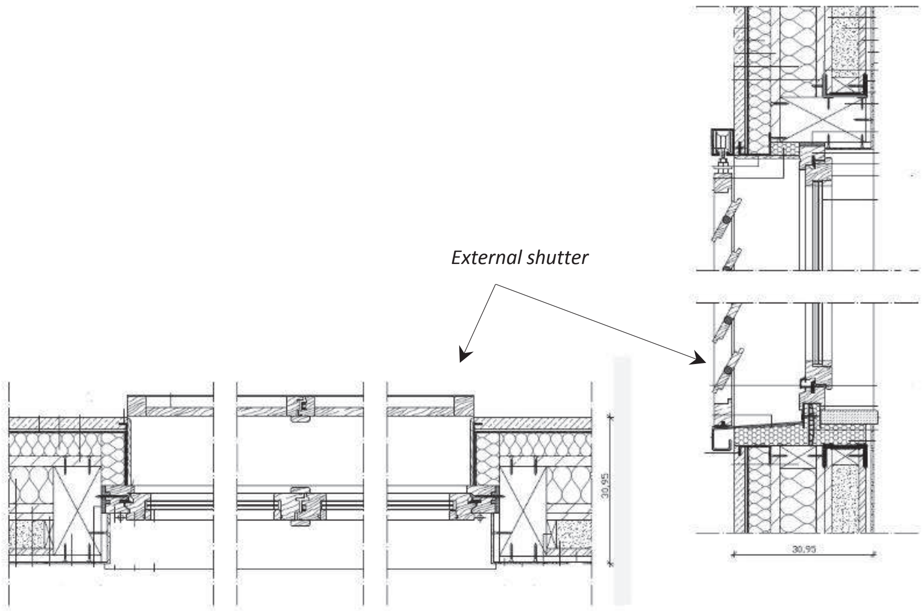


Fig. 4. Particulars of window/wall connection.

5. Energy performances evaluation

The results listed in Tab. 5 do not allow for the identification of the best typology of opaque elements, which provide the best building configuration with the minimum values of heating and cooling requirements. Generally, a good compromise between thermal losses, energy gains and thermal storage has to be identified. Well-insulated walls reduce the heating needs but, at the same time, impede the beneficial thermal losses during summer, with consequent cooling demand growth. Analogously, large windowed surfaces could decrease heating demands but the overheating risk in summer increases. Therefore, typical solutions exploited to limit heating energy requirements always produce an increment of the cooling demands, and vice versa. An accurate choice of the main design parameters of the building envelope must be carried out in order to obtain the minimal energy requirements at annual level. In order to achieve this target, also the thickness of the insulation layer in the considered wall configurations, was varied. For this reason, energy evaluations developed by DesignBuilder code on a reference building located in Cosenza (Italy, 39.3 °N), varying the typology of the considered opaque walls, were carried out with actual climatic data [13].

The common parameters of the reference building (Fig. 5) concern:

- the size (gross dimensions of 9.24×13.8×3 m);
- 5 m² and 9 m² of windowed surface on North and South exposures, realized by low-emissivity triple-pane 3/13/3/13/3 with Argon ($g_{\perp}$=0.474, U = 0.78 W·m-²·K-1) and wooden frame (20%);
- an overhang of 1.5 m South facing;
- a nightly natural ventilation of indoor environment in the summer months starting from 23:00 p.m. to 7:00 a.m;
- absence of internal mobile shading devices;
- external window shutters closed only during night;

- verified absence of interstitial condensation phenomena inside the walls;
- set point air temperature of 20 °C in winter and 26 °C in summer;

Windowed surfaces on the East and West exposures are not present in order to allow the assembly of larger structures (modular building fabric). Regarding the vertical surfaces, the percentage of glazed surface is 10%, the roof solar reflectance is 70% and the solar absorption coefficient of external walls is 35%. The envelope transmission mean loss coefficient is 0.286 $W \cdot m^{-2} \cdot K^{-1}$, about a half of the limit value set by the current Italian legislation. The ratio of the equivalent summer area of glazed surfaces to the useful floor area is slight lower than 0.03, in accordance with the regulations for the containment of summer energy consumptions. The equivalent area was determined with a shading reduction factor due to the overhang of 0.525 for the windows South facing and a correction factor of the incident solar radiation equal to 0.924. The limit values of the thermal energy requirements for heating and cooling, calculated in function of a reference building with the same size and with standardized thermal parameters, are respectively 35.7 $kWh \cdot m^{-2}$ and 6.7 $kWh \cdot m^{-2}$. The latter value is very limited due to the presence of mobile shading devices in the reference building that provide a reduced corrected solar transmittance value (g_{gl+sh}=0.35). Verifications on the plants concerning heating, cooling and DHW have not been carried out because the analysis is limited only to the thermal energy requirements.

Fig. 5. The reference building considered for energy evaluations.

The results of the several simulations have shown:

- the best wall configuration is W.7, but increasing the thickness of insulation layer to 12 cm and removing the OSB panel in the middle to contain the global thickness, obtaining a thermal transmittance of 0.196 W·m-²·K-1, a time shift slightly greater than 17 h and attenuation factor of 0.078;
- the best configuration for the pitched roof is represented by the C.4 solution;
- the best solution for the ground floor is B.4 reducing the insulation thickness to 10 cm because this choice allows for a reduction of cooling requirements that prevails on the heating demand growth, obtaining a thermal transmittance of 0.288 W·m-²·K-1and a slight decrement of the superficial mass.

The low value of the normal solar transmittance of glazing allows for a rational exploitation of solar radiation during summer, and the reduced value of the thermal transmittance, that provides limited thermal losses in the same season, is compensated by the exploitation of the nightly free-cooling. The role of the latter is significant, because it allows for the removal of the energy gains stored into the massive layers during the day. The absence of the free-cooling does not allow the achievement of cooling energy requirements lower than 15 kWh/m². Finally, the reference building in the analyzed configuration and equipped with the identified solution for the opaque walls is characterized by a seasonal heating energy requirement of 14.5 kWh/m² and a seasonal cooling energy requirement of 12.9 kWh/m². The latter can be further reduced by exploiting mobile shading device obtaining a seasonal cooling demand lower than the limit value of 6.7 kWh/m².

Conclusions

The sustainable building involves not only its management, but also its construction, the supply of raw materials, their transportation and the reuse of the same after the building disposal. Therefore, appropriate materials have to be chosen in the design phase in order to attain these objectives. In this paper, a building envelope equipped with dry assembled walls realized by traditional and natural materials, was investigated. The proposed opaque wall configurations combine different aspects concerning technological innovation, energy saving and rational exploitation of resources. Passive house in continental climatic contexts are designed mainly to reduce heating energy demands, by using elevated insulation thickness in the opaque wall and large windowed surfaces toward South. The same approach in warm climatic is inappropriate, because the risk of indoor air overheating is marked, especially in summer. For this reason, dynamic properties of opaque walls assume a significant role. In order to make the building envelope more responsive to the climatic characteristics of the Mediterranean area, the employment of dry loose sand inside the structures, to increase the thermal mass, was considered. Dry sand represents an abundant and cheap material largely available on the construction site. These walls can be modelled in appropriate size directly in the construction site to reduce the material wastage, successively these can be mounted on metallic frame by screw systems reducing the construction time and respecting the seismic standards. Different installation techniques to contrast the thermal bridge effect in the structural nodes have been analysed and appropriate solutions were proposed. Dynamic simulations carried out by Design Builder software have highlighted the good dynamic properties of the investigated opaque walls, and have allowed to identify the best envelope configuration able to minimize the annual thermal energy requirements. The results show the significant role in summer of the combined use of thermal storage located in the internal side of the wall and the nightly free-cooling. For the South exposure, windows with triple panes appear appropriate because they represent a good compromise between the reduction of thermal losses and the exploitation of solar gains. In particular, the decrement of the winter thermal losses prevails on the reduction of the solar gains due to the limited solar transmittance value. In summer, the latter represents an advantage, and the cooling demand growth due to limited thermal losses is compensated by the employment of the nightly free-cooling. A reference building designed applying the identified solutions and located in the South Italy has provided thermal energy requirements lower than 15 kWh/m² both in winter and in summer, respecting the limit suggested by the *passivhaus* standard in its extended formulation. The cooling energy requirements value were determined avoiding the use of movable internal or external shading devices, therefore further improvement can be reached.

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2.2 Are ICFs suitable building envelope solutions for Mediterranean climatic conditions? A critical analysis concerning thermal properties and cooling energy performances

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(Submitted version)

Abstract

The ICF (Insulated Concrete Forms) constructions, consisting of insulating permanent formworks filled with cast-in-place reinforced concrete, are widely used in Continental climates. The present work addresses the adaptation of ICF systems to the Mediterranean climate, by evaluating through dynamic simulation the effect of certain adjustments in wall layering aimed at making more exploitable the internal thermal mass. The results show that the replacement of the internal insulating form with alternative materials, characterized by a higher thermal conductivity, allows to lower internal air temperature peaks up to 1,4 °C compared to standard ICFs, and reduce cooling energy consumption by 20%. The alternative solutions are also effective in terms of costs and construction time. Modified ICF solutions can be profitably used for zero energy buildings even in warm climates.

1. Introduction

Latest Standards introduced nearly Zero Energy Buildings (nZEBs) that require a minimum amount of fossil energy for their operation (Directive 2010/31/EU). The high efficiency is based primarily on the minimisation of energy requirements for air conditioning. Generally, the reduction of the heating demand is easily achievable, through an adequate envelope insulation and a profitable exploitation of solar gains. On the contrary, in climatic conditions in which the cooling demand prevails, the containment of energy consumption becomes more challenging. However, experiences of low-energy buildings in different climatic contexts can be found in the literature. For example, (Schnieders et al., 2015) analysed the possibility of realising Passive Houses in all the world's relevant climate zones by adjusting building's shape and orientation, insulation level, window quality and mechanical services in each individual case, maintaining architectural quality and internal comfort. (Harkouss et al., 2018) proposed best practices to reduce building energy demand for cooling and heating by improving the passive design. Twenty-five different climates were simulated in the study showing that an optimal passive solution can produce a potential saving up to 54% for cooling demand and up to 87% for heating demand, with respect to the initial configuration. Basic principles for the design of nZEBs in Mediterranean climate are provided by (Ascione et al., 2016a). (Ascione et al., 2016b) sought to identify integrated design procedures able to minimise both winter and summer energy demand of a residential case study in four Mediterranean cities (Madrid, Nice, Naples, Athens) and evidenced the difficulty of assuring high thermal comfort when looking for the nZEB objective. A parametric analysis aimed at the optimisation of the envelope of a passive building in South Italy is shown in (Bruno et al., 2015) proving that a proper layering of the external elements can decrease cooling requirements. The design and monitoring of a high-performance home in Mediterranean climate are reported in

(Causone et al., 2017) by highlighting the key role played by the control of heat gains and the correct use of the thermal mass. The role of thermal storage capacity as a passive strategy to maintain internal comfort is also emphasised by (Rodriguez-Ubinas et al., 2014). As discussed in (Lizana et al., 2017) thermal energy storage is essential to accomplish the low-carbon energy goal in the building sector, allowing to reduce energy consumption and promote the use of renewable energy sources.

(Fadejev et al., 2017) demonstrated how interior thermal mass of enough thick concrete layers can enable utilisation of solar and internal gains resulting in a significant reduction of peak loads both for heating and cooling and in a reduction of total energy need. (Al-Sanea et al., 2012) investigated the effect of amount and location of thermal mass in insulated building walls with the same nominal resistance, on total and peak transmission loads, time lag, decrement factor, and dynamic resistance. They found out that, a maximum saving in yearly transmission loads of about 17% for cooling and 35% for heating is achievable with the optimisation of the thermal mass and that, for a given thermal mass, external insulation gives better overall thermal performance than internal insulation. (Siddiqui et al., 2017) found that the use of thermal mass in Net-Zero Energy houses contributes for 10 – 15 % to energy savings and considerably contributes to the comfort of the occupants. The influence of the thermal storage mass on summer thermal stability of a passive house in the Czech Republic is described by (Němeček and Kalousek, 2015), by analysing different construction variants including wooden and brick-built envelopes. The sensible heat stored in the building materials was considered and a curve illustrating the effectiveness of thermal mass in preventing overheating was drawn. Experimental and theoretical analysis of the energy performance of lightweight and massive wall systems is presented by (Kosny et al., 2001.). Dynamic thermal performance of 16 alternatives for the wall stratigraphy was investigated for residential buildings and the potential energy savings were presented for ten U.S. climates proving that thermal mass can help in the reduction of building annual energy use. Therefore, massive building envelopes can be utilised as one of the simplest ways of reducing building heating and cooling loads. As widely known, constructions made in masonry or earth are able to provide the structure with a high thermal inertia. Furthermore, concrete has also been demonstrated to have suitable thermal storage capacity (Shafigh et al., 2018) and solutions based on Insulated Concrete Forms (ICFs) can represent a valid alternative to traditional construction methods. ICFs structures consist of cast-in-place concrete walls that are sandwiched between two layers of insulation material. This building system offers numerous advantages. It provides continuous insulation without thermal bridging, acoustic insulation, air sealing, waterproofing, high structural strength and seismic safety. Moreover, it allows fast and easy construction and high flexibility. Several studies focused on mechanical and structural properties of ICFs (E.Arunraj; Arun Solomon; G Hemalatha, 2014) (Arun Solomon and Hemalatha, 2017) (Bhatti, 2016) (Amer-Yahia and Majidzadeh, 2012) while few works investigated its thermal characteristics and energy behaviour. The thermal response of ICF assembly subjected to different Canadian climate conditions was analysed by Maref et al., 2012. Ekrami et al., 2015a investigated thermal behaviour of the concrete in ICF walls embedding PVC pipes in order to store thermal energy and make it available when there is a demand, in particular reusing it as an input of other mechanical systems such as heat pumps. (Ekrami et al., 2015b) used a test facility to evaluate the application of Insulated Concrete Forms walls combined with Ventilated concrete Slabs in order to experimentally verify the effect of thermal energy storage systems on the overall performance of a coupled photovoltaic/thermal and air source heat pump. ICF technique has been widely used in cold climates thanks to its ability to control heat losses and meet higher energy code mandates with less complicated construction. However, its application in warm/hot climates is still relatively unexplored. An example in this direction is given by the study carried out by (Selvapandian A., 2014), which examined the feasibility of using ICFs in a hot and humid climate. Hygro-thermal performances of ICF walls and traditional concrete walls for a building in Oman were studied with reference to the peak summer months and the results indicated the ICFs are comparatively better than normal concrete block walls.

The present paper deals with the use of ICF structures in Mediterranean climate for obtaining nearly zero energy buildings. Steady and dynamic thermal properties are determined by considering different wall layering and the overall energy performance of a building is evaluated. In particular, solutions based on the replacement of the internal insulation layer of the formwork with material characterized by higher thermal conductivity are examined, in order to make the activation of the thermal mass involved in the wall more effective. Finally, an economic analysis is performed in order to identify the most cost-effective solution, being able to reduce construction time and operating costs.

2. Data and methodology

The methodology can be divided into the following phases:

- Presentation of the case study and simulation hypotheses
- Detailed description of the analysed stratigraphies for external walls and calculation of the steady and dynamic thermal characteristics
- Analysis of the results in terms of trend in indoor air temperature and energy requirements for cooling
- Economic projections for the identification of the most cost-effective solution.

2.1 Case study and simulation assumptions

A single-family house was considered for the analysis. The layout of the designed building is shown in figure 1. The net surface is of 118,7 m2. The window to wall ratio is equal to 27% for the South exposure, and equal to 16% and 30% for the North and East exposures, respectively. A horizontal overhang of 1,5 m is provided on the windows facing South. The windows are double-paned (4-12-4 mm with air) with wooden frames (Uw=1,9 W/m2K).

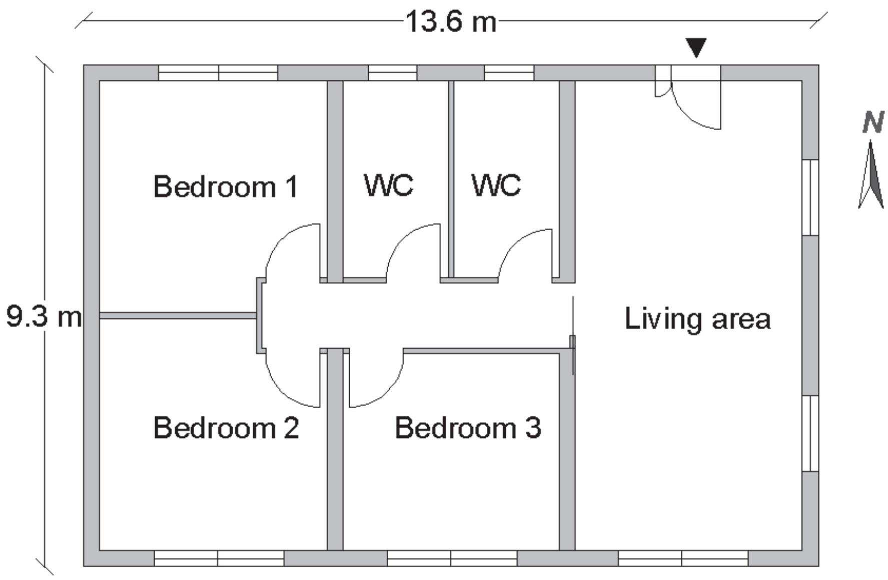

Figure 1. Layout of the single-family house assumed for energy performance assessment.

Internal gains are calculated according to the Standard (UNI/TS 11300–1, 2014) and are equal to 3,80 W/m2. A natural ventilation rate of 0,3 ach is assumed according to the standard (UNI/TS 11300–1, 2014). Regarding climatic conditions, a weather file generated with Meteonorm (Meteonorm, 2017) for a city located in southern Italy (Cosenza) is used in the analysis. The maximum external air temperature is 36,4 °C, the maximum value of the direct normal solar radiation is 0,997 kW/m² while the maximum value of the diffuse solar radiation on a horizontal surface is 0,489 kW/m². Cooling Degree Day are equal to 148, referring to a temperature of 26 °C (UNI 10349–3, 2016). The building is equipped with a chilled ceiling connected to an air-water heat pump (EER 5,5) supplied by electricity from the grid.

The study focused on the evaluation of the building energy performance during the cooling season. For this purpose, energy simulations were conducted for six months, from 1st May to 31st October, using the DesignBuilder software (DesignBuilder Software Ltd, 2016) based on the EnergyPlus engine (EnergyPlus, 2015).

The cooling set-point temperature was set to 26°C with activation of the cooling system for ten hours a day, from 12:00 to 22:00. This operation schedule allows highlighting the effect of the thermal inertia of the building envelope. Simulation results are reported in terms of internal air temperature trends and electric energy for cooling.

2.2 Description of the types of layering analysed for external walls

The building is in load-bearing walls. Several types of external walls were analysed in the present study. All the considered solutions include thermal insulation in order to verify the limit values of thermal transmittance suggested by the current Italian regulations (D. M. 26 June, 2015) in function of the climatic zone. In particular, the location selected for the design of the building is within the climatic zone C (D.P.R. 412, 1993) and a value of U = 0,34 W/m2K is prescribed for the refurbishment of existing building envelopes. Three construction solutions were considered, as illustrated in figure 2, generating a set of seven technical alternatives in total.

The first wall type, named as Brick, is traditional brick masonry with ETICS (External Thermal Insulation Composite System). The second wall type, identified as Reference ICF (Ref ICF) consists of a standard ICF system. This type of construction, corresponding to the ICF system currently available on the market, uses permanent formworks consisting of insulation material, containing the concrete cast. The thickness of the insulating formworks can vary according to the specific needs. For the examined location, two EPS formworks with a thickness of 5 cm are satisfactory. However, this technology presents a limit due to the insulation layer located on the inner side that prevents full exploitation of the thermal mass included in the wall. For this reason, the third type of wall was introduced, assuming the replacement of the internal formwork, usually made of EPS or other insulating material, with alternative materials characterized by a higher thermal transmittance, in order to take greater advantage of the thermal mass inside the wall.

In particular, five substitute materials were examined, selected among those commercially available: cellular concrete panel, wood-cement board, gypsum fibre panel, plasterboard, and glass fibre reinforced lightweight concrete board. These are indicated with the codes ranging from ICF mod_1 to ICF mod_5. All the considered materials can fulfil the formwork function, as an alternative to the EPS layer provided in the reference ICF wall and all these materials have a higher thermal conductivity than the EPS panel.

Since the analysis was conducted assuming a constant thermal transmittance U, in the alternative ICF walls in which the internal formwork is replaced with a more conductive material, the thickness of the outer insulating layer is increased in order to reach the same thermal transmittance value for all the studied cases.

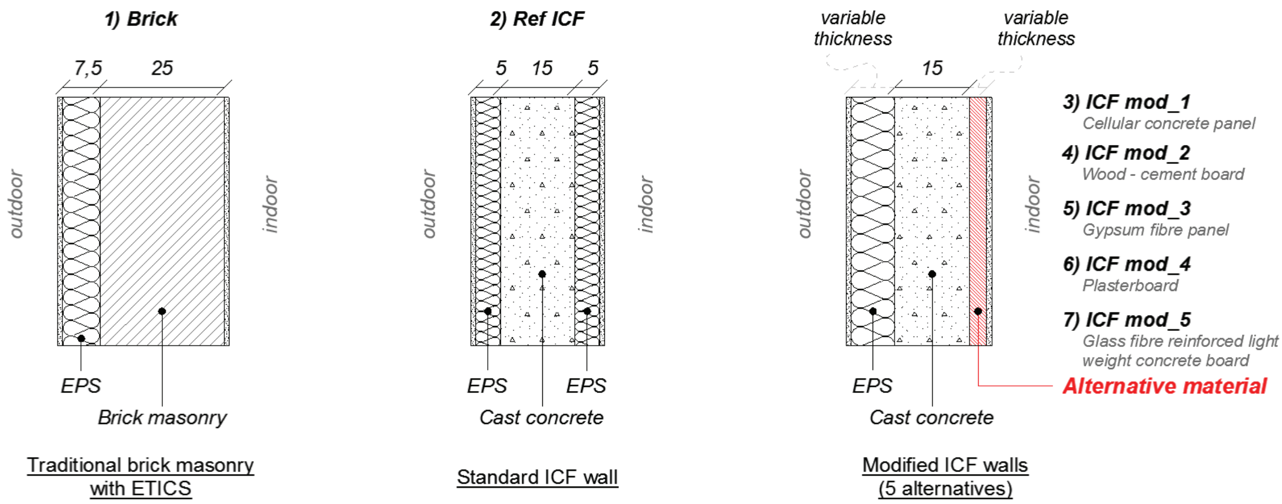

Figure 2.Technical solutions analysed for external walls.

The thermo-physical properties of all the materials used in the analysed types of wall are listed in Table 1. Table 2 shows the detailed stratigraphy of all the seven technical alternatives, while Table 3 display the steady and dynamic thermal characteristics of the various component examined.

Table 1. Thermo-physical properties of the materials used in the wall layering. λ: Thermal conductivity [W/mK], ρ: density [kg/m3], cp: specific heat [J/kgK].

	λ [W/mK]	ρ [kg/m³]	c_p [J/kgK]
Plaster	0,400	1000	1000
Brick masonry	0,313	796	837
Cast concrete	2,300	2300	1000
EPS (Expanded Polystyrene)	0,034	25	1255
Cellular concrete panel	0,152	550	1050
Wood-cement board	0,101	550	1506
Gypsum fibre panel	0,320	1150	1100
Plasterboard	0,210	900	837
Glass fibre reinforced light weight concrete board	0,173	1000	1000

Table 2. Detailed stratigraphy of the seven technical solutions investigated for external walls.

Traditional brick masonry wall with ETICS						
Code	**Plaster [m]**	**EPS [m]**		**Brick masonry [m]**	**Plaster [m]**	**Thickness [m]**
Brick	0,010	0,075		0,250	0,010	0,3450
Reference ICF wall						
Code	**Plaster [m]**	**Outer formwork (EPS) [m]**	**Cast concrete [m]**	**Inner formwork (EPS) [m]**	**Plaster [m]**	**Thickness [m]**
Ref ICF	0,010	0,05	0,150	0,050	0,010	0,2700
Alternative ICF walls						
Code	**Plaster [m]**	**Outer formwork (EPS) [m]**	**Cast concrete [m]**	**Inner formwork (alternative materials) [m]**	**Plaster [m]**	**Thickness [m]**
ICF mod_1	0,010	0,0888	0,150	Cellular concrete panel 0,050	0,010	0,3088
ICF mod_2	0,010	0,0882	0,150	Wood-cement board 0,035	0,010	0,2932
ICF mod_3	0,010	0,0981	0,150	Gypsum fibre panel 0,018	0,010	0,2861
ICF mod_4	0,010	0,0971	0,150	Plasterboard 0,018	0,010	0,2851
ICF mod_5	0,010	0,0975	0,150	Glass fibre reinforced light weight concrete board 0,0125	0,010	0,2800

Table 3. Steady and dynamic characteristics of the different walls.

Wall type	U [W/m^{2}K]	Y_{ie} [W/m^{2}K]	f_a [-]	φ [h]
Brick	0,310	0,058	0,188	10h 1'
Ref ICF	0,310	0,015	0,048	7h 40'
ICF mod_1	0,310	0,027	0,087	8h 19'
ICF mod_2	0,310	0,026	0,084	8h 21'
ICF mod_3	0,310	0,053	0,171	7h 22'
ICF mod_4	0,310	0,048	0,156	7h 23'
ICF mod_5	0,310	0,051	0,164	7h 19'

3. Results and discussion

3.1 Energy performance

The exploitation of the thermal inertia of the envelope allows for the reduction of the internal air temperature peaks and, consequently, the required maximum cooling power. Figure 3 shows the results obtained for free-floating simulations. The indoor air temperature trends are reported together with the outdoor air temperature and the direct normal solar radiation.

As can be seen from the graph, all the five alternative ICF wall solutions have a very similar temperature trend. This shows that, once the thermal insulation layer on the inner side (EPS, λ= 0,034 W/mK) has been removed, the use of one of the substitute materials considered for the internal formwork (0,101 W/mK < λ < 0,210 W/mK) leads to analogous results. Table 4 details the temperature reductions that can be achieved by using the alternative materials for the internal formwork with respect to the Ref ICF wall. The most suitable solution seems to be represented by the gypsum fibre panel. The use of this material on the inner side of the wall in place of EPS, in fact, allows a reduction of the temperature peaks of nearly 1 ° C. Therefore, in the following graphs only this solution will be reported, defined as ICF md_3, in order to avoid overlapping of temperature trends and to have clearer and more readable graphs. Moreover, since alternative materials offer comparable energy performances, the choice will then be oriented by economic effectiveness, addressed later in the paper.

Table 4. Decrement of internal air temperature peaks [°C] achievable using the modified ICF solutions compared to the Ref ICF solution (free-floating simulation).

ICF mod_1	ICF mod_2	ICF mod_3	ICF mod_4	ICF mod_5
0,70 °C	0,67 °C	0,95 °C	0,88 °C	0,89 °C

Temperature profiles for the three construction typologies (Brick, Ref ICF, and ICF mod_3), when the cooling system is operating, are compared in figure 4.

In the time interval in which the cooling system is active, the air temperature reaches the fixed set-point value. Focusing on the hours in which the cooling plant is switched off, a higher and faster increase of indoor air temperature is registered for the Ref ICF wall compared to the traditional brick wall and modified ICF wall, proving that the internal thermal mass of the Ref ICF wall is not adequately exploited. On the contrary, the modified ICF wall exhibits a higher thermal inertia with respect to the other two solutions and it makes possible a reduction of the maximum temperature peak up to 0,5 °C compared to the Brick wall and up to 1,4 °C with respect to the Ref ICF wall. Table 5 indicates the decrease in air temperature that can be attained using the modified ICF solutions in place of the Ref ICF wall.

Table 5. Decrement of internal air temperature peaks [° C] achievable using the modified ICF solutions compared to the Ref ICF solution (simulation with HVAC).

ICF mod_1	ICF mod_2	ICF mod_3	ICF mod_4	ICF mod_5
0,80 °C	0,78 °C	1,39 °C	1,26 °C	1,31 °C

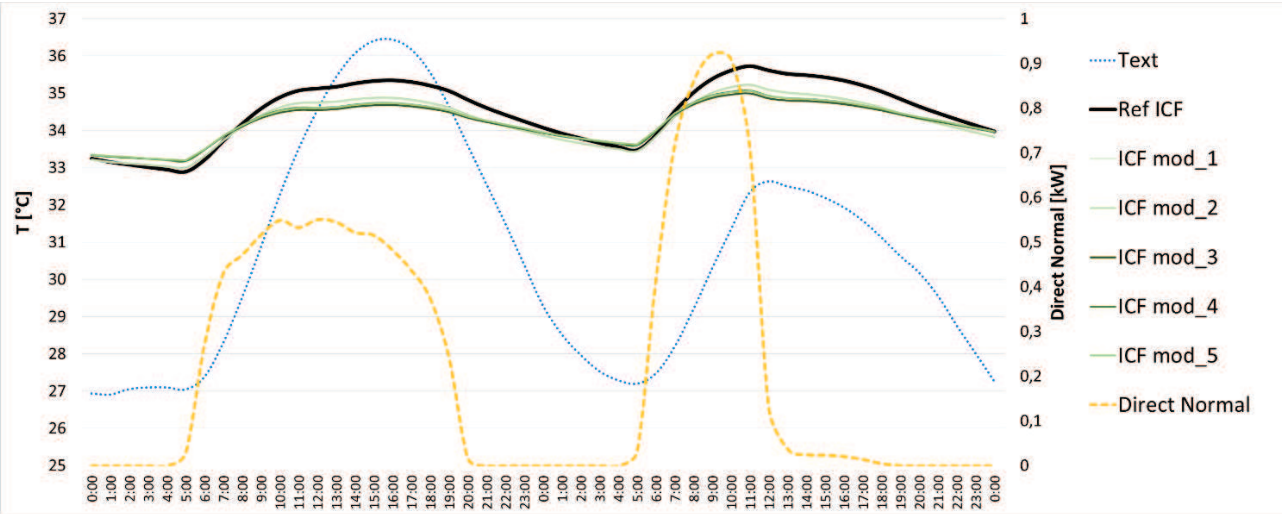

Figure 3. Comparison between the internal air temperature obtained using the Reference ICF wall and the five ICF alternative walls for two days, 21st and 22nd July - (Free-floating simulation).

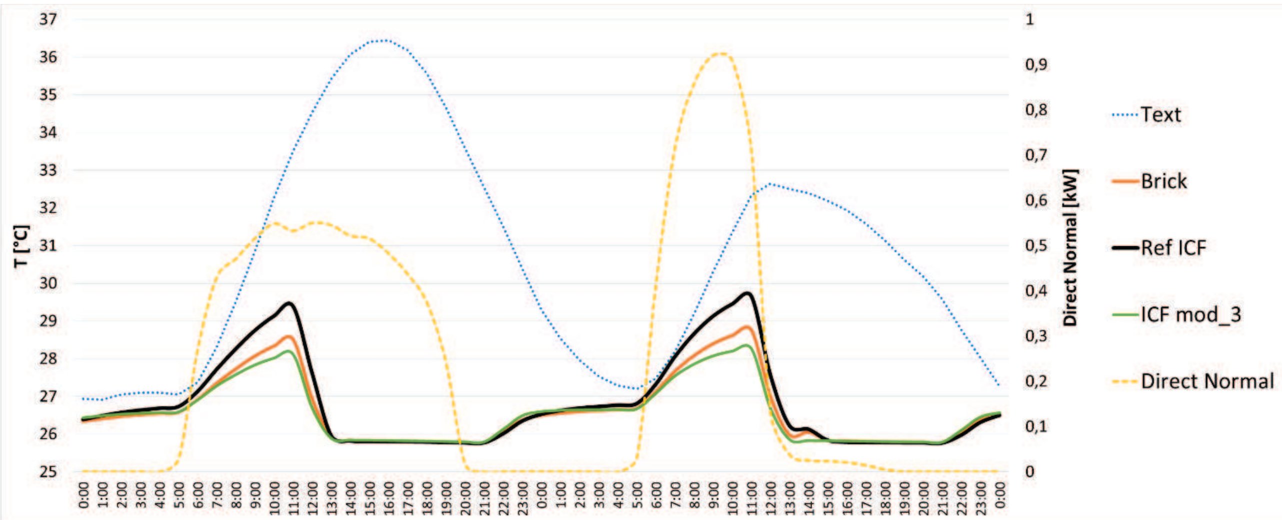

Figure 4. Comparison between the internal air temperature obtained using Reference ICF, Brick, and ICF mod_3 walls, for two days, 21st and 22nd July – (Simulation with HVAC).

Figure 5 displays the cooling primary energy for the entire simulated period and for the seven constructive alternatives analysed.

As expected, the standard ICF solution involves a greater amount of energy for cooling compared to the traditional brick wall. Instead, the alternative ICF solutions allow to guarantee similar performances of the traditional masonry wall and in some case even better. This is a very interesting outcome because, in addition to the advantages obtained in terms of energy, it possible to benefit from all the advantages of ICF technology compared to traditional masonry (executive speed, ease of installation, flexibility, seismic safety, etc.). The percentage reductions in cooling primary energy for alternative ICF solutions with respect to the Ref ICF wall are summarized in table 6.

Table 6. Percentage reduction in cooling primary energy for alternative ICF solutions compared to the reference ICF wall.

ICF mod_1	ICF mod_2	ICF mod_3	ICF mod_4	ICF mod_5
12,9 %	11,7 %	20,2 %	19,5 %	19,4 %

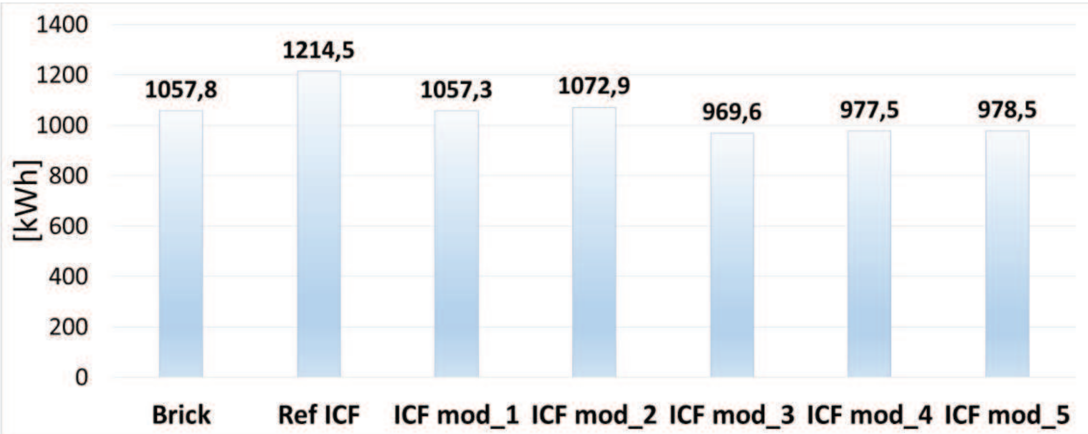

Figure 5. Cooling primary energy for the complete simulated period (from 1st May to 31st October) for all external wall types.

Regarding ventilation strategies, separate simulations were performed in order to explore the effect of introducing a nightly free cooling from 23:00 to 7:00, when the outdoor temperature decreases allowing to remove thermal energy stored in the building structure during the day. From this analysis, it turned out that nighttime ventilation decreases the difference in temperature between the various solutions and tends to equalize the energy needs. Furthermore, the current analysis focused only on the calculation of sensible loads, therefore relative humidity and latent loads were not considered in the present study.

3.2 Economic analysis and construction times

An economic analysis was conducted with the aim of assessing the cost effectiveness of the various analysed solutions. Firstly, the cost of construction of the walls for the different alternatives was estimated by referring to regional price lists and market survey (Regional Price List, 2018). Table 7 displays the cost of construction, distinguishing between material costs and labour costs.

Table 7. Construction cost and impact of materials and labour for each technical alternative.

Wall Type	Total cost [€/m²]	Materials cost [€/m²]	Labour cost [€/m²]	Materials incidence [%]	Labour incidence [%]
Brick	156,54	69,60	86,94	44	56
Ref ICF	136,74	75,23	61,51	55	45
ICF mod_1	116,77	55,06	61,71	47	53
ICF mod_2	119,33	57,16	62,17	48	52
ICF mod_3	125,47	62,20	63,28	50	50
ICF mod_4	112,42	51,50	60,93	46	54
ICF mod_5	130,45	66,28	64,17	51	49

The standard ICF system saves about 13% of the total construction cost compared to the traditional brick wall. This saving is attributable to the lower labour cost of ICF system as it permits a faster construction than masonry. In fact, in spite of the increase in material costs of 7,5%, the Ref ICF wall allows a saving on labour of almost 30% compared to the Brick wall. The construction time estimated based on the percentage of labour costs is, in fact, of 3,00 h/m2 for the brick wall while an execution time of 2,12 h/m2 is required for the ICF wall. Therefore, the reference ICF wall has a lower initial cost than the brick masonry wall. However, with regard to energy consumption, the Ref ICF wall determines a slightly higher annual cooling energy than the traditional masonry wall. In order to assess the cost-effectiveness of these first two solutions, discounted cash flows were calculated, considering a discount rate of 4%, an average electricity cost of 0,25 €/kWh, and an inflation rate of 3%. Starting from the initial extra-cost generated by the brick construction, the discounted annual savings have been subtracted. The net present value over a period of 30 years is negative. This means that the higher initial cost incurred to realize the brick construction, that consumes less annual cooling electricity than the Ref ICF wall, is not repaid by the lower running costs of the building in 30 years. The annual saving achievable is, in fact, very low and does not allow to payback the investment in the time considered. Therefore, the Ref ICF wall is more cost-effective than Brick wall. A very high inflation rate of energy costs (i.e. 10%) would lead to repay the extra-cost in 26 years. The two scenarios are illustrated in figure 6. Concerning the modified ICF solutions, these imply an initial expense lower than both the Brick wall and Ref ICF wall. The saving is, in this case, mainly due to the lower cost of the used materials, which are cheaper than the insulating material used in the Ref ICF wall. Furthermore, all the modified ICF walls, expect the ICF mod_2 alternative, involve an annual energy consumption lower than both the Brick and the Ref ICF walls. At this starting benefit, the annual savings due to the lower energy cost spent to cool the building can be added. In order to identify the most economically viable solution among the five proposed ICF alternatives, the initial savings and the discounted annual saving are outlined in figures 7 and 8, reporting the savings of the modified ICF walls, with respect to the brick wall and to the reference ICF wall, respectively.

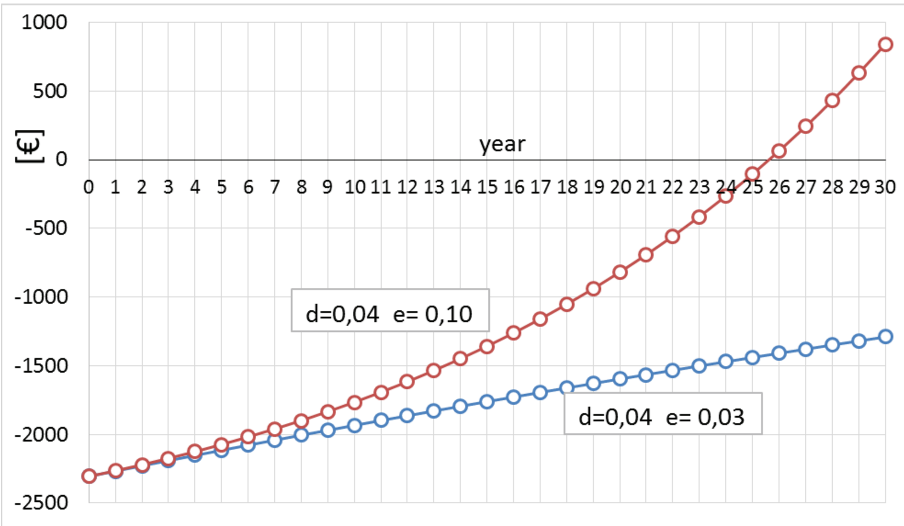

Figure 6.NPV trend of the difference in costs between the Brick wall and the Ref ICF wall over a 30-year period and upon variation of the inflation rate.

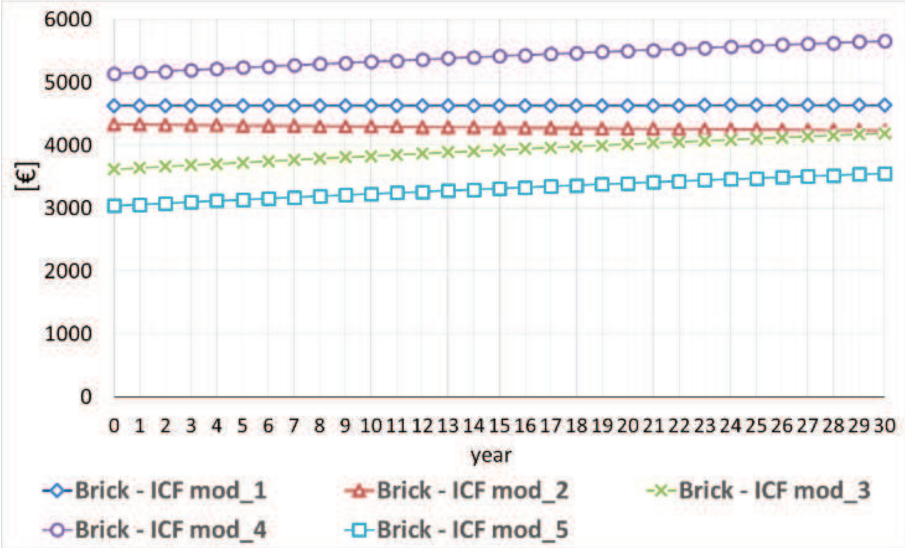

Figure 7. NPV trend of the difference in costs between the modified ICF walls and the Brick wall over a 30-year period (d=0,04, e=0,03)

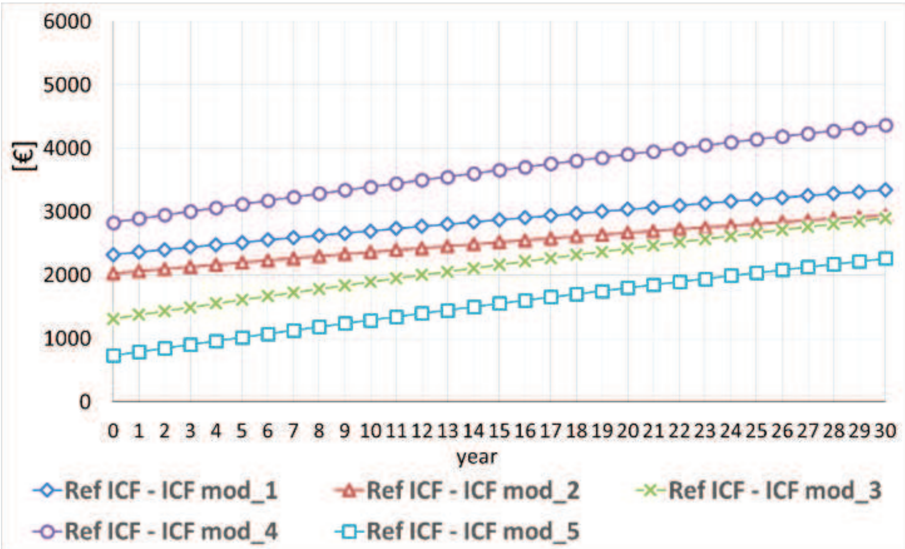

Figure 8. NPV trend of the difference in costs between the modified ICF walls and the Reference ICF wall over a 30-year period (d=0,04, e=0,03)

As shown in figure 7, the modified ICF walls guarantee a saving on the initial cost that varies from 3038 € (ICF mod_5) and 5037 € (ICF mod_4). The ICF mod_2 solution presents an initial gain of 4333 €, but this beginning advantage is partly depleted by the increased annual energy consumption with respect to the brick masonry building. The ICF mod_1 solution has an initial gain of 4631 €, but the annual consumption is approximately equal to the Brick wall, so no significant additional annual earnings during the 30 years are registered. Among the remaining four modified ICF alternatives, the most cost-effective one is the ICF mod_4 which allow for a total saving of 5658 € over 30 years.

Regarding the comparison between the modified ICF solutions with respect to the Ref ICF wall (Figure 8), all the proposed alternatives offer savings compared to the Ref ICF wall, both on the initial construction cost and on operating cost. In particular, savings on initial cost range between 732 € (ICF mod_5) and 2832 € (ICF mod_4). Considering a 30-year period, the most advantageous solution is the ICF mod_4 which saves 4367 € over the analysed period.

4. Conclusions

The study analysed the performance of upgraded ICF constructions modified in order to be adapted to a warm climate, such as the Mediterranean. A simple change consisting in the replacement of the insulating internal formwork with a layer made of material with a higher thermal conductivity has proved to be successful. This solution, in fact, allows to keep all the advantages offered by the ICF technique (flexibility, seismic safety, rapid construction, waterproofing, thermal and acoustic insulation, limitation of thermal bridges, ease of technical system integration). And, in addition, it increases the thermal inertia of the envelope, allowing to better exploit the thermal storage capacity of the concrete mass inside the wall, which otherwise remains unused as it is shielded by the thermal insulation layer. Various alternative materials were considered in order to replace the internal formwork, resulting in an improved behaviour with respect both to a traditional brick wall and to a standard ICF wall. The best energy performance is provided by the material with the highest thermal conductivity (gypsum fibre panel). However, the most cost-effective solution is represented by the plasterboard, which allows considerable savings on the initial construction cost and a reduction of 19.5% of the annual cooling energy.

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Chapter 3

Thermal energy storage

Massive building envelopes can be utilized as one of the simplest ways of reducing heating and cooling loads. Significant energy savings can be achieved in the design stage of the building and on a relatively low-cost basis. An optimized materials configuration combined with a proper amount of thermal insulation can help to reduce the building cooling and heating energy demands and building-related CO_2 emission. In fact, besides the structural function, a massive construction can also serve as actively charged thermal mass to store thermal energy and then passively release it to assist space heating or cooling. The benefit of thermal mass in residential buildings is well understood in warmer parts of Europe, but it is also becoming increasingly relevant to other regions where the impact of climate change is leading to more frequent occurrences of overheating. For centuries, buildings have been built with massive walls technologies, using earth, stone, solid wood, concrete and making life without air conditioners relatively comfortable, even in countries with hot climates, such as Spain, Italy or Greece. Numerous studies demonstrate that thermal mass involved in the building can provide better energy performance results, by reducing temperature swing and by absorbing surplus energy both from solar gains and from heat produced by internal energy sources such as occupants, lighting and appliances. In addition, massive building envelope components delay and flatten thermal waves caused by exterior temperature swings.

As shown in figure 1, thermal mass reduces the speed at which internal temperature increases due to solar radiation or internal sources. Consequently, the same thermal mass can reduce the speed at which internal temperature decreases when the sources are removed.

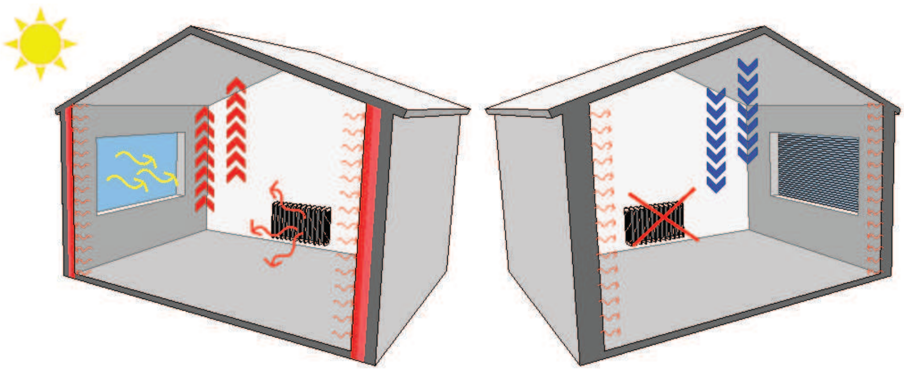

Figure 1. Storage and release cycle of thermal energy within the thermal mass of the building fabric.

During warm weather, much of the heat gain in heavyweight structures is absorbed by the thermal mass of the fabric, helping prevent an excessive temperature rise and reducing the risk of overheating. This makes naturally ventilated buildings more comfortable and, in air-conditioned buildings with thermal mass, the peak cooling load can be reduced and delayed.

Therefore, the ability to absorb and release heat enables buildings with high thermal mass to respond naturally to changing conditions, helping stabilize the internal temperature and provide a largely self-regulating environment. This effect is studied in the paper presented in Section 3.1 analysing the dynamic interaction between thermal mass and air conditioning systems for a theoretical case study and highlighting the role of thermal storage on the maintenance of internal conditions. The study reported in Section 3.2, instead, is based on data measured on a real building and it demonstrates how the building structure can be exploited as a long term storage system to accumulate excess energy supplied by renewable sources.

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

3.1 The role of the thermal mass in nZEB with different energy systems

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Contribution of the candidate: the candidate devised the research methodology. She conducted the simulations using DesignBuilder software and produced all the graphs in the document. She wrote sections 1, 2, and 3 of the paper.

Abstract

European and Italian standards establish high levels of energy performance of buildings that have to be designed considering their energy balance near zero. To achieve this goal, the reduction of energy demand, attainable by improving energy efficiency of the construction, and the use of renewable energy available both on site and off site are effective solutions to be applied. In particular, in buildings that use energy produced from renewable sources, due to their unstable and unpredictable nature, having the right strategy to compensate the variations is essential. A technical solution reevaluated as a consequence of passive design principles, is to provide an adequate thermal inertia in order to store energy when it is offered and to use it when the source is not available. In these cases, the ability of construction elements to retain heat becomes fundamental as they contribute to maintain internal comfort conditions. This paper aims to investigate how various types of heating and cooling systems, based on different modes of heat transfer, are able to interact differently with the thermal mass of the building, producing a different level of its activation. The investigation considers a case study used to carry out dynamic simulation by means of DesignBuilder which is a user interface of EnergyPlus. The model consists of a building with elementary geometry and a single thermal zone, delimited by walls with outside thermal insulation and a heat accumulation layer inside. The variation of the internal temperature by using different types of conditioning system is analyzed in order to individuate the technology that takes the greatest advantages from the thermal mass.

Keywords: Thermal storage; Thermal inertia; Radiant temperature; Air temperature; NZEB; Heating/cooling terminal units.

1. Introduction

The recent legislation, accepting the provisions dictated by the Directive 2010/31/UE [1], imposes high standards of energy efficiency in constructions and compels the adoption of measures that could lead to building energy consumption close to zero. Having a zero energy balance means that the building must have a very low consumption and this limited energy should be covered largely by energy from renewable systems, so that the use of traditional sources becomes almost null. To reduce the energy consumption, the energy efficiency of buildings has to be improved, primarily. This objective should be achieved by providing a good insulation of the envelope and by involving a high level of thermal inertia in the construction. Thermal mass depends on density and specific heat of the materials and it measures the heat storage capacity of the element. When exposed to external heating, materials with high thermal mass, generally heavier and denser materials, are able to store more heat than lightweight materials. On the other hand, it will also take longer for materials with good thermal mass to release the stored heat once the heat source is removed [2].

Actually thermal inertia is one of the most important parameters for improving thermal comfort conditions and for reducing heating and cooling energy demands of buildings [3][4][5]. Several authors analysed the effect of the thermal characteristics on energy performances of buildings upon variation of insulation and inertia [6][7][8] proving that significant energy saving can be achieved depending, however, on the distribution of mass and insulation inside the wall. Other authors evaluated the influence of the position of a massive layer and of an insulation layer, also finding substantial differences in air conditioning consumption in intermittent regime for the different technical solutions [9][10]. Numerous studies demonstrated that the placement of the inertial mass on the internal side of the building envelope is recommended, both for energy saving and for comfort. Many researchers have shown that the solution with external insulation and high internal mass is preferable to the assembly with inner thermal insulation and external mass, as it allows greater energy savings [11][12].

Thermal inertia is generally proposed as a passive strategy for energy saving in buildings. The thermal mass has positive effects on the indoor conditions during the summer and winter periods. The energy available from the high solar gains during the day is stored and then is slowly released into the indoor environment at a later time. In winter, the stored heat is transferred back into the room during the evening hours, when it is most needed, satisfying part of the heating load and avoiding overheating and discomfort conditions during the high solar radiation periods of the day. In summer, heat is stored in the thermal mass, thus reducing the cooling loads peaks [13]. According to Karlsson [14], passive energy storage through high thermal mass can significantly change the power consumption pattern, which can give significant benefits. Heavy constructions, characterized by high heat capacity inside the envelope, offer various advantages: they can reduce energy consumption; the energy demand of the building may be decreased or shifted to times when loads are lower and indoor temperatures result more stable. Thermal mass is therefore an essential element of passive solar design, primarily because of the need to store the solar energy received by the building during the day and then to gradually release it overnight [2]. However, many studies show that passive thermal designs alone are not enough to fully exploit the potential for energy efficiency in buildings: in fact, harmonizing the active elements for indoor thermal comfort with the passive design of the building can lead to further improvements in both energy efficiency and comfort [15]. Thermal mass generally reduces the speed at which internal temperatures increase as a result of external solar radiation or internal heat emissions. Consequently, the same thermal mass may reduce the speed at which internal temperatures decrease when heating effects are removed [16].

This study aims to analyze the dynamic interaction between the thermal mass involved in a conditioned environment and the air conditioning system. The study is carried out by performing dynamic simulations on a simplified model by using DesignBuilder [17] which is based on the computation engine EnergyPlus [18]. The trends of indoor air temperature and radiant temperature are analyzed upon variation of the heating/cooling terminal units, which use different modalities of heat transfer. The analysis leads to verify the possibility of exploitation of the thermal mass in the structures to store the energy produced through renewable systems and make it usable when the sources are not available. In fact, a proper design of the building obtained by equipping the construction with suitable thermal inertia, may be insufficient if it is not adequately exploited. The most profitable solution is one which allows to minimize variations of the indoor temperature which should remain constant and close to the comfort values by means of the minimum contribution of the air conditioning system.

2. Methodology

This paper intends to study, in the case of intermittent operation of the conditioning system, the evolution of the internal air temperature and radiant temperature. In order to assess the capacity of the thermal mass to release the previously stored energy, the solar forcing is considered null and the outside air temperature is assumed constant and equal to values commonly used for winter and summer design in Italian locations. The results obtained with these hypotheses will be useful to choose the most suitable thickness of thermal mass in order to perform, successively, simulations in real conditions, considering solar radiation, ventilation, and variable hourly temperature.

Dynamic simulations were performed on a basic model by means of DesignBuilder and EnergyPlus. The study was carried out after bringing the system to stabilized periodic conditions. The aim is to analyze the influence of different energy supplying systems on the activation of the internal thermal mass, and to verify the possibility of using the building structures for the storage of energy produced by means of renewable sources. In fact, in a heating/cooling system, the accumulation is not always present, and when present it is, however, limited. Using the building components to store energy allows optimization of the system taking full advantage from the energy produced by free sources. This concept can be used when the source is not available making the realization of nZEB buildings more feasible.

2.1 Description of the geometric model

The test model consists of an air-conditioned space 5mx5m with 1mx1m transparent surface on each façade in order to have equivalent conditions on all exposures (see figure 1). The ceiling and the floor are adiabatic and they were modelled with a negligible mass in the first phase of the study. The investigation focused on the walls as these elements contribute significantly to the energy saving of the building mediating the heat exchanges between the internal and outdoor environment [19][20]. External walls include two layers, 8 cm brick layer inside (c=840 J/kg K) and 8 cm thermal insulation layer outside (λ=0,040 W/m K), with total transmittance U=0.438 W/m^2 K. Windows have metallic frame with thermal break and clear double glass 4-12-4 mm with air in the gap.

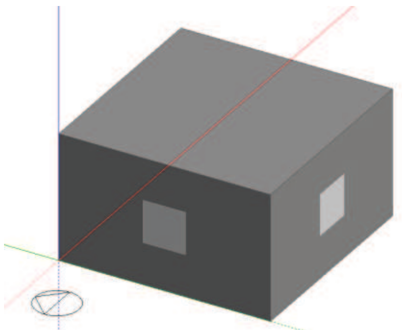

Fig. 1. DesignBuilder 3D view of the analyzed model.

2.2 Test conditions and settings

The heating set point temperature is fixed equal to 20 °C, the cooling set point temperature is 26 °C. Other settings include:

- Absence of internal gains due to occupancy, lighting and equipment;
- Absence of solar radiation. Windows are considered in order to contemplate heat losses through glazed surfaces;
- Absence of natural and mechanical ventilation.

Furthermore, the outdoor temperature was considered constant and equal to 0°C in winter and 35°C in summer. For this model in which boundary conditions were maintained unchanged and external or internal perturbations were not present, the effect of the dynamic interaction between the thermal mass and the forcing provided by the plant was analysed. To achieve fixed internal comfort conditions, the heating/cooling system was simulated by using different terminal units: fan coils, radiators and heated floor in winter; fan coils and chilled ceiling in summer. The operation of the system is intermittent with daily activation from 8:00 to18:00.

3. Results

The trend of the average air temperature and of the radiant temperature was analyzed upon variation of the heating/cooling terminal units. Figure 2 shows the temperature profiles for a winter day (a) and for a summer day (b), respectively.

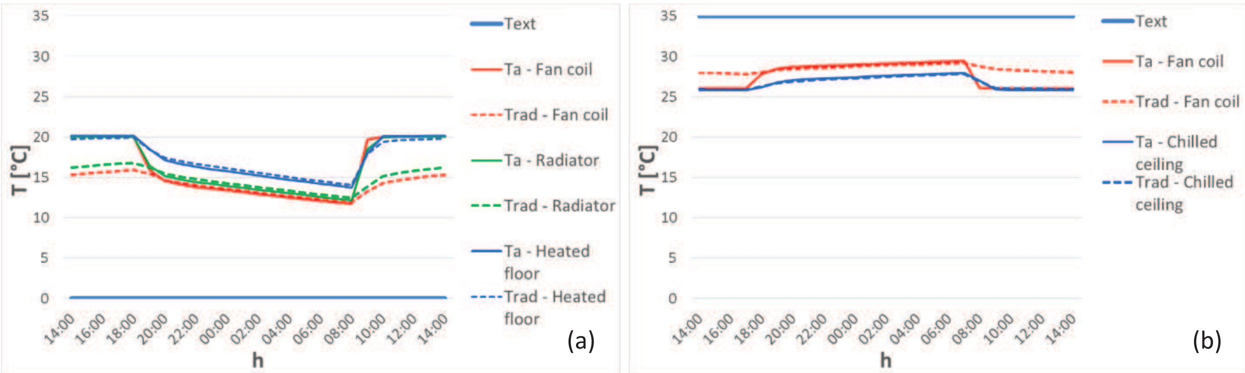

Fig. 2. Trend of the mean air temperature (Ta) and of the radiant temperature (Trad) in the room for a winter day (a) and for a summer day (b), at variation of terminal units.

The intermittent operation of the system causes temperature fluctuations in the conditioned space. In the winter period, when fan coils are used for convective heat transfer, the radiant temperature remains at low values during the hours when the heating is active, distant from the air temperature. Also using radiators, with 30% radiant fraction, the surface temperatures are 4 – 5 °C lower than the air temperature. Therefore, when the internal source is stopped, the air temperature rapidly falls down and decreases until it reaches the values of the radiant temperature. Conversely, in the case of radiant heated floor, air temperature and radiant temperature evolve together and when the plant is switched off the air temperature is reduced less and more slowly compared to the other two systems. This effect is because the heated floor is able to activate a greater thermal mass, and when the heating is not operating the mass is warmer and the surface temperatures result higher. In the case of the other systems, the radiant temperature reaches the maximum value of 16 °C remaining 4 – 5 ° C lower than the air temperature. Turning off the heating, the air reaches the radiant temperature and cools rapidly, passing from 20°C to 14°C in two hours. In case of radiant units, the air temperature reduction is softer and slower because the mass surface was previously heated, and it has a higher capacity than the air, so the structures are able to transfer heat to the air.

Similar considerations can be made for the summer period when fan coils and cooled ceiling were utilized. Using air systems, the radiant temperature is maintained 2 – 3 °C higher than the air temperature, and switching off the cooling the air temperature in the room quickly rises, passing from 26 °C to 29°C in three hours. Using a cooled ceiling, instead, the temperature oscillations are more restrained. The influence of the thickness of the thermal storage layer on the maintenance of internal comfort conditions was evaluated for fan coils and radiant systems. Maintaining unvaried the external insulation layer, the internal accumulation layer was varied between 0 and 30 cm.

Figure 3 shows the daily profiles, for a winter day, of the air temperature and of the radiant temperature in the case of heating system with fan coils and heated floor. Using fan coils (Figure 3a), without a thermal storage layer (0 cm thick), the air temperature decreases rapidly to the value of the outside temperature. Progressively increasing the mass layer located on the inner side of the wall, the temperature reduction becomes more contained. Even if a consistent thickness of the heat storage is present, the convective heating system is not able to involve the mass. The radiant temperature remains low, even in the case of 30 cm of inertial mass and, consequently, the air temperature turns down when the plant is switched off.

In the case of heated floor (Figure 3b), in the absence of thermal storage (0 cm thick), the behavior is similar to the case of the plant with fan coils. Instead, if there is a thermal mass layer, the heated floor allows to involve the mass in a greater extent and more attenuated changes in temperature are registered. It should be noted the important role played by the surface thermal mass on the temperature decay, due to the transfer of previously stored heat. The results show that thicknesses higher than 8 cm lead to very similar behaviors. Thus, the thermal mass that can be activated in the charge/discharge cycle of 24 h consists of the first 8 – 10 cm. Higher thicknesses do not determine significant changes in the evolution of the temperature. The overlap between the air temperature and the radiant temperature occurs for all the analyzed thicknesses.

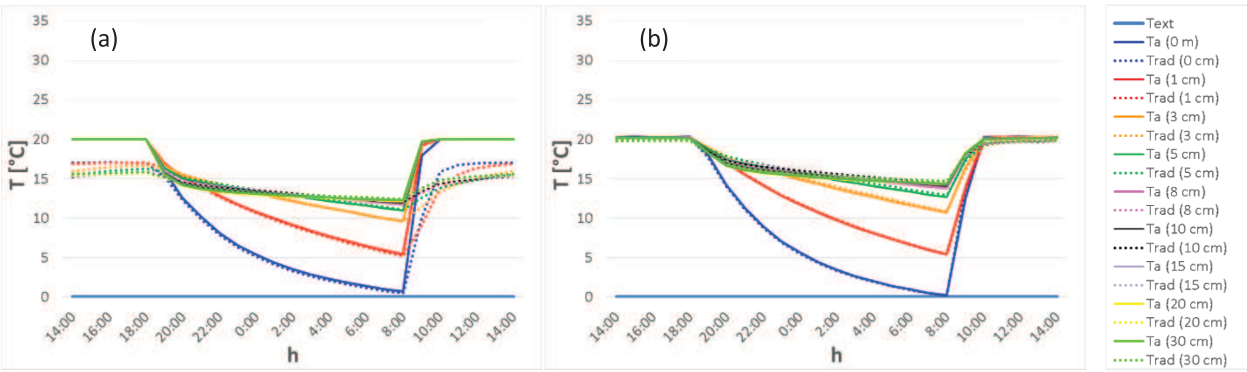

Fig. 3. Mean air temperature and radiant temperature at variation of the thermal storage layer thickness in the walls (cm), for heating with fan coils (a) and heated floor (b).

The same analysis was carried out for summer conditions. Figure 4 shows the temperatures for a day upon variation of the thickness of the heat storage layer. Cooling by means of fan coils and chilled ceiling, were considered. In both systems, in the absence of thermal mass and during periods in which the plant is not active, the air temperature reaches high values (over 32 °C) because the structure is not able to mediate the heat wave coming from the outside. If the heat storage layer is provided, the combination between the mass and the radiant system leads to a more efficient operation by reducing temperature fluctuations. Even in the cooled season, the mass layer that can be actively involved consists of the first 8 - 10 cm. Higher thickness do not provide an appreciable effect.

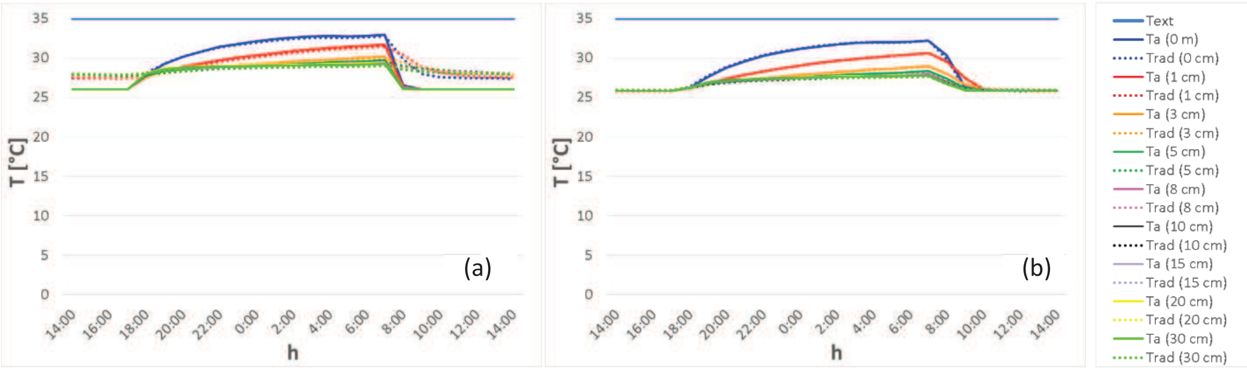

Fig. 4. Mean air temperature and radiant temperature at variation of the thermal storage layer thickness in the walls (cm), for cooling with fan coils (a) and chilled ceiling (b).

4. Analysis in the transient at variation of the thermal storage layer thickness

In order to examine the results of the numerical simulation at the stage when the conditioning system is switched off in more detail, the trend of the radiant temperature was analyzed in the transitional period. The air temperature evolution was not considered because, for some type of terminals, it undergoes a sudden drop at the moment when the plant is turned off displaying a discontinuity point. The functions used to describe the profile of the radiant temperature are (1) for the winter period and (2) for the summer period:

$$T_{rad,w} = A_{0w} exp^{(-t/\tau_w)} \quad (1)$$

$$T_{rad,s} = A_{0s}\left(1 - exp^{(-t/\tau_s)}\right) + T_s \quad (2)$$

where: $T_{rad,w}$ is the radiant temperature in winter [°C]; A_{0w} is the value of the radiant temperature at the beginning of the transient period, in winter [°C]; $T_{rad,s}$ is the radiant temperature in summer [°C]; A_{0s} is the difference between the outdoor temperature and the value of the radiant temperature at the beginning of the transient period indicated with T_s, in summer [°C]; t is the time step [h]; τ_w is the time constant in winter [h]; τ_s is the time constant in summer [h]. These functions are able to describe with good approximation the trends obtained by simulation allowing the calculation of the time constants τ_w and τ_s. Values of R-squared (coefficient of determination) higher than 85% were obtained for both the equations.

Figure 5 shows the good agreement between the trend of the radiant temperature obtained by the simulations and the corresponding interpolating functions.

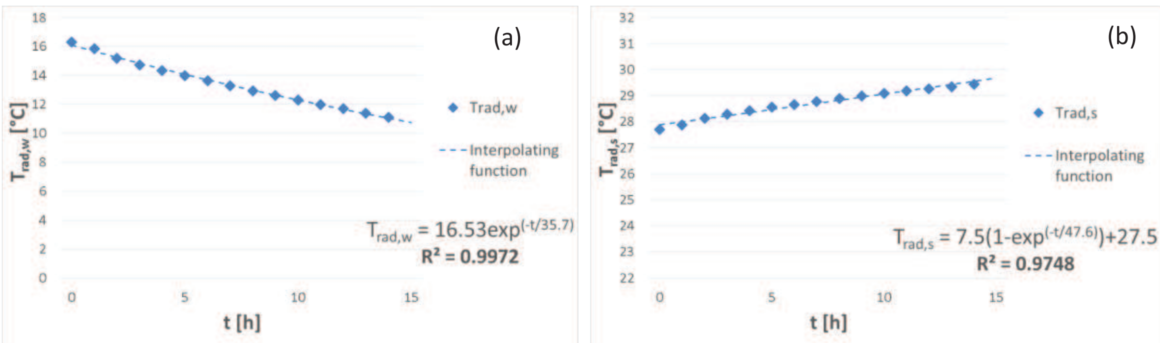

Fig. 5. Trend of the radiant temperature in the transient period (from 19:00 to 8:00) for heating system with fan coils (a) and cooling system with fan coils (b), in the case of walls including 5 cm of thermal storage layer.

For each simulation carried out upon variation of the thermal storage thickness in the range 0 – 30 cm, the parameters A_{0w} and τ_w in winter, and A_{0s}, T_s and τ_s in summer were calculated with reference to the best function that fits the curve of simulated values. The analysis performed for all the thicknesses showed that for a thermal storage layer greater than 10 cm these parameters become constant. Only when a heated floor is used, the thermal mass thickness beyond which there are no further variations in A_{0w} and τ_w is 8 cm.

4.1 Winter period

4.1.1 Heating with fan coils

Figure 6(a) shows the values of τ_w at variation of the thermal storage layer thickness for heating with fan coils. The graph highlights an increasing trend of the time constant for growing thicknesses, until 10 cm. After this value, τ_w becomes constant. Figure 6(b) illustrates the trend of A_{0w} that decreases with the thickness of the accumulation layer, since increasing the heated mass a lowering of the surface temperature is obtained.

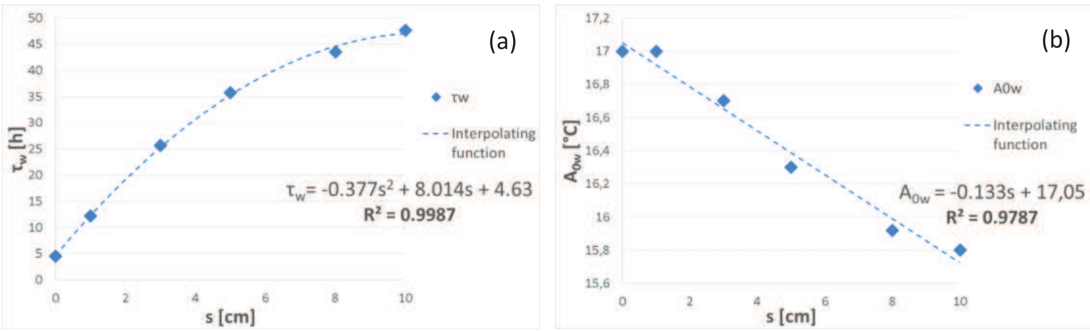

Fig. 6.Trend of τ_w (a) and A_{0w} (b) at variation of thermal storage layer thickness s [cm] in the case of heating with fan coils.

4.1.2 Heating with heated floor

Figure 7 shows the profile of τw in the case of heating with heated floor.

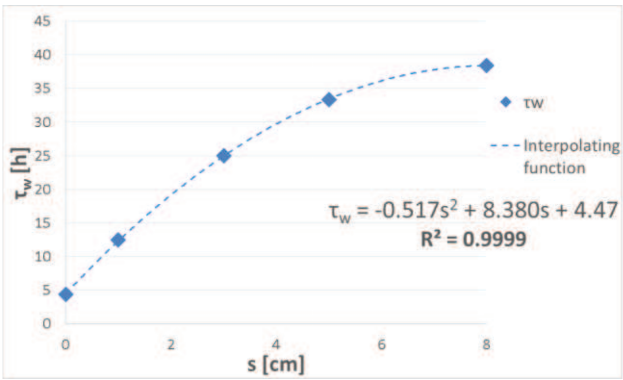

Fig. 7.Trend of τ_w in the case of heating with heated floor.

In case of heating with heated floor, as the radiant temperature at the beginning of the transient period reaches the air temperature value, A_{0w} is constant and equal to 20 °C.

4.2 Summer period

In the cooling season, using fan coils, the initial radiant temperature T_s is higher than the set point temperature (fixed to 26 °C) and it assumes a constant value equal to 27.5 °C, and therefore A_{0s} assumes the steady value of 7.5 °C. In the case of a chilled ceiling, as the initial radiant temperature T_s is equal to the air temperature (26 °C), A_{0s} assumes the constant value of 9 °C.

It is interesting to observe that the time constant τ_s has the same trend both for fan coils and chilled ceiling. The increase of τ_s with the thermal storage layer is shown in figure 8. The graph illustrates that the values obtained in the summer period are slightly higher than those obtained in the winter season (see figure 7).

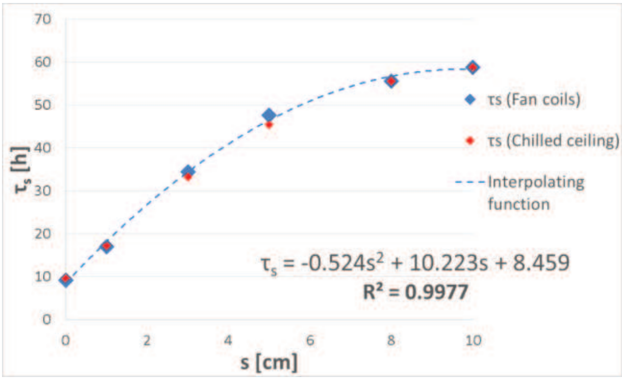

Fig. 8.Trend of τ_s in the case of cooling with fan coils and chilled ceiling.

5. Conclusions

The heat storage in the structure of buildings by using the internal surface thermal mass was investigated. The analysis of the dynamic thermal behavior of a simple case study allowed assessment of the possibility of accumulating energy produced from renewable sources, such as that produced by a chiller powered by photovoltaic panels. This solution could be particularly useful in the realization of nZEB. The study points out that, including the same amount of thermal mass in the construction, the thermal storage capacity results higher if radiant system are used for conditioning the environment. In fact, by using these systems the surface temperatures of the building components reach values close to the air temperature, resulting in greater energy stored.

Considering this effect and in the case of free energy availability, it should be profitable to bring the radiant temperature to higher values in winter and to lower values in summer than the air temperature, in order to increase the thermal storage capacity. Therefore, the thermal mass of the building is most stimulated to perform its function of energy accumulator.

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3.2 PV driven heat pumps for the electric demand-side management: experimental results of a demonstrative plant

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Contribution of the candidate: the candidate processed the measured data and produced the graphs. She wrote sections 1 and 2 of the paper.

Abstract

The energy performances of a smart air-conditioning plant installed at the University of Calabria, constituted by heat pumps and a storage tank, are introduced. The same plant is configured as an alternative electric storage system because connected, by means of an appropriate internal electric micro-grid, to a 4kWp PV generator. The electric micro-grid manages the electrical fluxes in order to increase the self-consumed rate. The storage tank covers the mismatching between solar energy availability and heating requests, by accumulating the PV electricity surpluses under the form of hot/cold water. Moreover, a long-term storage system is represented by the conditioned building: a radiant system, in fact, is exploited to activate the building thermal mass. A suitable control strategy was developed to activate overheating or undercooling strategies in presence of a saturated tank, in order to avoid the transfer of PV electricity to the external grid, increasing the system profitability. The conceived system coordinates the operation of the air-conditioning plant with other electric loads, favoring the building-plant system to be less dependent from the external grid.

Keywords: Electric DSM; Thermal Storage; Smart control; Building thermal storage;

Research Funding: Italian Ministry of Research and University: PON3PE_00050_2

1. Introduction

In Italy, the primary energy demand in 2015 was approximately 156 Mtoe (million tons of equivalent oil), with an increment of 3.4% compared to the prior year. In particular, in the residential sector the augment was approximately 10% reaching 32 Mtoe, with a fraction of 70% to satisfy exclusively the building air-conditioning requirements [1]. Therefore, an actual reduction of the energy needs can be attained by means of air-conditioning plants with high efficiency indexes, where renewable sources can be integrated easily [2]. PV driven heat pumps represent a reliable generation system to reduce heating and cooling demands drastically, however an appropriate control has to be developed in order to rationalize the exploitation of the renewable electricity [3]. Heat pumps can be considered as an “alternative” electric storage system, transforming in thermal energy eventual PV electricity surpluses [4]. Thus, the air-conditioning plant can be included in the management of the electric energy demand (DSM, demand side management), allowing for a projection of the absorbed electricity and the coordination of the heat pumps operation with other electric loads [5]. In a future scenario of development of the Smart Cities models, the cooperative use and the predicted energies produced by renewable sources, allows for the definition of appropriate management plans of the internal grids that make the aggregated users less dependent from the external environment. In addition, limited aggregations such as condominiums can benefit of such air-conditioning plant, considering that a PV generator can supply only common loads (legislative constrains), without a direct advantage for single users. PV generators connected to heat pumps, instead, transform electric energy in storable thermal energy, to use for heating/cooling applications or production of DHW also in deferred manner. Later, each apartment can employ the thermal energy measuring it by energy flowmeters.

In the specific case of air-conditioning plants made by PV driven heat pumps, consolidated technology as storage tanks are necessary to manage the mismatching between the energy request and the availability of renewable electricity [6]. This need is more evident in winter, due to frequent presence of overcast conditions and to the nightly heating demands. In summer, instead, a sort of synchronism occurs because cooling loads are frequently required during the hours with solar irradiation availability. However, the storage volumes can be limited because in a building-plant system also the same edifice can be considered as a long-term storage device. Thus, PV surpluses can be transferred by means of overheating or undercooling strategies from the tank to the building making the first available for a short-term storage again [7]. The building effective thermal mass can be activated by an appropriate emission system that establishes a prevalent radiant exchange (radiant panels). In this paper, the energy performances of an experimental smart air-conditioning plant with the mentioned features and installed at the University of Calabria (Italy), are presented.

2. Equipment description

Fig. 1 shows the demonstrative plant used to supply heating and cooling loads to an office building hosting a research center, operating every day from the 8:00 a.m. to the 6:00 pm, excluding weekends.

Fig. 1- The demonstrative plant installed at the DOMUS research center of the University of Calabria

It is constituted by:

- N° 2 air-water heat pumps operating with R410A as refrigerant fluid and equipped with inverters;
- a PV generator of 4 kWp tilted of 30° and exposed toward south with polycrystalline silicon modules;
- an internal micro-grid that manages the electricity fluxes inside the building and exchanged with the external environment, privileging the provision of internal loads by the PV electricity [8];
- a pellet cogenerative boiler with Stirling engine, as integrative/auxiliary system for the winter period, installed inside the building with nominal electric and thermal powers of 1 kWhe and 14 kWhth respectively;

- a 800 liter vertical tank to store sensible thermal energy, both for heating and cooling applications;
- suspended radiant ceilings in mineral fiber (not integrated in the structure) as emitters of heating and cooling loads and for the activation of the effective building thermal mass.

In Fig. 2 is represented the modelled edifice, where the proposed air-conditioning plant serves only the ground floor, for a conditioned useful surface and volume equal to 337 m² and 1250 m³ respectively. Thermal transmittances of opaque and transparent walls are respectively equal to 0.47 W/m²K and 2.83 W/m²K, the latter are constituted by a clear double pane glazing system with normal solar factor of 75%. The average surface mass of opaque walls is slightly lower than 300 kg/m², characterizing a building fabric with an appreciable thermal inertia. The peak loads calculations have considered a natural air-change of 0.5 volumes per hour and internal gains equal to 6 W/m², mainly due to the presence of electric appliances. Fig. 3 summarize the obtained results with the TRNSYS software, by using the TRY concerning the locality of Cosenza (Italy, Lat. 39.3° N) highlighting very different design peak loads in winter and in summer, mainly due to the presence of the containment wall in front of the windows toward South [9]. Consequently, elevated heating loads were determined in winter because solar irradiation is not exploited adequately, whereas the same condition resulted beneficial for cooling loads [10, 11]. In order to overcome these issues, the air-conditioning plant has been equipped with two heat pumps.

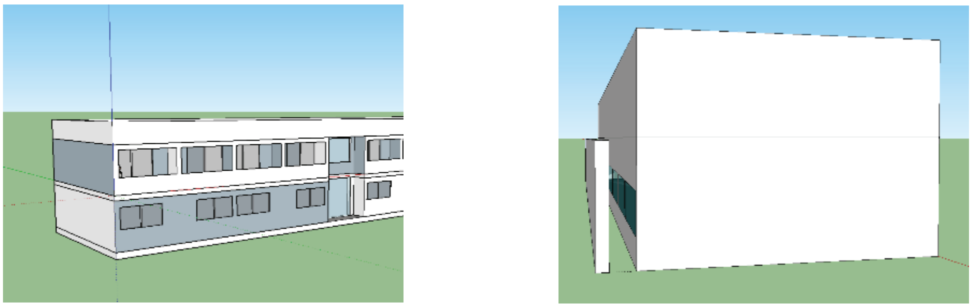

Fig. 2- Some views of the modelled building in TRNSYS environment employed for the design of the generation system

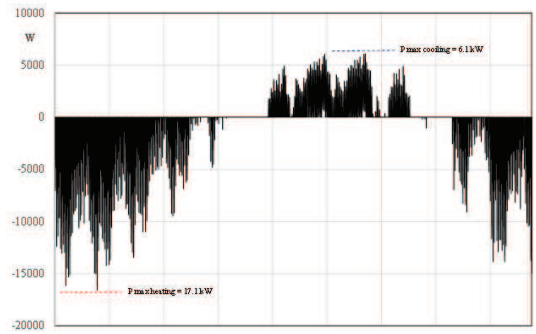

Fig. 3- Trend of the heating (-) and cooling (+) loads determined for the considered building

In this manner, two devices can be activated in cascade during winter, while in summer the operation of a single heat pump is sufficient. The latter is characterized by a nominal power of 5 kW in heating operation (for a supplied water temperature of 35°C and an external air temperature of 7°C), and of about 4 kW in cooling operation (chilled water of 15°C for external air temperature of 30°C). In order to justify the generation system size, in Fig. 4, the time percentages with heating and cooling loads included in a precise range, are presented. In particular, only for a percentage of 7% of the operative hours, a heating power greater of 10 kW is required. Similarly, in summer a percentage of 15% of the operative hours is characterized by cooling power greater than 4 kW. The thermal/cooling energy is transferred to the lowest part of the storage tank by means of a proper heat exchanger. In winter, in absence of PV electricity, the minimal temperature level of 35°C in the storage tank has to be guaranteed. In these circumstances, the control system activates, in relation to produced thermal energy cost, the pellet boiler supplied by biomass or the heat pumps supplied by the external grid (if operative limits did not occur). The first is connected to the storage system by means of a heat exchanger located at the middle height of the tank.

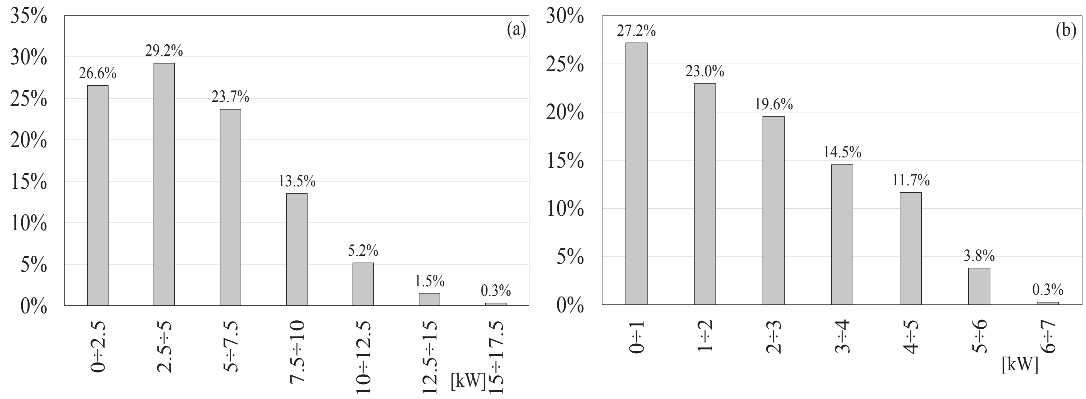

Fig. 4- Percentage of hours during heating (a) and cooling (b) seasons when a precise power is required

PV size was determined in function of the estimated electric energy demand: for the considered location, an annual electric production slightly lower than 6000 kWh_e can be attained. The internal electric micro-grid represents the smart core of the whole system because the air-conditioning plant is inserted in a wider research project for the management of the electric energy fluxes, in relation to energy availability and to economic criteria. The micro-grid assumes the air-conditioning plant as a *sui generis* electric storage system to manage PV electricity surpluses. The latter supply the heat pumps converting electricity in thermal energy that can be managed in a brief period by means of the vertical storage tank, though heating or cooling loads are not required to regulate the indoor set-point temperatures. If the storage tank is saturated, thermal energy can be stored in the building structure with overheating or undercooling strategies, by modifying the internal set-point values by means of the developed control system that acts on the zone thermostats. In these conditions, thermal energy produced by heat pumps by PV surpluses is transferred from the tank to the building. In order to avoid discomfort conditions, indoor temperatures higher than 21°C in winter and lower than 25 °C in summer, are avoided.

The exploitation of the building fabric as further thermal storage is made by the employment of the suspended radiant ceiling as emitters [12]. The active surface amounts of about 125 m² to heat/cool four different rooms. Because of the tank set point was set to 10°C in summer and 55°C in winter, whereas the inlet emitters' temperature was set respectively to the indoor dew point temperature and to 35°C for cooling and heating applications, a motorized three-way valve after the tank regulates the emitters' inlet temperature. Thermal and cooling flow rates are extracted directly from the top of the storage tank, without using a heat exchanger. Thus, a better mixing of the water contained in the storage tank can be attained, limiting the effects connected to the thermal stratification. The choice to impose an inlet temperature equal to the dew point value in summer allows for the avoiding of water vapor condensation on the active surfaces of radiant ceilings, with the indoor humidity control regulated by natural ventilation. Moreover, radiant panels permit the achievement of adequate comfort conditions, mainly connected to the reduced indoor air temperature stratification in vertical direction, and allow for a better exploitation of the generation system due to the advantageous inlet temperatures than traditional emitters as fan-coils.

A suitable data acquisition system (DAQ) was provided for the monitoring of the air-conditioning plant, evaluating different parameters at local and energy levels. In particular, energy flowmeters were located on the inlet and outlet hydraulic circuits of the storage tank, whereas electric counters are used to measure the electricity absorbed by heat pumps. The data acquisition system was developed in labVIEW® environment, namely a data-flow programming language used not only for data acquisition, but also for data analysis and data presentation. A chassis that can hold eight possible I/O modules interfaced with temperature, analog, digital and counter sensors, makes the I/O hardware. In Fig. 5, the LABVIEW® front panel of the smart air-conditioning system, is shown. Two energy flowmeters are located on the heat pumps and the integration system supply circuits, a third one on the extraction side to determine the thermal energy transferred to the emitters, exploiting RTD PT100 to monitor the several temperatures in the fluid distribution network (see Fig. 6).

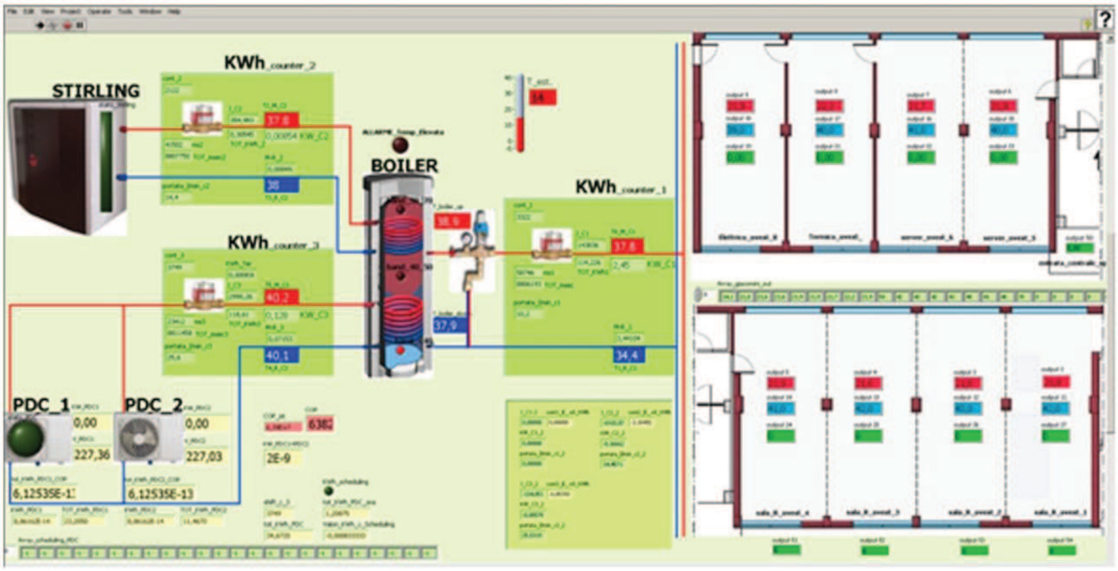

Fig. 5- LabView front panel concerning the data acquisition system

The probes signals are transferred to a signal-conditioning module; successively, an Ethernet cable sends data to a personal computer where they are analyzed, visualized and stored. In order to evaluate the magnitude of the temperature stratification in the storage tank, two values are measured at the bottom and at the top. Finally, also the indoor air temperatures in each conditioned rooms were detected to verify the correct operation of the air-conditioning plant, as well as the state of the ON/OFF electro-valves employed for the activation of precise radiant circuits. The electric powers absorbed by heat pumps allows for the calculation COP/EER at local or average levels. Moreover, the DAQ is integrated with the control system to activate heat pumps in accordance to a suitable strategy. The micro-grid, in fact, manages the PV electricity and decides for its exploitation in function of the storage tank state and of the indoor air temperatures inside the rooms. Later, the DAQ system activates, by suitable actuators, the heat pumps. Finally, the control system determines the cost of the auxiliary thermal energy, establishing if it is cheaper to use the pellet boiler or the heat pumps supplied by the electricity absorbed from the external network.

3. Experimental results

In Fig. 7, for the period 1st November-31st December 2017, the trends concerning the electricity absorbed by the heat pumps, distinguished between self-produced and absorbed from the external grid, the PV surplus exploited by the overheating strategy and the storage tank average temperature, are shown. In the considered period, external electric energy (blue line) was integrated for few days only during December to guarantee the minimal thermal level in the storage tank. Obviously, the external electricity cost produced a more convenient economic frame than the employment of thermal energy produced by biomass. Moreover, the higher heating requirements and the overcast conditions registered during December days produced a larger extraction of thermal energy from the storage tank with consequent temperature decrement, justifying the intervention of the auxiliary heating system. The red line highlights the PV electricity surplus stored in the building fabric by the overheating strategy, detectable when the storage tank reaches the maximum thermal level.

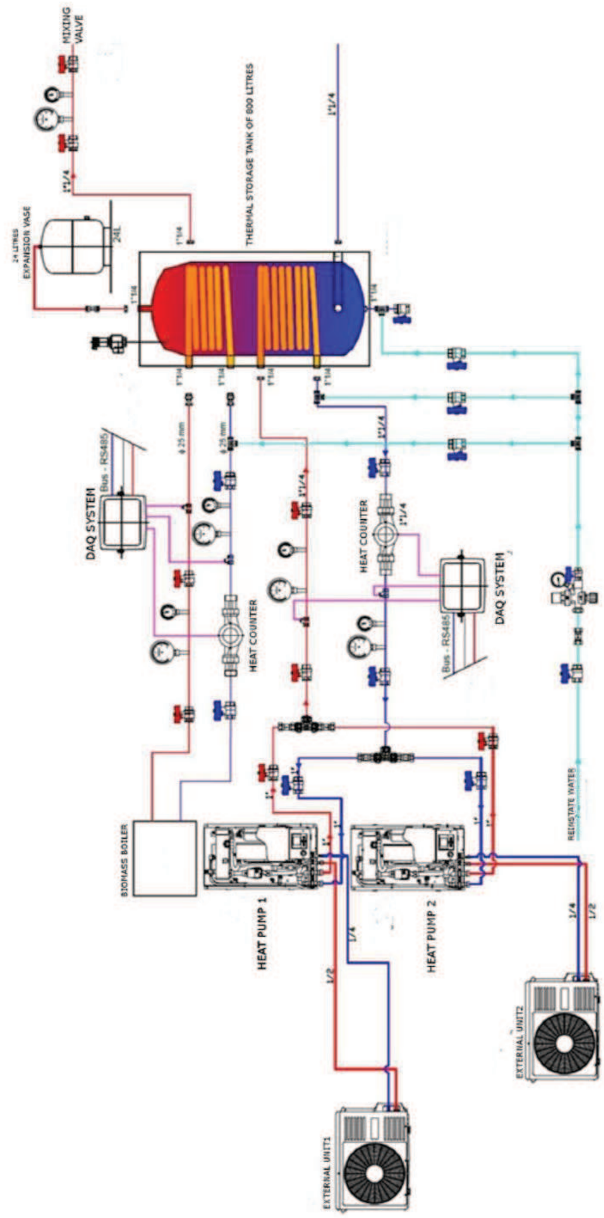

Fig. 6- Sketch plant of the air-conditioning system

Therefore, the control system raised the indoor set-point air temperature to 21°C acting on the zone thermostats and allowing the transfer of thermal energy from the storage tank to the building fabric. In the considered period, the overheating strategy was adopted for 18 days, with a major frequency during November. Indeed, in this month the limited heating requirements and the simultaneously solar radiation availability facilitated the achievement of the maximum temperature level in the tank. Therefore, the latter was discharged and the PV surpluses again used increasing the emitters' operation time. From the same Fig. 7, the storage tank temperatures varied in the interval of 35°C-55°C, observing in the coldest days with limited solar radiation and reduced PV electricity production, a consistent decrement of the thermal level. The latter aspect highlights the role of the storage tank in the short-period that is able to supply thermal power despite the generation system is switched-off.

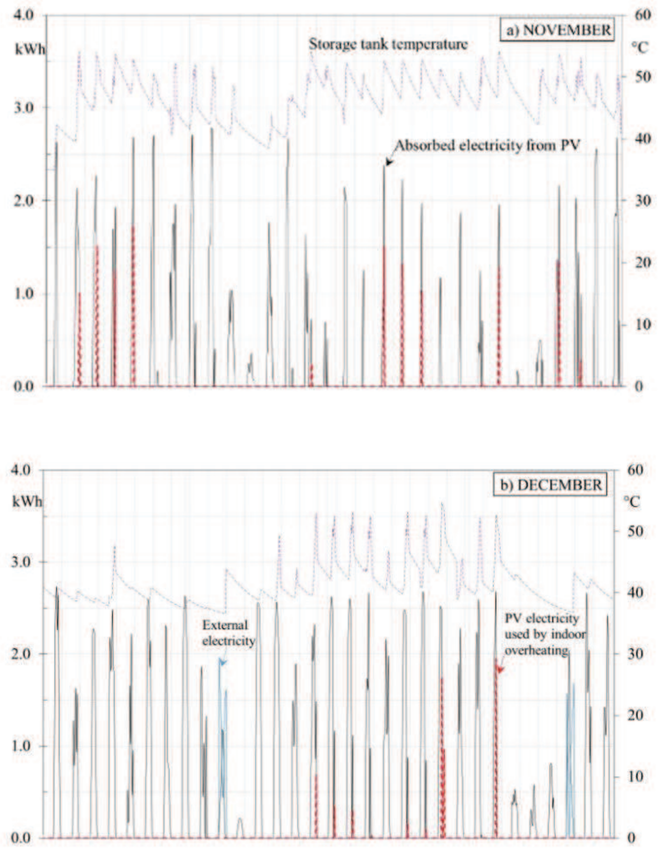

Fig. 7- Trends concerning the involved electric loads and the average tank temperature level registered during November (a) and December (b) 2017

However, in November the auxiliary thermal system was not employed, as well as PV surpluses sometimes transferred to the external grid. In December, instead, in some days the heat pumps was supplied by the external electricity and the tank temperature level is maintained slightly variable around the minimum value minimizing the absorption of electric energy from the grid.

From the point of view of absorbed electric energy, the building conditioning was attained in November by using 100% of PV surpluses. In December a percentage of 94.7% was assessed, demonstrating the central role of the thermal storage systems to reduce the dependence from the external network. In particular, storage tank and building fabric have allowed to use PV surpluses in deferred manner by means of their transformation in thermal energy. Furthermore, an evident economic advantage was achieved due to the considerable self-consumed electricity growth. Regarding the two monitored months, the air-conditioned plant lead to an economic saving of about € 115, compared to the hypothetical case where the required electric energy had been fully absorbed from the external grid, facilitating its "*island*" operation. The performance indexes determined by means the elaboration of the data provided by the DAQ system have highlighted elevated values in different operative conditions. In particular, in the following graphs mean hourly values concerning COP, temperatures and the supplied and extracted energies during a day with unfavorable conditions (1st March 2018 was a snowy day after other ones characterized by overcast conditions), are shown. Despite the high set-point value of heat pumps (55°C) and the reduced outdoor temperatures (T_{oa}), the COP resulted satisfactory, with an expected trend presenting a growth with the augment of the outdoor temperature (Fig. 8). The penalized COP during the third hour is due to the limited operation time of the heat pumps connected with the elevated absorbed electric loads in the first functioning phases. However, if outdoor temperature are variable around 10°C, COP close to 3 can be attained. The storage temperature (T_{tank}) slightly variable around the minimal level is due to the continuous extraction of thermal energy to supply emitters for the indoor set point achievement, combined with the minimization of the electricity absorbed from the external grid.

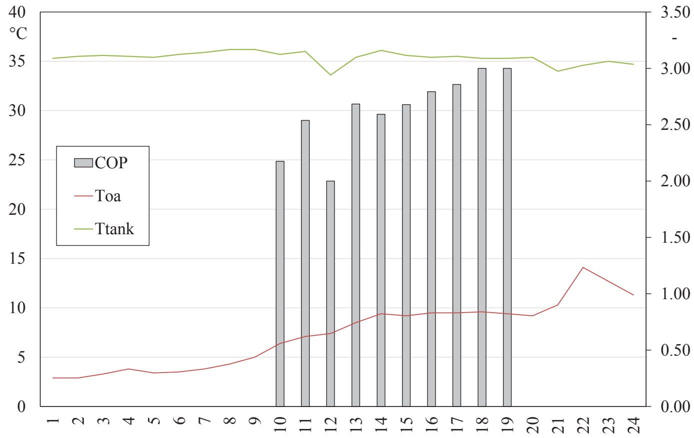

Fig. 8- Average values concerning the measured COP for both the heat pumps, the outdoor and the storage tank temperatures during 1st March 2018

The thermal energy extracted by the storage tank, almost the same of that supplied by emitters, presents a more modulated trend than the provided by heat pumps, due to the intervention of the three-way valve using the changeable outlet temperature from emitters (Fig. 9). During the first hours (limited availability of PV electricity) thermal energy was obtained from the storage tank; at the same manner, also around the 11:00 a.m. the role of the short-time storage can be observed. Generally, elevated powers were supplied in the first hours of the morning due to the high heating needs. Moreover, despite the tank temperature is almost constant, heat pumps provided higher thermal powers to compensate also the thermal losses. Fig. 10 illustrates the trends concerning the absorbed and produced electric energies, the latter contemplating exclusively the PV surplus. Only in the period around the 11:00 a.m. the renewable electricity has been stored inside the tank, whereas in the remaining hours the integration with grid electricity was necessary. The pellet boiler was not employed due to the lower cost of the thermal energy produced by heat pumps also when external electricity was absorbed. Regarding the whole day, a solar fraction of 30% was calculated, denoting the decent contribute of the renewable source also in unfavorable climatic conditions. Fig. 11 illustrates the same parameters of Fig. 9 but registered during a warmer day (10th March 2018). Taking advantage from the favorable climatic conditions in the prior period, the initial thermal level of storage tank is higher; in the successive hours, mainly due to the PV electricity availability, the temperature of the storage tank increased noticeably, reaching the set-point.

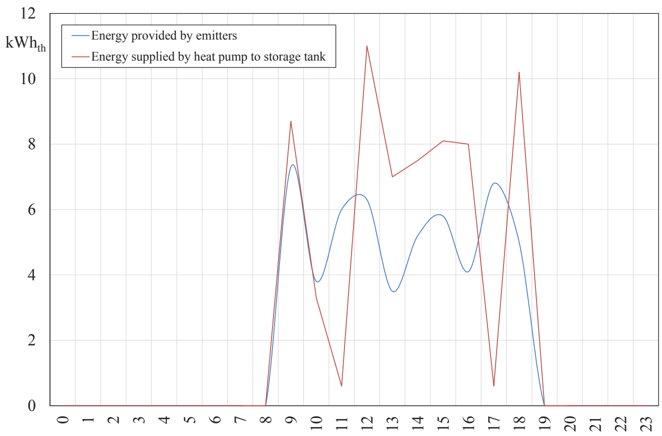

Fig. 9- Average thermal energy supplied and extracted from the vertical storage tank during 1st March 2018

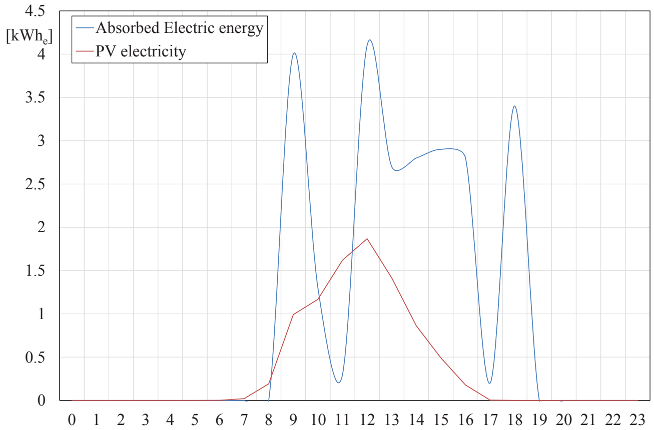

Fig. 10- Average electric energy produced by PV generator and absorbed by heat pumps during 1st March 2018

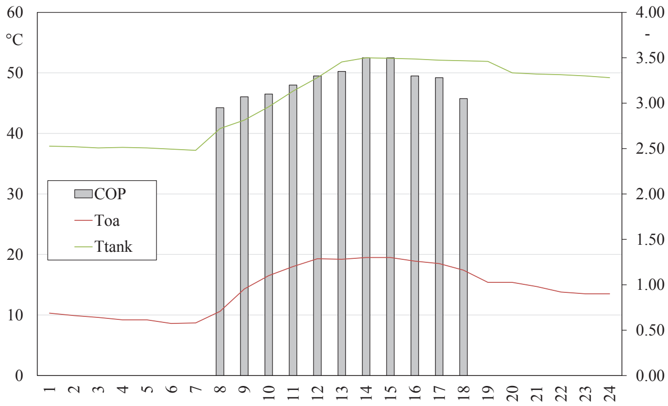

Fig. 11- Average values concerning the measured COP for both the heat pumps, the outdoor and the storage tank temperatures during 10th March 2018

Despite the attainment of the latter, heat pumps continued to operate supplied by the PV surpluses, but the tank temperature level remained almost constant due to the extraction of the thermal energy to carry out the overheating strategy. Solar fraction reached the 86% because during the first hours of the morning the PV surpluses was insufficient and external electricity was absorbed. However, in the successive day the thermal energy required at the plant switching-on did not show the peak of Fig. 9, due to benefit effects linked to the overheating operated in the prior day.

Other preliminarily evaluations were carried out during September 2017 (cooling applications), with trends reported in Fig. 12: tank temperature ranged from 7°C to 15°C, with a reduced heat pump operation time and a rapid temperature decrement due to the reduced magnitude of the required cooling loads. The PV surplus availability in presence of a saturated tank was exploited by the undercooling strategy, reducing the indoor set point air temperature from 26°C to 25°C. However, in other 7 days the absorption of external electricity was requested to guarantee the minimal temperature level in the tank. The absorbed PV surpluses amounted to 89 kWh, from which 11 kWh were transformed in cooling energy and stored in the building fabric. Moreover, other 7 kWh were absorbed from the external network, producing an overall cooling energy of 288 kWh; therefore the heat pumps were exploited with a mean monthly EER of about 3.

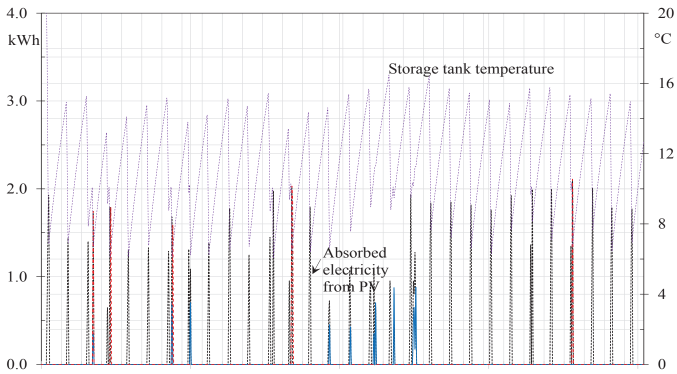

Fig. 12- Trends concerning the involved electric loads and the tank temperature level for September 2017 in cooling operation

4. Conclusions

Experimental data concerning a smart air-conditioning plant exploiting a PV driven heat pumps, were presented. The core of the whole system is represented by a suitable control strategy including an internal micro-grid for a rational management of the internal electric fluxes. Thus, the heat pumps connected to a vertical storage tank were seen as a *sui generis* electric storage system, transforming the electricity surpluses in thermal energy, to use in deferred way. Moreover, an emission system represented by radiant panels allowed for the storage of further thermal energy inside the building fabric, activating its thermal mass. Thus, by means of overheating and undercooling strategies, in presence of a saturated tank, the electricity surplus can be furthermore employed by transferring the stored energy from the accumulator to the conditioned building and maintaining the heat pump switched-on. The proposed air-conditioning plant was installed at the University of Calabria, activated at the end of August 2017, and continuously monitored. The measured data have provided excellent results: during winter, the role of the vertical storage tank is central especially in the coldest periods, in relation to the possibility to charge it in presence of electricity surpluses though heating is not required. In the warmer periods, instead, the thermal storage inside the structure is largely employed due to a frequent attainment of the set-point tank temperature. Due to the limited temperature difference producible in the storage tank during summer, the cooling energy storage inside the building by an undercooling strategy was largely employed. The conceived system allows for a consistent increment of the self-consumed PV electricity, with consequent economic advantages. Moreover, the micro-grid is able to coordinate the heat pumps operation with other electric appliances, therefore the appropriate management plans of the local grids can be defined making the users less dependent from the external electric network. These features can be used for aggregated users, allowing for the development of Smart Cities models, or to rationalize electric consumptions in smaller aggregations.

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Chapter 4
Retrofitting of existing buildings

In addition to new buildings, the goal of nearly Zero Energy is also extended to existing buildings undergoing renovation, representing a significant portion of the building stock. While the application of new high-efficiency standards in the design phase of new buildings is quite simple, the adaptation of existing buildings is more complex, as upgrading measures can be limited, due to intrinsic factors of the building and to external constraints set, for example, for historical heritage.

Retrofitting is not part of routine maintenance operations since it requires substantial actions aimed at improving the building and complying with energy efficiency and environmental sustainability requirements. Refurbishment measures necessary for the energy renovation of existing buildings and the achievement of expected performance standards, generally concern:

- opaque envelope, including solutions for thermal insulation, correction of thermal bridges and airtightness;
- glazed surfaces, with the replacement of existing windows and the possibility of installing new sunscreens;
- heating/cooling/ventilation systems and domestic hot water production, including integration of renewable energy systems.

The optimal solution depends on each specific case and needs to be identified in relation to climatic conditions and building characteristics.

Furthermore, according to the latest guidelines, interventions must be directed towards achieving the level of energy performance that is cost-effective, that is, the lowest cost during the estimated economic life cycle of the building.

The paper in Section 4.1 deals with the development of a predictive model to identify the parameters that mainly influence energy consumption of existing buildings and, consequently, to define the most appropriate strategies for the upgrading of buildings.

The study in Section 4.2 focuses on the issue of social housing renovation and it shows the results obtained with the application of a cost-optimal calculation method for identifying proper retrofit measures to reach cost-optimal levels and nZEB levels. The assessment considered an exhaustive set of renovation options and the obtained nZEB refurbishments resulted interesting also from an economic point of view.

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4.1 Statistical analysis of the heating demand in residential buildings located in Mediterranean climate and proposals for refurbishment

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Abstract

The paper deals with the investigation of the heating energy consumptions of a sample of residential buildings located in South Italy. A survey for the collection of data concerning energy performance certificates, characteristics of the building envelopes, air-conditioning plants and real consumptions, was carried out. A statistical analysis aimed at the identification of the main parameters affecting the energy requirements was developed using SPSS software. A multiple regression analysis was applied to obtain a forecasting tool that can be used to identify suitable action strategies for the retrofitting of buildings in the considered area.

Keywords: Mediterranean climate, existing buildings, energy consumption, statistical analysis, prediction model, building refurbishment

1. Introduction

The improvement of the energy performance of buildings accomplishes the dual purpose of reducing energy dependence on fossil fuels from other countries and of decreasing greenhouse gas emissions. In Italy, Ministerial Decree 26/06/2015[2], applying European directives, specifies the obligations to be met in constructions, with the goal of limiting energy consumption for the air conditioning. Consequently, all new edifices are built in compliance with the minimum requirements set by the Regulations. However, as a large part of the housing stock consists of existing buildings, the retrofitting of these structures to satisfy current energy efficiency and thermal comfort standards is firmly needed to concretely improve sustainability. An action spread throughout the territory is essential because, even if one single structure may not have any particular relevance, the system as a whole shows a network which constitutes the historic memory of the site [3]. Redeveloping the existing building stock represents an interesting opportunity to reach higher levels of environmental performance and reduce both energy consumption and CO_2 emissions required for its operation. As stated in Munarim and Ghisi [4], rehabilitation brings environmental and economic advantages. Also Martìnez-Molina et al. [5] confirmed the feasibility of preserving the built heritage while enhancing its energy efficiency and thermal comfort; furthermore, they claimed that Italy is leading the research in this field, thanks to the huge extent of its historical legacy. According to De Santoli [3] one of the fundamental processes of the energy upgrade of buildings is the energy audit. Several authors, e.g. Belpoliti and Bizzarri [6], Evola et al. [7], Droutsa et al. [8], propose the use of energy audits and data from energy performance certificates to briefly assess the energy consumption of entire building districts. In addition, building energy certificates should be used to produce an overview of the broad energy performance trends of buildings and drive improvements in energy performance by steering energy policy towards financial support of refurbishment strategies [9][10].

The estimate of building stock energy consumption is increasingly frequently carried out by extrapolating information from a wider database, created by assembling data collected through energy audits, but also by means of measurements, surveys, and simulations [11]. Forecasting models developed on the basis of large-scale investigations allow the prediction of the energy consumption of buildings, using few readily available parameters [12]. In Rhodes et al. [13] researchers performed a simulation model to predict the actual residential energy usage, with energy audits and surveys, under different scenarios of analysis. The combined IOA-LCA model proposed by Cellura et al. [14] aims to analyse the role of the building sector in the reduction of Italian energy consumption and CO_2 emissions. Koo and Hong [15]developed a dynamic energy performance curve for evaluating the historical trends in the energy performance of existing buildings. Recommendations on measures that can lead to a reduction in energy consumption are given in both Bojić et al. [16] and Ilić [17]; their recommendations essentially consist of different external insulation techniques, window replacement, installation of more efficient heating/cooling systems and application of renewable sources. The integration of several energy efficiency measures, if carefully planned, may even result in a Zero Energy Building after refurbishment, as shown by Corrado et al. [18] and Passer et al. [19] for residential buildings, and by Aksamija [20] for commercial buildings. All the forecasting models are based on the strong interdependence between energy consumptions and some variables such as building shape, compactness, building age, surface area, etc. [21][22][12].

The association of the independent input variables with the dependent output variables is often performed by means of statistical analysis tools. Jang et al. [23] evaluated the characteristics in old apartment buildings that need to be considered for energy requalification. They found that, by using multiple regression analysis, three main features should be used as priorities for refurbishment schemes, namely the conditions of building envelope, the heating methods and the sizes of building units. Aranda et al. [24] and Chen et al. [25] used a regression analysis to develop analytic correlations for the prediction of energy consumptions in both the residential and the banking sectors. As asserted by Fan et al. [26], the drivers are many, varied, and complex, and involve local climate, household demographics, household behaviour, building stock and the type and number of appliances. Economical assessments conducted in several studies, e.g. Garrido-Soriano et al. [27], Ilić [17] and Pikas et al. [28], confirm that investment in energy efficiency is not only environmentally important but that it also provides economic benefits on an individual and government budget level.

This paper seeks to identify the characteristics of heating energy consumptions in a sample of residential buildings located in the region of Calabria, located in Southern Italy, typified by a Mediterranean climate. The investigation shows an overview of the energy performances of residential buildings in the interested area, obtained by the collection of energy certificates for the houses scattered throughout the territory. The study has allowed for the identification of the complex variables that can influence the energy consumptions for heating and DHW production in the considered dwellings. The parameters that greatly affect the energy consumption are identified by means of a regression analysis. Moreover, a correlation between energy consumptions and a set of multiple variables is carried out and allows to predict the energy performance of existing residential buildings with good approximation. The purpose of the study is to provide a simplified procedure, that is handy and inexpensive, and which can be used as a valuable support for designers of the building energy retrofitting process. Moreover, the same tool can be employed to determine the energy saving potential for heating applications, in order to facilitate the planning of future energy strategies for the involved territory. In particular, the research intends to promote the creation of inter-territorial databases of energy certificates, useful for monitoring the trend of energy consumption over time, and from designers can extrapolate the information necessary to plan redevelopment.

2. Methodology

Data relating to energy use in the Region were collected through a survey carried out by means of questionnaires addressed to a sample of engineering students of the University of Calabria, from 2010 to 2015. The investigation was aimed at gathering information about the actual consumptions, the characteristics of the building-plant system, and the energy certificates of their homes. Globally, 363 households located in different climatic zones were interviewed. Analysis parameters were defined in order to assess the variability of energy consumptions in the sample. Statistical analysis of the variables was carried out by using the SPSS software [29]. Before any evaluation, all data was checked to verify a normal distribution. The variables that did not meet the condition of normality were transformed by applying a square root. Following this, a bivariate correlation analysis was performed to identify the relationship between the variables. Finally, a multiple linear regression analysis was applied to assess the effect of the different variables on energy consumptions, and to identify the opportunity of requalification.

2.1. Description of the sample

The survey regarded only residential buildings and sought to collect data related to: geographical location and general characteristics of the buildings, typology of external walls and windows, characteristics of the heating and domestic hot water (DHW) production systems, monitoring of electrical and heating/DHW consumptions for three consecutive years, renewable sources and energy performance certificates of the buildings.

In particular, this study sought to evaluate the relationship between a series of typical parameters of the buildings and the information that can be inferred from the energy certificates. The overall characteristics of the survey sample are shown below. Buildings are located in zones with different degree days [30]: 38.8% belongs to a climatic zone with degree days ranging between 900 and 1400, and 42.7% in a climatic zone with degree days varying between 1440 and 2100. Regarding the remaining part, 6.7% of the buildings are in locations characterized by degree days lower than 900 and 11.8% in a climatic zone with degree days greater than 2100. Regarding the building typology, more than half are apartments, whereas 41.3% are classified as detached houses, including single-family houses, two-family houses, and row houses (see Fig.1a). The average heated net floor area of the apartments is 107.66 m^2 (Std. deviation 32.25 m^2) while for the detached houses is 137.41 m^2 (Std. deviation 44.89 m^2). For the year of construction, four classes were provided, as depicted in Fig.1b.

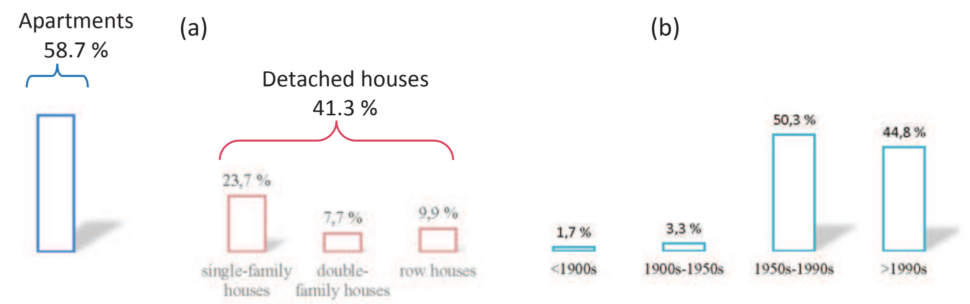

Fig. 1. (a) Building typologies in the sample; (b) year of construction of the buildings.

Technical characteristics of the windowed systems are displayed in Fig. 2a and Fig. 2b, respectively. The majority of the windows are equipped with a wooden frame and double-glazing.

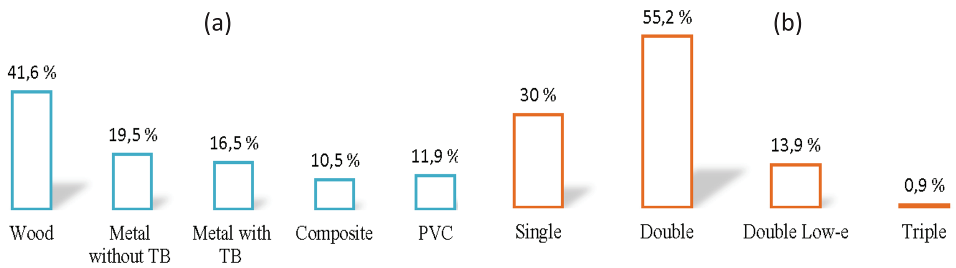

Fig. 2. (a) Typologies of windows frame; (b) Typologies of windows glass.

The correspondent average thermal transmittance value is 3.40 W/ (m^2·K) (Std. deviation 1.45 W/(m^2·K), whereas external opaque walls present a mean U-value of 0.84 W/ (m^2·K) (Std. deviation 0.39 W/(m^2·K)).

Regarding the heating plants, over 95% of the dwellings are equipped with autonomous systems. Most of them consist of independent boilers and fireplaces; a negligible percentage (about 1%) is provided with electrical heat pumps. The types of fuel employed to supply heat generators are presented in Fig. 3a, while Fig. 3b shows the typologies of emission terminals.

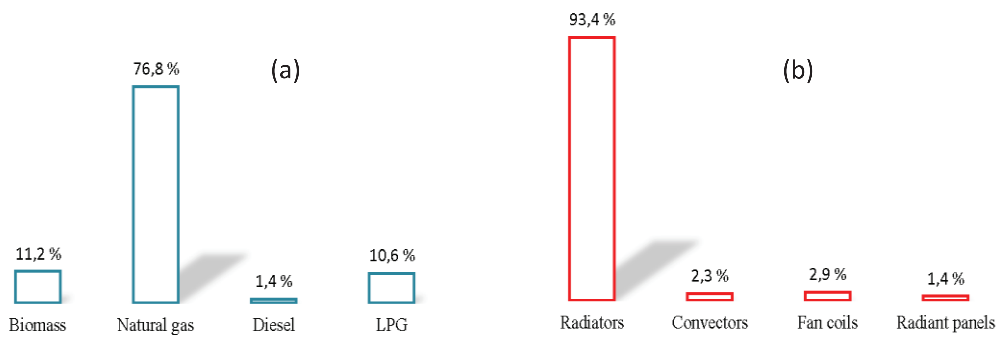

Fig. 3. (a) Fuel used by heating generators; (b) Types of emission terminals.

The most widely used control systems concern boiler thermostat (51.9%) and zone thermostat (28.1%). For 85.9% of the examined cases, the DHW production takes place through the same generator used for heating, and only 14.1% of cases have a separate DHW production system. Instead, regarding renewable energy, 5.8% of the participants interviewed have reported the presence of a photovoltaic system, 6.4% have solar collectors for DHW, and 2.8% have both photovoltaic and solar collectors.

The energy certificates of all the buildings in the sample were acquired in the survey. When the investigation was conducted, the former energy labelling system disciplined by Ministerial Decree 26 June 2009 [31] was in force in Italy, later replaced by the new Regulation [32]. Therefore, the energy labels provided for buildings ranged from “A”, the most efficient, to “G” the least efficient. Despite the regulations concerning the heating requirement provided after 1990, most of the existing buildings in the research area have a poor energetic quality, ranking in the labels E, F, and G, which generate the largest energy consumptions, as illustrated in Fig. 4.

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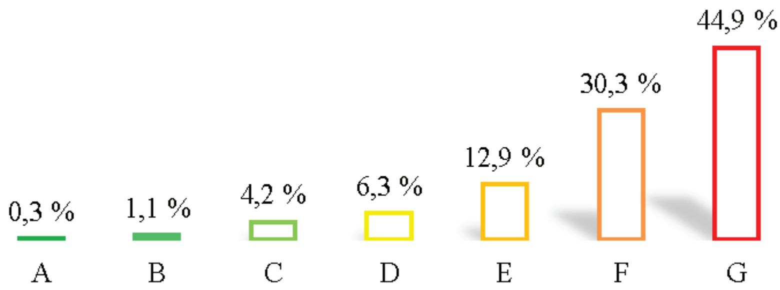

Fig. 4. Energy labels of the investigated existing buildings.

2.2. Definition of analysis variables

The study focused on the analysis of the variability of two energy performance parameters: net energy requirement for heating (Qh) and primary energy for heating and DHW (EPh), as a function of different independent variables. Three numeric variables that can potentially affect the energy consumption parameters described above were employed.

1. The S/V ratio, obtained by the Equation (1):

$$S/V = \text{dispersing gross surface} \,/\, \text{heated gross volume} \quad [m^{-1}] \qquad (1)$$

The dispersing surface includes all the opaque and glazed external surfaces, as well as surfaces adjacent to unheated spaces.

2. The mean heat transfer coefficient of the building envelope normalized with respect to the net floor area of the dwelling, calculated by the Equation (2):

$$H_m = [(S_w \cdot H_w) + (S_g \cdot H_g)] \,/\, S \quad [W/(m^2 \cdot K)] \qquad (2)$$

Where S_w is the area of the dispersing opaque elements [m^2], H_w is thermal transmittance of the opaque elements [$W/(m^2 \cdot K)$], S_g is the area of the dispersing glazed elements [m^2], H_g is the thermal transmittance of the glazed elements [$W/(m^2 \cdot K)$], S is the net floor area of the dwelling [m^2].

3. The solar energy transmitted through the glazed surfaces normalized with respect to the net floor area of the house, determined with the Equation (3):

$$I = (S_g \cdot \tau \cdot \Phi) \,/\, S \quad [W/m^2] \qquad (3)$$

Where S_g is the area of the glazed surfaces [m^2], τ is the normal solar transmittance factor, equal to 0.85 for the single glass and 0.75 for the double glass, Φ is the global solar radiation on vertical surfaces, calculated for all the exposures using UNI 10349 [33], S is the net floor area of the dwelling [m^2].

Due to the relevant heterogeneity of the geometrical characteristics between the different typologies of buildings, in order to perform the statistical analysis, the sample was divided into two subpopulations: apartments (N=213) and detached houses (N=150). In addition, after a preliminary analysis, the observations of incomplete or inconsistent values were removed. Table 1 outlines the investigated variables.

Table 1. Mean and standard deviation of the analysed variables.

	N	Mean	Std. Deviation
APARTAMENTS			
S/V[m^{-1}]	168	0.389	0.159
H_m [W/m^2K]	206	1.243	0.563
I [W/m^2]	191	176.262	82.549
Q_h [kWh/(m^2·year)]	199	62.87	38.24
EPh [kWh/(m^2·year)]	199	131.20	64.06
DETACHED HOUSES			
S/V [m^{-1}]	77	0.493	0.182
H_m [W/m^2K]	146	1.562	0.980
I [W/m^2]	135	93.495	93.495
Q_h [kWh/(m^2·year)]	116	100.30	49.76
EPh [kWh/(m^2·year)]	116	188.73	83.28

Since energy demands vary according to the climatic zone, all the values of the energy requirements (Qh and EPh) were divided by the heating degree days (HDD) [30] of the corresponding location to eliminate the variability due to different climatic conditions, obtaining the variables Qh' and EPh', calculated with the Equation (4) and (5), respectively:

$$Qh' = Qh / HDD \quad [kWh/(m^2 \cdot year)] \tag{4}$$

$$EPh' = EPh / HDD \quad [kWh/(m^2 \cdot year)] \tag{5}$$

Moreover, outliers identified by means of boxplot diagrams, were removed from the data set to avoid distortions in the results, thus reducing the sample. Therefore, no anomalous values appear in the considered data set, as illustrated in Fig. 5 for some of the analysed variables. Furthermore, a square root transformation was applied to all the variables to improve normal distribution. As shown in Table 2, all the transformed variables are normally distributed. Numerical measurements of the shape of data, skewness (index of asymmetry) and kurtosis (index of "tail") vary within the acceptable range [-1; 1]. Most of them are close to zero, denoting a good approximation of the data set with the standard normal distribution, as shown in Fig. 5.

Even the quantile graphs (Q-Q plot) demonstrate that the data are normally distributed, as proved by the linearity of the observed values (Fig. 5).

Table 2. Mean and standard deviation of the analysed variables.

	N	Mean	Std. Deviation	Skewness	Kurtosis
APARTMENTS					
S/V_SQRT	165	0.605	0.124	-0.030	0.440
H_m_SQRT	203	1.076	0.225	-0.045	-0.342
I_SQRT	187	12.750	2.568	-0.310	0.040
Q_h'_SQRT	193	0.194	0.052	0.342	-0.434
EP_h'_SQRT	192	0.285	0.060	0.268	-0.454
DETACHED HOUSES					
S/V_SQRT	76	0.685	0.127	-0.112	0.308
H_m_SQRT	139	1.150	0.297	0.261	-0.465
I_SQRT	130	12.396	2.675	-0.333	-0.010
Q_h'_SQRT	113	0.245	0.065	0.183	-0.772
EP_h'_SQRT	113	0.340	0.080	0.236	-0.765

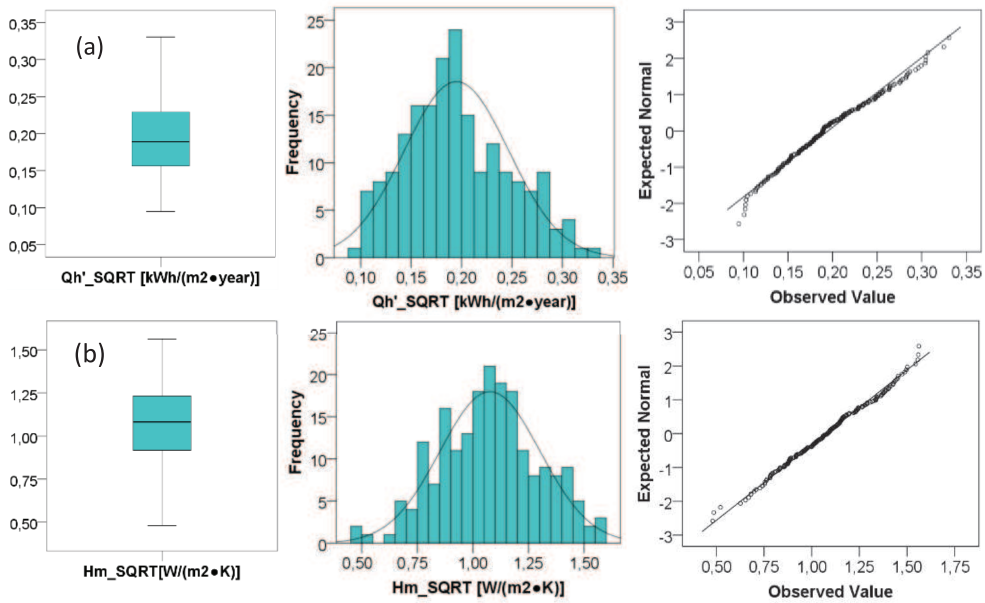

Fig. 5. Box plot, histogram, and Q-Q plot of the variables Qh'_SQRT (a) and Hm_SQRT (b) for the apartments dataset.

3. Results

First, a simple regression analysis was performed in order to evaluate the degree of correlation between the thermal energy requirement (Qh'_SQRT) and the previously presented numerical variables. The Pearson correlation coefficient was determined to measure the strength of linear dependence between two variables, with values ranging from -1 to 1. The proportion of variability in one variable accounted for by another variable was assessed through the coefficient of determination R^2 with values from 0 to 1. The p-value is a measure of the probability of obtaining a result at least as extreme as the one that is actually observed. Thus, the lower the value (usually below 0.05 or 0.01), the more significant the results. Subsequently, a multivariate regression analysis was carried out by evolving in three phases. The first model analysed the variability of the square root of net energy requirements for heating (Qh'_SQRT) as a function of the numerical variables (S/V_SQRT, Hm_SQRT, I_SQRT). The second model was still related to the variability of (Qh'_SQRT), but additional categorical variables were introduced in the analysis. The third model analysed the variability in the Primary Energy for heating and DHW (EPh'_SQRT) considering all the variables of previous steps, and by adding further variables that characterize the heating system.

3.1. Simple regression analysis

In the first instance, a bivariate correlation analysis was performed in order to examine the strength of the relationship between the net energy demand for heating and the independent variables previously described. The Pearson coefficient and its level of significance were determined for each correlation between the independent variables (S/V_SQRT, Hm_SQRT, I_SQRT) and the dependent variable (Qh'_SQRT). Table 3 contains the results of the simple regression analysis for the separate data set of apartments and detached houses.

Table 3. Correlations between Qh'_SQRT and the variables S/V_SQRT, Hm_SQRT, I_SQRT.

		S/V_SQRT	H_m_SQRT	I_SQRT
APARTEMENTS				
Q_h'_SQRT	Pearson	0.256**	0.235**	-0.040
	p Value (2-tailed)	0.001	0.001	0.308
	R^2	0.065	0.055	0.002
	N	152	182	158
DETACHED HOUSES				
Q_h'_SQRT	Pearson	0.368**	0.394**	-0.088
	p Value (2-tailed)	0.003	0.000	0.197
	R^2	0.135	0.155	0.008
	N	64	105	95

** Correlation is significant at the 0.01 level (2-tailed)

The square root of the net energy requirement for heating (Qh'_SQRT) is significantly correlated with the square root of S/V ratio (Pearson=0.256, $p < 0.01$ for apartments and Pearson = 0.368, $p < 0.01$ for detached houses) and with the mean heat transfer coefficient of the envelope (Pearson = 0.235 $p < 0.01$ for apartments and Pearson = 0.394 $p < 0.01$ for detached houses). In particular, in the apartment dataset, the variable S/V_SQRT has the largest correlation with the net heating demand; conversely, the variable Hm_SQRT has the highest correlation with the net energy heating need for detached houses. This is due to the greater dispersant surface that, generally, detached houses have compared to the apartments. A weak correlation was found between Qh'_SQRT and I_SQRT. However, although the solar energy transmitted through the glazed surfaces does not have a significant correlation with the energy thermal requirements, an indirect correlation cannot be excluded. The variables S/V_SQRT and Hm_SQRT are positively correlated to the net energy demand for heating, meaning that the greater extent of surface and its U-value, the greater net energy for heating is required (Fig. 6a and Fig. 6b). Instead, the relationship between I_SQRT and Qh'_SQRT is negative (Fig. 6c), thus the higher the value of I_SQRT, the lower amount of net energy for heating is needed. S/V_SQRT accounts for 6.5% of the variation in thermal heating requirements of apartments, and for 13.5% of the variation in detached houses. The variable Hm_SQRT explains 5.5% of the variation in Qh'_SQRT for apartments and 15.5% for detached houses.

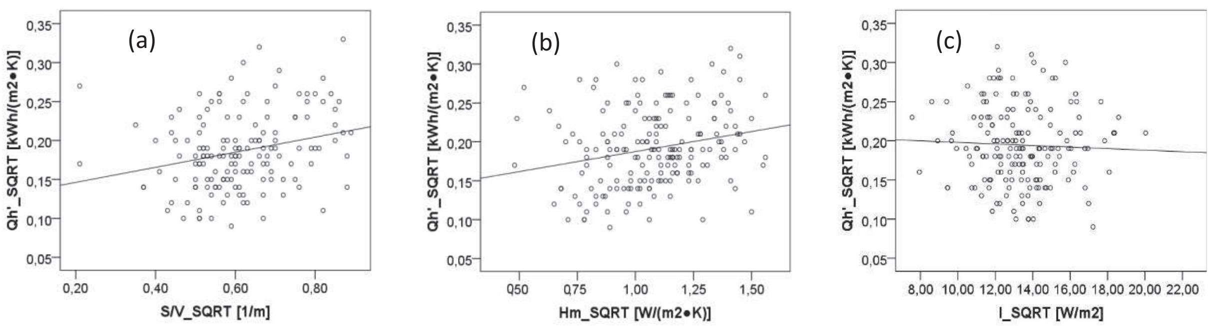

Fig. 6. Scatter plot of Qh'_SQRT and S/V_SQRT (a), Qh'_SQRT and Hm_SQRT (b), Qh'_SQRT and I_SQRT (c).

3.2. Multiple regression analysis

First regression model

A multiple regression analysis was performed to explore the potential causal relationship between the net energy requirement for heating and all the variables, in order to obtain a model based on the Equation (6):

$$Y = B_0 + B_1 X_1 + B_2 X_2 + \ldots\ldots\ldots\ldots + B_n X_n + e \tag{6}$$

able to explain the variation in the dependent variable Y according to the variation of the independent variables X. The first analysed multiple regression model assumed as dependent variable Y = Qh'_SQRT and as independent variables: X_1= S/V_SQRT, X_2 = Hm_SQRT, X_3 = I_SQRT, resulting in the Equation (7) for apartments and Equation (8) for detached houses.

$$Y = 0.106 + 0.020\ X_1 + 0.101\ X_2 – 0.003\ X_3 \quad (R^2=0.293) \tag{7}$$

$$Y = 0.071 + 0.099\ X_1 + 0.108\ X_2 – 0.002\ X_3 \quad (R^2=0.213) \tag{8}$$

By applying the obtained equations in all the units of the two separate samples, and by comparing the calculated results with the observed data, a medium relative error of 29.32% is achieved for the apartments, and of 16.63% for detached houses. Numerical variables alone are not able to explain the phenomenon, therefore the analysis was enhanced to make the model more accurate, and additional categorical variables were introduced in the study.

Second regression model

The second multiple regression model considered the variables illustrated in Table 4. For the categorical parameters, dummy variables were created and the "mode" (the class with the maximum frequency) was used as reference.

Table 4. Numerical and categorical variables used in the second regression model exploring the variation in Qh'_SQRT.

DEPENDENT VARIABLE					
Net energy requirement for heating				Q_h'_SQRT	Y
INDEPENDENT VARIABLES					
Square root of S/V ratio	S/V_SQRT	X_1	Window frame	Wood	X_8
Square root of mean heat transfer coefficient of the envelope	H_m_SQRT	X_2		Metal without TB	X_9
				Metal with TB	X_{10}
Square root of the solar energy transmitted through glasses	I_SQRT	X_3		Composite	X_{11}
				PVC	X_{12}
Year of construction of the building	<1900s	X_4	Window glass	Single	X_{13}
	1900s-1950s	X_5		Double	X_{14}
	1950s-1990s	X_6		Double Low-e	X_{15}
	>1990s	X_7		Triple	X_{16}

The relations obtained with the second regression model are represented by the Equation (9) for apartments and Equation (10) for detached houses:

$$Y = 0.072 + 0.040\ X_1 + 0.088\ X_2 – 0.003\ X_3 – 0.012\ X_7 – 0.010\ X_8 – 0.011\ X_9 + 0.002\ X_{10} + 0.004\ X_{11} + – 0.003X_{12} + 0.055\ X_{13} + 0.042\ X_{14} + 0.037\ X_{15} \quad (R^2=0.291) \tag{9}$$

$$Y = 0.074 + 0.104\,X_1 + 0.092\,X_2 - 0.002\,X_3 + 0.022\,X_4 + 0.064\,X_5 + 0.001\,X_6 + 0.005\,X_9 + 0.018\,X_{10} + {}$$

$$- 0.012X_{11} + 0.015\,X_{12} - 0.005\,X_{13} - 0.005\,X_{14} + 0.007\,X_{16} \quad (R^2=0.402) \qquad (10)$$

The considered parameters are able to explain about 30% of the variation in the square root of the thermal requirement of the apartments, and slightly more than 40% of the variation in detached houses. A medium relative error of 17.07% and 14.11% is obtained for apartments and detached houses, respectively.

Third regression model

The latest statistical model moves a further stride forward and analyses the variability in Primary Energy for heating and DHW (EPh'_SQRT). All the independent variables previously listed are included in the model and further variables related to the characteristics of the plant are added, as explained in Table 5.

Table 5. Numerical and categorical variables used in the third regression model exploring the variation in EPh'_SQRT.

DEPENDENT VARIABLE					
Primary energy for heating and DHW				EP_h'_SQRT	Y
INDEPENDENT VARIABLES					
Square root of S/V ratio	S/V_SQRT	X_1	Year of installation of the heating system	<1990s	X_{17}
Square root of mean heat transfer coefficient of the envelope	H_m_SQRT	X_2		1990s – 2000s	X_{18}
				2000s – 2010s	X_{19}
Square root of the solar energy transmitted through glasses	I_SQRT	X_3		>2010s	X_{20}
Year of construction of the building	<1900s	X_4	Control system	Boiler thermostat	X_{21}
	1900s-1950s	X_5		Zone thermostat	X_{22}
	1950s-1990s	X_6		Zone thermostat plus outdoor sensor	X_{23}
	>1990s	X_7		Room thermostat	X_{24}
Window frame	Wood	X_8	Heating set point temperature in the dwelling	T	X_{25}
	Metal without TB	X_9			
	Metal with TB	X_{10}			
	Composite	X_{11}	Number of occupants	Occ	X_{26}
	PVC	X_{12}			
Window glass	Single	X_{13}	Presence of renewable sources (PV or solar collectors)	Ren	X_{27}
	Double	X_{14}			
	Double Low-e	X_{15}	No renewable sources	NRen	X_{28}
	Triple	X_{16}			

The analysis leads to the Equation (11) for apartments and Equation (12) for detached houses

$$Y = 0.066 + 0.049\,X_1 + 0.087\,X_2 - 0.002\,X_3 + 0.006\,X_7 - 0.001\,X_8 + 0.015\,X_9 - 0.018\,X_{10} + 0.025\,X_{11} + 0.010\,X_{12} + 0.019\,X_{13} - 0.02\,X_{15} - 0.099\,X_{16} + 0.030\,X_{17} + 0.017\,X_{18} - 0.022\,X_{22} + 0.016\,X_{23} + 0.008\,X_{24} + 0.002\,X_{25} - 0.001\,X_{26} + 0.079\,X_{28} \quad (R^2=0.408) \qquad (11)$$

$$Y = -0.462 + 0.313\,X_1 + 0.083\,X_2 - 0.043\,X_4 + 0.006\,X_5 - 0.009\,X_6 + 0.157\,X_8 + 0.245\,X_9 + 0.253\,X_{10} + 0.278\,X_{12} - 0.204\,X_{13} - 0.162\,X_{14} - 0.191\,X_{15} - 0.056\,X_{16} - 0.060\,X_{17} - 0.039\,X_{19} + 0.105\,X_{20} + 0.112\,X_{21} + 0.022\,X_{22} + 0.106\,X_{23} - 0.002\,X_{24} + 0.024\,X_{25} - 0.003\,X_{26} - 0.123\,X_{28} \quad (R^2=0.950) \qquad (12)$$

The latest models, expressing the variation in primary energy for heating and DHW, seem to be the most complete and reliable. The considered parameters are indeed able to explain 40.8% of the variation in EP_h'_SQRT in the case of apartments, and 95% of the variation in the case of detached houses. The obtained medium relative error is equal to 12.46% for the apartments dataset and 9.71% for detached houses. Standardized regression coefficients "Beta" were calculated in order to assess the influence of the individual parameters on the variation of EP_h'_SQRT. The analysis reveals that Hm_SQRT is the variable which has the maximum weight, with an influence of 12% in the variation of EP_h'_SQRT for apartments, and an influence of about 20% in the case of detached houses. The S/V_SQRT is the second most influential variable in both samples.

4. Proposals for refurbishment

Statistical data reports that 760094 "dwellings occupied by residents" are present in the Region [34]. With reference to the distribution detected in the survey, 58.7% are apartments and 41.3% are detached houses. A typical apartment and a typical detached house were defined according to the most widespread features found in the sample. By applying the calculation models (11) and (12), it was possible to predict an average consumption of 116.44 kWh/m^2year for the apartment and of 194.36 kWh/m^2year for the detached house. The regression analysis revealed that H_m_SQRT, namely the square root of the mean global heat transfer coefficient of the building envelope, is the most influential variable among those considered. Consequently, a refurbishment scenario that provides for the reduction of this parameter was estimated, assuming for example the replacement of windows and the thermal insulation of external walls. In particular, assuming to reduce the value of the mean heat transfer coefficient by 50%, a saving of 36.33 kWh/m^2year and 48.44 kWh/m^2year could be achieved, respectively for the apartment and the detached house. Knowing the number of housing units in the Region and their medium floor area, the assessment can be extended at a territorial level, resulting in a saving of 6272 TJ/year for the refurbishment of the apartment stock and 7530 TJ/year for the intervention on detached houses. Since most dwellings are equipped with a gas boiler, and the most widely used fuel is natural gas, a saving of about 350000 tCO_2/year for apartment and of 420300 tCO_2/year for the detached houses can be estimated with the considered refurbishment interventions.

5. Conclusions

A statistical survey on heating consumptions was conducted on a sample of existing residential buildings in the region of Calabria, a typically Mediterranean Region. The survey sought to collect data on the characteristics of the buildings and plants, and energy performance certificates of the dwellings. The data set was divided into two different groups, apartments and detached house, because of the considerable differences in the characteristics of the two types of accommodation. After presenting the general features of the sample, a bivariate regression analysis allowed identification of the level of significance of the analysis variables. Subsequently, a multivariate regression analysis developed in three steps, led to the definition of two equations, which can be used to forecast the heating consumptions in existing residential buildings, to be applied according to the type of dwelling (apartment or detached house). In particular, the mean global coefficient of heat transfer was found to be the variable with the highest weight on heating consumption variation. Therefore, the primarily recommended refurbishment strategy consists in the improvement of the building envelope and should seek to reduce the heat losses through the external surfaces. For example, the replacement of existing windows with other more performant (using low energy glass and isolated frames) and the thermal insulation of external walls, could be subsidized. A broad assessment of the existing residential stock in the Region showed that through the implementation of refurbishments, it could be possible to halve the mean global heat transfer coefficient, resulting in the achievement of an overall saving of 770392 tCO_2/year. In particular, since the highest saving is given by the energy renovation of detached houses, decision makers should plan and encourage this action.

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4.2 Social housing refurbishment in Mediterranean climate: cost-optimal analysis towards the n-ZEB target

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Abstract

The cost-optimal analysis represents a useful tool to stimulate the refurbishment of existing buildings, highlighting the minimal global cost that private or public users have to sustain in order to attain appreciable energy savings in the building life span. The identification of precise interventions on the building-plant system could steer legislators to the emanation of appropriate financial incentives in order to make the refurbishment of existing edifices more attractive. However, the cost-optimal solutions cannot be generalized as they are strongly influenced by the initial conditions and by the climatic context. In this paper, a traditional social housing unit, realized in Italy during the 1970s, largely widespread and strongly energy-consuming, was analysed in two different climatic zones belonging to the Italian territory. Suitable interventions were identified for the reduction of energy requirements for heating, cooling and domestic hot water production. These analyses were carried out by using the same simulation tool for energy and economic performances, highlighting the deviances among the cost-optimal solutions, the n-ZEB target and the minimal interventions for the containment of energy consumptions imposed by the current Italian legislation for buildings subjected to refurbishment.

HIGHLIGHTS

- cost-optimal analysis was carried out for a traditional Italian social housing unit;
- cooling requirements were also considered in relation to the climatic context;
- the reference building was investigated in two different climatic zones;
- interventions for optimal solutions, n-ZEB target and minimal energy requirements were identified;
- best cost-efficient measures were identified.

Keywords: *Buildings refurbishment; Social housing; Mediterranean climate; Cost-optimal analysis; n-ZEB target; Financial support policies*

1. Introduction

The 2010/31/UE Directive (EPBD recast) marked a decisive moment in the history of the regulatory framework for the improvement of energy performances in buildings, introducing the concept of the nearly-Zero Energy Building (n-ZEB), namely building-plant configurations where the small amount of primary energy demand is satisfied by renewable sources [1]. The n-ZEB model represents the natural destination of a pathway begun long ago, with the first measure issued by the European Union in 2002 and aimed at progressively improving energy performances in buildings [2]. However, the real innovation is related not only to the achievement of high energy performance buildings, but also to demonstrate their economic sustainability, to be sought in terms of cost-optimal levels. The n-ZEB models represent the result of a careful design process aimed at minimizing energy consumptions and whilst respecting contained global costs. However, the majority of edifices in the building stock is represented by existing constructions, therefore legislators have to identify solutions to promote the refurbishment of these structures. In this context, the cost-optimal analysis can contribute to identifying appropriate measures to sustain by means of targeted financial incentives. For this reason, Regulation 244 supplementing the 2010/31/UE directive, established a comparative methodological framework which specifies the rules for comparing different energy efficiency measures [3]. Moreover, the optimal cost evaluation for each individual construction is a problematic procedure to assess because it is difficult to generalize. Therefore, Member States of the European Community have to define some reference buildings to adopt as samples which are characterized by their functionality in relation to the climatic context.

The current literature provides different examples of implementation of the EPBD methodology: in [4] different steps for determining the optimal solutions for the refurbishment of Portuguese residential buildings are described. By analysing 35,000 combinations of packages of measures, the interventions on the building roof provided the best cost-efficient results and the synergic effects due to the combination of different solutions produced better results than single measures. The EPBD methodology was applied exclusively for the winter period also to investigate the requalification of the Italian residential building stock [5], by contemplating 120 different building types located in five climatic zones and described in the European TABULA project [6]. By means of the monthly quasi-steady procedure for the energy performances calculation, four retrofit interventions were considered: thermal insulation of the opaque envelope, replacement of the windowed surfaces, replacement of the heat generator and installation of solar thermal collectors for the DHW production. Also, in this case, different interventions combined in a package of measures resulted the most cost-effective solution, especially for small old buildings located in the coldest climates. Similar results were determined by a cost-optimal analysis by analysing 54 combinations of energy efficiency measures on three different types of detached residential buildings located in three different climate zones of Turkey [7]. In [8] and [9] cost-optimal solutions were identified for existing multi-family buildings under different climatic conditions, whereas the effect of different interventions applied to a new multi-residential building was assessed in [10]. A wide number of combinations of energy saving measures was considered in [11] to find the cost-optimal solution for an n-ZEB single-storey construction under Finnish climatic conditions. The study concerning the identification of the energy performance leading to minimum life cycle cost, calculated with the net present value method for an Estonian reference detached house, can be found in [12], by evaluating that the n-ZEB target required an extra construction cost of about 20%. In [13], an elevated number of building configurations were analysed for French climatic contexts, by adopting a transient code for the energy performance evaluations and an optimization program for the cost-optimal methodology. In [14], another document concerning the matching between energy requirements and economic targets can be found for conditions in Northern Italy, where 16 different energy scenarios were tackled in the design phase of a new high performing single-family house. With reference to the same location, a multidisciplinary approach was adopted in

[15] in order to select the most viable solution for the retrofitting of a single house, among five project solutions ranging from the low energy building, the *Passivhaus Standard,* the n-ZEB label and a "*plus energy*" balance configuration. Other 40 economically and technically feasible energy efficiency measures for a single-family n-ZEB are described in [16], devoting special attention to the HVAC system configurations; the authors stated that the possible solutions were economically not practicable, because of the global cost growth (about 10%) and a relevant increment in investment cost (about 20%). Another study that focused on the application of the cost-optimal methodology in a warm climate is described in [17], which considered 168 combinations of energy saving measures and performed the analysis both in terms of financial and macroeconomic calculations.

With reference to the Mediterranean area, the assessment of the profitability of energy refurbishment was addressed in [18], by considering a series of packages for a residential building envelope located in Southern Spain, also contemplating passive techniques. Other renovation interventions for residential and non-residential existing buildings were investigated in [19], covering a wide variety of edifices, with different climatic and framework conditions, due to the dissimilar construction characteristics of the involved participating countries [20]. A critical review concerning the criteria used to assess the impact of energy retrofits in historic and traditional buildings is contained in [21], whereas the requisite to consider the benefits provided by energy renovation in addition to energy savings and costs, is further highlighted in [22].

Regarding the specific case of cost-benefit analysis for the energy renovation of social housing buildings, several studies are available, however the employed models do not implement the procedure described by the 2010/31/UE directive. The renovation of social housing plays a decisive role in reducing energy consumptions because these are largely widespread to satisfy the vast demand of residential buildings registered in the second half of the twentieth century. Policies to support the upgrading of these edifices, in fact, are often inadequate and ineffective, and frequently underestimate the potential benefits that a refurbishment action could imply. The economic sustainability of different retrofitting strategies of an Italian social housing quarter, considering the efficiency of different refurbishment options through the Cost of Conserved Energy (CCE) and the pay-back of the investments (ROI) methods, was investigated in [23]. The Net Present Value (NPV), instead, was used in [24] as comparison parameter between various energy efficiency measures applied to a social housing sample in Mexico. A method to evaluate the energy demands of a precise building stock and to determine possible strategies for the energy planning, was proposed in [25]. This study focused on public social housing, however the same methodology could be extended at town level to determine the most effective energy policies and strategies. Starting from a building categorization according to the construction age, technical features and energy renovation interventions were suggested, quantifying energy demands before and after the refurbishment interventions.

In the majority of the mentioned studies, energy performances are calculated using dynamic simulation codes, while the methods to determine the cost-optimal were diversified in function of the number of analysed cases. Usually, optimum solutions can be detected comparing primary energy demands and global costs in a suitable chart, alternatively appropriate algorithms implemented in software or computing codes allow for the identification of the same points. In [26] a more complex procedure was proposed, where a simulation process was flanked by the generation of artificial neural networks combined with the employment of a multi-objective optimization algorithm. A probabilistic LCC based on uncertainty and sensitivity analysis via Monte Carlo methods, instead, was proposed in [27] in order to overcome the limitation due to the hypothetical assumption on input parameters, which could affect the results.

In this paper, different energy retrofit alternatives for a social housing subjected to the Mediterranean climate conditions, are analysed and discussed also considering the cooling requirements. Since the studies available in literature frequently consider new edifices designed to be already highly energy efficient, in this document a social housing unit characterized by inefficient and obsolete solutions, was considered as the reference building. Consequently, the research seeks to investigate how the limited energy performances of the reference building affect the attainment of the optimal levels, by identifying the most cost-effective retrofit measures with particular reference to those required for the achievement of the n-ZEB label. For each package of cost-effective retrofit actions, the annual primary energy savings were determined employing the procedure dictated by the 2010/31 UE directive, applying the EN 15459:2017 standard for the calculation of the global cost [28]. Conversely to the mentioned studies, energy evaluations and economic optimization were performed using the same calculation tool, which includes modules both for energy performance in transient regime and for the optimal solutions identification by means of genetic algorithms. Successively, the effective solutions for the upgrading of a precise social housing stock were identified, with the purpose of addressing suitable strategies towards the strengthening and revitalization of this significant fraction of existing edifices. Thus, appropriate investment programs and the allocation of financial incentives for refurbishment actions that result economically feasible, can be planned. In particular, the possibility to convert the considered social house sample into n-ZEB has been considered, assessing the economic viability of the interventions. Since other documents reported that n-ZEB thresholds are difficult to reach in the absence of subsidizes, the present work could contribute to increasing awareness among legislators to undertake targeted routes, in such a way as to encourage actions that can best take advantage from economic, social and environmental points of view.

2. Methodology

The cost-optimal point is defined as the energy performance level that leads to the lowest cost during the estimated economic lifecycle of the building. Therefore, the optimal solution does not match the highest energy performance, because this could result in a high initial investment cost which could be difficult to recover over the lifetime of the building, despite the limitation of operational costs. Conversely, the goal is the identification of a good compromise between investment and operational costs, estimated considering all the components involved throughout the life cycle of the building and the corresponding energy performances. In the optimization process, annual energy consumptions for heating, DHW production and cooling have been considered. Global costs faced during the building lifespan and energy from renewable sources are also evaluated, by considering the net primary energy delivered between the building-plant system and the external environment. The latter could assume a negative value when the self-produced energy is greater than the absorbed energy from the building-plant system. The method is based on a comparative methodological framework that, through various phases, leads to the evaluation of the parameters that affect the energy performances of the analysed building and their correspondent costs, estimated on the supposed edifice lifespan. The methodology can be summarized in the following steps:

a) Definition of the reference building;
b) Identification of the input data;
c) Selection of the Energy Efficiency Measures (EEMs) and the possible combination in packages;
d) Calculation of the primary energy requirements for each package of measures applied to the reference building by means of simulation campaigns;
e) Global cost estimation for each package of measures applied to the reference building;

f) Elaboration of the results and calculation of the distance between the optimum level and other targets.

2.1 Definition of the reference building

Reference buildings can belong to residential and non-residential categories, both new and existing. As stated in [29], the reference building can be defined on the basis of three methodologies:

a) "*Example reference building*" created on the basis of experts' assumptions and studies when no statistical data are available;

b) "*Real reference building*" selected among real existing buildings such as that characterized by average characteristics, observed through statistical analysis;

c) "*Theoretical reference building*" defined by assembling the most common features statistically detected in a building category.

The three approaches mentioned can be used independently or simultaneously, namely they can be used together to collect the different subsets of needed data, depending on the available information. For example, the reference building could be framed as a "*Real building*" concerning aspects such as shape, geometry, envelope and technical systems, whereas it could be framed as an "*Example building*" in order to consider occupation and operation modes.

2.2 Identification of the input data

The comparative methodological procedure requires an initial effort to define correctly the input data for calculations in terms of costs/energy related to the reference building. The more inputs are precise and detailed, the more reliable and realistic the overall analysis turns out to be.

The initial data required for the implementation of the comparative methodology are:

- Definition of the reference building geometry;
- Identification of the climatic context;
- Description of the structural elements of the building fabric and parametrization of the thermo-physical properties (thermal transmittance, solar factor, airtightness, etc.);
- Characterization of the technical systems and their components in terms of power, auxiliary consumptions and efficiency;
- Definition of the reference building user profiles.

2.3 Energy Efficiency Measures and combination in packages of measures

Once the reference building and its features have been defined, improvements for the identification of the best compromise between energy consumptions and economic effectiveness have to be identified. Therefore, different EEMs are hypothesized, intended as possible interventions to adopt for the reduction of the primary energy requirements [30]. On a practical level, this consists of the employment of upgraded elements, the replacement of obsolete equipment with more modern devices or more technologically advanced systems, in order to achieve optimal energy performances and, simultaneously, whilst trying to ensure occupant thermal comfort. Energy efficiency measures are combined in "*packages*", since the aggregation of different interventions creates synergies that allow better results, in terms of costs as well as in energy performance, compared to those obtainable with single measures. Firstly, the contemplated interventions have to ensure compliance with the minimum requirements specified by National regulations and, successively, appropriate measures to obtain improved levels can be introduced. Moreover, EEMs should have a commensurate global cost so that they can compete in reaching the optimum point. By applying the comparative methodology, an evident issue is represented by the necessity to consider all the feasible measures that could provide an impact on the primary energy use and on the global cost, keeping the calculation manageable and proportionate. Different EEMs on the reference building, in fact, can easily result in thousands of calculations. However, in addition to the reference scenario, a number of combinations greater than ten is suggested, with an adequate computational effort of simulation tools that, as in the present study, automatically process a large number of evaluations.

2.4 Calculation of the energy requirements of the considered energy efficiency measures

The annual energy demands in terms of primary energy (kWh/m²year) in the current state and for each package of measures applied to the reference building, have to be determined. The supplied primary energy to the building was calculated on the basis of the quantities delivered and exported by energy carriers (for instance electricity or natural gas), using appropriate conversion factors. For the assessment of energy performances, the graphic interface DesignBuilder developed in the EnerglyPlus environment, was employed [31].

2.5 Global cost estimation for each package of measures on the reference building

After the analysis and the calculation of the energy performances obtainable through the application of the considered EEMs on the reference building, the correspondent economic expenses have to be quantified. The actual purpose is the comparison among the overall cost resulting from the application of the EEMs. The global cost is the sum of all costs that, in addition to the initial investment, are incurred for the use of the building during its lifespan. In the case of the cost-optimal methodology, the total cost related to each EEM applied to the reference building is calculated. For each intervention, the sum of all the costs necessary for the installation, the use, the replacement and the disposal of the technical and constructive systems influencing the energy performances of the building, is determined. For each measure, the respective cost related to the material, labour, business profits, operation, maintenance, taxes, replacement, disposal, general and professional expenses associated with the specific processing, is calculated. According to the Guidelines accompanying the Commission Delegated Regulation 244/2012 [30], the cost categories to be considered in the calculation of the global cost include capital costs and periodic or annual costs. The capital costs, or initial investment costs, include the rates required for the design, purchase and realization/installation of the energy efficiency measures related to the building, the energy supply for heating, cooling, ventilation and DHW systems and technologies exploiting renewable sources. The annual costs are divided into:

a) Management costs, including:
   - Costs for energy supply, considering annual constant tariffs;
   - Operation costs, related to insurance, regulatory periodic service, taxes, etc.
   - Maintenance costs, due to inspections, adjustments, cleaning, repairs and consumables.
b) Costs for periodic replacement of building components or systems, in relation to the lifespan. If the components have a useful life longer than the calculation period, the residual value estimated through linear depreciation, is considered.

Regarding each cost item, Regulation 244/2012 establishes that data related to the costs must be market-based or obtained through market analysis, consistently with the time and place of the costs of investment, management, energy and disposal, if applicable. Therefore, cost data should be collected from one of the following sources:

- Evaluation of recent construction projects;
- Analysis of the standard offers of construction companies;
- Use of databases on existing costs produced by market-based costs.

For energy costs, the price evolution of the various energy carriers has to be taken into account. The global cost is calculated by summing the different cost items and by applying a discount rate in order to express them in terms of Net Present Value. The term "global cost" corresponds to the concept that in literature is generally called "analysis of the cost of the life cycle". The calculation, in fact, refers to a period corresponding to the economic life cycle (LCC, Life Cycle Cost) of the studied objective. In this study, this period was fixed at 30 years for the considered residential building configurations.

2.6 Results analysis and calculation of the distance between optimum level and n-ZEB target

Once the energy performances and the global costs are defined, an iterative calculation is performed in order to obtain the package of measures that ensures the attainment of the cost-optimal level. Results are reported on a chart with the net primary energy on the x-axis, expressed in kWh/m^2 and determined for the considered building lifespan, and the global costs on the y-axis in €/m^2 (costs per conditioned surface area) for each considered package of measures measure/package/variant, as illustrated in figure 1. The cost-curve is delineated at the lower edge of the scatter plot (geometrical place named "*Pareto*") and the minimum of the curve reveals the combination with the lowest cost. The "*Pareto*" identified building configurations that cannot be characterized by better conditions.

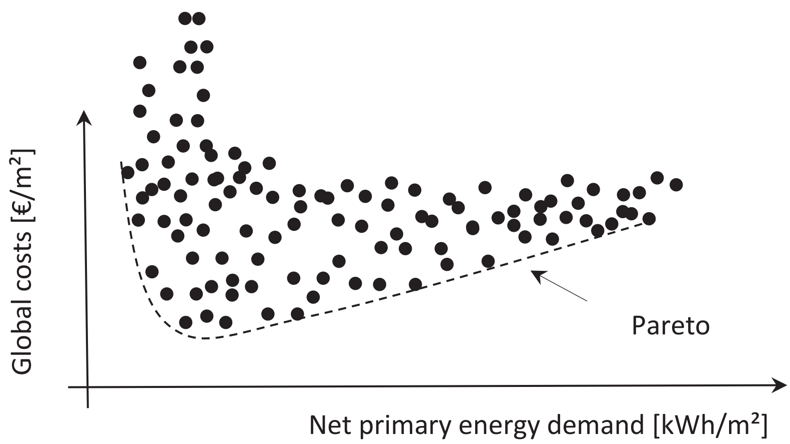


Figure 1. Example of cost-optimal graph concerning different EEMs and Pareto position

If packages exhibit similar costs, the definition of the cost-optimal level should be based on the package characterized by the lowest net primary energy consumption. The area of the graph closest to the ordinate axis identifies the solutions applied to the reference building leading to the best energy performances, regardless the cost parameter. These solutions meet the target of nearly zero energy building (n-ZEB) steering the construction towards a high energy efficiency model but implicating higher costs.

3. Data

3.1 The reference building

A considerable portion of the Italian building stock consists of social housing, which often presents the worst performance, both in term of energy performances and comfort conditions, due prevalently to the radiant asymmetry produced by a scarcely insulated envelope with windows equipped with a single pane. Moreover, periodic maintenance is lacking. These building fabrics were designed without measures concerning the containment of energy consumptions, as they were built before the 1960s, while the first regulations for the building energy consumption containment were dated at the end of the 1970s. Due to the common adopted design rules, homogenous features make these buildings suitable for the proposed study. The most widespread characteristics concern a reinforced concrete structure, with medium size housing units with about four rooms, central heating plant at high temperature, and a pitiful state of conservation. For the present analysis, a "*real existing reference building*" was selected with standard geometry and construction properties, while it was considered as a "*theoretical reference building*" for occupancy and operation points of view. In particular, the analyzed building is the first module of a line house, consisting of a basement, used as a garage and unheated cellar, and three floors with six independent apartments, two on each floor, served by a central staircase. The roof is tilted and the space under the roof is not heated. The considered housing block is the basic module used for multiple aggregations developed in length. Figure 2 shows the layout of a typical floor and the main façade. An external view is depicted in figure 3. Table 1 summarizes the main features of the building that is located in southern Italy where a characteristically Mediterranean climate can be observed. The climatic hourly data employed by the simulation tool were generated using Meteonorm software [32].

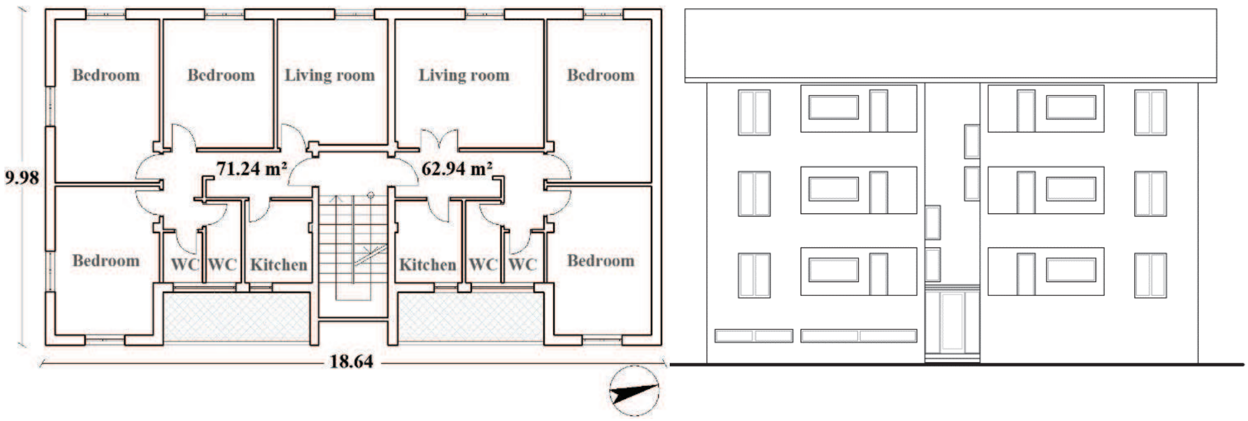


Figure 2. Sketch plan of the typical floor and main façade of the building.

Figure 3. External view of the real reference building involved in the investigation.

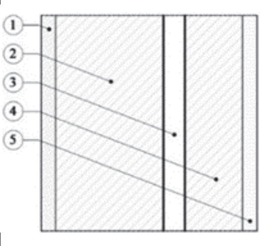
Table 1. Main characteristics of the reference building

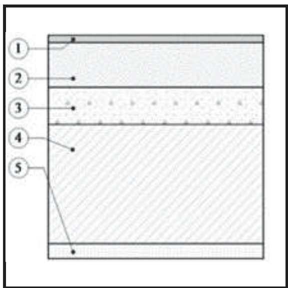
Floor number	**1 basement**
	3 floors above ground
Inter-floor height (m)	2.25 for the basement
	2.8 for the other floors
Length (m)	18.64
Width (m)	9.98
Gross heated volume V (m3)	1528.9
Gross dispersing surface S (m2)	933.11
S/V (m2/m3)	0.65
WWR (Windows to wall ratio)	South-East
	4.75%
	North-West
	5.32%
Prevalent exposure	South-East

The external walls, made by a double layered with an air-cavity, are not insulated, the floor decks are in reinforced concrete with hollow bricks as lightening elements. Table 2 shows the layering and the thermal properties of the dispersing elements of the building envelope. A centralized natural gas boiler provides heating and domestic hot water, suppling radiators as emitters.

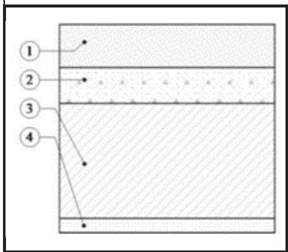
Regarding occupation and plant operation profiles, data provided by national standards was used because detailed information was not available. In particular, internal gains were calculated according to the Italian standard UNI/TS 11300-1 in function of the heated dwelling area and set to an average value of 5.62 W/m^2 [33]. With reference to the same standard, a natural air-change of 0.3 ach was imposed, whereas the DHW requirement was determined in accordance to the other standard UNI/TS 11300 – 2 in 1.61 l/m^{2}day for each apartment [34]. From the heating plant point of view, the centralized boiler is a single stage device operating at a constant temperature, the distribution network suppling the emission system is not insulated, thermostats for the indoor air temperature control are absent and the same emitters are old and installed on dispersing walls. Therefore, the efficiencies concerning the several heating-plant devices assume reduced values producing a consistent increment of the primary energy demand. For the energy evaluations carried out by the transient code, set-point temperatures were set in 20°C and 26°C for winter and summer respectively.

Table 2. Layering and thermal characteristics of the dispersing elements of the reference building envelope. For each layer: s = layer thickness [m]; λ = thermal conductivity [W/m·K]; c = specific heat [J/Kg·K]; ρ =density [Kg/m^3]. For the building components: U = thermal transmittance [W/m^{2}K]; Yie = dynamic thermal transmittance [W/m^{2}K]; fd = decrement factor [-]; φ = time lag [h].

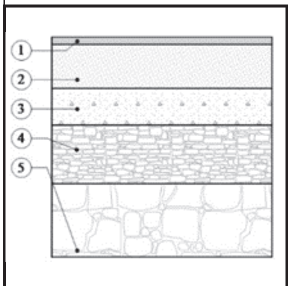
	**EXTERNAL WALL**	**s** [m]	**λ** [W/m·K]	**c** [J/Kg·K]	**ρ** [Kg/m^3]	**U** [W/m^{2}K]	**Yie** [W/m^2·K]	**fd** [-]	**φ** [h]
	1. Lime and cement plaster	0.02	0.90	1000	1800				
	2.Brick 15x25x25 cm	0.15	0.20	1000	565				
	3.Air gap	0.03	R = 0.18 [m^2·K/W]			0.654	0.266	0.407	9.26
	4.Brick 8x25x25	0.08	0.21	1000	625				
	5.Internal gypsum plaster	0.02	0.35	1000	1200				
	TOTAL THICKNESS	**0.30**							



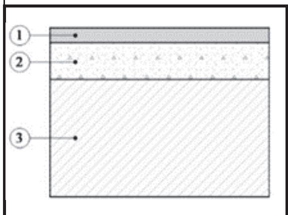
SEMI-EXPOSED FLOOR	s [m]	λ [W/m·K]	c [J/Kg·K]	ρ $[Kg/m^3]$	U $[W/m^2K]$	Yie $[W/m^2·K]$	fd [-]	φ [h]
1.Ceramic tiles	0.01	1.00	840	2300				
2.Lightweight slab	0.06	1.40	1000	2000				
3.Concrete	0.05	1.48	1000	2200	1.138	0.444	0.359	8.08
4.Brick 16x40x25	0.16	0.344	1000	435				
5.Internal gypsum plaster	0.02	0.35	1000	1200				
TOTAL THICKNESS	**0.30**							



SEMI-EXPOSED CEILING	s [m]	λ [W/m·K]	c [J/Kg·K]	ρ $[Kg/m^3]$	U $[W/m^2K]$	Yie $[W/m^2·K]$	fd [-]	φ [h]
1.Lightwigth slab	0.06	1.40	1000	2000				
2.Concrete	0.05	1.48	1000	2200	1.151	0.490	0.392	7.78
3.Brick 16x40x25	0.16	0.344	1000	435				
4.Internal gypsum plaster	0.02	0.35	1000	1200				
TOTAL THICKNESS	**0.29**							



GROUND SLAB	s [m]	λ [W/m·K]	c [J/Kg·K]	ρ $[Kg/m^3]$	U $[W/m^2K]$	Yie $[W/m^2·K]$	fd [-]	φ [h]
1.Ceramic tiles	0.01	1.00	840	2300				
2.Lightweight slab	0.06	1.40	1000	2000				
3.Concrete	0.05	1.48	1000	2200	1.58	0.400	0.229	9.80
4.Dry loose sand	0.08	0.60	1000	1700				
5.Stone chippings	0.1	0.70	1000	1500				
TOTAL THICKNESS	**0.30**							



ROOF	s [m]	λ [W/m·K]	c [J/Kg·K]	ρ $[Kg/m^3]$	U $[W/m^2K]$	Yie $[W/m^2·K]$	fd [-]	φ [h]
1.Clay tiles	0.02	1000	800	2000				
2.Concrete	0.05	1.48	1000	2200	1.268	1.010	0.646	5.08
3. Brick	0.16	0.344	1000	435				
TOTAL THICKNESS	**0.23**							

3.2 Energy efficiency measures

The contemplated energy efficiency measures involve the improvement of transparent and opaque surface properties, the replacement of the current generator system and the integration of active solar systems in the building envelope. The cost of each individual intervention was calculated based on the regional price list, or through market survey [35]. Regarding the building envelope, the application of external thermal insulation composite systems (ETICS) in the dispersing walls and the replacement of transparent components, were considered. Expanded polystyrene (λ = 0.036 W/m·K) was used for thermal insulation. In particular, four different levels of insulation have been supposed for vertical walls, roof, ground slab, semi-exposed ceiling and floor, in addition to the current state. Windowed surfaces involve the exploitation of double or triple pane systems, also with low-ε treatment, mounted on a wooden frame with different thicknesses. These solutions, as well as the size of the solar active systems, have been defined respecting the minimum levels of energy performance set by current Italian regulations [36, 37] supposing two improvement levels. Generally, the latter allow for appreciable mean radiant temperatures due to the attainment of well-insulated building envelopes and, consequently, appropriate winter comfort conditions. Other solutions that do not provide minimal interventions were also contemplated because they could provide the best-cost efficient measure, however the achievement of suitable comfort conditions is not guaranteed. With reference to the opaque components, table 3 shows the thermal performances and the correspondent costs referred to the square meters of conditioned surface for each considered energy efficiency measure. Similarly, in addition to the current state, a further three solutions were hypothesized for the windowed surfaces and are listed in table 4, including the minimum level of performance fixed by legislation. The calculation of the cost for the reference building is also required, as the technical-economic optimization process will identify the most efficient solutions according to the extra-costs incurred for the application of energy efficiency measures with respect to the current configuration that is taken as a reference.

Table 3. Energy efficiency measures for the opaque elements of the building envelope

	External walls		**Ground slab**		**Roof**		**Semi-exposed floor**		**Semi-exposed ceiling**	
	U [W/m²K]	Cost [€/m²]	U [W/m²K]	Cost [€/m²]	U [W/m²K]	Cost [€/m²]	U [W/m²K]	Cost [€/m²]	U [W/m²K]	Cost [€/m²]
Reference Building	0.654	104.87	1.580	77.23	1.268	99.47	1.138	127.80	1.151	101.01
Insulation Level 1	0.379	142.81	0.435	92.02	0.332	114.86	0.503	147.67	0.505	111.22
Insulation Level 2 (Regulation)	**0.267**	**174.41**	**0.293**	**100.90**	**0.243**	**164.14**	**0.322**	**165.1**	**0.324**	**120.02**
Insulation Level 3	0.206	206.01	0.221	109.78	0.191	183.42	0.237	182.55	0.238	128.82
Insulation Level 4	0.167	237.61	0.178	118.66	0.173	193.06	0.188	199.99	0.188	137.62

Table 4. Energy efficiency measures for the glazed elements of the building envelope

	Frame typology	**Glass typology**	**Solar heat gain coefficient (SHGC)**	**Visible transmittance (VT)**	**U_W [W/m²K]**	**Cost [€/m²]**
Reference Building	Wood (50 mm)	Single clear (5 mm)	0.853	0.892	5.0	239.78
Window 1	Wood (50 mm)	Double (4-16-4 with air)	0.764	0.812	2.8	297.98
Window2 (Regulation)	**Wood (60 mm)**	**Double (4-20-4 with air)**	**0.597**	**0.769**	**1.8**	**376.30**
Window 3	Wood (60 mm)	Triple (4-12-4-12-4 with air)	0.474	0.661	1.4	382.50

Regarding the HVAC generators, in addition to the current state, a condensing boiler and an air-water heat pump were analyzed. In the latter case, radiators were replaced by fan-coils, in order to employ the heat pump system in rational way, also for the cooling period. Active solar systems consider PV panels and thermal solar collectors, where the latter interacts with the HVAC system by means of a storage tank for the coverage of a fraction of DHW and heating needs. For the solar thermal collectors, two areas with selective coating were considered: 4.6 m² to meet minimum level required by current legislation [37] and 9.2 m² in order to increase the solar fraction. The combination of the thermal solar options with the different types of considered generators has provided nine configurations of the HVAC system, as illustrated in table 5, with the cost referred to the square meters of conditioned surface.

Table 5. Configurations taken into account concerning the HVAC plant (EEM0=Reference building)

	Type of generator			Solar thermal			Cost [€/m²]
	Gas boiler	Condensing gas boiler	Heat pump	Absent	4.6 m²	9.2 m²	
Reference	■			■			4.40
EEM1	■				■		8.43
EEM2	■					■	12.46
EEM3		■		■			6.83
EEM4		■			■		10.86
EEM5		■				■	14.89
EEM6			■	■			80.07
EEM7			■		■		84.10
EEM8			■			■	88.13

The photovoltaic system allows for the on-site production of electricity, by considering three installed peak powers. The first of 3.75 kW_p corresponds to the minimum value required by current regulations [37], whilst the other two solutions increase the renewable electricity rate consisting of PV generators with 7.5 kW_p and 15 kW_p. Mono-crystalline modules were supposed with a nominal efficiency of 15%. The photovoltaic alternatives and the related costs referred to the square meters of conditioned surface, are shown in table 6.

Table 6. Photovoltaic alternatives

	Description	Cost [€/m²]
Photovoltaic 1 (Regulation)	3.75 kWp – 15 Modules	7.99
Photovoltaic 2	7.5 kWp – 30 Modules	15.36
Photovoltaic 3	15 kWp – 60 Modules	28.76

The guidelines accompanying EU Regulation 244/2012 recommend conducting energy performance calculations using dynamic methods, in order to obtain reliable results in the evaluation of cost-optimal in function of the net primary energy demands. For the latter, appropriate conversion factors established at Italian level for electricity (1.95) and for natural gas (1.05) were applied [36]. The net primary energy demand could assume negative values when the energy produced on-site prevails, during the considered analysis period, on the absorbed energy to cover heating, cooling and DHW services.

3.3 Cost analysis

In addition to energy performances, the correspondent global costs were calculated for the involved energy efficiency measures by summing the Net Present Value concerning the initial investment to the management, replacement and operative annual costs, also including disposal costs. The considered time span in the analysis was 30 years, by employing a discount rate equal to 3% and an inflation rate of 0.3% to homogenize costs incurred at different times. These parameters were set with reference to the trend of the last year registered for the Italian situation [38]. The categorizations of costs for the application of the cost-optimal methodology is based on the EN 15459 standard [28].The investment costs correspond to the initial expenses involving construction costs. In order to define the value of the cost items, an analysis of the unit price of the elementary components or processes required by each energy efficiency measure, was carried out. The final price was determined as the sum of the costs related to human resources, construction products and equipment. Investment costs for each EEM are illustrated in the previous paragraph and reported in function of the conditioned building surface. The annual costs were calculated by the sum of all costs occurring in a year for management and periodic replacement. This category includes maintenance costs, operating costs and energy costs. Maintenance costs are related to annual inspection, cleaning, adjustment and preventive repair costs; the maintenance costs are assessed as a percentage of initial costs, according to Annex A of the standard EN 15459, as shown in table 7 [28].

Table 7 – Maintenance costs expressed as a percentage of investment costs (Co_{inv})

Typology	Equipment/systems	% of Co_{inv}
Building envelope	External coat insulation systems	-
	Windowed surfaces	1
HVAC systems	Traditional boiler	2
	Condensing boiler	1.5
	Heat pump	3
Active solar systems	Thermal solar collectors	0.5
	PV generators	1

Energy costs, depending on consumptions, building size, current rates and price predictions, are directly connected to the energy performance calculation results, and they include taxes. Regarding the energy carrier exploited by the considered generator systems, a tariff of 0.20 €/kWh for electricity (heat pump) and 0.08 €/kWh for natural gas (boilers) were employed considering trends in estimated price evolution. Furthermore, periodic costs referring to component replacement for aging and technological obsolescence, were added. Replacement costs, instead, are related to the component life span in accordance with Annex A of the standard EN 15459, as shown in table 8, including the disposal costs as a percentage of the construction costs.

Table 8 – Components and systems life spans

Typology	Equipment/systems	Life span [year]
Building envelope	External coat insulation systems	-
	Windowed surfaces	30
HVAC systems	Traditional boiler	15
	Condensing boiler	20
	Heat pump	15-20
Active solar systems	Thermal solar collectors	15-25
	PV generators	25
	Inverter	10

3.4 Optimization process

By means of a genetic optimization plugin, the DesignBuilder software allowed obtainment of all the possible combinations of the implemented project alternatives. A complete analysis was carried out by evaluating a high number of solutions in an automatic manner.The optimization module uses advanced evolution algorithms that, by means of a process of natural selection, seek to enhance energy performances of the building and determined the targeted objectives of the analysis. In detail, the best performing features are transmitted on the future computing generations and the process continues until the design optimum is identified. The setting of the objective functions of the analysis that minimized both the net primary energy and the present net value of the global cost, depending on several project variables, was carried out. Successively, a certain number of alternatives were associated for each variable. The analysis covered all the possible combinations of the speculated technical alternatives, whose energy and economic performances were evaluated in a short time. The settings of the process are outlined in figure 4. The packages of energy efficiency measures required by the cost-optimal comparative methodological framework, were randomly produced and analyzed during different generations. A variable number of iterations, each one corresponding to a package of measures, is analyzed in every generation cycle. The total number of developed iterations depends on the control options set in the genetic algorithms, which determine the way that the solutions evolve. In particular, each generation produces a number of iterations that varies between the size of the initial population, representing the minimum number of iterations produced per generation, and the maximum population size, representing the maximum number of iterations in each generation. The maximum number of generations to perform determines the time, size and complexity of the analysis. The points representing the results of each package produced by the generations, representative of the relative project variables, are displayed on a scatterplot by defining the Pareto front. The calculation procedure can be considered to have reached convergence if no new optimal solutions have been found in the last 10 generations. In the examined case, the process was stopped at the 37th generation, since convergence had been achieved.

The optimization genetic algorithms, working on 8 design variables and 41 technical alternatives (figure 4), with an initial population size of 50 and a maximum population size of 100, simulated 3314 combinations during 37 generations, providing a well-defined Pareto front, within which the cost-optimal solution can be identified.

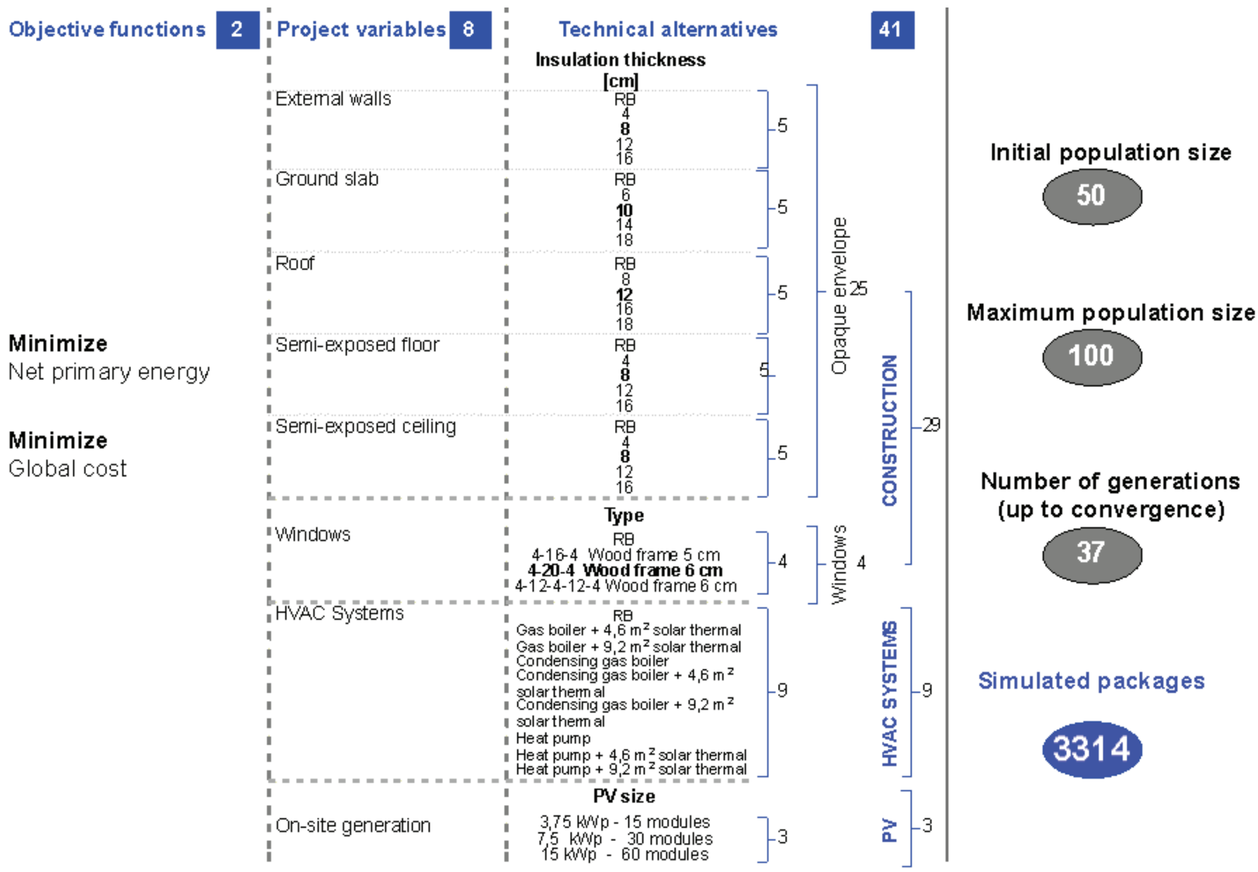


Figure 4 – Optimization procedure scheme

4. Results and discussion

The cost-optimal solutions concerning the reference building (RB) have been determined supposing two localities in two different climatic zones classified in accordance with Italian Regulation [39]: the first with 2897 heating degree days (Zone E), the second warmer with 913 heating degree days (Zone B). These two climatic zones were chosen because the majority of Italian edifices built before the emanation of laws concerning the containment of energy consumptions belong to the first, while the second one is characterized by elevated cooling demands. In particular, the first location is characterized by 553 cooling degrees day (CDD) whereas the second one by 1014, determined with a reference temperature of 18°C [40]. Moreover, the Italian standardization institute has introduced other indexes to define the summer climatic conditions, because in the Mediterranean area the outdoor temperature is not sufficient to define the cooling needs magnitude. Therefore, the “climatic vector” and the “climatic severity index” are employed to determine the summer climatic zones, obtaining the classification A for the first location (favorable summer climate) and G for the second one (worst climatic zone) [40]. In order to highlight the magnitude of the cooling requirements for the examined localities, two different types of analysis were carried out on the RB: the first involving exclusively heating and DHW production, the second by adding also cooling needs to quantify the deviances. In the chart three distinct zones have been highlighted concerning the attainment of n-ZEB or n-ZEB+ labels (the latter identifies a building configuration that during the considered analysis period produces an amount of energy greater than the absorbed one due to renewable sources), the optimal solutions (characterized by the lowest cost or by the best compromise between energy requirements and correspondent costs) and basic refurbishment level solution (BRL). The latter refers to an RB configuration where the interventions required to achieve minimal energy performances in accordance with the current Italian legislation have been adopted [36].

4.1 Analysis including heating and DHW production

The spot cloud representing the different packages on the RB located in Zone E considering exclusively heating and DHW production services, is shown in figure 5 highlighting the Pareto front. Global costs ranged between a minimal value of 1,163.1 €/m² and a maximum of 1,404.9 €/m², whereas the net primary energy is variable from -21.8 kWh/m² to 57.4 kWh/m². Package n° 969 is representative of the optimal point characterized by a building envelope scarcely insulated compared to the BRL configuration, but with an electric heat pump to supply fan-coils, 9.2 m² of thermal solar collectors and a photovoltaic generator with 3.75 kW_p. This package provided an energy requirement of 16.4 kWh/m² and a correspondent cost of 1,163.1 €/m² and, globally, it contemplated measures on the building envelope with reduced magnitude than technical plant interventions. Therefore, the best-cost effective measure indicates the adoption of a dispersing envelope where the greater heating demands are compensated by a large employment of renewable sources; however, adequate thermal comfort conditions are not guaranteed. Moreover, the BRL configuration provided great global costs with major energy requirements, because probably an appropriate synergy of different EEMs was not adequately considered by the legislator. However, other packages have provided similar results of the optimal configuration, such as cases n° 675, n° 1097 and n° 1492, that contemplated the same technical system but with a slight variation of the insulation thickness inside some opaque components, to further confirm that interventions on the envelope produce a marginal variation of the parameters.

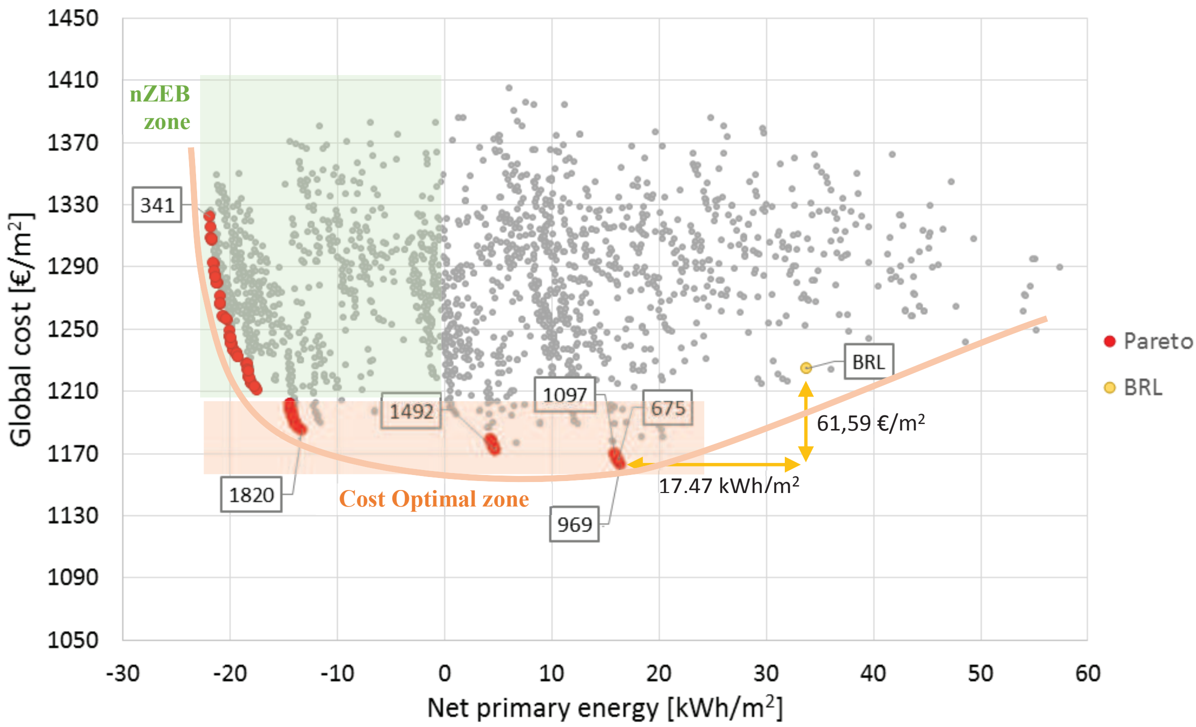


Fig. 5 – Cost-optimal chart for the RB located in climatic zone E considering only the heating and DHW production services

A noticeable improvement of the energy requirements with a slight worsening of the global costs, can be observed with package n° 1820 that allows for the attainment of an n-ZEB+ configuration. This result highlighted that actually the cost-optimal solution is not far from the achievement of a building configuration that produces an amount of energy larger than the absorbed one. In the latter case, the augment of the PV generator power peak in combination with the electric heat pump self-consumptions and fan-coils as emission system, has produced an improvement of the energy performances, while the major initial investment costs are largely counterbalanced by the reduction of the operational costs in the successive years. Moreover, the employment of a triple pane system and the adoption of important insulation thicknesses inside the ground slab and the semi-exposed ceiling allows for an improvement of the internal mean radiant temperature, therefore better thermal comfort conditions can be attained than package n° 969. Compared to the optimal solution, the detected global costs growth was of 21.9 €/m² with a correspondent decrement of the net primary energy of 29.7 kWh/m². Moreover, the latter result is also precautionary because in the amount of the global costs, the rate concerning the sale of the PV surplus electricity, was not considered. Package n° 341 concerned the building configuration with the best energy performances, and was characterized by the same technical plant of package n° 1820 and a highly insulated envelope: the detected global cost growth was of 158.9 €/m² compared to the optimal solution, but a correspondent improvement of thermal comfort can be detected due to the augment of the opaque wall surface internal temperature. In table 9, a brief description of the main interventions contemplated in the mentioned packages, is presented; in particular, insulation thicknesses in the opaque surfaces, distinguishing among external wall (VW), roof (RF), semi-exposed floor (SE_{floor}),semi-exposed ceiling (SE_{ceil}) and ground slab (GS), windowed typology and technical plant properties (including technologies exploiting renewable sources), are described.

Table 9 – Main interventions involved in the more significant packages for the RB located in climatic zone E and for heating and DHW production services: (*) indicates the cost-optimal solution, (**) the best compromise between global costs and net primary energy, (***) the package with the best energy performances.

N° package			BRL	969 (*)	1820 (**)	341 (***)
Building envelope	Insulation thickness [mm]	VW	80	-	-	160
		RF	120	-	-	160
		SE_{floor}	80	40	-	160
		SE_{ceil}	80	120	160	160
		GS	100	60	100	180
	Transparent surfaces		(Window 2) Glass 4-20-4; Frame in hard wood 60 mm	RB Glass 5 mm; Frame in hard wood 50 mm	(Window 3) Glass 4-12-4-12-4; Frame in hard wood, 60 mm	RB Glass 5 mm; Frame in hard wood, 50 mm
Technical plants	PV [kWp]		3.75	3.75	15	15
	HVAC		(EEM1) Traditional Boiler + Thermal solar coll. (4.6 m^2)	(EEM8) Heat pump + Thermal solar coll. (9.2 m^2)	(EEM8) Heat pump + Thermal solar coll. (9.2 m^2)	(EEM8) Heat pump + Thermal solar coll. (9.2 m^2)
Net primary energy [kWh/m²]			33.84	16.37	-13.3	-21.79
Global Costs [€/m²]			1,224.72	1,163.13	1,185.03	1,322.07

Regarding climatic zone B, the spot cloud produced by the several analyzed packages, is shown in figure 6 for the same services, observing this time a point concentration in accordance with three main directions. Obviously, the spots are characterized by lower net primary energy and lower global costs, due to the reduction of the heating requirements and of the correspondent operative expenses. Several points are closer, therefore the considered packages offer similar results. In particular, package n° 403 provided the optimal solution, corresponding to an n-ZEB+ configuration (-13.0 kWh/m²) and a correspondent minimal cost of 1091.9 €/m². Due to the favorable outdoor temperatures that produced limited thermal losses by transmission, in this configuration insulation layers in the vertical walls and in the roof result counterproductive, as reported in table 10. Analogously to the colder climatic zone, a considerable improvement of the energy performances is related to the employment of a heating system equipped with a heat pump, also supplied by a 7.5 kW_p PV generator and solar thermal collectors for 9.2 m². The BRL configuration already contemplated the minimal measures for energy efficiency required for the attainment of a quasi n-ZEB, and also of appreciable thermal comfort conditions related to the well-insulated envelope, however with a considerable extra-cost compared to the optimal solution. Therefore, also for this locality, the necessity to consider the interaction of different refurbishment measures is confirmed. In particular, a major attention paid to the technical plants rather than to the building envelope allows for the attainment of better net primary demands with a reduction of 69.5 €/m² in term of global costs when compared to the BRL configuration, but with a worsening thermal comfort. The better compromise is represented by package n° 2020 that, by means of a minimal variation of the global costs, induces a further reduction of 21.3 kWh/m² in terms of net primary energy. However, a major radiant asymmetry could be observed due to the employment of a single pane windowed system. Finally, package n° 1750 determined the best energy performances but with a cost growth of 138.5 €/m², corresponding to a highly insulated envelope equipped with heat pump and the largest PV generator, however this building-plant configuration could allow for the achievement of better thermal comfort conditions. Globally, for both the considered climatic zones, the minimal requirements for energy refurbishment of existing buildings imposed by the current Italian legislation seem to be more restrictive than those actually required, due to an incorrect and independent evaluation of each intervention. The majority of the EEMs involving the building envelope determined a considerable increment of the global costs to achieve reduced values of the net primary energy, by confirming a worsening of the economic frame in both the considered localities.

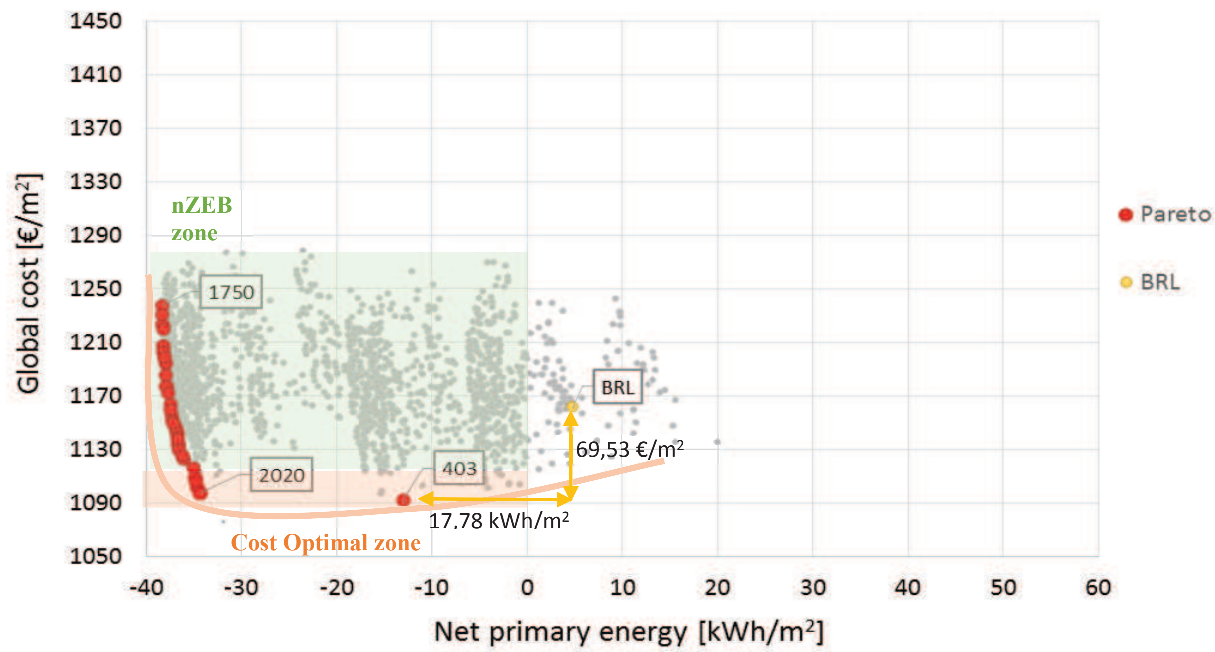


Fig. 6 – Cost-optimal chart for the RB located in climatic zone B considering only the heating and DHW production services

Table 10 – Main interventions involved in the more significant packages for the RB located in climatic zone B and for heating and DHW production services: (*) indicates the cost-optimal solution, (**) the best compromise between global costs and net primary energy, (***) the package with the best energy performances.

N° package			BRL	403 (*)	2020 (**)	1750 (***)
Building envelope	Insulation thickness [mm]	VW	40	-	-	160
		RF	80	-	-	80
		SE_{floor}	40	40	-	160
		SE_{ceil}	140	160	120	160
		GS	60	100	60	100
	Transparent surfaces		(Window 1) Glass 4-16-4; Frame in hard wood 50 mm	(Window 2) Glass 4-20-4; Frame in hard wood 60 mm	RB Glass 5 mm; Frame in hard wood 50 mm	(Window 2) Glass 4-20-4; Frame in hard wood 60 mm
Technical plants	PV [kWp]		3.75	7.5	15	15
	HVAC		(EEM1) Traditional Boiler + Thermal solar coll. (4.6 m^2)	(EEM7) Heat Pump + Thermal solar coll. (9.2 m^2)	(EEM8) Heat Pump + Thermal solar coll. (9.2 m^2)	(EEM8) Heat Pump + Thermal solar coll. (9.2 m^2)
Net primary energy [kWh/m²]			4.77	-13.01	-34.28	-38.23
Global Costs [€/m²]			1,161.46	1,091.93	1,096.75	1,230.38

Conversely, BRL constraints are able to considerably improve thermal comfort due to the well-insulated envelopes and the correspondent higher mean radiant temperatures. By comparing the charts obtained for the considered climatic zones, the net primary energy consumptions are lower in the warmer localities and, simultaneously, for the same investment, maintenance and replacement costs, the limited energy consumptions determined a reduction of energy costs with different economic performances for the considered packages.

4.2 Analysis including heating, cooling and DHW production

In order to quantify the effect of the cooling requirements on the cost-optimal solutions, the same analysis was carried out for the whole year and for both the localities considering exclusively the heat pump as generator system to provide heating and cooling loads, in combination with different surfaces of PV and thermal solar collectors. In figure 7, the chart concerning the locality with 553 CDD, is shown observing a spots distribution in accordance with prevalent vertical directions and global costs varying from 1158 to 1340 €/m², whereas the net primary energy demands are obviously greater when compared to the case with heating and DHW production only. The evaluated global costs were almost similar because the same generation plant is amortized for the whole year, and simultaneously the presence of the PV generator allowed for noticeable energy savings from the cooling operational costs (solar radiation is in phase with the cooling loads). The larger building energy request, this time, led to a difficult attainment of the n-ZEB energy label. The optimal configuration was represented by package n° 433 characterized by a minimum cost slightly greater than 1150 €/m² and a correspondent net primary energy of 19.8 kWh/m² where, newly, some opaque structures do not require insulation. Conversely, the insulation of the semi-exposed floor and ceiling appeared crucial, as well as the employment of glazed surfaces equipped with triple panes. The latter allowed for the compensation of winter thermal losses by transmission, and simultaneously provided a reduction of the summer solar gains due to the reduced solar factor values. Moreover, the better insulated structures allow for an improvement of winter thermal comfort, whereas in summer a worsening could be observed due to the reduction of the thermal losses during night. Regarding renewable sources, a PV plant of 7.5 kW_p and 9.2 m² of thermal solar collectors, represented the best compromise (see table 11). The position of the BRL configuration, in accordance with the current Italian regulations, was characterized by both higher costs and primary energy demands: the first was subjected to an augment of 107.2 €/m² and the second increased by 18.2 kWh/m². Also in this case, the respect of the thermal transmittance limits in the opaque structures led to energy needs similar to the optimal solution but with noticeable extra-costs, considering that HVAC plant necessitated lower PV and thermal solar collector surfaces. Conversely, limited transmittance values could provide positive effects for the winter thermal comfort. The best compromise was reached with package n° 792 that allowed for a reduction of the net primary energy at almost n-ZEB level with a global cost growth of 15.3 €/m². The net primary energy decrement is connected prevalently to the employment of the largest PV generator (15 kW_p). Finally, package n° 666 produces the minimum energy demand with a noticeable cost augment due to the adoption of elevated insulation thicknesses in the opaque components of the building fabric, but summer thermal comfort conditions should be evaluated carefully due to the risk of indoor overheating.

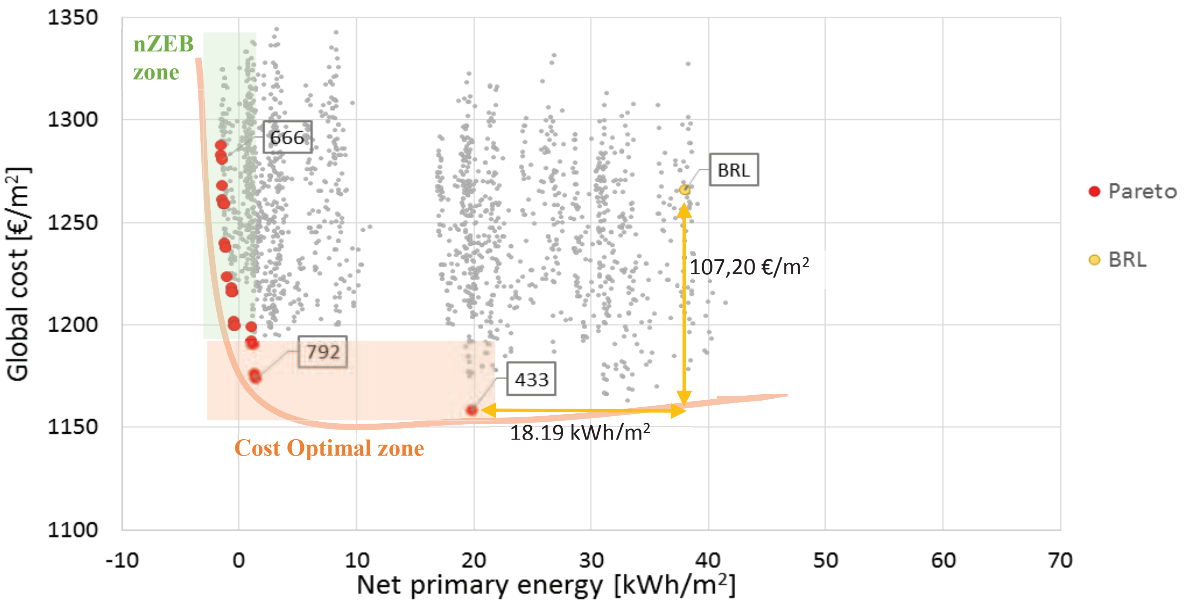


Fig. 7 – Cost-optimal chart for the RB located in climatic zone E considering heating, cooling and DHW production services

Table 11 – Main interventions involved in the more significant packages for the RB located in climatic zone E for heating, cooling and DHW production services: (*) cost-optimal solution, (**) best compromise between global costs and net primary energy, (***) the package with the best energy performances.

N° package			BRL	433 (*)	792 (**)	666 (***)
Building envelope	Insulation thickness [mm]	VW	80	-	-	160
		RF	120	-	-	80
		SE_{floor}	80	-	-	-
		SE_{ceil}	80	120	120	160
		GS	100	180	180	100
	Transparent surfaces		(Window 2) Glass 4-20-4; Frame in hard wood 60 mm	(Window 3) Glass 4-12-4-12-4; Frame in hard wood 60 mm	(Window 2) Glass 4-20-4; Frame in hard wood 60 mm	(Window 3) Glass 4-12-4-12-4; Frame in hard wood 60 mm
Technical plants	PV [kWp]		3.75	7.5	15	15
	HVAC		(EEM7) Heat Pump + Thermal solar coll. (4.6 m^2)	(EEM8) Heat Pump + Thermal solar coll. (9.2 m^2)	(EEM8) Heat Pump + Thermal solar coll. (9.2 m^2)	(EEM8) Heat Pump + Thermal solar coll. (9.2 m^2)
Net primary energy [kWh/m²]			38.01	19.82	1.42	-1.52
Global Costs [€/m²]			1,265.60	1,158.4	1,173.66	1,282.58

Regarding the locality with 1014 CDD (figure 8), the obtained spots resulted more distributed inside the chart; despite the employment of opportune PV surface, the attainment of an n-ZEB target was not detected due to the elevated cooling demand. The optimal solution is represented by package n° 1905, similar to 1586, where a global cost of 1147.5 €/m² and a correspondent energy demand of 46.1 kWh/m², were detected. However, this building configuration is characterized by the lowest installed PV peak power and elevated insulation thicknesses in the semi-exposed ceiling (table 12).

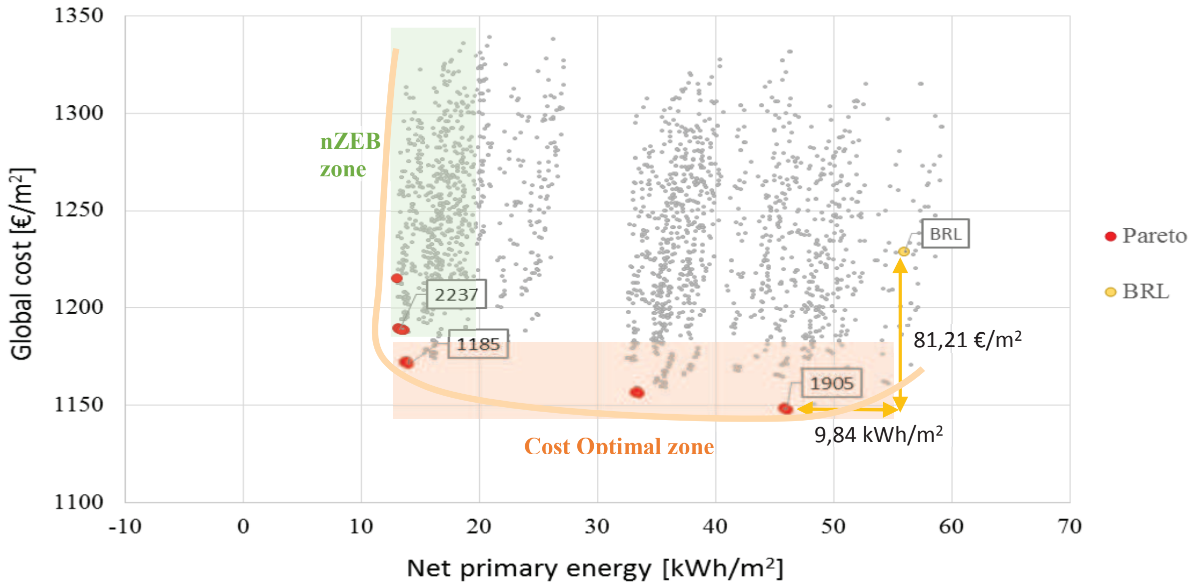


Fig. 8 – Cost-optimal chart for the RB located in climatic zone B considering heating, cooling and DHW production services

Table 12 – Main interventions involved in the more significant packages for the RB located in climatic zone B for heating, cooling and DHW production services: (*) cost-optimal solution, (**) best compromise between global costs and net primary energy, (***) the package with the best energy performances.

N° package			BRL	1905 (*)	1185 (**)	2337 (***)
Building envelope	Insulation thickness [mm]	VW	40	-	-	40
		RF	80	-	-	-
		SE_{floor}	40	-	-	-
		SE_{ceil}	40	120	120	-
		GS	60	180	100	100
	Transparent surfaces		BRL_0 Glass 4-16-4; Frame in hard wood 50 mm	BRL_2 Glass 5 mm; Frame in hard wood 50 mm	RB Glass 5 mm; Frame in hard wood 50 mm	BRL_2 Glass 4-12-4-12-4; Frame in hard wood 60 mm
Technical plants	PV [kWp]		3.75	3.75	15	15
	HVAC		EEM7 Heat Pump + Thermal solar coll. (4.6 m²)	EEM8 Heat Pump + Thermal solar coll. (9.2 m²)	EEM8 Heat Pump + Thermal solar coll. (9.2 m²)	EEM8 Heat Pump + Thermal solar coll. (9.2 m²)
Net primary energy [kWh/m²]			55.96	46.12	14.08	13.03
Global Costs [€/m²]			1,228.74	1,147.53	1,171.28	1,213.21

The employment of single glass provided better results because in summer it favours thermal losses during the nocturnal hours, but thermal comfort is likely to be compromised during winter. The best compromise was identified in package n° 1185, whereas n° 2237 offered the lowest net primary energy demand. Actually, the current BRL configuration presented a cost increment of 81.2 €/m² with an energy demand growth of 9.8 kWh/m² compared to the optimal solution, and the correspondent well-insulated envelope could negatively affect the summer thermal comfort.

5. Conclusions

The evaluation of the cost-optimal solutions concerning the refurbishment of a typical social house employed for the Italian territory, was carried out. These solutions were identified moving the reference building (RB) in two different climatic zones (the first colder, the second warmer), by considering in different way the services connected to heating, cooling and DHW production. When the analysis is focused prevalently on the winter period (heating + DHW production), the optimal solution in the coldest climatic zone is not far from the n-ZEB target (nearly-zero energy building), whereas the optimal solution corresponds already with the n-ZEB label in the warmer zone. However, in both the cases, the minimum interventions currently imposed by the Italian regulations in order to contain the primary energy consumptions (BRL configuration) produce worse energy performances and considerable extra-costs, however, potentially better winter thermal comfort conditions could be attained. The detected results highlight a regulation frame that seems to be more restrictive than those actually required, due to an incorrect and independent evaluation of each intervention from the legislator. In order to confirm the magnitude of the cooling requirements in the Mediterranean Area, significantly different results were obtained including the summer period: in any case, the n-ZEB label is far from the optimal point, and noticeable primary energy demands are required. A further worsening was observed for the BRL configuration, furthermore characterized by noticeable extra-costs. The results of the present analysis suggest that, in the field of the considered existing building refurbishment, a complete revaluation of the possible interventions for energy saving purposes in warm climates, is required. In particular:

- financial incentives, which are currently available, with the aim of attainment of a highly insulated envelope are justified because the cost of the insulation materials is still too elevated. However, the insulation thickness has to be chosen carefully, because at an annual level these interventions could produce a worsening of the primary energy demand due to the increment of the cooling needs, therefore they could result as unattractive for users producing a worsening of the economic frame. An increase of cooling needs with extra insulation thicknesses was always observed, and this increment is more marked for the location with 553 CDD. Moreover, thermal comfort is also strongly influenced by insulation thicknesses, because the augment of the internal mean radiant temperatures is desirable in winter, but could be counterproductive during summer, in particular at night.
- interventions focused on the technical plants, instead, provide an evident reduction of the primary energy requirements and are more sustainable from the economic point of view because they are closer to the optimal solution;
- equally significant is the integration of renewable technologies in the HVAC plant, especially in the presence of heat pump systems connected to PV generators in cooling applications that should be mandatory for this air-conditioning plant typology;
- in the presence of a storage system supplied by thermal solar collectors, the available solar radiation can be used not only the production of DHW during the whole year but can provide a noticeable fraction of heating demands when emitters can be supplied by reduced temperatures (45°) as fan-coils.

To conclude, exploiting the favorable climatic conditions, financial incentives for social housings located in the Mediterranean areas have to be addressed for the attainment of N-ZEB (Net zero energy building, namely a solution with a positive energy balance) by exploiting heat pumps and renewable sources rather than n-ZEBs with limited energy requirements, because the latter do not produce a solution that is actually economically sustainable.

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Chapter 5

The effect of occupancy on building energy performance

According to the International Energy Agency - Energy in the Buildings and Communities Program (IEA-EBC) Annex 53, energy use in buildings is influenced by six parameters:

- Climate
- building envelope
- building energy and services systems
- indoor design criteria
- building operation and maintenance
- occupant behaviour

Most of these parameters have been explored for a long time and by several researchers, whereas studies on occupant behaviour are more recent. Occupant behaviour in buildings refers to the occupants' presence and movement and interaction with building systems that have an impact on building performance (thermal, visual, acoustic, and indoor air quality). The interaction includes adjusting thermostat settings, opening or closing windows, dimming or turning on/off lights, raising or lowering window blinds, switching on or off plug loads, and consuming domestic hot water.

Occupancy and use of devices in buildings are influenced by environmentally- related and time-related variables. The first category includes physical aspects linked to the building characteristics and location, for example, solar orientation, envelope, building layout, and local climate. The second category refers to the occupants' routine and is influenced by time of day and day of the week. Generally, occupants tend to modify the surrounding environment (e.g., acting on indoor temperature, humidity level, lighting, CO_2) according to the desired comfort and considering their physiological, psychological and economic needs. The effect of these actions is inevitably reflected on energy consumption.

Therefore, it is evident that technologies alone cannot guarantee low energy use in buildings as the final consumption is strongly influenced by occupants' behaviour and lifestyle. Hence, a better understanding of human-building interaction and an accurate modelling of occupants' behaviour are essential to reduce the difference between predicted and actual building performance, especially for low-energy buildings.

The influence of occupancy on building energy use is debated in the present chapter.

In particular, in the first paragraph, the paper analyses the effect of different occupancy profiles on the energy use of an existing apartment in a multifamily building.

The second work aims at assessing the influence of users' patterns on the energy consumption of a nZEB designed as a net source energy building.

The third article explores this issue more deeply by focusing on a nearly Zero Energy building designed in the specific Italian context and investigates the impact of diverse occupancy scenarios and occupation modes on the final energy balance of the building, revealing that in some cases it is far from the expected "nearly zero" estimation.

The last paragraph in this section presents a study developed on the basis of measured data gained through the monitoring of a newly-built single family nZEB in Denmark.

5.1 Energy consumption of residential buildings and occupancy profiles. A case study in Mediterranean climatic conditions

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Contribute of the candidate: the candidate collaborated in the drafting of the questionnaire and she was actively involved in the data collection. She contributed to the creation of the occupancy profiles that are compared in the document. She modeled the case study on the DesignBuilder software, conducted the simulations, processed the results and outlined the graphs. She wrote the sections 2, 3, and 4 of the paper.

Abstract

Residential energy consumptions are determined by the interaction of many factors. Apart from physical characteristics such as climate, heating type, age, and size of the house, occupants' behavior and socio-economic aspects are critical. Furthermore, the relative impact of the occupants' characteristics and behavior seems to differ in various investigations confirming the importance of contextual analysis. In this study, different procedures for obtaining occupancy profiles are described and applied with reference to a residential building stock located in Mediterranean climatic conditions (Italy). The heating and domestic hot water (DHW) energy consumptions and indoor comfort conditions of a representative building were determined by introducing different occupant scenarios in dynamic simulations. The occupancy profiles were built by means of data collected at the University of Calabria using surveys, interviews, bills, and statistical elaborations. Considering different modes of use of the dwelling (Regulations, Current-use, and Statistical), in the simulation process all the inputs of occupancy, ventilation, lighting, DHW, and heating operation were modified. The Regulations occupancy profile produces an underestimation of heating energy consumption. Additionally, primary energy for DHW is strongly affected by the family composition. The effect of the occupants' preferences on the energy performance of the building was investigated: mainly energy consumptions and internal comfort conditions vary with the set point temperature and the duration of ventilation. The analysis provides reference procedures for obtaining occupancy profiles. Furthermore, the simulation results demonstrate the significant dependence of heating and DWH primary energy consumption on the characteristics and preferences of occupants in the Mediterranean climate.

Keywords: Occupants' behavior; Energy consumption; Residential Buildings; Heating, Domestic Hot Water; Thermal Comfort.

1. Introduction

For the past decade, occupant behavior in buildings with respect to energy consumption has been studied and identified as an important contributing factor to the uncertainty of buildings' performance prediction (IEA 2015; Yan et al. 2015). Despite the use of very advanced simulation methods, building performance does not usually meet expectations (Fabi et al. 2011). With regard to structures having similar characteristics (size, appliances, number of occupants, orientation, windows, and curtains) considerable variation in the energy consumption has been reported (Yan et al. 2015). Data demonstrated that one of the reasons for the gap between theoretical models and real building performance is the influence of human behavior and occupant preferences (Martinaitis et al. 2015). Hong et al. (2017), examined the answers to ten relevant questions in order to analyze the most important problems regarding energy performance related to occupant behavior research and its applications in buildings. According to the literature survey proposed by Frontczak and Wargocki (2011), it is necessary to understand how people behave indoors and how they operate the systems for controlling indoor environment and comfort conditions. The behavior of people in residential buildings has been investigated in many studies by considering the interaction with a single appliance or building component (windows, ventilation, lighting, blinds, and thermostat) (Iwashita and Akasaka 1997; Nicol 2001; Rijal et al. 2007; Fabi et al. 2012; D'Oca et al. 2014) and by using an experimental set-up to obtain data. Jones et al. (2015), identified not less than 62 factors which potentially have an effect on domestic electricity use. These include 13 socio-economic factors, 12 dwelling factors, and 37 appliance factors.

1.1. Physical and environmental factors

Building performance factors are used to analyze building efficiency. Wei et al. (2014), evaluated 27 factors in modeling that influence space-heating behavior. Regarding building factors, the following were identified: dwelling type, dwelling age, dwelling size, room type, house insulation. Investigations in the USA and the Netherlands have determined that building characteristics explain from only 40 - 54% of variation in energy use (Sonderegger 1978; Guerra-Santín 2010). Kane et al. (2011), investigated the relationship between indoor temperature and house type. By statistical analysis the indoor temperature in detached, semi-detached, end-terrace, mid-terrace and flat houses was compared at different times of the day, and the results have shown that the relationship is statistically significant for all the periods except the evening period. Steemers and Yun (2009), emphasized that the most significant parameter that determines energy use is the climate and the second is the usage of heating and cooling systems and their control. Andersen et al. (2009), used survey occupant control of the indoor environment in Danish dwellings and the results showed that outdoor temperature, outdoor humidity, and wind speed were related to the heating set point in housing units.

1.2. Behavioral, socio and cultural context

Occupancy patterns may be determined by cultural traditions, preferences, attitudes, aesthetic norms, comfort, personal background, household characteristics, and including social and economic variables (Wilhite et al. 1996; Guerra-Santin and Itard 2010). In China, studies on behavior and its impact on clothes-washing energy use showed that adoption of foreign technologies and technical standards, without having been calibrated to local cultural practices, could have unintended consequences for both energy use and the environment (Lin and Iyer 2007). To compare cultural differences between Japan and Norway regarding energy use, aspects such as infrastructure, climate, prices and income, dwelling size, work patterns, and gender roles were considered. The results indicate that the use of energy is related to the cultural patterns and customs of each region, so that one option to reduce energy consumption is to promote technologies that provide the same cultural service with less energy. Thus, energy savings can be integrated into every lifestyle while cultural patterns are maintained. In addition, it is important to raise awareness among users about energy flow in the home through better billing practices and the use of energy audits (Wilhite et al. 1996). Studies in Norway attempt to explain how the consumer is influenced by a combination of activities, preferences, values, technologies and material structures, and how the concept of "home" has been developed. House was classified as: the home as haven, the home as project, and the home as arena for activities; a person's conception about his or her home is related to dynamic energy consumption, rather than merely static consumption (Aune 2007). Following the idea of comparing different cultures, a study in Denmark and Belgium was conducted considering factors such as energy policies in each region. Individual variables were also compared. Related data were collected about building characteristics, ownership and use of appliances, washing and drying practices, lighting, PC, and TV. They concluded that despite having similar cultures, there are considerable differences in patterns and lifestyles, so that differences in energy consumption are important (Bartiaux and Gram-Hanssen 2005). Results by means of questionnaires have been achieved by S. Chen et al. (2010) in which data processing for China showed a negative correlation between occupant age and heating/cooling energy consumption. In order to explain this relationship, it is necessary to look at the thermal comfort perception of occupants and to take into account the distinctive development history of this country. In contrast, research in different contexts, such as in Australia, Denmark, Brazil, and Japan (Lenzen et al. 2006), found that age has a positive correlation with residential energy consumption. Guerra Santin (2010), established that occupant characteristics and behavior affect 4% of the variation in energy use for heating in the Netherlands, while the influence of building characteristics is 42%. Other studies conducted in China (Chen et al. 2013) reveal that household socio-economic and behavior variables can explain 29% of the variation in heating and cooling energy consumption.

1.3. Occupancy profiles in energy simulation

The influence of occupants' profiles and preferences, for example family size, ventilation, set point temperatures, and management of the heated area, on the indoor conditions are relevant to the final energy usage. For this reason, suitable use profiles should be introduced in energy calculations to deliver more accurate energy performance of buildings (de Meester et al. 2013; Motuziene and Vilutiene 2013; Martinaitis et al. 2015). User profiles can be defined as groups of households with similar characteristics that behave in a comparable manner (Guerra-Santin 2011). Currently, a wide variety of building simulation programs (BSPs) are available (ESP-r (ESRU 2001), TRNSYS (2012), DOE-2 (1982), Energy Plus (2015), IDA ICE (EQUA 2014), etc.) and each of them has simplified static and deterministic occupant schedules and profiles used as direct inputs. To include occupant behavior in BSPs, four main approaches have been used: 1) user defined profiles and rules (it includes specific deterministic rules), 2) user customized code (the user can write it to implement new or overwrite existing profiles), 3) user customized tools (for open source, users can add new code and changing existing code) and 4) co-simulation (modules developed by different programming languages can be executed in an integrated manner). ESP-r uses the approaches 1 and 3, and has an embedded behavior module, TRNSYS allows the approaches 1 and 3, DOE-2 adopts the approaches 1 and 2, Energy Plus allows all four integration approaches and IDA ICE allows the approach 1 through 3 (Yan et al. 2015) . The calculation codes do not give comparable results of energy consumption in buildings. The intervals of confidence depend on local normatives and different calculation models (Tronchin and Fabbri 2008). To define occupancy profiles, different procedures can be used. Some occupancy profiles are defined through Time-Use survey (TUS) data. In their research, Aerts et al. (2013), reported a methodology to obtain occupancy profiles based on the 2005 Belgian time-use survey with the aim of using it for user behavior modeling in building energy simulation. The authors of the study developed seven user profiles reflecting realistic user behavior in homes. Also, Richardson et al. (2008), defined occupancy profiles for UK households by using TUS data describing people's habits. The developed models indicate the number of occupants in the house at a given time in order to have an indication on the sharing of energy use. D'Oca and Hong (2015), applied a three-step data mining technique to discover occupancy patterns in office spaces. The results identified four archetypal working profiles that can be used as input in building energy modeling programs.

1.4. Set-point temperature and ventilation

Heating set-point and air change rate (natural ventilation and air infiltration) are two important parameters influencing energy consumption in dwellings (Andersen et al. 2013). Regarding indoor temperature, it has been shown that small changes (by about 0.5°C) can determine significant differences in energy consumption (Deurinck et al. 2012).

Besides, in many energy performance calculation tools of European countries, including Italian Technical Standard UNI/TS 11300-1 (2014), the indoor temperature is fixed at a constant value, independent of climate conditions or building envelope characteristics. Some countries, such as the UK and the Netherlands, incorporate temperature takeback options in their legal energy performance requirements (Deurinck et al. 2012). (Santamouris et al. 2007) studied different scenarios grouped according to income of Greek families, analyzing two variables: hours of heating per day and mean set point temperature. They found that the mean daily duration of heating is approximately 7.5 h/day and becomes 8.5 h/day in the richest groups. The average set point temperature for the heating period is close to 18.4°C with a difference of about 1°C between poorest and richest groups. Ren et al. (2015), investigated the occupants' behavior regarding thermostat settings and heating system operations in a 62-low-income housing complex in the U.S.A. The study was carried out by using data mining methods, and the results reveal that thermostat setting patterns could be used to represent the diversity of occupant comfort demand in building energy simulations. (Fabi et al. 2012) have defined a framework to explain different factors influencing occupants' window opening behavior, and they concluded that more attention should be paid to the driving forces for the actions on windows (opening and closing) instead of the state of the windows. The thermal load for ventilation is related to the air change rate and, consequently, it is affected by the occupants' behavior. This aspect has been studied by many researchers taking into account how often and for how long the windows are opened and also considering the degree of opening. In (Howard-Reed et al. 2002; Wallace et al. 2002) the air change rate is monitored, and the authors found that opening of a single window increases the air change rate by an amount proportional to the width of the opening. Other studies in Danish dwellings (Andersen et al. 2013), where mechanical cooling is hardly used, show that the indoor temperature depends on the heating set point in winter and on the air change rate in summer. The authors concluded that behavior differed between dwelling type (rented or owned, mechanical or natural ventilation) and within dwelling type. Also, the indoor CO_2 concentration and the outdoor temperature were the two most important parameters in determining the probability of opening and closing windows.

1.5. Domestic hot water (DHW)

One of the major end-use groups of secondary energy is DHW, defined as the energy required to heat water to an adequate temperature for occupant and appliance uses (Swan and Ugursal 2009). DHW uses have a significant influence on the total energy consumption of residential buildings. The variables related to the DHW can be summarized as follows: DHW temperature production, DHW uses for personal hygiene (bath or shower, frequency of bath/shower, duration of bath/shower), DHW for domestic purposes (washing dishes, hand laundry, house cleaning). Also, the influence of DHW in final energy use in relation to the family composition was studied. Barthelmes et al. (2016), found that the incidence on the total energy use of DHW production decreases from 9% to 4% depending on the household compositions scenarios. Martinaitis et al. (2015), defined three alternative DHW management schedules and the results showed differences in performance of the building with two and four occupants. Further considerations about DHW were explained by Guerra-Santin (2010) with reference to the influence of water heating in energy use in the Netherlands. It was determined that the presence of a bath is significant. In (Lindén et al. 2006), shower and bathing behavior results as an influencing factor of energy requirements for water heating.

1.6. Objectives of the investigation

It is known that the evaluation of building performance requires two input categories: data of the edifice and information on the type of occupants and activities performed within the internal spaces. Therefore, while data on the structural characteristics and plants are readily available and their modeling follows well-defined procedures, by contrast, information regarding the occupancy is often insufficient and, moreover, the procedure for modeling the occupants' parameters are varied and complex. Generally, if no details on the type of occupancy are given, parameters provided by Standards and Regulations are adopted. Another option is represented by direct interview with the user: in this case, precise and detailed information can be acquired, and a model that follows the actual use can be implemented. Whether the type of occupancy is unknown, surveys can be conducted in order to create typical occupancy profiles and typical uses of the dwelling by means of statistical procedures. It is evident that, depending on the selected procedure, the type of occupancy and the approach to modeling will change. Thus, the present study deals with all the outlined occupancy modeling procedures. In particular, different methods for obtaining occupancy profiles were applied considering a residential building stock located in Mediterranean climatic conditions (Southern Italy). The analysis was aimed to propose alternative procedures for modeling occupancy in buildings and, successively, to evaluate the influence of adopting the different approaches on heating and DHW energy consumption estimation. Three methodologies were proposed in order to represent the occupant and user activities in buildings: using surveys and interviews, applying the National Standards, and elaborating available statistical data. The effect of adopting various occupancy profiles on the variation in energy consumption was assessed by energy simulation, once the constructive characteristics of the building had been fixed. Furthermore, the internal comfort conditions and energy demand were studied on variation of the set point temperature and ventilation in order to evaluate the effect of occupant preferences.

2. Methodology

Occupancy profiles are necessary inputs in energy building simulation and their determination has been studied with different approaches. In particular, an existing building, selected according to the procedure illustrated below, is considered as the case study and energy simulations are conducted using the following occupancy profiles:

1. CURRENT-USE PROFILE defined by direct interview of the resident. The simulation results were compared with the actual consumption acquired by bills.
2. REGULATIONS PROFILE obtained by using the inputs provided by the National Standard UNI/TS 11300 part 1 and 2 (2014). The Standard provides a simplified procedure which allows for the calculation of internal gains due to occupants, lighting, and equipment in relation to the net surface area of the dwelling (m^2), without considering the family composition and occupants' habits.
3. STATISTICAL PROFILE built by combining information collected at the local level with the data of Hetus (Harmonised European Time Use Survey) for Italy (Hetus 2007).

The different occupancy profiles are scheduled by means of DesignBuilder (2015), varying occupancy and behavioral parameters (heating system operation and set-point temperature, DHW usage, lighting, equipment, and ventilation) in order to assess the variability of heating and DHW energy consumption. In the first phase of the study, the outcomes of a survey carried out in order to collect information on the characteristics of buildings and households in the research area, are presented. The collected data were used to identify the building assumed as case study. Subsequently, a detailed description of the three occupancy profiles and settings adopted in the simulation process is showed. In the last part, the results expressed in terms of energy consumption are presented and discussed.

2.1. Data Collection

A detailed survey was drawn in order to gather information about occupants' behavior and characteristics of housing in Southern Italy. A questionnaire was used with the aim of investigating user habits and household characteristics and their influence on determining energy consumption by simulations. The data set was submitted to statistical processing aimed at the identification of physical and behavioral variables affecting energy consumption (Mora et al. 2015). The survey responses are presented as categorical and continuous variables. All the parameters were checked for normality and outliers. Normality was verified by the analysis of skewness and kurtosis. In order to describe the relations between household energy consumptions and the physical and behavioral variables the General Linear Model was used. Regression analyses are used for continuous variables, a one-way analysis of variance (ANOVA) is applied for categorical variables and independent-samples t-tests were performed for dichotomous variables.

This paper reports a partial elaboration of the entire available data. The information collected in the sample was used to select a representative dwelling for the considered area, taken as a case study. The energy performance of the selected house was analyzed by defining the properties of the envelope and of the heating and DHW plants. The study is focused on residential buildings and the data set includes the energy consumption, the characteristics of dwellings and their occupants obtained from energy bills and surveys. Data collection started in 2012, and the participants were the families of engineering students of the University of Calabria. The investigated area is the Region of Calabria located in Southern Italy typified by Mediterranean climatic conditions as shown in Figure 1. The region has a population of approximately 2 million people.

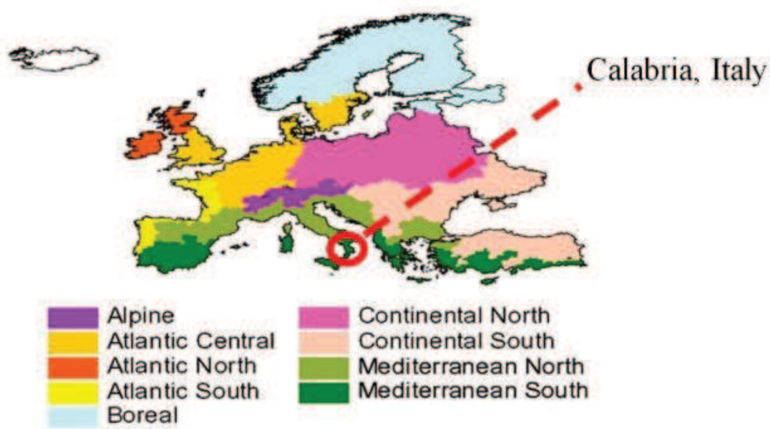


Fig. 1 Climatic zones in Europe and location of the investigated Region of Italy (Climate Change Post 2015)

Overall, 112 households were interviewed. The survey consists of 63 questions divided into six groups of parameters as represented in Figure 2. In particular:

1. general information containing the main characteristics of the building and the family;

2. energy consumption obtained by bills;
3. conditioning and DHW includes plant typology and the main control strategies;
4. appliances and their use;
5. occupant behavior regarding daily routine in the use of heating system, cooling system, and DHW, window opening and lighting;
6. renewable energy systems comprising thermal and PV panels.

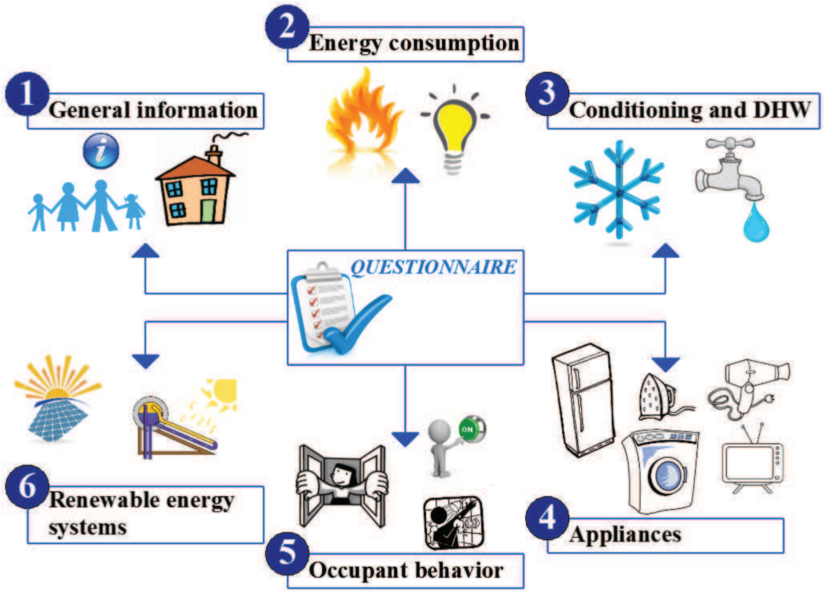


Fig. 2 Information collected by the questionnaire divided in six sections

Table 1 shows the results of the survey in terms of number of responses and percentage in the entire sample. The majority of survey responses are categorical variables, age of household members, energy consumption, floor area, and heating degree day are collected as continuous variables and summarized in the table by using classes. The questions regarding occupants' behavior refer to one dwelling and the answers are representative of the family's habits. No responses were obtained for the section about renewable energy systems.

Table 1 Summary of responses for group parameters of the questionnaire.

		Responses	N	%		Responses	N	%
GENERAL INFORMATION	**Age of household members**	1. Less than 19	22	6.1	**Gender**	1. Female	181	53.7
		2. 19 – 30	167	46.3		2. Male	156	46.3
		3. 30 – 50	33	9.1	**Prevalence of gender**	1. Male	24	21.4
		4. 50 – 65	117	32.4		2. Female	43	38.4
		5. More than 65	7	1.9		3. Equality	25	22.3
		6. Not answered	15	4.2		4. Not answered	20	17.9
	Number of household members	1. 1	1	0.9				
		2. 2	13	11.6				
		3. 3	23	20.5				
		4. 4	41	36.6				
		5. 5	19	17.0				
		6. 6	1	0.9				
		7. Not answered	14	12.5				
	Type of house	1. Single house	27	24.1	**Structure**	1. Reinforced concrete	87	77.7
		2. Apartment	63	56.3		2. Stone	7	6.3
		3. Double house	8	7.1		3. Wood	0	0
		4. Other	1	0.9		4. Other	4	3.6
		5. Not answered	13	11.6		5. Not answered	14	12.5
	Year of construction	1. Before 1980	32	28.6	**Type of windows**	1. Double glass	67	59.8
		2. 1980 - 1990	18	16.1		2. Single glass	28	25.0
		3. After 1990	49	43.8		3. Other	3	2.7
		4. Don't know	0	0		4. Don't know	0	0
		5. Not answered	13	11.6		5. Not answered	14	12.5
	Floor area (m^2)	1. Less than 70	9	8.0	**Type of external walls**	1. With thermal insulation	45	40.2
		2. 70-150	62	55.4		2. Without thermal insulation	50	44.6
		3. More than 150	27	24.1		3. Not answered	17	15.2
		4. Not answered	14	12.5				
	Climate zone / Heating degree day	1. A (less than 600)	0	0		5. E (2101-3000)	10	8.9
		2. B (601-900)	8	7.1		6. F (more than 3000)	0	0
		3. C (901-1400)	28	25.0		7. Not answered	27	24.1
		4. D (1401-2100)	39	34.8				

ENERGY CONSUMPTION	**Electricity (kWh)**	1. Less than 1500	18	16.1	**Heating and DHW by natural gas (kWh)**	1. Less than 5000	13	16.7
		2. 1501-3000	62	55.4		2. 5001-10000	42	53.8
		3. More than 3000	23	20.5		3. More than	15	19.2
		4. Not answered	9	8.0		10000	8	10.3
						4. Not answered		
CONDITIONING AND DHW		**H E A T I N G**				**D H W**		
	Typology	1. District heating	3	2.7	**Typology**	1. Centralized system	37	33.0
		2. Building Centralized system	0	0		2. Decentralized system	56	50.0
		3. Autonomous system	93	83.0		3. Not answered	19	17.0
		4. Not answered	16	14.3				
	Generation system	1. Air source heat pump	2	1.8	**Energy source**	1. Natural gas	68	60.7
						2. LPG	4	3.6
		2. Electricity	8	7.1		3. Natural gas +	0	0
		3. Wall mounted gas	62	55.4		Solar	0	0
		boiler	15	13.4		4. LPG + Solar	7	6.3
		4. Fireplace	0	0		5. Electricity	0	0
		5. Pellet	11	9.8		6. Pellet	0	0
		6. Other	14	12.5		7. Electricity + Solar	16	14.3
		7. Not answered				8. Other	17	15.2
						9. Not answered		
	Fuel	1. Natural gas	78	69.6				
		2. LPG	10	8.9				
		3. Diesel	1	0.9				
		4. Biomass	9	8.0				
		5. Other	2	1.8				
		6. Not answered	12	10.7				
APPLIANCES	**Appliance owned**	1. Small TV (<40 cm)	73	79.3		12. Dryer	6	6.5
		2. Big TV	67	72.8		13. Mixer	29	31.5
		3. Fridge with freezer	91	98.9		14. Cooking Robot	16	17.4
		4. Dishwasher	46	50.0		15. Minipimer	21	22.8
		5. Washing machine	86	93.5		16. Hi Fi	28	30.4
		6. Coffee machine	16	21.1		17. Home Theater	9	9.8
		7. Oven	70	76.1		18. Hair dryer	79	85.9
		8. Micro oven	39	42.4		19. Straightener	28	30.4
		9. Desktop PC	60	65.2		20. Only freezer	28	30.4
		10. Laptop	70	76.1		21. Only fridge	6	6.5
		11. Fan	33	35.9		22. Not answered	20	17.9

OCCUPANT BEHAVIOR							
B E H A V I O R							
Thermal sensation	1. Very satisfied	22	19.6	**Frequency of shower during winter**	1. Almost every day	32	28.6
	2. It doesn't matter	11	9.8		2. 3-5 times/week	43	38.4
	3. Satisfied	44	39.3		3. 1-2 times/week	15	13.4
	4. Not satisfied	19	17.0		4. Other	7	6.3
	5. Not answered	16	14.3		5. Not answered	15	13.4
Kind of shower	1. Only shower	67	59.8	**Average shower time**	1. More than 2 hours	0	0
	2. Shower + bath in a tub	31	27.7		2. 1 hour	6	5.4
	3. Bath in a tub	0	0		3. Half an hour	11	9.8
	4. Other	0	0		4. 10-20 minutes	64	57.1
	5. Not answered	14	12.5		5. Less than 10 minutes	14	12.5
Frequency of shower during summer	1. Almost every day	80	71.4		6. Other	3	2.7
	2. 3-5 times/week	9	8.0		7. Not answered	14	12.5
	3. 1-2 times/week	0	0				
	4. Other	9	8.0				
	5. Not answered	14	12.5				
W I N D O W S				**L I G H T I N G**			
Opening - Living room	1. Always open	18	16.1	**Type of lighting**	1. All are energy saving	29	25.9
	2. Always closed	7	6.3		2. Some are energy saving	61	54.5
	3. Open at fixed time	31	27.7		3. No energy saving lamps	8	7.1
	4. Other	35	31.3		4. Not answered	14	12.5
	5. Not answered	21	18.8				
Opening - Bedroom	1. Always open	11	9.8	**Switch lamp - Living room**	1. Always switch on as long as entering the room	9	8.0
	2. Always closed	2	1.8		2. When too dark	82	73.2
	3. Open at fixed time	41	36.6		3. Other	4	3.6
	4. Other	36	32.1		4. Not answered	17	15.2
	5. Not answered	22	19.6				
				Switch lamp - Bedroom	1. Always switch on as long as entering the room	8	7.1
					2. When too dark	82	73.2
					3. Other	5	4.5
					4. Not answered	17	15.2

The collected information was compared with the data provided by the National Institute of Statistics (Istat 2014) to check its representativeness. The average age of interviewees was 36.9 years consistent with the average age of the population of 42.9 years. In particular, 46.3% of the respondents were males and 53.7% females, in accordance with the regional gender distribution (48.7% males and 51.3% females). The average annual household electricity consumption was 2723 kWh and consistent with the average regional value of 2509 kWh. The most common type of dwelling in the sample was the apartment (56.3%) followed by the single house (24.1%). The majority of the constructions were built after 1990 (43.8%). The average area of dwellings was 141 m^2, a large percentage of buildings had reinforced concrete structure (77.7%), exhibit uninsulated external walls (44.6 %) and had double-glazed windows (59.8%). With regard to the heating system, 83% of the houses were equipped with an autonomous generator, 55.4% of the respondents had a wall mounted gas boiler and natural gas was the most used fuel both for heating and domestic hot water production; 13.4 % of houses were heated by fireplaces, and minor percentages were heated by air source heat pump (1.8%) and electric heater (7.1%).

Climatic conditions were considered by means of climatic zones defined according to heating degree days (HDD) as established by the national regulation (DPR 412 1993). The majority of buildings were located in C and D climatic zones (25.0% and 34.8% respectively). Information about the quantity per household of 21 appliances was asked. The most used appliances were fridge with freezer and washing machine (98.9% and 93.5%, respectively). Data reveal that 80.4% of the houses used energy saving lamps. About occupants, on average families consisted of 3.7 members. Most of the interviewed subjects (46.3%) were in the age class of 19 - 30 years. 39.3% of occupants were satisfied with the internal comfort, and the majority of them used to have a shower with average duration of 10-20 minutes. Shower frequency is higher during the summer. Occupants switch lamps on when it is too dark and generally they open windows at fixed times. Electricity consumption refers to equipment and lighting and 21% of the cases included air conditioning. Figure 3 illustrates the distribution of fuels for heating and DHW production resulting from the surveys compared with national data (Union Oil 2003). Comparable percentages of natural gas and liquefied petroleum gas (LPG) are found, whereas differences emerge for diesel and biomass: in the sample diesel consumption is lower than the national value while biomass seems clearly higher in accordance with the local tradition that adopts firewood for domestic use. The percentage of other fuels is negligible. Renewable energy systems are not in the selected sample.

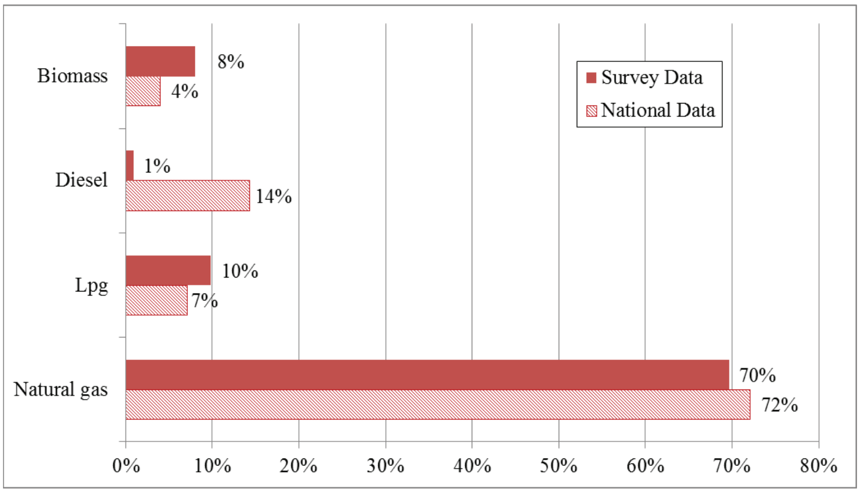


Fig. 3 Fuel types for heating and DHW resulting from the surveys compared with National data for the civil sector (Union Oil 2003)

2.2. Representative case study

The data processing evidences the characteristics of the analyzed building stock in terms of building types, climatic conditions, family composition, and equipment. Also, representative occupants' behavior in managing windows and lighting are evidenced. In order to investigate the importance of the use of detailed occupancy profiles in determining energy needs by simulation, a case study was chosen according to the results of the data analysis. Table 2 shows the most frequent physical parameters and characteristics of residents.

Table 2 Summary of the data obtained by analyzing the sample of buildings

	BUILDING	
Type of house	Apartment	56.3 %
Year of construction	After 1990	43.8 %
Floor area (m²)	70 – 150	55.4 %
Structure	Reinforced concrete	77.7 %
Type of windows	Double glass	59.8 %
Type of external walls	With thermal insulation	40.2 %
	HEATING	
Typology	Autonomous system	83.0 %
Generation System	Wall mounted gas boiler	55.4 %
Fuel	Natural gas	68.8 %

	D H W	
Typology	Decentralized	56.6 %
Fuel	Natural gas	60.7 %
	H O U S E H O L D	
Age of household members	19 - 30	46.3 %
	50 - 65	32.4 %
Number of household members	4	36.6 %
	B E H A V I O R	
Thermal sensation	Satisfied	39.3 %
Bath or shower	Shower	59.8 %
Frequency of shower during summer	Almost every day	71.4 %
Frequency of shower during winter	3 – 5 times/week	38.4 %
Average shower type (minutes)	10 – 20	57.1 %

These results allowed identification of a representative building in the sample that has been considered by the authors for the successive study regarding the creation of occupancy profiles and energy simulation. The selected real building is characterized by technical properties (type of house, year of construction, floor area, structure, type of windows and external walls, heating and DHW systems) that are aligned with the major features of the sample. In particular, the representative dwelling is an apartment built in 2008 with a gross floor area of 80 m^2. It is located on the second floor of a six storey edifice (see Figure 4). As described in the technical report of the project, the building structure is made of reinforced concrete. The external walls consist of double hollow brick layers with an internal air gap partially filled with expanded polystyrene, resulting in a U value of 0.6 W/m^2K. The windows are formed by double glazing and frame with thermal break. The generation system, used both for heating and DHW production, is an autonomous wall mounted gas boiler, natural gas is the fuel and the efficiency of the system is 88%. A zone thermostat regulates the operating of the heating system and the heat emitters are aluminum radiators. The dwelling is situated in the climate zone C, and the heating period is from 15 November to 31 March. The climatic file used for dynamic simulations was created from the data reported in the Standard UNI 10349 (1994) for the city of Cosenza.

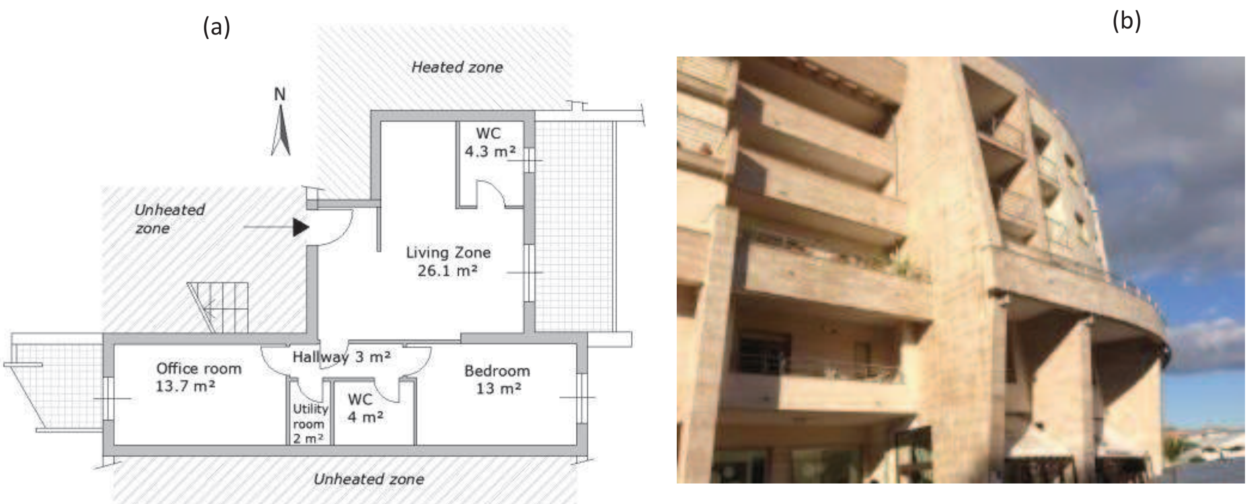
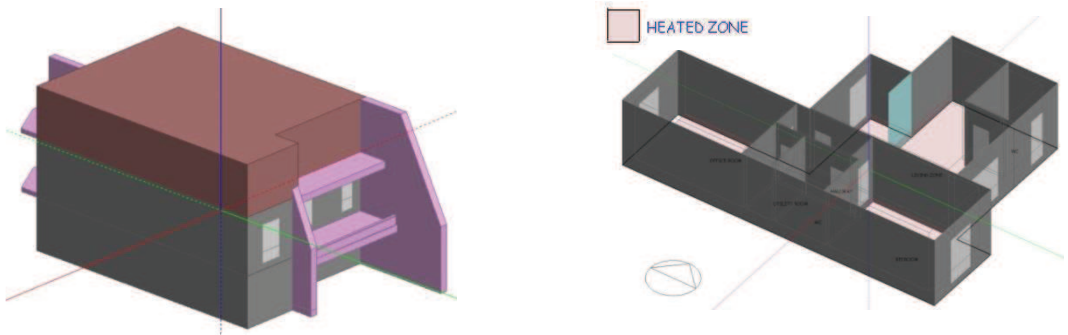


Fig. 4 Plan (a) and external view (b) of the selected apartment in condominium (Provincial Land Registry Office of Cosenza)

Figure 5(a) reports an isometric view of the building modeled by DesignBuilder. Downstairs there is an unconditioned thermal zone, an adiabatic block is upstairs where there is another heated dwelling. Horizontal and vertical overhangs were shaped through standard component block considered by the software in shading calculation. As shown in Figure 5(b), the apartment was defined by means of the creation of heated thermal zones whose environmental control parameters vary according to the occupancy profile. In particular, depending on the used occupancy profile, the characteristic parameters of the thermal zones are changed in terms of occupancy density, occupation period, management of the heating system as both activation period and set point temperature, ventilation mode, appliances, and artificial lighting.



(a) (b)

Fig. 5 DesignBuilder model (a) building, (b) apartment and heated zones

2.3. Energy consumptions from bills

Bills concerning gas and water consumption of the last three years were provided by the owner. In order to determine the gas consumption for DHW production, an average monthly value was estimated by considering the bills of the period when the heating system does not operate. Thus, the DHW annual primary energy was determined as equal to 1813 kWh. Subsequently, by using the difference from the total energy consumption (4473 kWh), the heating energy consumption was calculated (2660 kWh). The hot water consumption rate in l/m^2day is required in DesignBuilder. By means of the water consumption from bills equal to 2.94 l/m^2day and the primary energy for DHW production, the rate of consumed hot water is calculated in proportion equal to 1.23 l/m^2day.

2.4. Occupancy profiles and calculation methods

The dynamic simulations were performed by using the occupancy profiles illustrated in Table 3.

Table 3. Description of occupancy profiles

Occupancy profile	Information source	Family composition	Operation of heating system
Regulations	Inputs by National Standard UNI/TS 11300 [35, 41]	Not specified	Continuous operation $T_{set\ point}$ = 20°C
Current-use	Questionnaire, interview, and bills	1 person	Operation schedule: 18:30-23:00 weekdays 15:00-24:00 Saturday 9:00-24:00 Sunday $T_{set\ point}$ = 23°C
Satistical	Questionnaires and Hetus	4 people, parents, and two sons	Operation schedule: 6:30-8:00/16:00-22:00 weekdays 7:30-10:30/15:00-23:00 Saturday 8:00-23:00 Sunday $T_{set\ point}$ = 23°C

In the following sections, a detailed description of the three occupancy scenarios is provided.

2.4.1. Regulations occupancy profile (according to UNI/TS 11300-1)

The operation of the heating system is in continuous regime with a fixed set point temperature of 20°C. The internal heat loads are evaluated by using the relation:

$$\Phi_{int} = 7.987A_f - 0.0353A_f^2 \quad (1)$$

where A_f is the usable floor area of the house [m^2].

The calculated value amounts to 5.56 W/m^2. Following the indications of the Standard, in DesignBuilder internal loads were entered through a single value, grouping all contributions of occupancy, miscellaneous equipment, catering process, and lighting.

Regarding natural ventilation, the Standard assumes a constant air change that includes both the effect of infiltrations, due to air permeability of the envelope, and external flow rate provided for environmental comfort.

The air flow rate $q_{ve,k,mn}$ is calculated according to the procedure of the "Ventilation flow in reference conditions":

$$q_{ve,k,mn} = q_{ve,O,k} \times f_{ve,t,k} \quad (2)$$

where $q_{ve,O,k}$ is the minimum amount of outdoor air [m^3/s]; $f_{ve,t,k}$ is a correction factor representing the fraction of time in which takes place the k-th air flow and considers the use profile and infiltrations that occur even when the ventilation is not operating, its value is set at 0.60, $q_{ve,O,k}$ is evaluated using the relation:

$$q_{ve,0,k} = n \times {}^{V}\!/_{3600} \quad (3)$$

where *n* is the air change for hour and *V* is the net volume of the thermal zone, including kitchens, bathrooms, hallways, and utility rooms. The flow rate obtained is equal to 0.3 ach.

In DesignBuilder the ventilation mode which permits to set the air changes per hour for each zone was adopted.

Primary energy for domestic hot water is calculated as a function of the water flow rate needed for different uses and the difference between outlet and inlet water temperature (UNI/TS 11300-2 2014). For residential buildings, the volume of water required for domestic uses does not take into account the number of users, it is estimated considering the area of the dwelling by means of the equation:

$$V_w = a \times S_u + b \quad \text{[l/day]} \quad (4)$$

where *a* and *b* are parameters tabulated as a function of the housing surface S_u [m^2]. The value to be entered in DesignBuilder is related to the net area of the apartment and it is equal to 1.6 [l/m^{2}day]. The supply temperature of cold water is set to 15°C while the delivery temperature is set to 60°C.

2.4.2. Current-use profile

The apartment is occupied by one person, a woman working from Monday to Friday and at home at weekends. From questionnaire and interview it was possible to characterize her specific habits and by using the collected information a more detailed simulation model was created.

Internal gains are defined in DesignBuilder by separating the contribution of occupancy, equipment, and lighting. Dedicated schedules specify the use-profile for each zone. The presence of occupants is detailed considering the sensible and latent heat load related to the specific activity (AICARR 2005). Figure 6 depicts hourly occupancy density in a day.

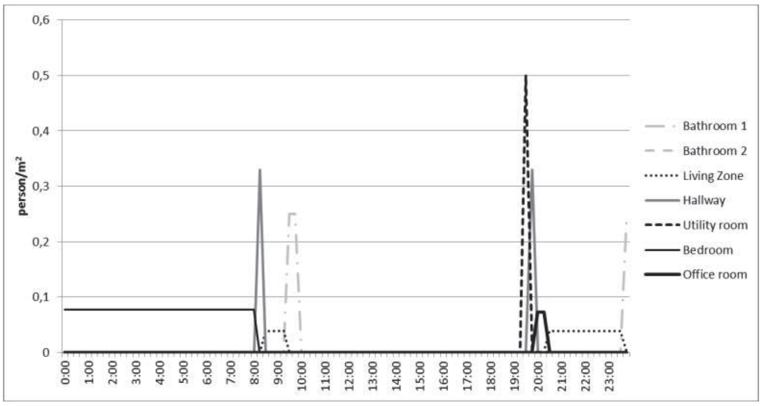


Fig. 6 Daily occupancy profile for the Current-use

Knowing the electrical power and the hourly usage of each appliance, the corresponding thermal power per unit area was obtained. The hourly average value of internal thermal contribution due to equipment was calculated for each room, as described in Table 4.

Table 4. Equipment for each room of the apartment with the corresponding thermal load

Room	Appliances	Thermal power [W/m²h]
Living zone	Microwave Refrigerator TV DVD Iron	4.47
WC 1	Hairdryer	1.88
Utility room	Washing machine	3.30
Office room	PC	0.04

Schedules were created for lighting operating and the thermal input was calculated taking into account that 75% of the electric power is converted into thermal power (see Table 5).

Table 5. Lighting schedule for the apartment in the Current-use

Room	Thermal power [W/m²]	Usage per day [h]
Living zone	4.09	4
WC 1	3.52	0.75
Bedroom	3.46	1
Utility room	19.69	0.25
Office room	3.28	0.5
Hallway	7.50	0.5

Air changes were treated by adopting a calculation mode in the simulation software, which allows determination of the airflow between internal and external environment, according to the building orientation and wind exposure, envelope air permeability, and windows opening. The occupant stated that the living room and bedroom windows were opened every morning from 8am to 9am. This ventilation schedule was applied for the whole year, both for weekdays and weekends.

2.4.3. Statistical occupancy profile

The Statistical occupancy profile was built with reference to data collected by means of questionnaires and statistical elaborations. By combining data collected at the local level with the more extensive Hetus data for Italy a family-model was created. In particular, according to the information collected through the questionnaire and statistical data (Istat 2014), the most common family consists of four people. Moreover, the most populated age groups are those between 50 and 65 years, and from 19 to 30 years. Consequently, a family of four with two parents belonging to the first age bracket and two sons of the second age range was assumed. Regarding the employment, Hetus reveals that the percentage of employed people in the 50-65 age group is of about 65% for males and 45% for females (data 2015). Therefore, one person working full-time and one part-time were hypothesized. Concerning the sons, in the age range between 20 and 24, less than 24% have a job, while the percentage of employment is more than 50% between 24 and 30 years. Therefore, the two young members of the family were considered to be a student and a full-time worker. The different household composition determines modifications in the occupancy density of the rooms of the house, as illustrated in Figure 7, in which the occupancy inputs for the Current-use and Statistical-use are compared.

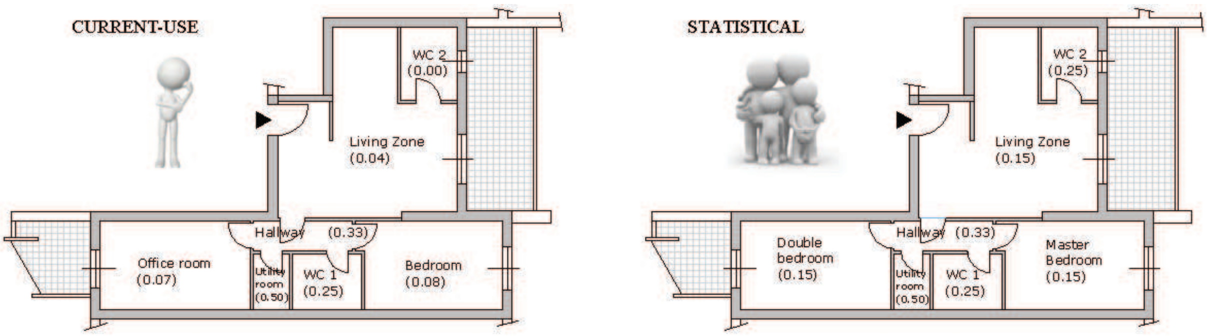


Fig. 7 Use of the dwelling in the Current-use and in the Statistical occupancy profile. Details of the maximum value of occupancy density for each room [person/m^2]

With respect to the Current-use profile, in the Statistical profile the occupancy mode varies in terms of number of occupants and occupancy hours. The family spends more hours at home, and the Statistical occupancy profile was defined detailing the activities in the different rooms of the apartment. Table 6 describes some data of Hetus used for the investigation. Figure 8 depicts the daily occupancy density and Figure 9 reports, as an example, the specific occupancy schedule for the living room in DesignBuilder, where occupancy density is entered as a fraction of the maximum occupancy.

Table 6 Data on time use for Italy from Hetus survey (Hetus 2007)

Room	Activity	Time per activity (hh:mm)	Time in the room (hh:mm)
Living room	TV and video	01:40	07:33
	Reading, except books	00:13	
	Leisure, social, and associative life	04:35	
	Household upkeep except cleaning dwelling	00:06	
	Cleaning dwelling	00:47	
	Study	00:12	
Kitchen	Eating	01:54	03:00
	Food management except dish washing	00:46	
	Dish washing	00:20	

Bedroom	Sleep	08:18	09:15
	Homework	00:08	
	Resting	00:32	
	Computer games	00:01	
	Hobbies and games except computing and computer games	00:08	
	Reading books	00:05	
	Radio and music	00:03	
Bathroom	Other and/or unspecified personal care	01:01	01:01
Unoccupied dwelling	Activities taking place outside	03:11	03:11
Total			**24:00**

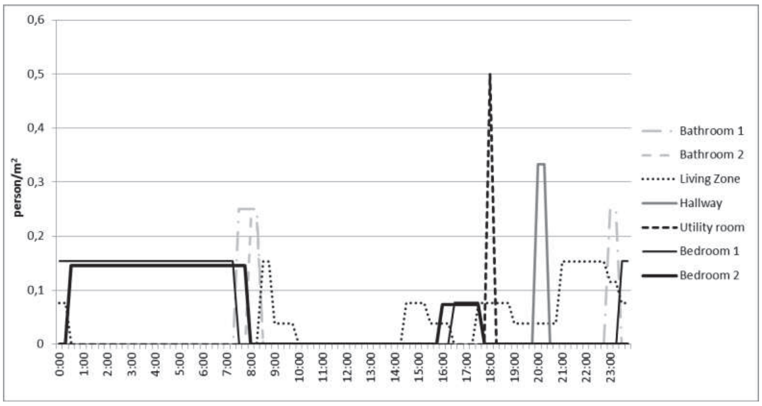


Fig. 8 Daily occupancy profile for Statistical use

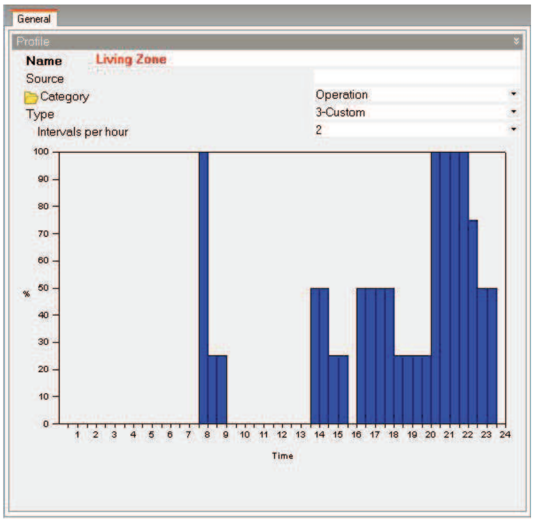


Fig. 9 Daily occupancy pattern for the living zone (maximum occupancy rate equal to 0.15 person/m^2)

Since there is no detailed information on equipment use, the internal load due to appliances is considered as in the Current-use case while the lighting is modified (see Table 7).

Table 7 Lighting operation for the apartment in the Statistical occupancy profile

Room	Thermal power [W/m²]	Usage per day [h]
Living zone	4.09	10.5
WC 1	3.52	1.5
Master bedroom	3.46	2.75
Utility room	19.69	0.25
Double bedroom	3.28	2.75
Hallway	7.50	0.25
WC 2	3.27	0.5

With regard to domestic hot water demand, considering, an average consumption of 60 l/day per person (Engineering & Construction 2010), the DHW rate results equal to 3.53 l/m^2day.Regarding natural ventilation, such as in the Current-use case, the air changes were determined considering window opening and the percentage of open windows.

It was assumed that occupants open the windows every morning for one hour (from 8:00 to 9:00) in the living zone and in the bedrooms, and for half an hour (from 8:00 to 8:30) in the two bathrooms. In the afternoon windows are opened from 14:30 to 15:00 in the living zone and in the bedrooms. The percentage of open windows was set equal to 70%.

2.5. Comfort

The analysis was carried out for a typical winter day (January 15th), with the aim of knowing how the comfort index PMV (Predicted Mean Vote) varies with the set point temperature and windows opening. The Standard (UNI 10349 1994) provides the mean monthly values of the outdoor dry bulb temperature equal to 8.1 °C and of the beam and diffuse solar radiation on the horizontal plane of 0.89 kWh/m^2 and 1.25 kWh/m^2, respectively. The mean wind speed is 2.4 m/s. The study takes into consideration the main rooms of the house, the living zone and the bedroom, both for the Current-use and Statistical profile. Thermal resistance of clothing was assumed equal to 1.0 clo for the living zone and a value of 1.50 clo was chosen for the bedroom. The metabolic rate per person was calculated including both contributions of sensible and latent thermal loads. For the living zone, a metabolic rate corresponding to a light activity (116 W/person) was set while for the bedroom a value of 97 W/person was calculated considering people resting.

3. Results

The three occupancy profiles were simulated considering the selected building. The aim was to highlight how different occupancy scenarios lead to substantial differences in energy consumption. The energy actually consumed, obtained from bills, allowed verification of the reliability of the model. The ASHRAE Guideline 14-2002 (2002) was used for calibration. The Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE) were calculated by comparing the predicted results obtained through simulation, and the measured data deduced from energy bills. The procedure was applied on a monthly scale and values lower than the acceptable limits were obtained for both NMBE (<5%) and CVRMSE (<15%), considering energy consumption for heating, DHW, and total consumption. After the model's reliability was verified and once proven that it is able to adequately represent the actual behavior of the building, the model was used for simulation of the previously defined occupancy profiles.

1.1. Energy consumption for the different occupancy profiles

Figure 10 shows the values of primary energy for heating obtained for the three analyzed use profiles.

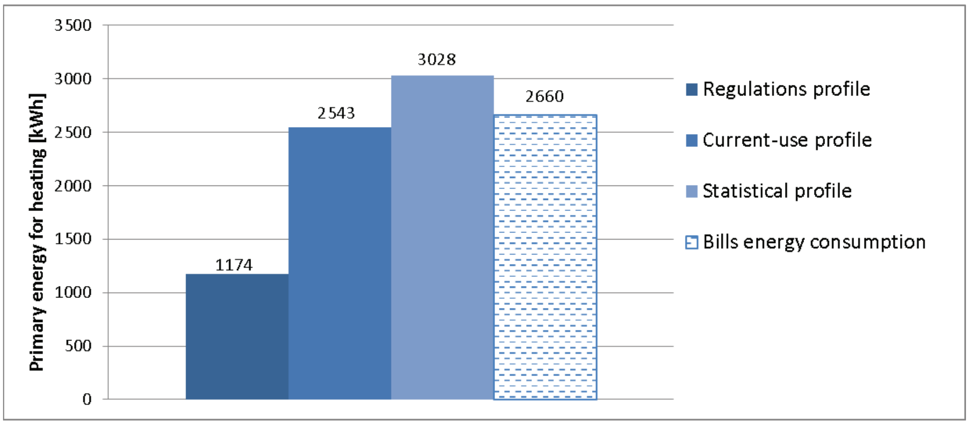


Fig. 10 Primary energy for heating obtained for the three occupancy scenarios and consumption from bills

Compared with the Current-use, the Regulations occupancy profile produces a significant underestimation, while considering the Statistical profile the consumption for heating increases by 19%. The energy consumption for DHW production is illustrated in Figure 11.

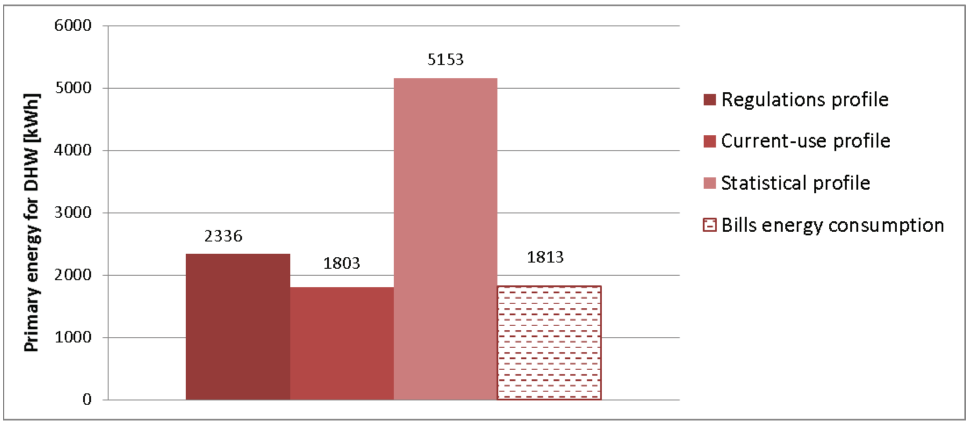


Fig. 11 Primary energy for DHW obtained for the three occupancy scenarios and consumption from bills

Considering the DHW consumption obtained by the standard and determined as a function of the area of the apartment, the primary energy turns out to be higher than the ones calculated for the Current-use by an amount of 23%. For the Statistical profile, the energy requirement considerably increases. Figure 12 represents the total primary energy consumption obtained for the analyzed occupancy profiles. The figure highlights that the simplified model proposed by the Regulations produces results that are not suitable to correctly represent all the occupancy scenarios.

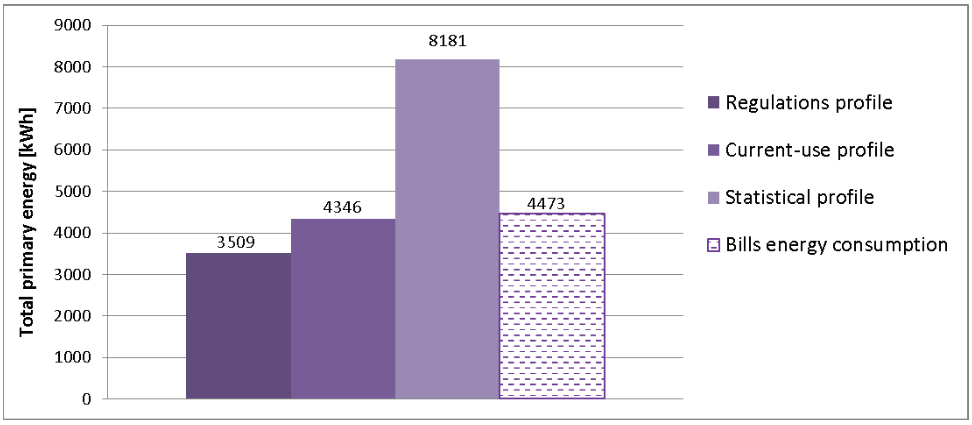


Fig. 12 Total primary energy obtained for the three occupancy scenarios and consumption from bills

The differences resulting in energy consumption are due to the ways of using the dwelling that determine variations in heat losses and gains. With reference to ventilation strategies some detailed results were analyzed. Figure 13 and Figure 14 report the ventilation rate and heat losses due to ventilation, respectively.

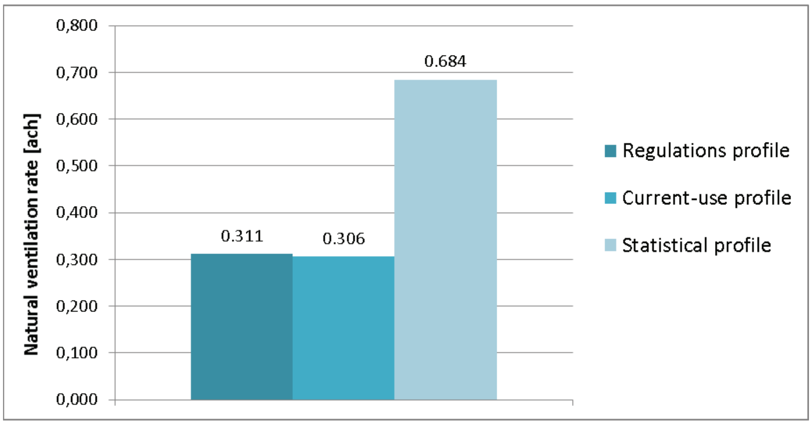


Fig. 13 Natural ventilation rate obtained for the three occupancy scenarios

The ventilation rate estimated by the standard is close to the ones obtained in the Current-use case of occupancy by a person. When the number of occupants increases, the windows are opened more frequently and for more time and, consequently, the volume of air change and energy losses for ventilation enhance substantially.

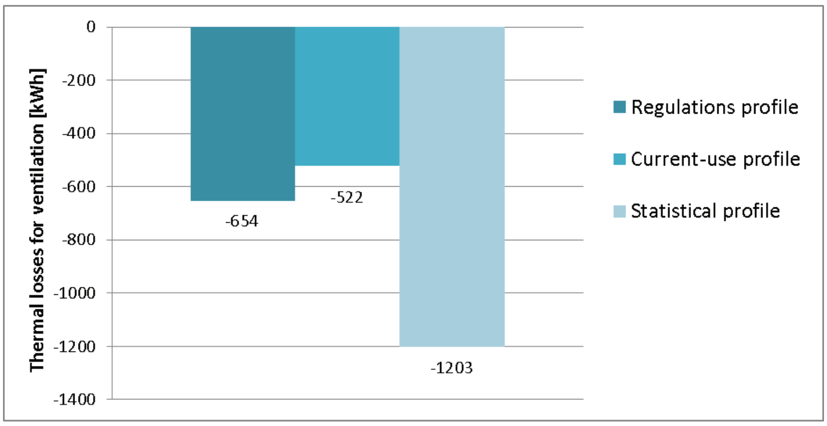


Fig. 14 Thermal energy losses due to ventilation obtained for the three occupancy scenarios

The thermal gains differ with a variation in the number of occupants. Figure 15 details the internal gains for occupancy in both Current-use and Statistical profiles. For the Regulations profile the contribution of occupancy is not specified separately.

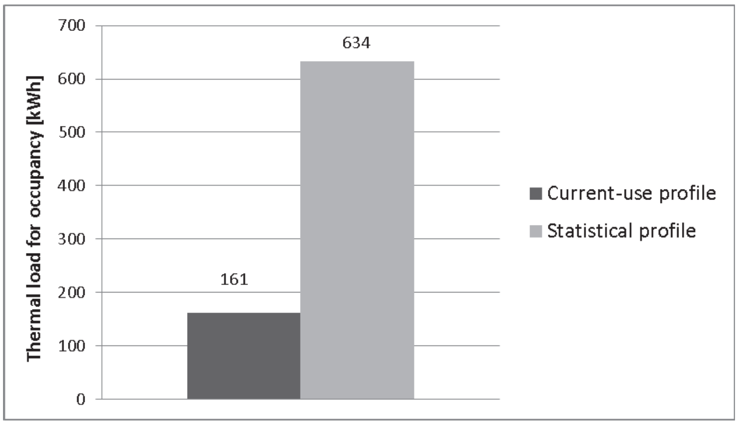


Fig. 15 Thermal energy contribution due to the occupants for the Current-use and Statistical profiles

It can be noted that as the number of family members increases, sensible and latent thermal loads due to the occupants proportionally enlarge.

3.2. Influence of heating set point temperature, DHW temperature production, and ventilation on energy consumption

Figure 16 presents the percentage increase in heating primary energy if the set point temperature is modified.

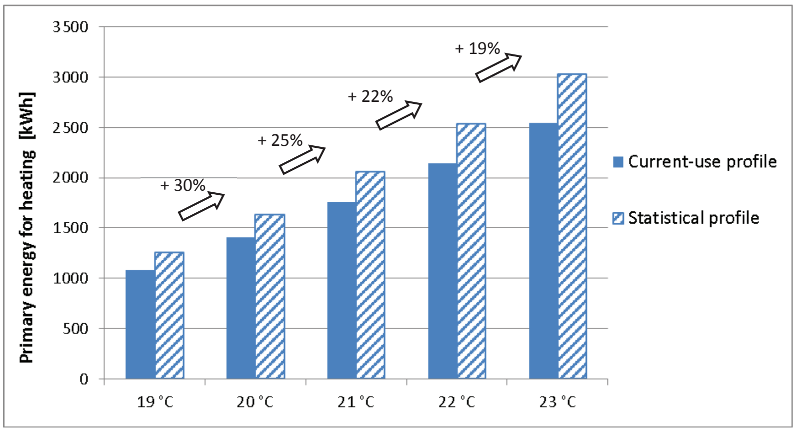


Fig. 16 Heating primary energy for different values of the set point temperature

Figure 17 shows the primary energy required for DHW for the two different occupancy profiles increasing the production temperature by 5°C progressively. This increment determines constant absolute increases of the DHW primary energy and different relative percentages of increase. The results are equivalent for the two analyzed profiles. The occupant can decide to adjust the temperature to a higher or lower value according to the use he intends. Heating the water to 60°C instead of 45°C will lead an increase of 50% more energy consumption.

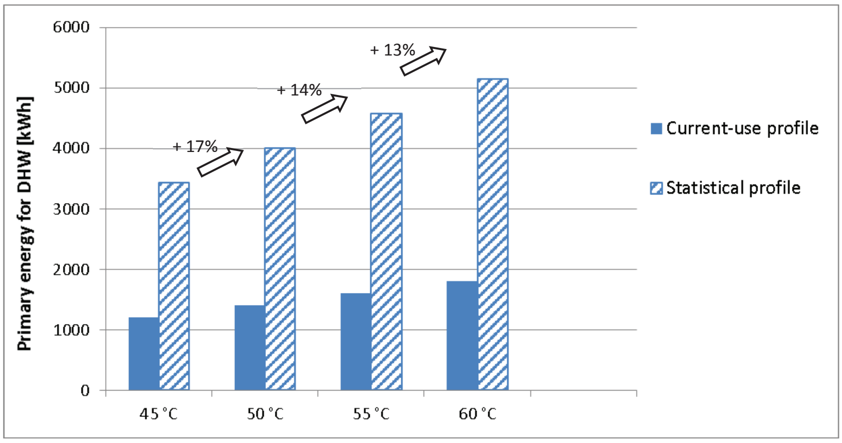


Fig. 17 Primary energy for DHW on variation of temperature production

The effect of ventilation on energy consumption was analyzed through the variation of two parameters: the percentage of the open glazed surface and the time that the windows are open. By varying the percentage of open windows between 50% and 100%, not significant variations on primary energy for heating were registered. More interesting results were obtained with regard to the duration of ventilation, as reported in Figure 18. In particular, the effect of an increase and of a reduction of half an hour of ventilation in the morning was analyzed because in the investigated area it is customary to open windows at this time of the day. In the case of Current-use profile, when only two rooms are ventilated, this change leads to a variation in the energy consumption for heating by 6%. Considering the Statistical profile, where more spaces are occupied and simultaneously ventilated, an increase of half an hour of opening windows in all rooms could increase heating primary energy by 21%.

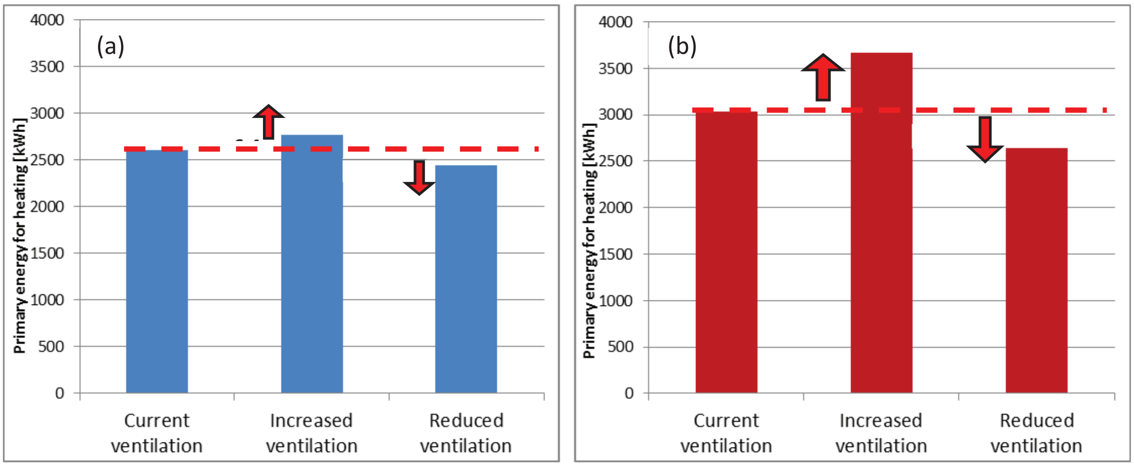


Fig. 18 Heating energy consumption as a function of the time of windows opening in (a) Current-use profile and (b) Statistical profile

3.3. *Occupant preferences and comfort*

In Figure 19 the presence of occupants at home in a week-day is reported. For the Statistical profile, the unoccupied period of the dwelling is five hours shorter compared to the Current-use occupancy scenario.

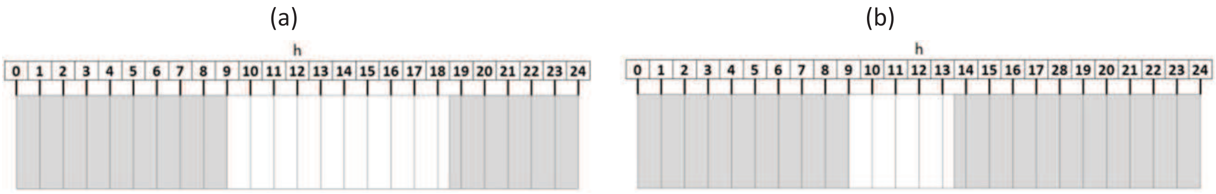


Fig. 19 Occupied (dark) and unoccupied (white) hours of the dwelling in a week-day for the Current-use profile (a) and for the Statistical profile (b)

The trends of PMV index at variation of the heating set point temperature and the external temperature are compared in Figure 20 for the living zone and in Figure 21 for the bedroom. The hours of occupancy, the operation of heating system and the ventilation modes are also reported in order to visualize their influence on comfort perception.

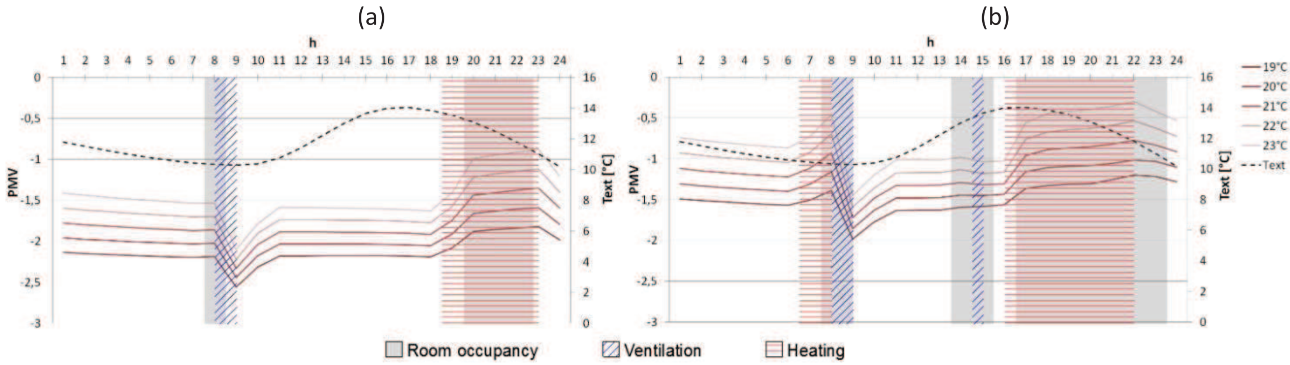


Fig. 20 Hourly PMV values on January 15th in the living zone for (a) the Current-use occupancy profile and (b) the Statistical occupancy profile obtained by varying the heating set point temperature from 19°C to 23°C. T_{ext} is the external air temperature

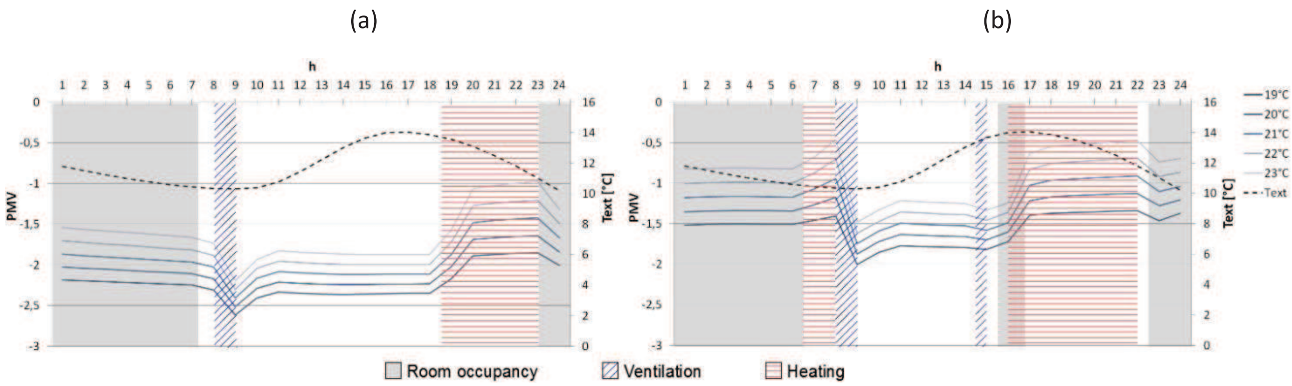


Fig. 21 Hourly PMV values on January 15th in the bedroom for (a) the Current-use occupancy profile and (b) the Statistical occupancy profile obtained by varying the heating set point temperature from 19°C to 23°C. T_{ext} is the external air temperature

The heating plant operates contemporaneously in all the rooms and ventilation is performed by the users. Consequently, as the graphs report only two rooms of the house, it can be noticed that heating and ventilation occur even when the selected room is not occupied, because the presence of people is expected in other zones of the house in that period, as shown in figure 19. In general, the hourly trends of PMV show heating results in an improvement of the comfort conditions, but they appear unsatisfactory when ventilation takes place. If the temperature is set to 20°C, as required by the

Standard, the perceived sensation is cool in both rooms and for both occupancy profiles. If the apartment is used according to the Statistical profile, higher values of PMV are registered as the heating system is switched on for more hours during the day. This setting leads to slightly higher internal temperature. The choice of the set point temperature greatly affects internal comfort conditions. In both scenarios, as the set point temperature increases a progressive improvement of the comfort conditions is recorded.

4. Discussion

The study is focused on the use of occupancy profiles obtained by different procedures: by applying the National Standard, by means of survey, interview and bills, and by statistical elaborations carried out both at local and European level. The effects of occupant's preferences on energy consumption and indoor comfort conditions were also analyzed.

Three occupancy scenarios are scheduled, Regulations, Current-use, and Statistical created by considering occupancy, lighting, ventilation, and equipment use. The analysis showed that different approaches of modeling occupancy can lead to considerable variations in building performance. Regulations occupancy profile produces a significant underestimation of heating energy consumption if compared to the Current-use scenario. For the Statistical family, the consumption for heating increases by 19%. DHW primary energy obtained for Regulations occupancy is higher than the one calculated for the Current-use by 23%. For the Statistical profile, this energy requirement considerably increases.

Successively, occupant preferences were investigated in terms of internal set point temperature, DHW temperature production, and windows opening. In particular, heating primary energy for different values of the set point temperature was determined. The percentages of increment are almost identical in the two analyzed cases (Current-use and Statistical occupancy profile): 1°C increase in the heating set point temperature will lead to a progressive decrease in the increment of heating primary energy. Increasing the set point temperature from 19°C to 20°C leads to a requirement for 30% more energy; instead, an increase from 22°C to 23°C requires 19% more energy. It is interesting to note how changing from a temperature of 20°, which is the value provided by the standard, to 23°, the value set in the apartment (Current-use), gas consumption for heating increases by 81%. Considering the DHW, heating the water to 60°C instead of 45°C requires 50% more primary energy. The change in the percentage of open windows does not result in significant variations in primary energy. By contrast, the extension of the duration of ventilation can increase primary energy for heating by 21% if the Statistical profile is considered.

Concerning thermal comfort, in the case of Current-use occupancy, raising the temperature from 19°C to 23°C does not improve the comfort conditions significantly; in fact, in the living zone the comfort sensation could pass from cool/cold to cold/neutral. In the bedroom, the perception is slightly cold because the heating does not operate during the night. Considering the Statistical profile, the temperature of 23°C allows to obtain acceptable comfort conditions in both rooms. The ventilation occurs when the heating system is switched off. The PMV index drops when ventilation takes place during the morning following the occupants' habits. If the ventilation takes place during the early afternoon, slight negative impacts on comfort conditions are registered.

5. Conclusions

The study shows different procedures to create occupancy profiles and reveals the influence of their use as input in the energy simulation of buildings. The profile created through direct interview of the user seems to be the most reliable, but at the same time, it could be the most expensive and could not always be applicable, since in some cases the type of user is not known, for example in the design phase. A viable alternative might be the use of statistical data. But generally, currently available databases are not sufficiently detailed. Therefore, targeted surveys should be developed in order to create exploitable datasets for this specific purpose. Furthermore, analyses at a local level are needed since the habits and behaviors of users vary significantly depending on the geographical area.

The analysis highlighted how the availability of data and information concerning occupancy is essential for the modeling of the profiles to be used in design or assessment phase. In fact, the prediction of energy consumption differs significantly according to the way in which occupancy is modeled. On the other hand, the modeling procedure depends on the level of detail of the available information. Generally, designers refer to Regulations and Standards, if no other sources are available. The study demonstrated that the forecasted energy consumption could be unrepresentative of the real energy performances. The simplified and generalized approach, currently proposed by the Regulations, seems to be not suitable to describe adequately the usage scenarios of the dwelling, and leads to great differences in energy consumption prevision.

Interesting implications can be deduced from the outcomes of the performed study. First, in-depth analyses are required in this research field, by considering that the investigation sectors are varied and multifaceted. Delving into the variables related to occupancy, which can potentially affect energy consumption, is required. Therefore, on the one hand, investigations addressing the collection of data on a large scale and in different contexts are necessary, and on the other hand, encoding of user behavior that affects energy consumption should be developed. A step forward should be done in modeling procedures, in order to harmonize occupancy characteristic parameters and variables needed by simulation software. In addition, with more relevant survey samples, advanced statistical analyses could be carried out. The research results should guide decision makers in addressing the shared objective of energy saving policies, to achieve the goal of internationally agreed CO_2 emission reductions. Policy makers and researchers should encourage the formulation of specific Standards which can more appropriately represent the contribution of occupancy and occupant behaviors in buildings. The results provided by this investigation can constitute a reference for designers that should carefully perform energy building assessments, and address the planning choices by paying more attention towards occupancy and its effect on energy consumption. Especially in the design of low energy buildings, adequately considering the influence of occupants is crucial for the achievement of the target. In fact, occupants can act differently from the supposed model and can degrade the performance of the building. In this regard, activities aimed at increasing user awareness should be promoted, as users have to be conscious of how their actions can produce significant variations in energy bills and comfort perception. Specific guidelines should be produced for creating references for both occupants and modelers.

6. Future work

The paper analyzed different approaches to address the problem of occupancy modeling in the building energy simulation. In particular, the study considered an existing building in order to exclude the influence of technical-constructive characteristics of the dwelling, rather focusing on the occupancy typologies and on how to describe occupancy in determining the heating and DHW energy consumption. Being a real building, the climatic conditions considered in the study are those of the site (Mediterranean location). Future studies could consider different dwelling typologies in order to assess the influence of occupancy in buildings with specific design features, such as old buildings or those designed according to high standards of energy efficiency. Furthermore, buildings could be selected in different climatic conditions in order to explore the interaction between energy performances, climatic factors, and occupancy profiles. Additional occupancy scenarios could also be adopted with the aim of further investigating household compositions and modes of use of the house.

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5.2 The effect of different users profiles on energy performances of a Nearly Zero Energy Building

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Contribute of the candidate: the candidate planned and developed the research methodology. She designed the building used as a case study, conducted the simulations and processed out the results. She defined the occupancy profiles and behavioral patterns used in the analysis. She wrote sections 2, 3, 4, and 5 of the paper.

Abstract

In addition to technical characteristics, in the operation and maintenance of buildings the action of users results crucial. Recent studies report that as buildings become more energy efficient, the behavior of occupants plays an increasingly role in consumption. This paper aims to assess the influence of users' patterns on the energy consumption of a nZEB for residential use. The nZEB is designed in accordance with the definition net zero source energy and the occupants' behavior is investigated by modifying the occupancy and the modalities of use of equipment, lighting, ventilation, heating and cooling setting. Improving the understanding of occupants' behavior and quantifying its impact on the use of technologies and on energy performance can help to limit resources consumption and bridge the gap between design stage and utilization phase.

Keywords: Zero energy building; occupant behavior; occupancy profiles; electricity consumption.

1. Introduction

The existing buildings stock in European countries accounts for over 40% of final energy consumption in the European Union (EU) member states. An increase of building energy performance can constitute a valuable instrument in the efforts to mitigate the EU energy import dependency (currently at about 48%) and comply with the Kyoto Protocol to reduce carbon dioxide emissions. Italy is among of the four countries of the member states with a higher final energy consumption in the residential and tertiary buildings [1]. The 2010/31/UE directive dictates as the Standard for the new buildings the Near Zero Energy (nZEB), meaning that the "nearly zero or very low amount of energy" required by the building should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby [2]. To make a building high performance, a careful design aimed to reduce the energy consumption and to optimize the construction is required. In addition to technical characteristics, in the operation and maintenance of the building, the action of users is essential. According to the framework proposed by Sartori et al. [3], the common denominator for the different possible nZEB definitions is the balance between weighted demand and supply. The general definition proposed by Torcellini et al. [4], is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies. The concept of a zero energy building can be defined in a number of ways, determined by the boundary and the metric. Four mostly used definitions are: net zero site energy, net zero source energy, net zero energy costs, and net zero energy emissions. A building may be designed to achieve one or more nZEB definitions, but may not achieve a net-zero energy position in operations every year. In terms of final energy uses, the amount of energy used by residential buildings is dedicated to electrical uses such as lighting, appliances, and air conditioning, and thermal uses mainly satisfied by fossil sources for space heating (higher percentage), domestic hot water (DHW) and cooking [5]. It is necessary to understand how people behave and how they operate the systems for controlling indoor environment and comfort conditions [6]. Now, with the implementation of new technologies oriented to energy saving and green building certifications, a new approach is emerged and related to how it affects the use of energy due to occupants' behavior [7]. Recent studies report that as buildings become more energy efficient, the behavior of occupants plays an increasing role in consumption [8–10]. Therefore, a construction designed to be a Nearly Zero Energy Building might generate higher consumption than expected if the assumptions made in the simulation process are not respected during the effective use. In fact, the occupant in order to reach his comfort condition, can modify different control parameters (thermostat set point, ventilation rate, lighting level and equipment use) invalidating the ideal designed efficient model. For this reason, it is essential to establish the right hypothesis on the schedule, utilization of appliances and comfort level of the building in order to obtained a good evaluation of the energy consumed in the actual buildings operation. In nZEB, indoor comfort (thermal and visual) should be achieved mainly thanks to free resources of energy such as solar radiation and natural ventilation. Consequently, the users' behavior has a high impact on the final energy use depending on the correct utilization of passive systems and the operating of active technologies. In low energy buildings, a significant contribution is also represented by the internal gains, and these have a direct relation with users' behavior and occupancy. The role of the occupant in the building performance and the resident's perceptions of low energy homes are not yet known [11,12]. Marshall et al. [13], investigated how occupancy patterns affect domestic energy consumption and energy savings for a broad range of Energy Efficiency Measures (EEMs), and the results explain that energy consumption depends on the appropriate matching between energy efficiency measurements and occupant type. Another important aspect to take into consideration regarding the low carbon buildings (LBOs) is the properly operation and manual maintenance. According to a study realized in the UK [14], there is poor information and inappropriate details that could not aid effective operation and maintenance.

The aim of this paper is to evaluate the influence of users' patterns on the energy consumption of a residential nZEB. The definition used to develop the building model was net zero source energy. The study takes into account the variability of the family composition and the occupancy scenarios. Also needs and preferences of occupants in using energy systems and equipment are considered.

2. Methodology

An energy efficient building was designed according to the Italian Standard. The construction was designed to consume low energy: the ratio between dispersing surface and air conditioning volume is set to minimize losses, all the housing components are well insulated, the air conditioning system has high efficiency and uses energy from renewable sources available on site. However, the actual consumption for the management of the house depends on the type of family will occupy the dwelling and on the interaction of the occupants with it. Two different occupancy scenarios (OSC) were proposed in order to understand how the occupancy typology and the various mode of use of the house and its facilities can affect energy consumption. For each OCS and mode of use, the annual energy balance was considered with the aim of verifying the achievement of the nZEB objective. Dynamic simulations were carried out using the DesignBuilder [15]. About climatic conditions, a Meteonorm file [16] for the City of Cosenza, in the Calabria region (South Italy) was adopted. The selected location is classified in climatic zone C (1317 HDD). The heating period is from November 15th to March 31st.

2.1. Description of the model

The model consists of a two stories detached house. The living zone is on the ground floor while the bedrooms are on the first floor. The total habitable area is 120 m^2, and the story height is of 2.7 m. The heated volume has a compact shape to reduce heat losses. The main exposure is to the South and presents a wide transparent surface to maximize solar gains in winter, and deep horizontal overhangs to avoid overheating in summer. Windows towards the North exposure are restricted to limit the heating demand. The roof is flat with an additional architectural element that fits with the main volume and provides a pitched roof 30° tilted suitable for the installation of solar systems. Figure 1 illustrates the plan of the two stories house and figure 2 shows the facades for the different exposures. In figure 3 the external view of the building and the DesignBuilder model are displayed.

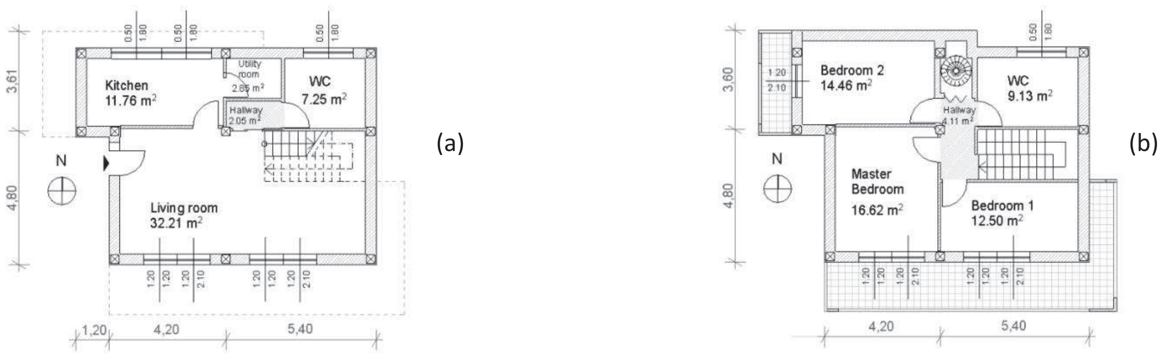


Figure 1. Ground floor (a) and first floor (b) of the detached house.

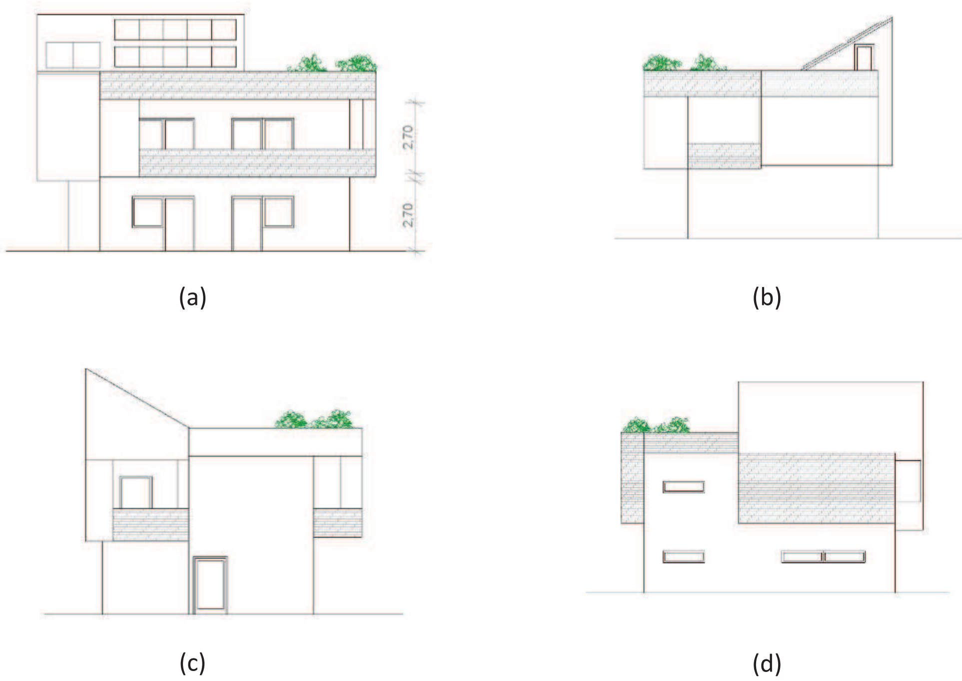
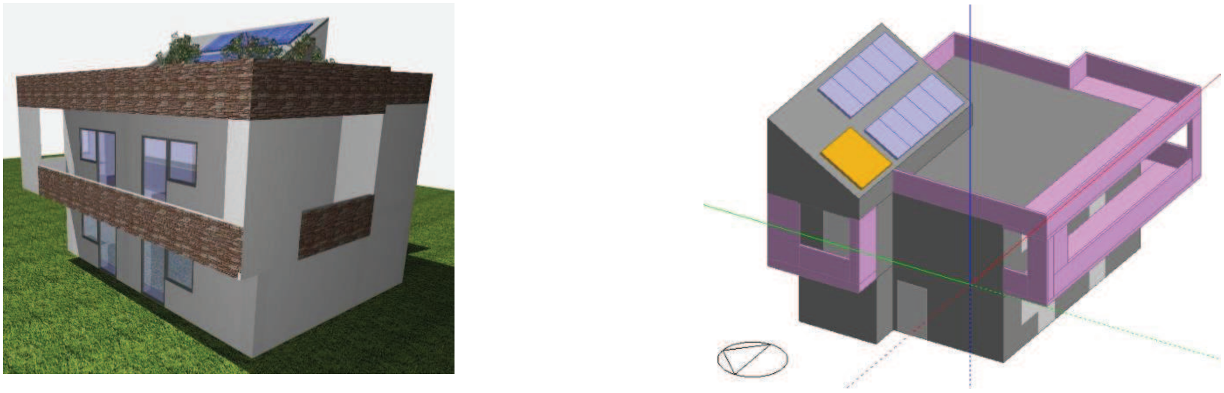


Figure 2. Building facades for the different exposures (a) South, (b) East, (c) West, (d) North.



(a) (b)

Figure 3. External view of the building (a) and the DesignBuilder model (b).

External walls are insulated on outside. The total thickness is 43 cm, and the thermal transmittance is of 0.243 W/m^{2}K. Also, the ground slab and the roof are thermally insulated (U value equal to 0.444 W/m^{2}K and 0.339 W/m^{2}K, respectively). Windows are LowE double-glazing 4-12-6 mm with argon in the cavity (Ug= 1.455 W/m^{2}K) and aluminum frame with thermal break.

According to the Italian law [17], the use of a given amount of energy produced from renewable sources for electricity, domestic hot water (DHW), heating and cooling is mandatory. In particular, energy from renewable sources should cover 50% of the DHW consumption and the installation of a minimum of 2 kW per 100 m^2 of photovoltaic peak power is required (constraint in place since January 1, 2017).

The DHW demand was calculated according to the UNI TS 11300-2 [18]. Going beyond the limit set by the law and assuming to cover all DHW requirement with energy produced by solar collectors, an absorbing surface of about 2 m^2 is needed. For the calculation selective solar collector were considered with technical characteristics shown in table 1. Two solar collectors are required.

Table 1. Technical characteristics of the thermal solar collectors.

Collector Typology	**Absorption area [m^2]**	**Efficiency η_0 [%]**	**Coefficient of heat loss k_1 [W/m^{2}K]**	**Coefficient of heat loss k_2 [W/m^{2}K^2]**
Flat plate solar collector with selective coating	1.97	70.2	-3,2828	-0,00992

The PV power is calculated as a function of the dwelling surface and is equal to 2400 Wp. The modules used in the simulation have the characteristics shown in table 2. Ten modules assembled in two strings are necessary.

Table 2. Technical characteristics of the PV modules.

Panel Typology	**Absorption area [m^2]**	**Maximum power at STC (Pmax) [W]**	**Module efficiency η_m [%]**
Polycrystalline silicon PV panel	1.48	250	15.2

Both solar collectors and PV modules are in adherence to the pitched roof with a slope of 30° and south facing in order to maximize the productivity.

The plant consists of air to water heat pump with fan coils used for both the heating and the cooling season.

2.1. Occupancy scenarios

Occupancy scenarios were formulated concerning the socio-demographic data provided by the National Institute of Statistics [19]. Data on "family structure" report that, for the Calabria region, four components households account for the majority. Moreover, at national level, an increase of childless couples has registered over the last years. Consequently, two possible occupancy scenarios were analyzed for the designed building with differences in the management of the occupied areas. In particular:

- Occupancy Scenario A (OSC_A): the building is occupied by four family members, parents, and two sons. In this case, all the rooms of the house are occupied and air conditioned;
- Occupancy Scenario B (OSC_B): the house is occupied by two family members who use all the area on the ground floor. O the first floor, only the master bedroom and the bathroom are regularly utilized while the other rooms are occasionally occupied.

Figure 4 displays the management of the rooms in the two different occupancy scenarios.

Figure 4. Use of the dwelling in Occupancy Scenario A (a) and Occupancy Scenario B (b).

In addition, of assuming two family typologies, the analysis considered various ways of using the building-plant system to understand how the occupants' behavior affects the energy efficiency of the building. In fact, the occupants operate on different control parameters to achieve comfort conditions that are subjective and can even disregard the calculation assumptions made in the design phase. Therefore, the actual consumption of the dwelling could be different than expected. The nZEB definition is grounded on zero annual balance among produced and consumed [20]. If the user does not pay attention to monitoring consumption, the energy balance might also be negative, leaving the nZEB condition.

Taking into account the previous considerations, several configurations of use were analyzed considering the variation of the following parameters:

- Daily heating hours
- Heating set point temperature
- Daily cooling hours
- Cooling set point temperature
- Windows opening
- Artificial lighting
- Equipment use

Tables from 3 to 8 describe the modes of use analyzed for each parameter.

Table 3. Mode of use for daily heating hours.

Tested variable	MOD_1	MOD_2	MOD_3	MOD_4
Daily heating hours	9:00-12:00 18:00-21:00	9:00-13:00 18:00-22:00	9:00-14:00 17:00-22:00	8:00-20:00

Table 4. Mode of use for heating set point temperature.

Tested variable	MOD_1	MOD_2	MOD_3	MOD_4
Heating set point temperature	19 °C	20 °C	21 °C	22 °C

Table 5. Mode of use for daily cooling hours.

Tested variable	MOD_1	MOD_2	MOD_3	MOD_4
Daily cooling hours	11:00-17:00	10:00-18:00	10:00-20:00	10:00-22:00

Table 6. Mode of use for cooling set point temperature.

Tested variable	MOD_1	MOD_2	MOD_3	MOD_4
Cooling set point temperature	27 °C	26 °C	25 °C	24 °C

Table 7. Mode of use for windows opening.

Tested variable	MOD_1	MOD_2	MOD_3	MOD_4
Windows opening	7:00-8:00	7:00-8:00 14:00-14:30	7:00-8:00 13:30-14:30	8:30-9:45 13:30-14:45

Table 8. Mode of use of artificial lighting.

	MOD_1	MOD_2	MOD_3	MOD_4
Kitchen	7:00-7:30 19:00-19:30	7:00-7:30 19:00-20:00	7:00-8:00 19:00-20:00	7:00-8:00 18:00-20:00
Living room	8:00-8:30 20:00-21-00	8:00-8:30 20:00-21:30	8:00-9:00 20:00-21:30	8:00-9:30 20:00-22:00
WC (ground floor and first floor)	7.30-8:00 19:30-20.00	7:30-8:00 19:30-20:30	7:30-8:30 19:30-20:30	7:30-8:30 19:30-20:30
Master bedroom	7.00-7.30 22.30-23:00	7.00-7:30 22:30-23:30	7:00-8:00 22:30-23:30	7:00-8:00 15:00-16:00 22:30-23:00
Bedroom 1 and bedroom 2	7:30-8:00 21:30-22:00	7:30-8:00 21:30-22:30	7:30-8:30 21:30-22:30	7:30-8:30 15:00-17:00 22:30-23:00

For equipment, the power in [W/m^2] was considered for each room and hourly use profiles were defined. Usage profiles are different for weekdays and weekends. Figure 5 shows, as an example, the mode of use of the equipment in the living room.

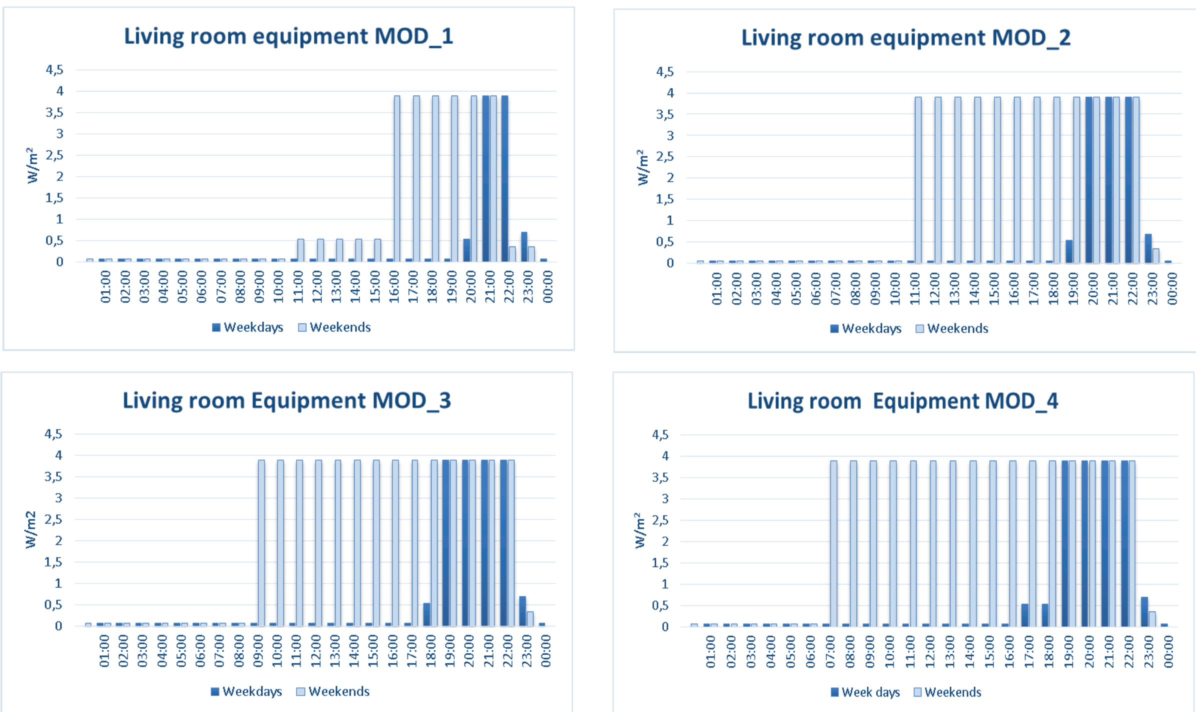


Figure 5. Equipment use for the living zone.

3. Results

The PV plant produces 3383 kWh/year. All the utilities and the energy requirements in the house can be related to electricity. Thus, the difference between the produced and the consumed electricity in a year was calculated for the two occupancy scenarios. A positive sign in the annual energy balance means that the building can produce more energy than it consumes, thus it is classified as nZEB.

3.1. Daily Heating hours

The first analyzed variable was the duration of heating hours per day. In this phase, all the remaining parameters were set in MOD_1, as presented in table 9, except for heating and cooling set point temperatures fixed at 20 °C and 26 °C, respectively, as these are the conventional values recommended by the regulation [21].

Table 9. Setting for the other variables when daily heating hours is analyzed.

Variables	Heating set point temperature	Daily cooling hours	Cooling set point temperature	Windows opening	Artificial lighting	Equipment use
Selected mode	MOD_2	MOD_1	MOD_2	MOD_1	MOD_1	MOD_1

By varying the heating time from six to twelve daily hours, the energy consumption does not undergo significant variations (see results in table 10). The construction is designed to have good performances from the thermal insulation point of view. Therefore, a longer activation of the heating system does not cause a significant increase in consumption. In the following evaluations, daily heating hours was always considered in MOD_3 (ten hours per day) that is the maximum duration indicated by regulation in the climatic zone C [22].

Table 10. Annual energy balance for different daily heating hours. **V** verified, **X** no verified.

Daily heating hours	OCS_A		OCS_B	
	Energy balance [kWh/year]	nZEB	Energy balance [kWh/year]	nZEB
MOD_1	352,04	V	969,70	V
MOD_2	303,09	V	890,92	V
MOD_3	294,80	V	868,45	V
MOD_4	132,87	V	778,78	V

3.2. Heating set point temperature

Variation in heating set point temperature ranged between 19 °C and 22°C. Other settings are synthesized in table 11. Results are presented in table 12.

Table 11. Setting for the other variables when heating set point temperature is analyzed.

Variables	Daily heating hours	Daily Cooling hours	Cooling set point temperature	Windows opening	Artificial lighting	Equipment use
Selected mode	MOD_3	MOD_1	MOD_2	MOD_1	MOD_1	MOD_1

For the OCS_A, set the heating temperature to values above 20 °C, with the heating system operating ten hours per day, leads to consumption that exceeds the produced energy.

Therefore, the building cannot be classified as nzEB for these uses. Instead, in the case of OCS_B users can heat the rooms even at higher values than 20 °C maintaining the consumption within the nZEB threshold.

Table 12. Annual energy balance for different heating set point temperature. **V** verified, **X** no verified.

Heating set point temperature	**OCS_A**		**OCS_B**	
	Energy balance [kWh/year]	nZEB	Energy balance [kWh/year]	nZEB
MOD_1	563,68	V	1118,66	V
MOD_2	294,80	V	868,45	V
MOD_3	-4,12	X	613,12	V
MOD_4	-345,13	X	331,78	V

3.3. Daily cooling hours

The effect of the duration of the operation was also studied for the cooling system. In table 13 is the summary of the settings for other variables and in table 14 the results are presented.

Table 13. Setting for the other variables when daily cooling hours is analyzed.

Variables	**Daily heating hours**	**Heating set point temperature**	**Cooling set point temperature**	**Windows opening**	**Artificial lighting**	**Equipment use**
Selected mode	MOD_3	MOD_2	MOD_2	MOD_1	MOD_1	MOD_1

Table 14. Annual energy balance for different daily cooling hours. **V** verified, **X** no verified.

Daily cooling hours	**OCS_A**		**OCS_B**	
	Energy balance [kWh/m^{2}year]	nZEB	Energy balance [kWh/m^{2}year]	nZEB
MOD_1	294,80	V	868,45	V
MOD_2	249,24	V	848,72	V
MOD_3	150,53	V	803,93	V
MOD_4	132,31	V	780,97	V

Also for cooling, the extension of the daily operation of the system does not affect the energy consumption significantly.

The annual balance remains positive also for twelve hours of cooling per day, for both the analyzed occupancy scenarios. For the following evaluations, ten hours per day (MOD_3) were considered for the operation of the cooling system.

3.4. Cooling set point temperature

Cooling set point temperature was varied between 27 °C and 24 °C. Table 15 shows the configuration for the other variables.

Table 15. Setting for other variables when cooling set point temperature is analyzed.

Variables	Daily heating hours	Heating set point temperature	Cooling hours	Windows opening	Artificial lighting	Equipment use
Selected mode	MOD_3	MOD_2	MOD_3	MOD_1	MOD_1	MOD_1

Table 16 shows that the set point temperature for cooling greatly affect the energy balance in the OCS_A as, for this occupancy scenario, a larger number of rooms should be air-conditioned. The nZEB target is not reached for a cooling set point temperature of 24°C.

Table 16. Annual energy balance for different values of cooling set point temperature. **V** verified, **X** no verified.

Cooling set point temperature	**OCS_A**		**OCS_B**	
	Energy balance [kWh/year]	nZEB	Energy balance [kWh/year]	nZEB
MOD_1	397,92	V	935,04	V
MOD_2	150,53	V	803,93	V
MOD_3	8,43	V	672,48	V
MOD_4	-182,96	X	492,25	V

3.5. Windows opening

Thermal losses for ventilation have a high impact on energy consumption. Natural ventilation is provided to the considered building. The percentage of opening is set at 20% for all the windows. The influence on energy consumption was studied by varying the duration of windows opening and the time of the day when ventilation occurs. Table 17 illustrates the summary of the settings for the other variables. In table18 are presented the results of energy balance at variation of windows opening.

Table 17. Setting for the other variables when windows opening is analyzed.

Variables	Daily heating hours	Heating set point temperature	Cooling hours	Cooling set point temperature	Artificial lighting	Equipment use
Selected mode	MOD_3	MOD_2	MOD_3	MOD_2	MOD_1	MOD_1

Table 18. Annual energy balance for different modes of windows opening. **V** verified, **X** no verified.

Windows opening	**OCS_A**		**OCS_B**	
	Energy balance [kWh/year]	nZEB	Energy balance [kWh/year]	nZEB
MOD_1	150,53	V	803,93	V
MOD_2	81,62	V	773,37	V
MOD_3	-560,76	X	381,38	V
MOD_4	-1243,81	X	-8,24	X

The net energy balance substantially reduces at the increasing of ventilation until becoming negative. In particular, the MOD_4 doesn't meet the nZEB target for any occupancy scenarios. This ventilation modality is particularly disadvantageous because the windows opening takes place during the hours in which the heating and cooling systems are active.

3.6. Artificial lighting

Table 19 shows the configuration of the other variables when the artificial lighting is studied.

Table 19. Setting for the other variables when artificial lighting is analyzed.

Variables	**Daily heating hours**	**Heating set point temperature**	**Cooling hours**	**Cooling set point temperature**	**Windows opening**	**Equipment use**
Selected mode	MOD_3	MOD_2	MOD_3	MOD_2	MOD_1	MOD_1

Electric consumption for lighting can greatly affect the energy balance of a nearly zero energy building. In these building, indeed, the consumption for heating and cooling is minimized. Therefore, the consumption related to the other services (generally lighting and appliances that are strongly linked to the users' habits) tend to assume increasing importance. The results in table 20 prove that a careless use of artificial light can lead to a significant increase in electrical consumption, up to spend more than the produced amount of electricity. Thus, in the operating of an nZEB, a profitable exploitation of the natural light is recommended.

Table 20. Annual energy balance for different modes of artificial lighting use. **V** verified, **X** no verified.

Artificial lighting	**OCS_A**		**OCS_B**	
	Energy balance [kWh/year]	nZEB	Energy balance [kWh/year]	nZEB
MOD_1	150,53	V	803,93	V
MOD_2	-53,75	X	686,96	V
MOD_3	-256,91	X	536,23	V
MOD_4	-609,56	X	334,34	V

3.7. Equipment use

Table 21 synthesizes the setting of the variables utilized to carry out the analysis of equipment use.

Table 21. Setting for other variables when equipment use is analyzed.

Variables	Daily heating hours	Heating set point temperature	Cooling hours	Cooling set point temperature	Windows opening	Artificial lighting
Selected mode	MOD_3	MOD_2	MOD_3	MOD_2	MOD_1	MOD_1

Table 22. Annual energy balance for different equipment modes of use. **V** verified, **X** no verified.

Equipment use	**OCS_A**		**OCS_B**	
	Energy balance [kWh/year]	nZEB	Energy balance [kWh/year]	nZEB
MOD_1	150,53	V	803,93	V
MOD_2	-3,33	X	693,33	V
MOD_3	-293,66	X	449,66	V
MOD_4	-628,87	X	221,85	V

The results contained in table 22 demonstrate that, similarly to the artificial lighting, an improper use of any equipment powered by electricity can result in unexpected balance.

4. Discussion

The net energy balance of a building depends on the real use of the house. For the analyzed case, if the dwelling is occupied by a four member family using all the rooms, the net energy balance could be negative for some mode of use. If the house is occupied by only two people, there are more chances for a positive balance, because energy services (heating, cooling, lighting, and appliances, ..) are limited to a fewer number of rooms.

If the building is appropriately designed regarding constructive features, the heating/cooling consumption accounts for little on energy balance and the occupants have a large degree of freedom in the operation of conditioning system.

On the other hand, ventilation, lighting, and equipment usage, have a high impact on energy consumption. Therefore, a careful control of these parameters is essential.

Generally, to address the problem due to an improper mode of the windows opening, low energy buildings are equipped with mechanical ventilation systems. Nevertheless, this solution is not very appreciated in residential building, particularly in Mediterranean regions, characterized by temperate/warm climatic conditions, because the impossibility to open the windows gives to the occupants a feeling of confinement. With regard to the lighting and equipment, electrical consumption for these uses could be limited adopting low-energy appliances and high-efficiency lighting (for example LEDs). Moreover, an aware use by the occupants is clearly requested.

5. Conclusions

A residential building was designed to be a nearly zero energy building. The envelope, both for the opaque components and the glazed surfaces, presents a very low thermal transmittance. The configuration of the building is planned to maximize solar gains, avoiding overheating in summer. Renewable sources, photovoltaic modules, and thermal collectors, are integrated for the production of energy in site, as dictated by the law. Two different occupancy scenarios were prefigured, and several modes of use by the occupants were analyzed. The assessments prove that the energy balance is strongly related to the actual use by the occupants, who can prefer different choices from the design assumptions.

For this reason, in order to make a building really nZEB, different strategies can be identified:

1. The building is designed with a wide confidence margin, enabling it to cover with own resources also the unexpected and unpredicted consumption;
2. The freedom of the users in managing the house is restricted in order to not affect the energy efficiency of the building;
3. Smart control systems are provided in order to:
    - actively interact with the users
    - advice incorrect utilizations
    - allow a constant monitoring of the consumption, even remotely
    - ensure comfort conditions and simultaneously optimize energy use.

Recent regulatory measures are aimed at promoting the last option.

Finally, it should be pointed out that in this paper only the independent variation of each parameter was considered, but in practice all the variables interact together. Also, the variability in the use of domestic hot water was not considered. Future studies will attempt to address these issues considering the combination of all modes of use and the influence of DHW uses, in order to analyze more deeply the effect of occupants' behavior on the energy balance of an nZEB.

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5.3 Behavioral variables and occupancy patterns in the design and modeling of Nearly Zero Energy Buildings

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Abstract

The objective of obtaining high performance energy buildings can be reached considering the contemporaneous effects of technical characteristics and occupancy. Recent studies report that as buildings become more energy efficient, the behavior of occupants plays an increasing role in consumption. Therefore, a construction designed to be a Nearly Zero Energy Building (nZEB) might generate higher consumption than expected if the assumptions made in the simulation process are not respected during the real use. The occupant can modify the control strategies of internal variables (heating/cooling system operation, set-point temperature, ventilation, lighting) and the users' behavior has a high impact on the utilization of plants and equipment. A significant contribution is also represented by the internal gains that have a direct relation with occupancy. The aim of this study is to assess the influence of housing occupancy patterns on the definition of residential nZEB in Italian climatic conditions.The investigation has been carried out considering a case study consisting of a building designed according to the National Standards. Successively, different conditions of the building usage are analyzed using dynamic energy simulations that allow exploration of the different occupation modes. The variability of the family composition and the occupancy scenarios are defined based on the data collected in the specific context. The investigation provides information regarding the effects of human variables (occupants' needs and preferences) on the final energy performance of low energy buildings and highlights the combination of variables that are important in the definition of nZEB as net zero source energy.

Keywords: Zero energy building, occupant behavior, occupancy profiles, electricity consumption

1. Introduction

According to European Policies, from the end of 2020, all new buildings will be nearly zero-energy buildings (Directive 2010/31/EU). In Europe, the built environment consumes 40% of the produced energy. An increase of building energy performance can constitute a valuable instrument in the efforts to mitigate the EU energy import dependency (currently at about 48%) and comply with the Kyoto Protocol to reduce carbon dioxide emissions. Italy is one of the four countries of EU member states with a higher final energy consumption in the residential and tertiary buildings (Poel et al. 2007). In Italy, out of a total energy use in 2013 of 126.6 Mtoe, the residential and services sector employed 49.6 Mtoe or 39.1% of the total energy use (ENEA 2015). The 2010/31/EU Directive dictates the Near Zero Energy (nZEB) as the Standard for the new buildings; this means that the "nearly zero or very low amount of energy” required by the building should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced either on-site or nearby (Directive 2010/31/EU). To make a building highly energy efficient, careful design aimed to reduce the energy consumption and to optimize the construction is required. In addition to technical characteristics, operation and maintenance of the building and the action of users are essential. Following this proposal, it is very important to define criteria to be applied in order to reach the goal of nZEB. According to the framework proposed by Sartori et al. (2012), the common denominator for the different possible nZEB definitions is the balance between weighted demand and supply.The general definition proposed by Torcellini et al. (2006) is a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied by renewable technologies. The concept of a zero-energy building can be defined in some ways, determined by the boundary and the metric. Four of the most used definitions are: net zero site energy, net zero source energy, net zero energy costs, and net zero energy emissions. A building may be designed to achieve one or more nZEB definition, but may not reach a net-zero energy position in operation every year. Williams et al. (2016) emphasize the importance of having an international universal zero energy Standard because, while the definition of zero carbon buildings can be relevant, actually the number of buildings built has been small and uncommon, and, moreover, the specific requirements have not been stipulated (Mlecnik et al. 2012).

On the other hand, it is necessary to understand how people behave and how they operate the systems for controlling indoor environment and comfort conditions (Frontczak and Wargocki 2011). Now, with the implementation of new technologies oriented to energy saving and green building certifications, a new approach has emerged and is related to how it affects the use of energy due to occupant behavior (IEA 2015). Recent studies report that as buildings become more energy efficient, the behavior of occupants plays an increasing role in consumption (Yan et al. 2015; de Wilde 2014; Wei et al. 2014). The passive and active effects of the occupant interactions with the building have to be taken into consideration. More emphasis on nZEB is required because these are primarily heated by the sun, the users’ metabolic heat (called passive effect) and by heat emitted from domestic electrical appliances (called active effect). Wei et al. (2014) identified 27 factors influencing occupant space-heating behavior and demonstrated the relevance of the factors related to the users described as occupant age, occupant gender, household size and others. The authors (de Meester et al. 2013) evaluated the influence of three parameters about human behavior (family size, management of the heating system and heated area) and the results showed the importance of the insulation levels in Belgian climatic conditions. Martinaitis et al. (2015) investigated the importance of occupancy information through dynamic energy simulation, varying occupancy profiles (standard profile, household consists of 4 persons, retired couple, and young couple), heating strategies, ventilation and lighting control and evaluated the influence of climate. The results in terms of primary energy demand for the occupancy profile of 4 persons reveal differences below 5% compared with the standard profile, while for the other two profiles it varied from 14% to 21% in relation to the default profile. The influence of dwelling and occupant characteristics on domestic electricity consumption patterns was analyzed by statistical approaches in (McLoughlin et al. 2012). The authors found that dwelling type, number of bedrooms, and household composition had a significant influence on the total domestic electricity consumption. Furthermore, Chen et al. (2013) determined that occupant age is a more important factor than income and revealed that the household socio-economic and behavior variables can explain 28.8% of the variation in heating and cooling energy consumption.

Some studies on the effect of occupant behavior in nZEB have been specifically developed. Barthelmes et al. (2016) investigated a residential nZEB located in Northern Italy by means of energy simulations. The authors took into consideration different occupant behavior lifestyles (low consumer, standard consumer and high consumer) and household composition (family of 4 people, old couple and young couple) to evaluate their effect on energy performance and thermal comfort conditions. The high impact of these two variables was demonstrated. Also, it was concluded that the variation of different types of households increases the discrepancy of the final energy consumption in the several scenarios (~240%). Brahme et al. (2009) compared the impact of occupant behavior of a typical and high efficiency residence. They considered three profiles of users (conservation behavior, design point, and wasteful behavior) and concluded that conservation oriented behavior could reduce energy consumption by nearly half in a high efficiency residence. Love (2012) examined the impact of different occupant heating behaviors on a typical semi-detached UK dwelling. The researchers evaluated three different behaviors scenarios (low, middle and high) and three aspects were defined: set point temperature, number of heated rooms, and daily heating periods. They found applicable results about policy regarding the occupant effect in inefficient dwellings and the necessity of selecting the right policies and behavioral change programs.

Some authors considered the effects of occupant variables in high energy efficiency buildings. Mlecnik et al. (2012) conducted end-user surveys of low-energy houses in Germany, Switzerland, and Austria to determine levels of satisfaction, considering various comfort parameters such as winter thermal comfort, summer thermal comfort, indoor air quality, and acoustics with the intention to provide recommendations for the improvement of quality and comfort and promoting nearly zero-energy dwellings. The main problems reported are related to the perception of insufficient summer comfort and/or air quality. Lenoir et al. (2011) presented a study regarding the importance of the user's behavior to calculate the energy consumption in high-performance buildings taking into consideration measurements during the operation of the building for parameters such as ventilation and air-conditioning, lighting, plug loads and UPS (Uninterruptible Power Supply), lifts and ceiling fans and compared with data obtained during design phase. From this comparison, the authors concluded that the differences between the design calculations and the measurements can be up to 50%. There are further examples available in literature that demonstrated that a construction designed to be a Nearly Zero Energy Building might generate higher consumption than expected if the assumptions made in the simulation process are not respected during the effective use.

Becchio et al. (2016) evaluated the energy performance of a high-performance building in the Italian context and identified a large difference between the energy consumptions calculated during the design phase and the monitored phase: +50% for space heating, +19% for DHW and +16% for electricity uses. The authors concluded that these differences were not related to the building features, but, instead, to the occupant behaviors. A study developed in the UK (Gill et al. 2010) on a site of 26 'low energy' dwellings evaluated the energy performance of the buildings in terms of water and electricity consumption, and the comfort of users. The authors identified differences in consumption of similar homes by using behavioral surveys and statistical analysis. The researchers found that energy-efficient behaviors account for 51%, 37%, and 11% of the variance in heat, electricity, and water consumption, respectively. In fact, in order for the occupant to reach his comfort condition, he can modify control parameters (thermostat set point, ventilation rate, lighting level and equipment use) invalidating the ideal designed efficient model. For this reason, it is essential to establish the right hypotheses on the air conditioning schedule, utilization of appliances, and comfort level of the building in order to obtain a proper evaluation of the energy consumed in the actual building operation. In nZEB, indoor comfort (thermal and visual) should be achieved mainly thanks to free resources of energy such as solar radiation and natural ventilation. Consequently, the users' behavior has a high impact on the final energy use depending on the correct utilization of passive systems and the operating of active technologies. In low energy buildings, a significant contribution is also represented by the internal gains, and these have a direct relation with the users' behavior and occupancy. The role of the occupant in the building performance and in the resident's perception of low energy homes is not yet known (Berry et al. 2014; Judd et al. 2013). Marshall et al. (2016), investigated how occupancy patterns affect domestic energy consumption and energy savings for a broad range of Energy Efficiency Measures (EEMs), and the results explain that energy consumption depends on the appropriate matching between energy efficiency measurements and occupant type. Brandemuehl and Field (2011) studied the effect of occupant behavior in residential nZEB located in different states of the United States to evaluate the effect of house type and climate in the ability to achieve a zero energy goal. The comparison between a conventional single-family residence and a very energy efficient single-family residence confirmed that random fluctuations in the schedules and the level of miscellaneous electrical loads have the highest influence on the second group. Murano et al. (2016) demonstrated that the effect of the outdoor climatic data is an important factor in the evaluation of the energy performance of building and is crucial for nZEB.

The aim of this paper is to evaluate the influence of user patterns on the energy consumption of a residential nZEB in Mediterranean climatic conditions. Furthermore, the investigation takes into account the socio-demographic context by means of the collection and accurate analysis of national and local statistical data. The definition used to develop the building model is net zero source energy and a case study was built according to the CEN. EN ISO 13790 (2008) and European Directive (Directive 2010/31/EU) that have been applied by considering its transposition in National Standards (UNI TS 11300-1; UNI TS 11300-2 2014) and Regulations (D.M. 26/6/2015-1). The study considers the variability of the family composition and the occupancy scenarios. Furthermore, the needs and preferences of occupants in using energy systems and equipment are included in the energy performance assessment. The investigation was conducted by considering important aspects contemporaneously: nZEB definition and technical issues, application of Standards and Regulations that do not consider the "occupancy" variable in their formulation, adaptability of renewable energy systems in relation with the occupancy profiles, identification of a simple method for creating housing occupancy patterns by using free available data.

2. Methodology

An energy efficient building was designed according to the Italian Standard (D.M. 26/6/2015-1). The construction was intended to consume low energy: the ratio between dispersing surface and air conditioning volume is set to minimize losses, all the housing components are well insulated, the air conditioning system has high efficiency and uses energy from renewable sources available on site. However, the actual consumption for the management of the house depends on the type of family occupying the dwelling and on the interaction of the occupants with it. Two different occupancy scenarios, defined according to statistical data (ISTAT 2014), were proposed in order to understand how the occupancy typology and the various modes of use of the house and its facilities can affect energy consumption. For each occupancy scenario and mode of use, the annual energy balance in terms of primary energy (kWh/m^{2}year) was considered with the aim of verifying the achievement of the nZEB objective. Dynamic energy simulations were carried out by using DesignBuilder (2015). Regarding climatic conditions, (Meteonorm) file for the City of Cosenza, Calabria Region (South Italy) was adopted. The site, classified as "Csa" according to the Köppen climate classification (Kottek et al. 2006) is characterized by a typically Mediterranean climate, with hot and dry summers and mild, wet winters, resulting in a dominant cooling demand. The mean annual value of the outdoor dry bulb temperature is equal to 16.3 °C; the direct normal solar radiation is 1564.8 kWh/year and the diffuse solar radiation on the horizontal plane is 613.8 kWh/year. The heating system functions from 15th November to 31st March, according to Italian Regulations for climatic zone C (HDD=1317), in which Cosenza is located (DPR 412 1993). The cooling season is comprised of the remaining months, and the cooling system operates only when the internal temperature exceeds the set-point value.

2.1 The building design

The building is a two storey detached house with a total net area of 110 m^2. The ground floor consists of the living area while bedrooms are on the first floor. The building is characterized by a low surface area to volume ratio (S/V=0.82 m^{-1}) in order to reduce heat losses. The main exposure is to the South and presents wide glazed surfaces to maximize solar gains in winter. The window to wall ratio is 27% on the south wall and horizontal louvers on the windows prevent overheating in summer. The roof is flat with an additional architectural element that fits with the main volume and provides a 30° tilted pitched roof suitable for the installation of solar systems. Figure 1 illustrates the plans of the two storey house while the DesignBuilder (2015) model is presented in Figure 2.

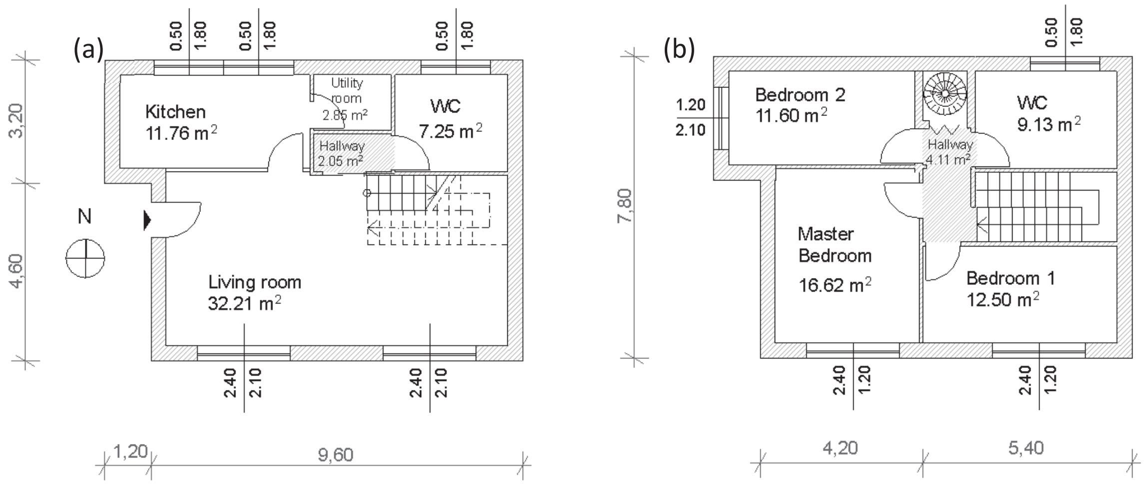

Fig. 1 Detached house plans: (a) ground floor and (b) first floor

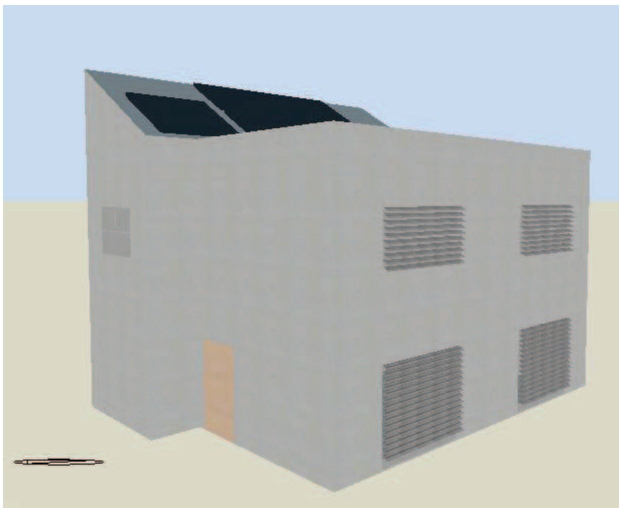

Fig. 2 DesignBuilder model of the designed nZEB

The structure is in masonry, and the external walls are in thermal bricks with exterior insulation and finishing system; the total thickness is 43 cm. The ground slab and the roof are also thermally insulated, with a total thickness of 34 cm and 35 cm, respectively. Characteristics of the building envelope are analyzed in terms of thermal transmittance U [W/m^{2}K]. For external walls and roof, exposed to solar radiation, also the thermal mass Ms [Kg/m^2] and time lag φ [h], are reported (Table 1).

Table 1 Characteristics of the opaque components of the building envelope

	U [W/m²K]	M_s [Kg/m²]	φ [h]
External walls	0.225	321	23.63
Ground slab	0.305	-	-
Roof	0.285	271	9.61

Window frames are metallic with thermal break. For the South and West exposures, Low-e double glass with Argon are used, while North facing windows use Low-e triple glass with Argon. In Table 2, the thermal transmittance (U), the solar heat gain coefficient (SHGC), and the visible transmittance (VT) of the windows are shown.

Table 2 Characteristics of the windows

	U [W/m²K]	SHGC	VT
South and West facing windows	1.873	0.670	0.540
North facing windows	1.546	0.512	0.680

The infiltration flow rate of 0.3 ach was assumed according to UNI TS 11300-1 (2014). The total value of the internal gains is calculated with the relation (UNI TS 11300-1 2014):

$$\Phi_{int} = 7.987\ A_f - 0.353\ A_f^2 \quad [W] \quad (1)$$

Where A_f is the net floor area of the dwelling. An internal load of 4.104 W/m² is obtained.

The air conditioning system consists of an electric air to water heat pump with a coefficient of performance (COP) equal to 3, and an energy efficiency ratio (EER) of 3. Fan coil units are used for both the heating and the cooling seasons. A photovoltaic system provides electricity production on-site. Ten grid-connected modules are assembled in two strings, with a total installed peak power of 2.5 kWp. A 3 kW inverter is used. Its efficiency was fixed to 0.90, lower than the maximum value (0.95) in order to consider the degrading effect which takes place when operating at low power levels. PV characteristics are shown in Table 3.

Table 3 Technical characteristics of the PV modules

Typology	Absorption area [m²]	Maximum power at STC (Pmax) [W]	Module efficiency η_m [%]
Polycrystalline silicon PV panel	1.48	250	15.2

Solar collectors, with characteristics illustrated in Table 4, are used for the DHW production. A total absorbing surface of 4 m² is installed with reference to a DHW requirement of 1.40 l/m²day, calculated according to the Standard UNI TS 11300-2 (2014) and a 300 l storage tank is provided. Both solar collectors and PV modules are in adherence to the pitched roof with a slope of 30° and south facing in order to maximize productivity. In Table 5 the main features of the building energy model are summarized.

Table 4 Technical characteristics of the solar collectors

Typology	**Absorption area [m²]**	**Efficiency η_0[%]**	**Coefficient of heat loss k_1 [W/m²K]**	**Coefficient of heat loss k_2 [W/m²K²]**
Flat plate solar collector with selective coating	1.97	70.2	-3.2828	-0.00992

Table 5 Summary of the designed building energy model

Net surface area	110 m²
Number of floors	2
Total dispersing surface (S)	405.96 m²
Gross air conditioned volume (V)	492.75 m³
S/V	0.82
Window to wall ratio (South)	27.5 %
Window to wall ratio (West)	4.1 %
Window to wall ratio (North)	4.2 %
Infiltration rate	0.3 ach
Internal loads	4.104 W/m²
Heating/cooling system	Electric air to water heat pump with fan coils
Solar collector surface area	4 m²
Photovoltaic power peak	2.5 kW_p
Photovoltaic surface area	14.78 m²

2.1.1 nZEB design according to the Italian Standard

According to the Regulations currently in force in Italy, a nearly zero energy building is a building, whether existing or newly built, meeting specific technical requirements (D.M. 26/6/2015-1):

1) $H'_T < H'_{T,lim}$

H'_T represents the mean heat transfer coefficient, calculated by the relation:

$$H'_T = H_{tr,adj} / \sum_k A_k \; [W/m^2K] \quad (2)$$

$H_{tr,adj}$ is the global heat transfer coefficient of the building envelope calculated with reference to the Standard UNI TS 11300-1 (2014), A_k is the k[th] component surface of the envelope.

The value of the parameter H'_T must be lower than a limit value, defined according to the climatic zone and the S/V ratio. For the designed model, located in the climatic zone C and having an S/V ratio equal to 0.8, $H'_{T,lim}$ is equal to 0.55 W/m²K while the calculate value of H'_T is 0.37 W/m²K. Therefore, the first requirement is satisfied.

2) $(A_{sun}/A_{us}) < (A_{sun}/A_{us})_{lim}$ (3)

A_{sun} is the sum of the solar summer equivalent areas determined for each window with the relation:

$$A_{sun} = \sum_k F_{sh,ob} \cdot g_{gl+sh} \cdot (1 - F_F) \cdot A_{w,p} \cdot F_{sun} \; [m^2] \quad (4)$$

$F_{sh,ob}$ is the reduction factor for shading related to the external elements for the solar collection area of the k^{th} window, for the month of July.

g_{gl+sh} is the total solar energy transmittance of the window calculated in July, when the solar shading is applied.

F_F is the fraction area of the frame, obtained by the ratio between the area of the frame and the total area of the window;

$A_{w,p}$ is the window area;

F_{sun} is the correction factor for the incident radiation, derived as the ratio of the average irradiance in July, for the location and for the considered exposure, and the average annual irradiance of Rome, on the horizontal plane.

The Standards UNI TS 11300-1 (2014) and UNI 10349 (1994) provide all these terms.

A_{us} represents the useful floor area of the dwelling [m^2].

The limit value of this parameter is established by the regulation equal to 0.30 while the calculated value for the building is 0.022.

3) The performance indices:

$EP_{H,nd}$ – useful thermal performance index for winter conditioning [kWh/m^2year]

$EP_{C,nd}$ – useful thermal performance index for summer conditioning [kWh/m^2year]

$EP_{gl,tot}$ – global energy performance index [kWh/m^2year]

must be lower than the value of the same indices calculated for a reference building.

Table 6 summarizes the results obtained for the energy performance indices of the designed building, compared with the respective limit values.

Table 6 Energy performance indices of the designed building and limit values [kWh/m^2year]

$EP_{H,nd}$	$EP_{H,nd,lim}$	$EP_{C,nd}$	$EP_{C,nd,lim}$	$EP_{gl,tot}$	$EP_{gl,tot,lim}$
18.9	30.1	13.5	13.7	50.7	91.6

4) The efficiencies of the heating, cooling and hot water systems (η_H, η_C, η_W) must be higher than the limit values ($\eta_{H,lim}$, $\eta_{C,lim}$, $\eta_{W,lim}$).

In Table 7 the efficiency of the adopted plants is reported together with the efficiencies of the reference systems.

Table 7 Efficiency of the adopted plants and limit values

η_H	$\eta_{H,lim}$	η_C	$\eta_{C,lim}$	η_W	$\eta_{W,lim}$
0.9	0.6	2.2	0.9	0.6	0.5

5) Finally, a given amount of energy produced from renewable sources for electricity, domestic hot water (DHW), heating and cooling must be fulfilled. In particular, energy from renewable sources

should cover 50% of the DHW consumption, and the minimum installation is of 2 kW per 100 m^2 of photovoltaic peak power is required (D.Lgs. 28/2011). Both the solar thermal and the photovoltaic system have been sized in compliance with these minimum requirements.

2.2 Occupancy scenarios and house management

The building is now defined by its physical characteristics and it is classified as nZEB according to the Italian Standard. However, different types of households could occupy the house. Moreover, the family members, following their typical habits and needs, may decide to use the amenities of the dwelling differently. Therefore, the actual consumption of the building may differ from that estimated, negating the “zero” balance. In order to analyze the variability of consumption under different types of occupancy, the use of the house by different family typologies has been supposed. Two occupancy scenarios have been created from statistical data, describing the socio-demographic situation of the concerned area. Data regarding the “family structure” provided by the National Institute of Statistics ISTAT (2014) report that in the region of Calabria, four component households account for the majority in families with children, representing 46% of the total in the last two years. Consequently, the first selected scenario for the occupancy of the house consists of a four member family (F4); in this case, all the rooms of the house are generally occupied.

The second scenario has been assumed considering that the house could be inhabited by a two member family (F2), for example, a young couple that occupies only a few rooms in the house, while others are not used. Figure 3 displays the management of the rooms in the two different occupancy scenarios.

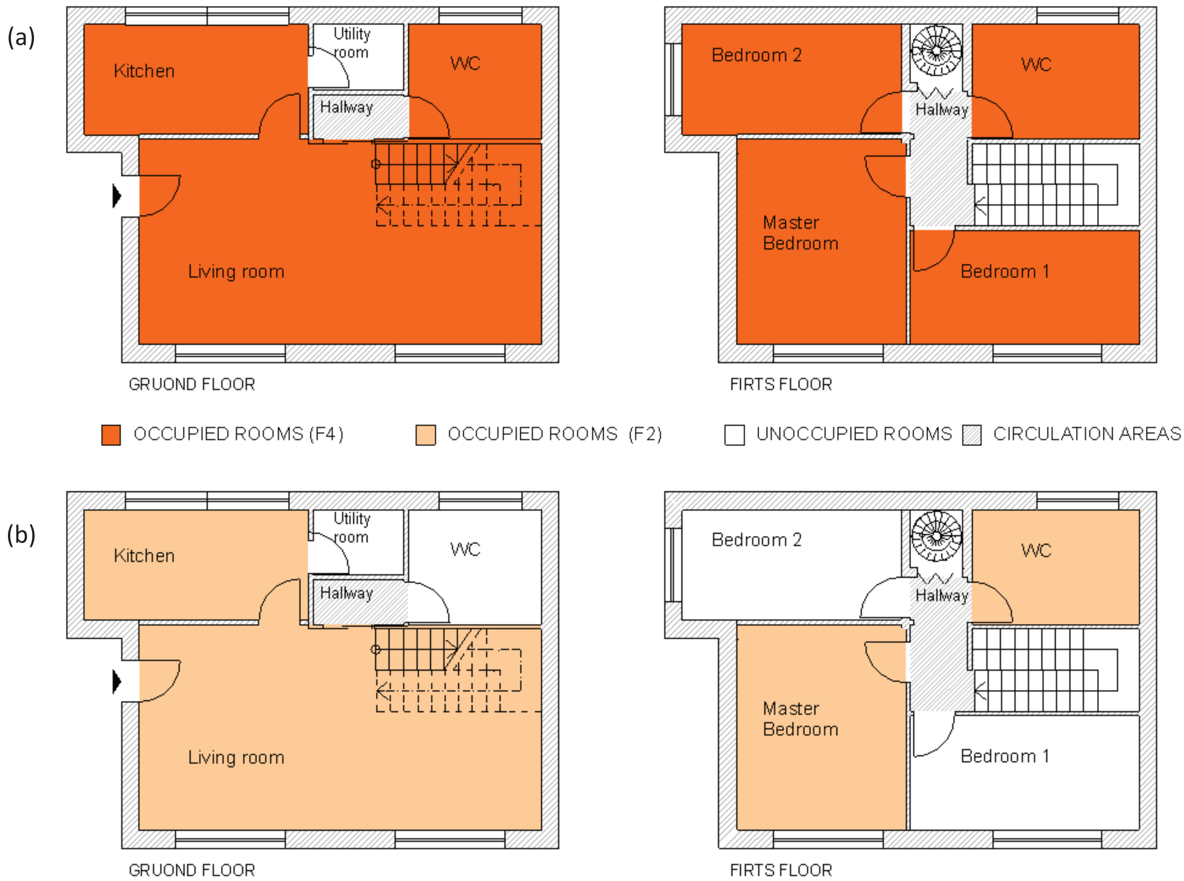

Fig. 3 Use of the dwelling in occupancy scenario F4 (a) and occupancy scenario F2 (b)

2.2.1 *Occupancy profiles*

Occupancy density (person/m^2) is calculated for each room and varies according to the number of components. To define how much time people spend at home, data on time use provided by ISTAT (2014) have been examined. The respondents reported the daily time dedicated to different activities for each interval of 10 minutes. In particular, investigations on the activities were carried out and allowed for identification of the total number of hours that a person spends on average at home, in relation to the size of the family. With reference to a "weekly average day", a person spends on average 16 hours per day at home for a family of four, while 17 hours per day are spent at home in the case of a two member household. Data showing the frequency of people participation in the frequented places have been considered to identify the periods of time during the day when people are at home (see Figure 4).

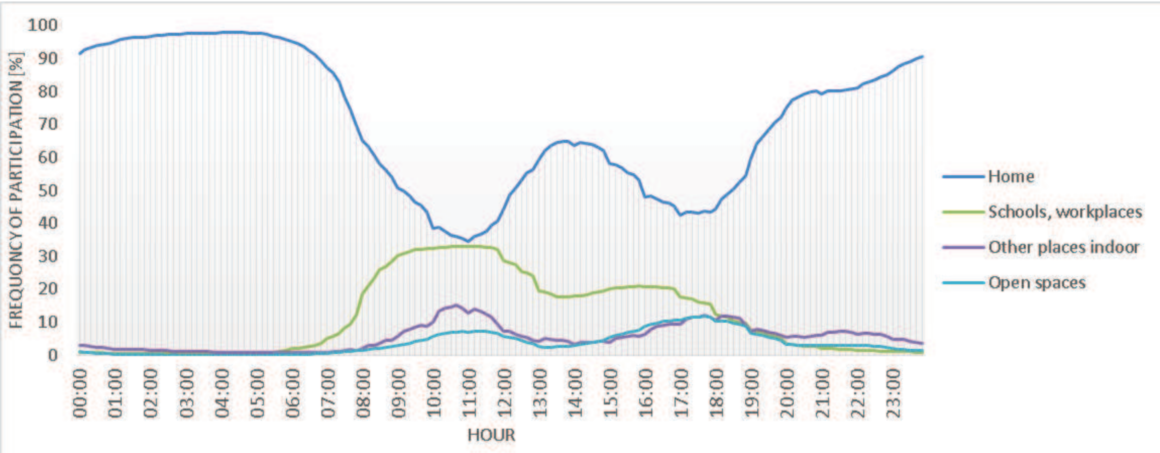

Fig. 4 Frequency of participation of people to the places frequented in a weekly average day (Istat, 2014)

The time ranges reveal that the greatest percentage of people at home is overnight and in the early morning, in two hours at lunch, and in the evening after 7 p.m. Combining the information about the number of hours of presence at home and the most populated time bands, occupancy profiles for the average weekly day have been constructed for both F4 and F2 scenarios, as shown in Figure 5.

Fig. 5 Occupancy profiles for the F4 (a) and F2 (b) occupancy scenarios for an average weekly day

2.2.2 Lighting

Statistical data (Istat, 2014b) show that for the considered geographic area, artificial lighting is used on average less than four hours per day (about 75%). 22% of people use artificial lights from 4 to 12 hours per day and only a very small fraction (3%) turns on the lights for more than 12 hours per day. Consistently, in the designed building the use of artificial lighting has been set at less than four hours in each room. Furthermore, two types of lighting have been analyzed in the study: traditional light bulbs, for example halogen bulbs, with a lighting power density (LPD) equal to 10.2 W/m^2, and energy saving light bulbs, such as compact fluorescent lights (LPD=7.5 W/m^2).

2.2.3 Equipment

The provision of dwelling appliances is typical of a contemporary house (Istat, 2014b). The appliance typology and positioning for both the family compositions is shown in Table 8.

Table 8 Equipment positioning and usage for the considered families F4 and F2

Room	Equipment	Equipment power density [W/m^2]		F4		F2	
		Label A	Label G	Frequency of use	Hours of use	Frequency of use	Hours of use
Kitchen	Fridge-freezer	3.25	8.13	Every day	Always ON	Every day	Always ON
	Oven	71.24	160.28	2 times per week	1 hour	1 time per week	1 hour
	Dishwasher	89.05	222.62	6 times per week	1 hour	4 times per week	1 hour
	Vacuum cleaner	89.05		1 time per week	0.083 hour	1 time per week	0.083 hours
Living room	Stand-by	0.13		Every day	Always ON	Every day	Always ON
	TV 40" + decoder	2.26	7.53	Every day	4 hours	Every day	4 hours
	Iron	38.95		1 times per week	0.5 hour	1 time per week	0.25 hour
	Vacuum cleaner	25.97		1 time per week	0.083 hour	1 time per week	0.083 hour
WC ground floor	Hairdryer	224.55		Every day	0.16 hour	-	-
Master bedroom	Stand-by	0.19		Every day	Always ON	-	-
	TV 32"	2.48	8.51	1 time per week	1 hour	-	-
	Vacuum cleaner	62.15		1 time per week	0.083 hour	1 time per week	0.083 hour
Bedroom 1	Vacuum cleaner	82.78		1 time per week	0.083 hour	-	-
Bedroom 2	Laptop	3.12		Weekdays	1 hour	-	-
	Vacuum cleaner	89.05		1 time per week	0.083 hour	-	-
WC first floor	Washing machine	273.99	554.91	6 times per week	1 hour	3 times per week	1 hour
	Hairdryer	173.41		Every day	0.16 hour	Every day	0.16 hour

The frequency and hours of use were defined by considering available statistical data. In particular, the ISTAT survey reveals the use of the washing machine and the dishwasher on variation of the family size, as illustrated in Figure 6.

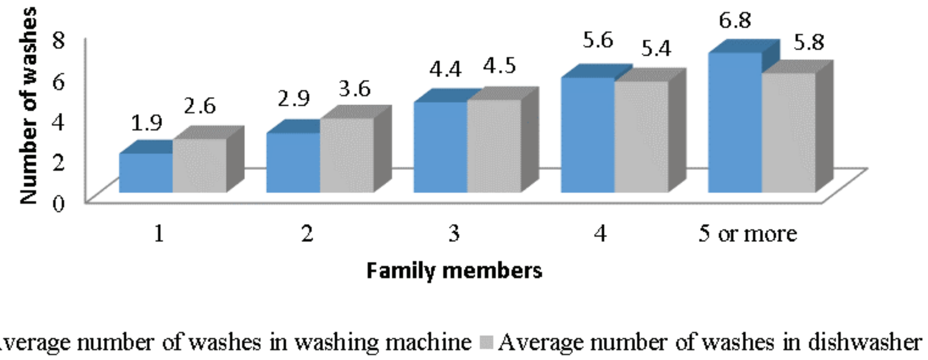

Fig. 6 Average number of washing machine and dishwashing washings per week, at the variation of the number of family members (Istat, 2014b)

Generally, a family of four components, on average, does about six washing machine and dishwasher washings per week, while a two member family uses the washing machine three times per week, and the dishwasher four times per week.

Since the building is expected to be zero energy, the installation of low energy appliances is suggested. However, in order to evaluate the influence of the energy efficiency of the equipment on the annual consumption of the house, the use of different energy labeled household appliances has been analyzed (see Table 8), considering different levels of energy efficiency for appliances for which energy labelling is mandatory (Council Directive 92/75/EEC 1992; ENEA 2013).

2.2.4 Heating and cooling system

Settings on the operation of the heating and cooling systems have been made according to statistical information for the considered climatic conditions (Istat, 2014b).

The heating system, on average, is switched on for about seven hours per day, while the cooling system operates four hours per day. The hourly distributions are shown in Figure 7.

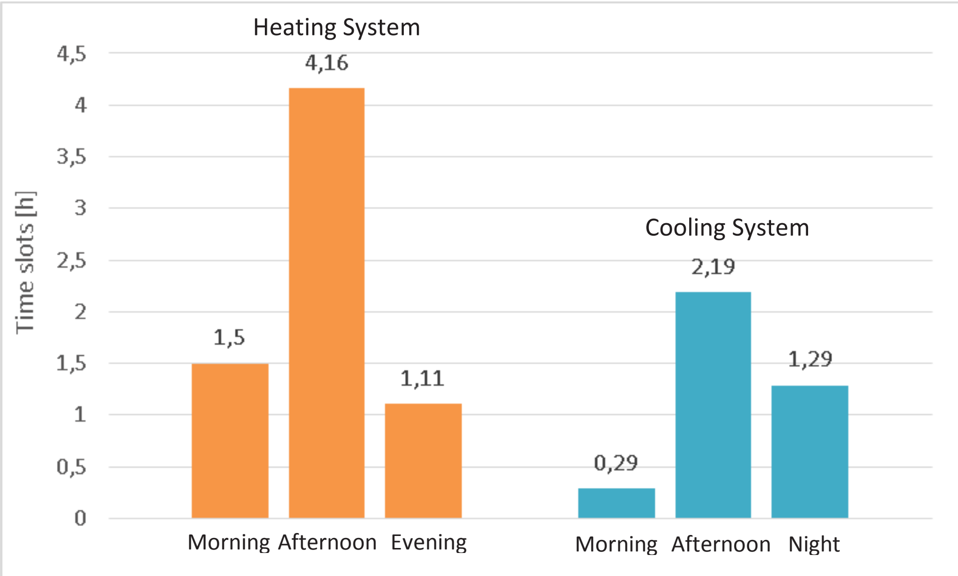

Fig. 7 Average daily hours per time slot of operation of the heating and cooling system for winter day and summer day (Istat, 2014b)

2.2.5 DHW production

The demand of domestic hot water has been fixed in 60 l/day per person (Engineering & Construction 2010), with 55 °C hot-water temperature production. The solar system is prioritized for the production of the DHW. However, an integration system is provided to satisfy the DHW demand when the solar source is not sufficient, consisting of an electrical resistance with a maximum heater capacity of 1.5 kW installed in the 300 liter storage tank.

3. Behavioral variables

Thanks to statistical information from the Italian National Institute for Statistics (ISTAT 2014), two occupancy profiles have been formulated. Therefore, the use of the house by families with diverse sizes implicates differences in the number of rooms generally used and in the occupancy density of each room. Also, the utilization of heating and cooling systems, DHW, lighting, and household appliances has been defined.

However, variables related to the users' choices regarding heating and cooling set point temperature, and ventilation control strategies are not provided by the statistical survey. With reference to these variables, occupants can behave differently in the house management. In particular, a category of users could have a more aware behavior aimed at saving energy. On the other hand, users could also have a wasteful behavior, without caring about the amount of energy spent and often persisting in squandering habits. In many studies considering different occupancy profiles in energy consumption investigations, differences in baseline temperature assumptions were considered to assess their impact. Set-point temperatures have been chosen by individual approaches, such as starting from values of local Standards (Martinaitis et al. 2015), in other cases the set point values were estimated by means of contextual data (Hong and Lin 2012; Barthelmes et al. 2016).

In order to analyze the impact of occupants preference on final energy consumption, and therefore, on actual building nZEB performance, different behaviors have been analyzed for both F4 and F2 family models. The set point temperatures were established by assuming the reference values indicated in the Standards and Regulations (UNI TS 11300-1 2014) in order to define the medium profile. Saver and Waster behaviors were obtained by considering lower and higher set point temperature values, respectively.

- Saver – "S": set point temperature is 19 °C for heating and 27 °C for cooling. Ventilation takes place when the plant is switched off: half an hour before turning on the system in the morning in the bedroom area and half an hour before turning on the system in the afternoon in the living area.
- Medium – "M": heating set point temperature is 20 °C, while cooling set point temperature is 26 °C. Ventilation is the same for all areas, from 7:00 to 8:00 in the morning and in all the rooms, and it overlaps in part with the period when the plant is switched on.
- Waster – "W": the user who does not care about energy saving sets the heating temperature at 23 °C and the cooling temperature at 24 °C. He opens the windows when the system is operating.

Both family compositions have been simulated with the three occupants' behaviors typologies and considering, alternatively, the installation of traditional or low energy consumption appliances and lights.

4. Results and discussion

The designed house is an "all-electric" building; no fossil sources are used to satisfy the energy services provided to the dwelling. The PV plant produces 3383 kWh/year. In order to verify whether the building performs at the zero-energy definition, the annual net energy balance between the consumed electricity and the electricity produced through the on-site photovoltaic system has been considered.

Figure 8 shows the annual energy balance carried out for all the analyzed scenarios.

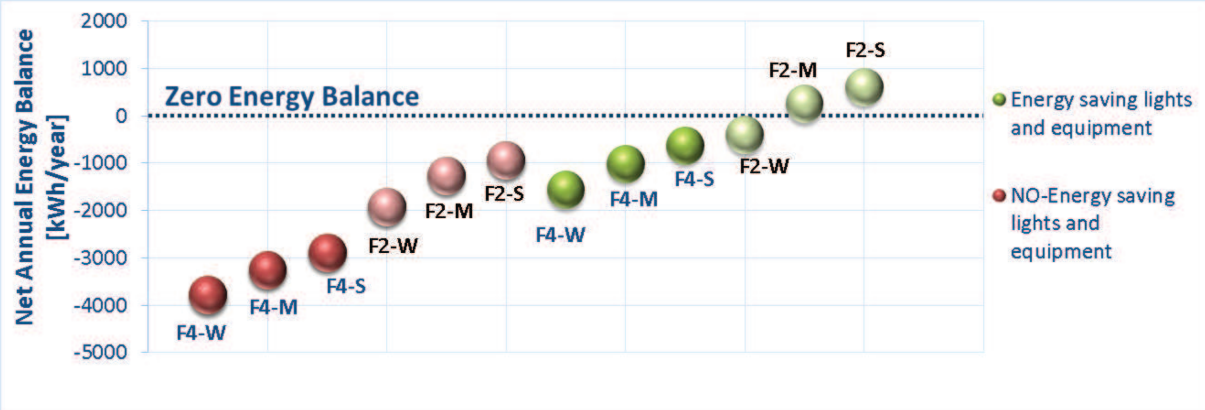

Fig. 8 Net annual energy balance of the building for the F4 and F2 occupancy profiles, in presence or absence of low energy consumption lighting and household appliances, and for three different occupants' behaviors (Waster, Medium, Saver)

The results demonstrated that in the case of using no energy saving appliances and traditional lightings the annual energy balance is always negative. A positive balance is achieved only in the case of a two member family who uses the house partially, and by equipping the rooms with energy efficient appliances and lights. Moreover, it is noteworthy that even in this configuration, if the users belong to the category of "Wasters", the annual energy balance is negative.

Consequently, the house that is classified as a nearly zero energy building according to the calculation procedure proposed in the National Regulations cannot satisfy this qualification because it consumes more energy than it produces throughout a year.

Further processing of the results has been made in order to more thoroughly investigate the reasons for this inconsistency.

First of all, the incidence of the different energy uses on the total annual consumption has been determined.

In particular, the percentages of the annual total energy consumption for the different family scenarios, occupant behaviors, and both the equipment and lighting typologies are represented in Figure 9.

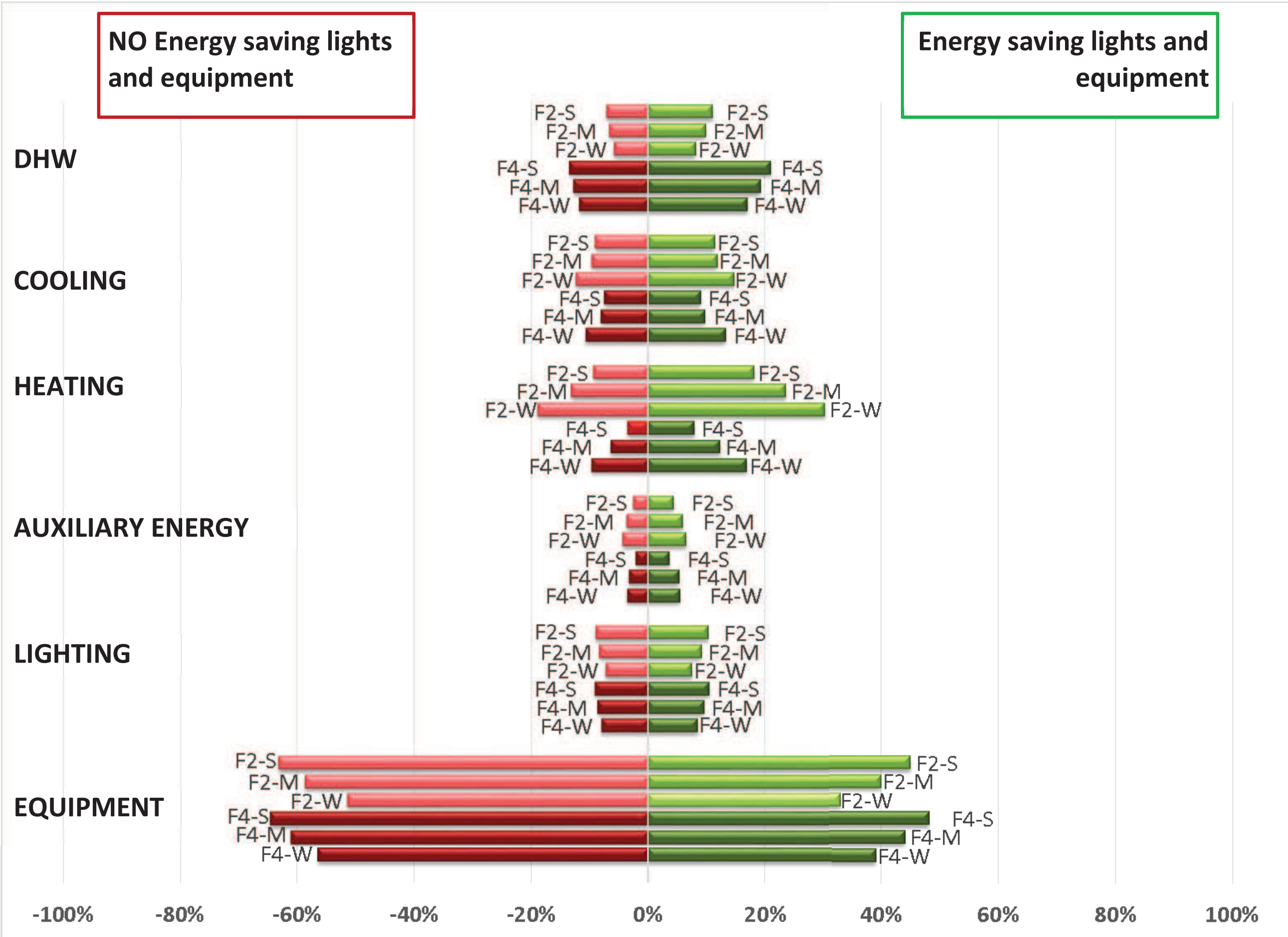

Fig. 9 Influence of separated energy uses on final energy consumption upon variation of family size, occupants' behavior, and equipment typology

The incidence of various electric uses on the total consumption of the house seems to be the same for both the cases "NO-energy saving lights and equipment" and "Energy saving lights and equipment." In particular, it is worth highlighting that in all the analyzed cases, the household appliances are responsible for the major fraction of electrical consumption of the dwelling. Moreover, it is interesting to note that moving from the Waster profile to the Saver one, the percentage of consumption attributable to household appliances, artificial lighting, and domestic hot water production tends to have an increasing impact on the total consumption, while the energy for heating, cooling and plant auxiliary decreases with the improvement of occupant behavior. In the case of the use of traditional household appliances, the equipment consumption reaches 65% while using energy efficient equipment their consumption weights up to a maximum of 50% and more influence is associated with heating, cooling and DHW. The fraction of consumption due to artificial lighting varies from 7% to 10%.

The energy produced on site is not enough to cover all the energy uses of the house. Thus, the building classified as nZEB according to the Italian Regulations is not zero energy. The reason is that Italian Legislation does not consider electrical purposes (lighting and appliances) in the calculation of the energy performance of buildings, and consumptions associated with these uses tend to have an increasing importance upon the decrease of consumption for air conditioning. This means that the more the building is carefully designed to contain the energy demand for winter heating and summer cooling, the more electricity consumption for lighting and appliances has a higher weight in the final energy balance.

The building designed according to the reference calculation model certainly offers good performances in terms of air conditioning energy requirements and hot water production. In fact, considering only the consumption for heating, cooling, DHW, and auxiliary systems, the annual energy balance is positive for all the occupancy profiles and utilization modalities, as reported in Figure 10.

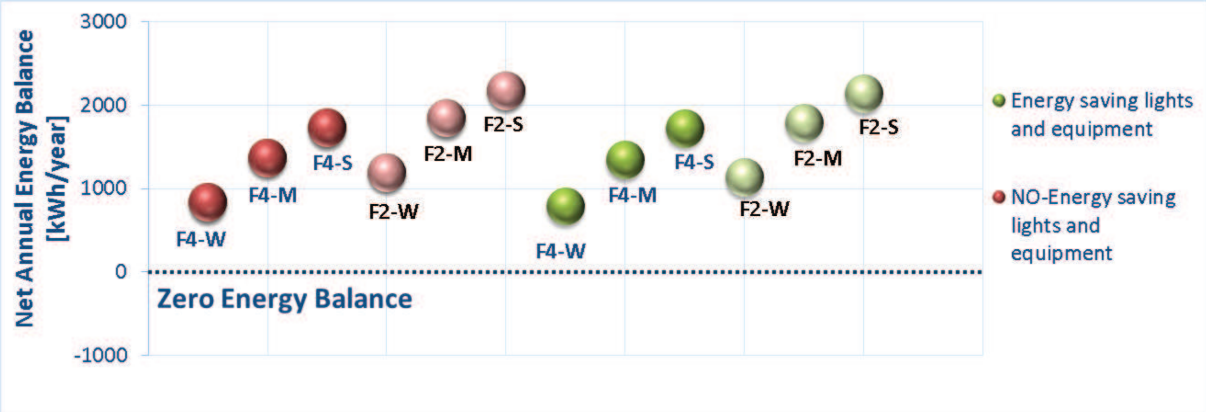

Fig. 10 Net annual energy balance considering only consumption for heating, cooling, DHW and auxiliary energy

The amount of surplus energy, over these uses, allows the fulfillment of a certain percentage of consumption for lighting and equipment that is variable depending on occupancy scenarios as shown in Table 9. The remaining fraction is the amount off-balance, which therefore leads to the annual deficit.

Table 9 Percentage of consumption for appliances and lighting that can be satisfied through the on-site PV system in addition to air conditioning, DHW, and auxiliary energy

NO Energy saving lights and equipment						**Energy saving lights and equipment**					
F4-W	F4-M	F4-S	F2-W	F2-M	F2-S	F4-W	F4-M	F4-S	F2-W	F2-M	F2-S
18%	30%	37%	38%	59%	70%	33%	57%	73%	74%	>100%	>100%

Since the consumption of the F2 profile for air conditioning and DHW is lower than that obtained for the F4 profile, a greater amount of useful energy exploitable for the other electrical uses of the rooms is available. The same consideration can be stated for the profiles with energy saving equipment and lights compared to the ones with traditional facilities: the former offers more possibilities than the latter to meet other energy needs in addition to heating, cooling and DHW.

However, the family composition and the set of appliances and lights being equal, the occupants' behavior makes the difference. The behavioral variables related to the choice of heating/cooling set point temperature and ventilation habits allow having larger or smaller quantity of energy available for other uses. The cases F2-M and F2-S, as previously affirmed, have a positive balance. In all other cases, the energy produced annually is lower than the consumed energy and hence the difference burdens the electric network. In the case of the F2 profile, if the users do not behave adequately, the net balance becomes negative. In the case of F4 occupancy scenarios, additional energy to the renewable generated on-site one is always needed to satisfy all the uses, but if the occupants have a saver behavior the lack is 27%, instead if users have a wasteful behavior the deficit reaches a significant percentage equal to 82%. Furthermore, for the same family size and behavior, the availability of low consumption equipment and lights allows doubling the consumption covered through renewable sources. Indeed, in the case of family of four, if the behavior is wasteful, the fraction of consumption satisfied is 18% in the presence of traditional appliances and lights, and it becomes 33% with energy efficient appliances and lights. If the behavior is saver, the covered fraction passes from 37% to 73%. In the case of the two-member household, if the behavior is wasteful, the share satisfied rises from 38% to 74% depending on the type of appliances used, whereas, if the behavior is saver, the percentage evolves from 70% to over 100%, representing an excess of energy than that needed.

5. Conclusions

A nearly zero energy building has been designed by applying the calculation model contained in the Italian Legislation and Standards. In order to be nZEB, the building must comply with specific envelope characteristics and plant performances defined on the basis of a reference building. External walls must have a high thermal insulation to reduce the energy demand for heating. Good thermal storage capacity of opaque components and strict properties for the window areas are fixed to limit cooling demand. Moreover, the energy performance indexes for heating, cooling, and global energy performance must be lower than the corresponding performance calculated for the reference building. Furthermore, the efficiency of the heating and cooling system and the DHW production systems must be higher than the efficiencies of the plants provided for the reference building. Moreover, the installation of systems for the production of defined shares of energy from renewable sources is mandatory. In the design of the building all the listed requirements have been met, consequently the building is classified nZEB according to the Italian Standards.

However, the design process does not take into account the different uses of the building by various possible types of occupants. Therefore, the study sought to verify the actual performance of an nZEB under diverse occupancy scenarios and to determine the annual balance between the energy consumed and the energy produced by the on-site photovoltaic system. Quantifying the difference in energy is useful to understand if the balance is approaching or moving away from the zero level and assessing if it is positive (the total produced energy exceeds that consumed, confirming the definition of nZEB), or conversely if it is negative and therefore the building does not perform as expected.

Using statistical data from National source (ISTAT 2014), two occupancy scenarios have been formulated, assuming a different number of components of the family. In particular, the first type of occupancy consists of a family of four members, which uses all the rooms in the house, while in the second scenario the house is occupied by a family of two members, which use continuously only a part of the dwelling, and some rooms are occasionally occupied. Thanks to statistical information, it was possible to define typical uses of the heating and cooling system, DHW production, lighting and household appliances. Two types of artificial lightings and room equipment have been analyzed: traditional lights (halogen lamps) and low energy lights (compact fluorescent lamps), traditional and energy saving appliances (with energy label “G” and “A” respectively). In addition, three different occupant behaviors have been simulated (waster, medium, and saver), with reference to the choice of heating and cooling set point temperature, and ventilation mode.

The analysis leads the authors to conclude that the assertion of a “nearly” zero energy building is justified, as the fact of being zero energy is not linked exclusively to the construction and plant solutions, but is also dependent on occupant related factors. In fact, minimizing the energy consumption for heating and cooling by adopting high-efficiency envelope and plants, the consumption of lighting and appliances depending on user behavior becomes prevalent.

Therefore, to facilitate the achievement of a balance as close as possible to zero, the adoption of energy saving appliances and lights should be forced, because it permits to obtain a reduction of the energy consumption independently of the use. In fact, the results show that even the wasteful family, who does not care about the use of air conditioning and ventilation, could almost double the surplus energy to be allocated to electrical needs. Indeed, the percentage of consumption that can be covered by renewable sources passes from 18% to 33% using low-power electrical appliances and lights.

In order to fulfill the remaining consumption due to equipment and lighting, it would be interesting to increase the mandatory extent of photovoltaic power to be installed, which is currently fixed by regulations at a minimum of 2 $kW_p/100\ m^2$ while currently technologies can offer on average 15 $kW_p/100\ m^2$. In particular, considering that the producibility depends on the orientation on the pitched roof and that often roofs are divided into several slopes, the constraint currently in force could be raised from 2 to about 7 $kW_p/100\ m^2$, contemplating the collocation of photovoltaic modules on the surfaces with the best exposure.

However, to obtain buildings concretely nearly zero energy, technical parameters associated with the energy consumption for electricity uses inside the dwelling (equipment and lights), should be included among the requirements to be complied with for classification as nZEB. In fact, the total energy consumed by the building also includes these uses, which are closely linked to the behavior of occupants, and which tend to have an increasing impact on the final energy balance, at a decrease of consumption for conditioning, as happens in nZEB.

Moreover, in the evaluation of energy performance of buildings, not only a reference building should be considered, but also a reference occupancy and a reference users' behavior. Otherwise, the designed building is likely to move away from the theoretical formulation of nZEB, real consumption could be very different from predicted consumption, and the final balance may mismatch the estimated zero goal.

6. Future work

The study is focused on the application of occupant behavior modeling in nZEB. The investigation underlines the lacks in the current European and National Standards concerning the calculation of internal loads, of energy consumption due to equipment and lighting, and of the dimensioning of renewable energy systems.

The authors approached this problem with a different method from the cases available in literature. They did not use data collected by survey or monitoring campaigns but free available data obtained by means of an accurate investigation. This methodology could constitute a reference example for future studies in other countries. Furthermore, it emphasizes the necessity to include in National surveys some questions about occupancy and the use of the houses. Generally, this information is poor and fragmented.

The authors used a deterministic approach for modeling occupant behavior in the specific case of nZEB in order to highlight the main issues and provide results that constitute the starting point of future investigations. Future work could include: diverse climatic conditions, building typologies, different approaches for occupancy modeling (probabilistic nature of occupant presence, use of space by utilizing stochastic models), investigation of new procedures for the sizing of renewable energy systems in relation with the occupancy profiles and their modeling.

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5.4 Energy performance gap of a nearly Zero Energy Building: influence of occupancy modelling and effectiveness of simulation

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Abstract

Evolution of energy standards led to high-performance buildings requiring very low energy for their operation. Since constructive and technical characteristics have been progressively improved, the variable that now actually has the greatest impact on energy performance of nearly Zero Energy Buildings is occupancy. Occupants influence energy use in buildings as they contribute to internal gains, interact with systems and modify indoor conditions with their behaviour. Assumption about occupancy schedules are usually adopted in energy models for compliance calculation and when experimental data is not available. These theoretical profiles might be far from real conditions and frequently generates a mismatch between expected and actual performance. The present work analyses six-month monitored data from a nZEB in Denmark. A simulation model is used to analyse the effect of three different occupancy profiles on the final energy use: the “Compliance profile”, defined on the basis of regulations, the “Standard profile”, built on average data obtained from surveys, and the “Actual profile”, customised on measured data from the actual building case. Significant differences are detected in the three different occupancy profiles as well as in the results achieved by applying the three occupancy models in performance prediction.

Keywords: nZEB, monitoring, occupancy profiles, occupancy loads, building simulation, household appliances.

1. Introduction

The building sector is increasingly oriented towards nearly zero energy use [1]. According to this goal, all buildings, new or renovated, must be designed for low energy demand, and the very limited amount of energy required should be covered by renewable sources. Thus, the impact on the environment is eliminated or, at least, minimised. The role of zero energy buildings has been recognised as crucial for the transition to those scenarios described as post-carbon in a reality where 70% of greenhouse gas emissions is attributable to urban centres [2]. Several experiences have been carried out by evaluating the performance of energy efficient buildings in different climatic contexts [3] [4] [5] [6]. Innovative solutions were developed [7] [8], both for new constructions [9] [10] and for the renovation of existing buildings [11] [12], also aimed at a technical-economic optimisation [13] [14] [15] [16]. Nevertheless, the nZEB concept is unstoppably evolving into further efficient concepts, such as prosuming [17] and energy-positive buildings [18].

However, even though the building is designed for a low energy demand, it can be inefficient during normal use if unsuitable management strategies are applied by occupants. Users, in fact, interact with the construction and its systems, and if their behaviour does not match the hypotheses established during the design stage, the total amount of energy may critically differ from the estimated performances. Occupants' features significantly affect final consumption, as proved by many studies analysing the variation in energy demand due to occupancy variables [19] [20] [21].

Making reliable predictions on how users operate within the building is a very demanding challenge and this is the reason why substantial discrepancies between expected and actual consumption are often detected. In [22] a literature review on the gap between predicted (computed) energy performance of buildings and actual measured energy use once buildings are operational is presented. From the revised work it emerges that occupant behaviour is especially complex and hard to capture and it is often different from the assumptions made in the design stage; this is often cited as the main reason for the performance gap. [23] reviewed the energy performance of 16 buildings finding that "*There was very little connection between the values that tend to be found in completed buildings and the assumptions made in design estimation and computer models*" due to the occupancy related unpredictable factors. [24] demonstrated that the rebound of human attitudes and behaviour directly impacts energy use. In particular, using measured results, the authors showed that the gap between heating consumption predicted by means of calculation tools, which typically assume standard dwelling use, and the measured consumption, is due to the direct rebound behaviour of the inhabitants affecting temperature, ventilation and internal gains. As debated in [25], the actual use of housing is often neglected by building regulations whilst the knowledge about the use and management phase of the building is essential for understanding energy use. The study outlines the main issues due to the exclusion of the user's perspective and suggests how to redesign building regulations in order to accommodate occupancy aspects and user practices.

The influence of the occupants becomes particularly relevant in low-energy buildings. As reported by numerous researches, the occupants' role tends to have a much higher relative impact on final energy use the less energy demand the building is designed for. [26] analysed the experimental data of a low energy multifamily complex in Switzerland and found that the gas energy use index of the building was 50% higher than it was initially predicted, because the theoretical value does not take into account the real conditions of utilisation. A large-scale study of around 200000 dwellings in the Netherlands is reported in [27], by comparing labels and theoretical energy use with data on actual energy use. The results showed that dwellings with a low energy label actually consume much less energy than predicted by the label, but on the other hand, energy-efficient dwellings consume more than predicted. Clearly, the theoretical values are merely an estimation of the actual consumption, since they are based on standard values and do not take into account the lifestyle of the occupants. The investigation carried out in [28] provides information regarding the effects of human variables (occupants' needs and preferences) on the final energy performance of a nearly zero energy building designed according to the Italian regulations. In particular, the analysis demonstrated that a construction designed to be a nZEB might generate higher consumption than expected, if the assumptions made in the simulation are not representative for the real use. The authors of [29] used building simulations to demonstrate the potential impact of different occupant behaviour lifestyles on the energy use of a Mediterranean residential nearly-zero energy building and a reference building. The results confirmed that the total energy performance gap due to the implementation of different behavioural patterns has a higher effect on the nZEB scenario rather than on the reference-building scenario. Indeed, since in the high performing building the performance of envelope and systems are optimised, the unpredictable loads generated by the occupants gain greater influence with respect to low performance building scenario. In particular, as regards the nZEB scenario, the most influencing occupant-driven variables on final energy consumption are related to the equipment and the lighting use. The authors of [30] examined the contribution of behaviours to the actual performance of low-energy dwellings in a UK EcoHomes site with an 'excellent' rating and highlighted how human factor issues need to be addressed more adequately as standard practice in low-energy/carbon design.

Energy efficiency and energy conservation in buildings can be improved by implementing monitoring and control strategies steering occupants' habits towards more conscious behaviours [31] [32] [33] [34] [35]. Energy consumption metering was used in [36] to determine the energy use during the operational phase of a residential building proving that, in the first whole year of the occupied building, energy consumption was much higher than the energy generated on-site. Therefore, it seems imperative to ensure that the simulation accurately reflects how the building will actually be managed once occupied to avoid mismatching between the design and the operation phases. Consumption monitoring can be used as a valid support for achieving the zero balance towards which nZEBs strive for. For example, in [37] the results of a nZEB monitoring in Canada report significant differences between the simulated model and the registered consumption for space heating/cooling, domestic hot water, heat recovery ventilator and photovoltaic system generation. Therefore, the authors suggested to use the collected data for conducting energy calibration and improve energy sizing for the future design of nZEBs. As proved by the findings showed in [38], the use of a dynamic simulation model calibrated on data obtained through a post-occupancy analysis, can lead to more coherent results of the thermal response in the analysed apartments, compared to the simplified monthly and hourly methods. However, subjective parameters and actual living conditions of the residents can generate some deviations in the simulation results with respect to the measured data.

Furthermore, monitored data can be used to control indoor comfort conditions [39] [40] [41] [42] and to explore heating and electricity patterns as well as occupancy profiles [43] [44] [45] [46]. As illustrated in [47], the results of two monitoring campaigns undertaken in Spain and in the Netherlands were employed to obtain detailed and understandable data on the occupancy patterns. In particular, three types of data were collected through sensors and meters: gas and electricity consumption, indoor parameters and contextual data, data on thermal comfort and energy related practices of the occupants. The methods proposed in this paper allow to develop occupancy and heating profiles for building simulation programs, decreasing the uncertainty related to complexity of occupants' behaviour.

In the present study, an experimental data set acquired from six-month monitoring of a nearly zero energy building located in Denmark, is examined. The analysis revealed a discrepancy between the expected energy use as resulting from the compliance calculation and the measured energy use. Therefore, the paper is aimed at exploring whether this performance gap can be explained by the difference in occupancy modelling. In particular, occupancy loads are analysed in detail with reference to three occupancy profiles (Compliance profile, Standard profile and Actual profile) seeking to understand if the gradual accuracy increase in occupancy modelling can lead to a higher reliability of the results. Evaluation are carried out by means of a simulation model and the suitability of the simulation itself in reproducing the actual behaviour of the occupants is discussed.

2. Data

2.1. Description of the building

The case study building is a detached one-storey house, located in the province of Aarhus, in Denmark. The building was completed in 2017 and it is rated as nearly zero energy building according to the Danish energy labelling standard [48].

The housing consists of two volumes with a rectangular base, slightly offset in plan and placed on two different levels, with a difference in height of 0,53 m. An unheated space, used for storage, is located on the east side of the building, while a carport is adjacent to the north side. The net area is equal to 132 m^2 and the treated volume is 360.6 m^3. Large windows are present on the South, East and Western façades, equipped with sunscreens, some of which can be automatically controlled. The plant, elevations and section of the house are reported in figure 2 while figure 3 shows some external views of the building.

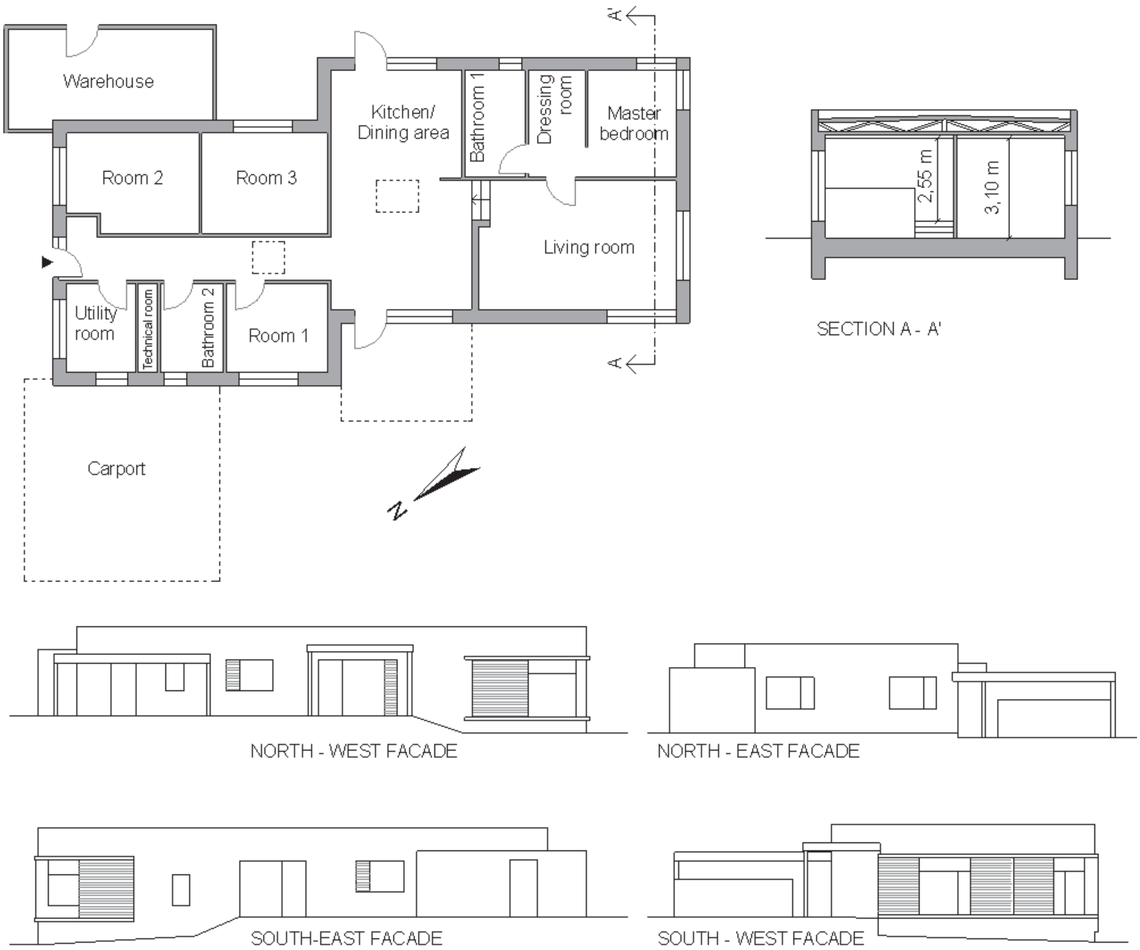

Figure 2. Plant, section and elevations of the house.

Figure 3. External views of the nZEB located in Aarhus, Denmark.

The structure is in masonry. The external walls consist of an outer layer of façade stone and an internal layer of aerated concrete blocks, with a thermal insulation layer interposed. The roof is flat and it is made of reticular beams, OSB panels and 41 cm of paper wool insulation. The inner side of the flat roof is finished with an acoustic plaster ceiling. The internal partitions are in aerated concrete blocks and have a thickness of 10 cm. The ground slab is in concrete, with 32 cm of EPS and wooden floor. Transmittance values of the opaque components of the building envelope are summarised in table 1.

Table 1. Thermal transmittance of the opaque components of the building envelope.

Building components	U [W/(m^2·K)]
External walls	0.15
Flat roof	0.09
Ground slab	0.08

The windows have a 48 mm triple pane glazing with argon, and composite aluminium and wood frames with thermal break. The U-value is of 0.9 [W/(m^2·K)]. Artificial lighting is LED. The main appliances are: washer and dryer, in the utility room, cooking plate, oven, refrigerator and cooker, in the kitchen.

2.2. Description of the systems

The dwelling is equipped with a floor heating system supplied by district heating. A compact unit, integrating an air-to-water heat pump, provides ventilation with heat recovery (85%) and production of domestic hot water. The ventilation system allows individual control of the air supply in all living and sleeping areas, as well as of the extraction in the kitchen, bathrooms and utility room. The supplied airflow is adjusted based on the CO_2 and relative humidity level in each room. Additionally, automatically controlled external shading, natural ventilation grids and skylights intend to create a pleasant indoor environment, while reducing the energy consumption. The unit is always running with a minimum airflow when the house is unoccupied or when the indoor conditions do not demand a higher air supply. Finally, the ventilation is deactivated when the windows and doors are opened to provide natural ventilation. The ventilation system is operating in 4 steps, proportional to the number of open dampers, as explained in Table 2, while the ventilation set points are summed up in the table 3.

Table 2. Operating steps of the mechanical ventilation system

Step 1	Step 2	Step 3	Step 4
Open dampers < 3	2 < open dampers < 6	5 < open dampers < 9	8 < open dampers

Table 3. CO_2 and Relative Humidity set-points for mechanical ventilation.

	Open dampers	Close dampers
CO_2	900 ppm	700 ppm
Relative Humidity	70 %	50 %
Bathroom Relative Humidity	60 %	50 %

In order to achieve natural ventilation in the dwelling some of the windows have been equipped with a new ventilation system with louvers. The louvers are taking up 5% of the window area and are located in rooms with overheating risk. The louvers can be opened in several steps in order to control the supply of fresh air, as represented in Figure 4. Additionally to the window louvers, two skylights have been installed in the living room and kitchen, respectively.

Figure 4. Details of ventilation louvers installed in the windows.

External solar shading devices have been installed in the living room and bedroom. The selected sunscreens consist of thin horizontal wooden lamellae, able to protect the spaces from direct solar radiation, without obstructing the view to the outside. Both natural ventilation and shading systems can be controlled automatically based on the temperature, CO_2 level, relative humidity, and occupancy. However, the control strategy will be implemented by the end of summer of 2018.

A monitoring apparatus is set up in the house, data registration takes place every 5 minutes, approximately, in all rooms of the dwelling. The monitored quantities and the sensors installed are listed in table 4 and table 5, respectively. Figure 5 illustrates the CO_2 and relative humidity sensors in the living room and the control system in the technical room. Six months of measured data, from December 1st 2017 to May 31th 2018, were available at the time the study was developed.

Table 4. Parameters registered by the monitoring set up.

Energy consumption	**Compact Unit**	**Water Consumption**
District heating [MWh]	Outdoor air temperature [^oC]	Cold water consumption [m^3]
Floor heating pump [kWh]	Return air temperature [^oC]	Hot water consumption [m^3]
Ventilation system [kWh]	Return air relative humidity [%]	
Control system [kWh]	Hot water temperature [^oC]	
Cooking plate [kWh]	Supply air temperature [^oC]	
Refrigerator [kWh]	Heat pump temperature [^oC]	
Cooker [kWh]	Ventilation speed [steps]	
Dish washer [kWh]		
Dryer [kWh]		
Washing machine [kWh]		
Other consumption [kWh]		

Table 5. Sensors installed for indoor air quality control.

	Temperature [°C]	CO_2 level [ppm]	Relative humidity [%]	Damper opening [min/ max]
Master Bedroom	X	X	X	X
Wardrobe closet	X			X
Living Room	X	X	X	X
Kitchen/ Dining Room	X	X	X	X
Room 1	X	X	X	X
Room 2	X	X	X	X
Room 3	X	X	X	X
Bathroom 1	X		X	X
Bathroom 2	X		X	X
Utility Room	X		X	X

Figure 5 - Indoor air quality sensors (CO_2, temperature and relative humidity), and control system in the technical room.

3. Methodology

Three occupancy profiles were modelled and compared in the present study. The construction of the user profiles implied the definition of the schedules of presence at home, the use of the heating system, the production of domestic hot water, and the use of appliances. Ventilation habits were not considered in this case study because ventilation is regulated by the compact unit and the control system for the management of natural ventilation grids has not yet been implemented at the moment in which first experimental data used in this analysis were collected.

The first model, defined as Compliance profile, is based on the indications provided by current Danish regulations and it represents a simplified model generally used for the design of the building. The second model, characterised by a quite higher level of detail and named Standard profile, is defined on the basis of average values obtained from surveys. This model can be used to describe a building occupied by a typical family using the house according to a standard use. The third model, labelled Actual profile, is tailored on the measured data and it offers the highest compatibility with the current occupancy, returning the closest energy use to the measured one.

The influence of the three different occupancy profiles on the energy use of the building was assessed considering a six months' time interval, corresponding to the period for which data on real consumption of the building are available. The energy model was developed with DesignBuilder software [49], a graphical interface of EnergyPlus simulation engine [50]. All geometrical, constructive and plant features were recreated in the model. The climatic data used for the dynamic simulation were generated through Meteonorm [51]. The simulation model was calibrated using metered data and assessments concerning how much the simulation can reliably describe the actual occupancy were carried out.

3.1. The Compliance Profile

The compliance profile is defined on the basis of summary information provided by the Danish legislation [48]. This approach for occupancy modelling can be adopted when no more detailed information is available. Synthetic and generalised values are determined according to the dwelling surface. In particular, a load of 1,5 W/m^2 is prescribed for persons, 3,5 W/m^2 have to be considered for electricity, and a consumption of 250 l/m^2*year is estimated for DHW uses. Since the regulations do not specify the hourly distribution of the loads, the time schedules obtained from [52] were used for the compliance case in the simulation software.

3.2. The Standard Profile

The Standard Profile was defined according to the information provided by the report [52] in which persons and consumption profiles obtained from surveys and statistical databases are described. Seasonal distribution of domestic hot water and electricity consumption are analysed in the report and hourly profiles representative of a large part of the population are developed.

Regarding occupancy, person profiles are delineated on the basis of studies that investigate the period of residence of people in the home and hours at work. An average load of 2.62 persons is indicated for detached houses with an hourly distribution that follows the standard patterns shown in figure 12, differentiated for the various days of the week.

Figure 12 – Standard occupancy profiles for different days of the week.

Concerning domestic hot water, the average use for detached houses is estimated at 40 l/person *day. This consumption is scheduled during the day based on the relative profile presented in figure 13.

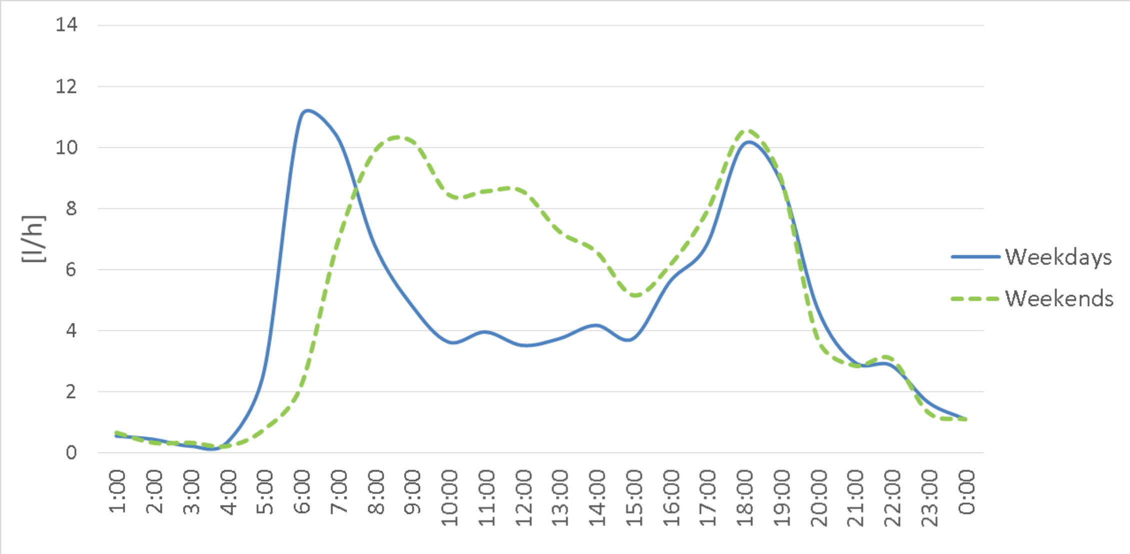

Figure 13 – DHW profile for Standard use.

As regards electricity profile, the survey reported in [52] highlighted a connection between the electricity consumption and the household size and housing size. The average electricity load can be estimated using the general equation (1), assuming a family size of 2,62 persons for the Standard case, and considering the gross area of the dwelling (160 m^2) according to Danish regulations.

$$530\ [\text{kWh}] + \text{dwelling surface}\ [\text{m}^2] \cdot 12\ [\text{kWh}] + \text{person number}\ [\text{n°}] \cdot 690\ [\text{kWh}] \quad (1)$$

Moreover, hourly profiles for power consumption are designed based on measurements made in different detached houses and using Danish Power Supply statistics [53] to investigate seasonal distribution. A seasonal breakdown of four seasons is estimated, with different profiles for weekdays (Figure 14) and weekends (Figure 15).

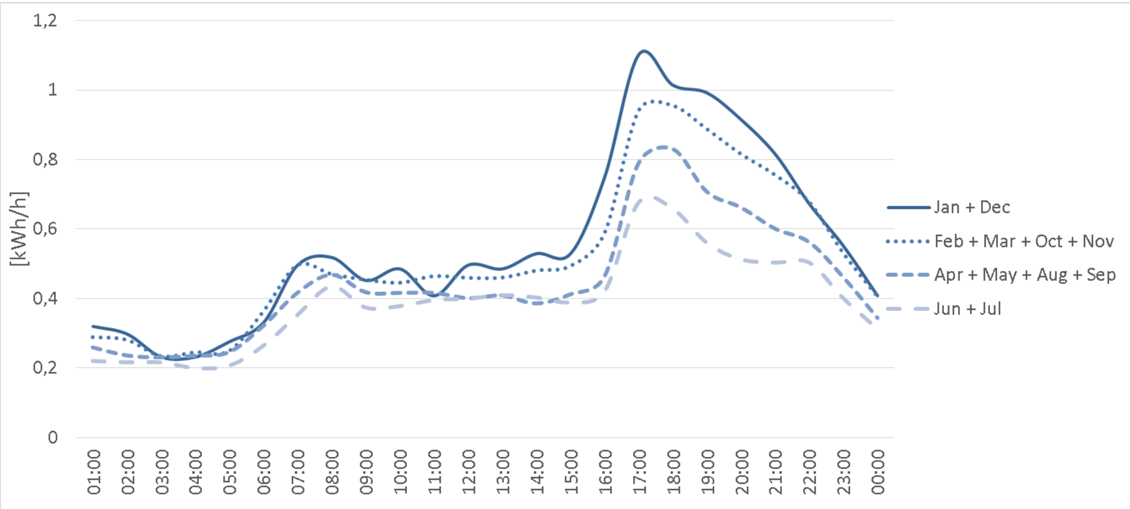

Figure 14 – Electricity profiles for weekdays with a four season breakdown.

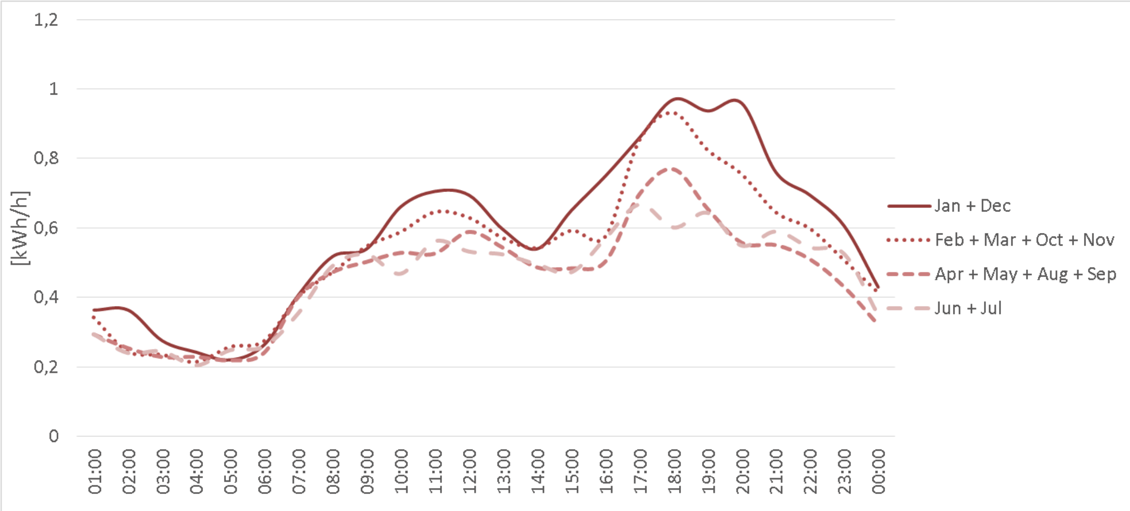

Figure 15 – Electricity profiles for weekends with a four season breakdown.

3.3. *The Actual profile*

The Actual Profile was defined using energy use data, house monitoring data and information collected through a face-to-face interview during which occupants were asked to figure a typical daily routine and to explain how they interact with the systems.

The house is currently occupied by a young couple, both workers and without children. The daily routine can be summarised as follows: both leave the house around 8:00 in the morning, have breakfast and lunch outside; they return in the evening around 18:00 and go to sleep at different hours, earlier the husband (around 21:00) and later the wife (around 23:00). The rooms of the house that are usually occupied are the Kitchen/dining room, the living room, the master bedroom, the bathroom 1, and the utility room, where the laundry is located. Sporadically, room 2 and bathroom 2 are used. Indoor monitoring data were used in order to build hourly occupancy schedules. In particular, hours with higher CO_2 concentration were considered as occupied. For example, figure 6 reports CO_2 level obtained from the average of all values measured for each time step throughout the analysed period, for the master bedroom. In particular, the mean values that define the profile shown in the figure are calculated by taking the average of each time step (five minutes data acquisition) of every day during the entire six month period. A cyclical increase of CO_2 concentration during the night hours emerges from the graph, proving that the selected room is presumably occupied from 21:00 to 7:00.

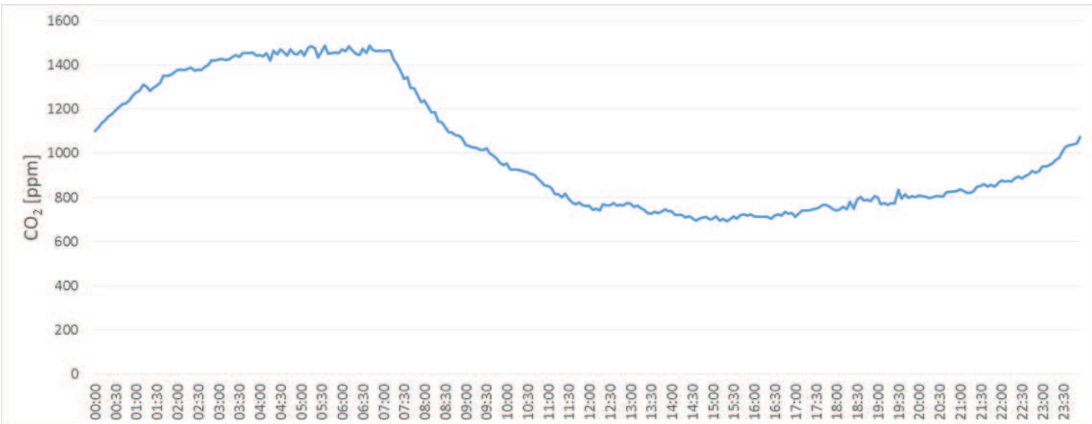

Figure 6 – Average 24 hour CO_2 concentration profile in master bedroom traced by calculating each time step as average of all the time steps during all the days for the six month period analysed.

Moreover, detailed information gathered during the interview and electricity consumption resulting from the use of household appliances were adopted to perfect the presence schedules.

Concerning the heating system, it is activated in all rooms with a set-point temperature of 21°C. For the DHW production, data recorded on hot water consumption [m^3] were used. Figure 7 displays the monthly use of DHW. A total consumption of 10.56 m^3 was recorded in the analysed period. Therefore, an average consumption of 1.76 m^3 per month is obtained, corresponding to a DHW demand of 58.67 l/day.

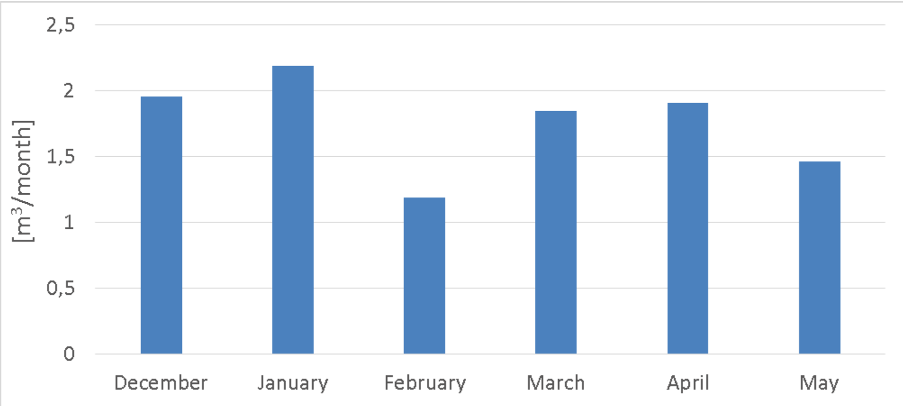

Figure 7 – Monitored amount of DHW use for each month.

The DHW production temperature is fixed to 40°C. The frequency of consumption was analysed to identify at what time during the day the DHW is used. For this purpose, the 24-hour daily interval was divided into 5-minute time steps, corresponding to the data monitoring frequency. A 0 to 1 scale was applied to the registered data, by associating a value equal to 1 to those intervals in which a DHW supply is recorded, while a value equal to 0 was assigned to time steps in which no DHW is required. By summing all the uses occurring at each time step of all the days for the whole six-month analysed period, the frequency distribution shown in figure 8 is obtained. The analysis reveals that DHW is required more often in the early hours of the morning and in the evening.

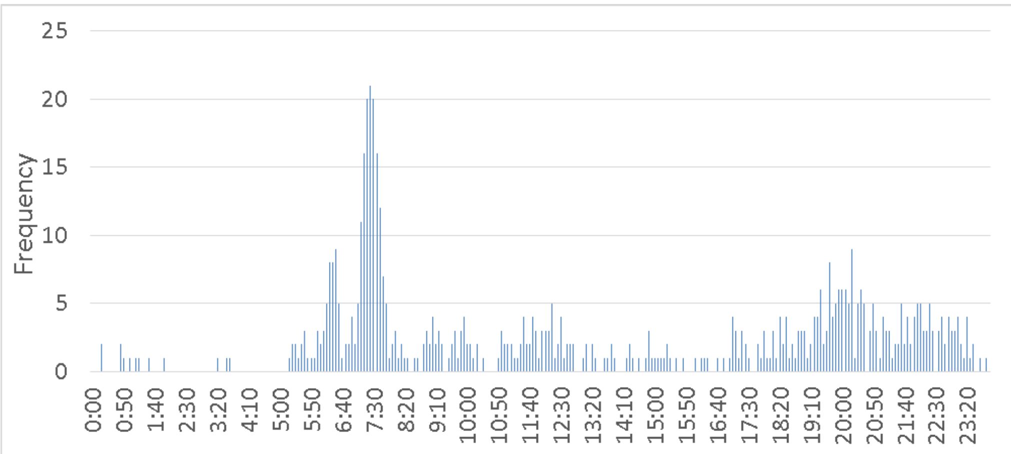

Figure 8 – Frequency distribution of domestic hot water use over 24 hours based on 5 minute intervals. A 0 – 1 scale was applied to each time step (0 = no DHW usage 1 = DHW usage) and the calculation was extended to the whole six-month period.

Electricity meters are installed in order to monitor the main appliances. Thanks to the registered consumption, it was possible defining typical usage schedules for cooking plate, cooker, dishwasher, washing machine, and dryer. In particular, at first the number of usage per week for each appliance was calculated and the most frequent value was assumed as "typical". The analysis period (6 months) includes 25 weeks at all and the frequency of usage on weekly basis is reported in figure 9.

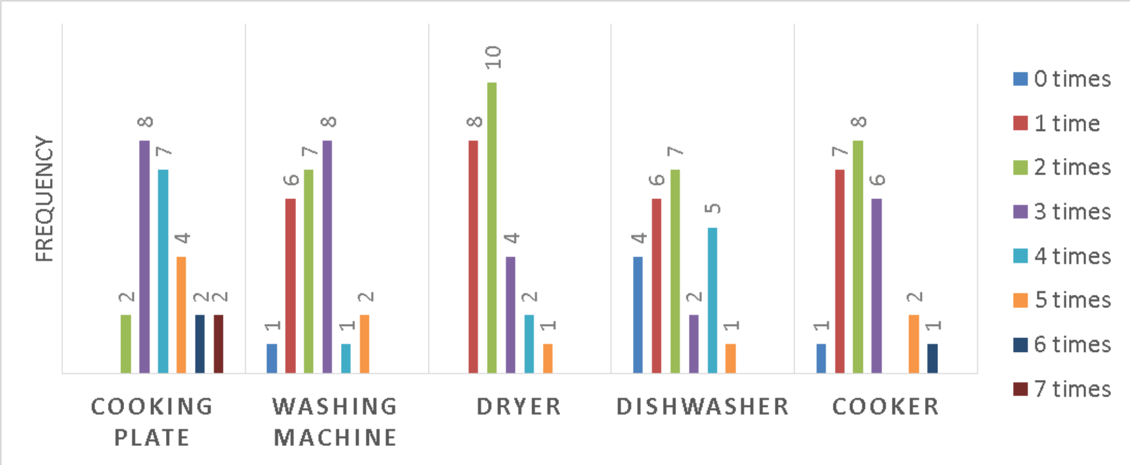

Figure 9 – Frequency of the number of usage per week of household appliances. Analysis carried out over six-month period involving a total of 25 weeks.

For cooking plate and washing machine the highest frequency occurs for three uses per week while dryer, dishwasher and cooker are used more frequently twice a week. Successively, the days of the week in which the use of each household appliance is more frequent have been identified as illustrated in figure 10.

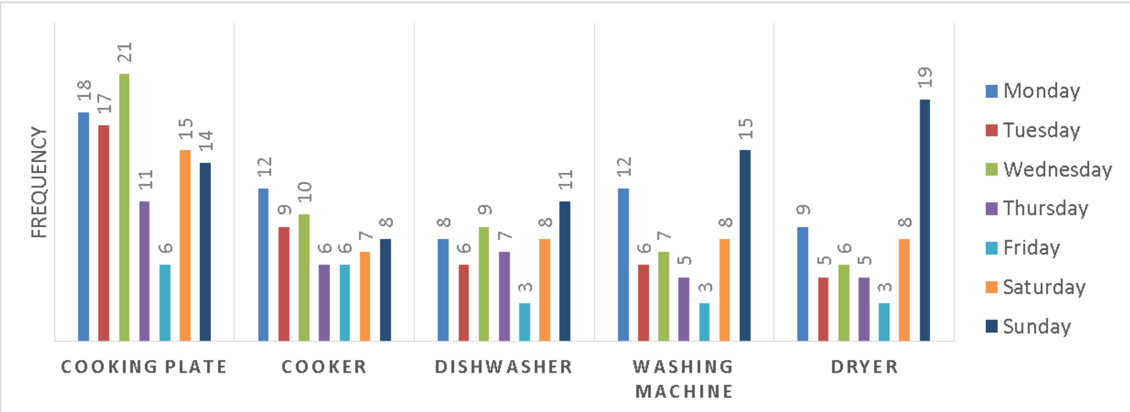

Figure 10 – Frequency of the days of usage of the appliances during the week (25 weeks period).

The highest values were considered based on the number of times per week the appliance is used. For example, since the cooking plate is assumed to be used three times per week (according to the previous analysis), the weekdays selected for the simulation schedule will be Wednesday, Monday and Tuesday. Finally, the time spans of the most recurring use during the day were identified for each household appliance, as shown in figure 11. The daily 24-hour interval was subdivided into 5-minute steps and a 0 to 1 binary scale was used to mark the ON/OFF modes recorded at each time step and for every day of the analysed period. Therefore, the usage time of each appliance was set with reference to the time intervals exhibiting the highest frequency values.

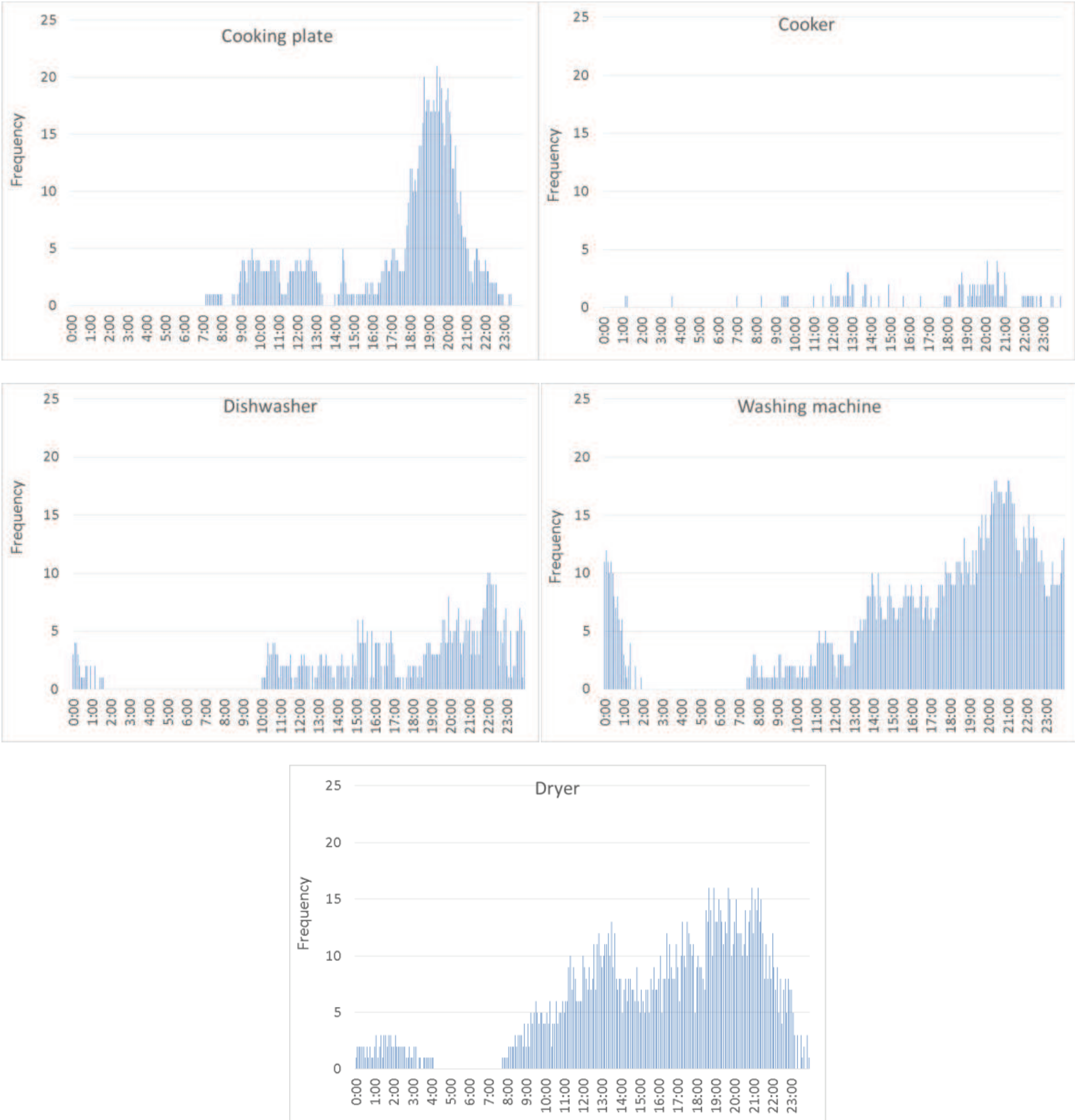

Figure 11 - Frequency distribution of home appliances usage over 24 hours based on 5 minute intervals (0 = OFF; 1 = ON), for six months.

The analysis allowed to define typical usage schedules, described in table 6. Moreover, considering the area of the rooms in which the appliances are located, the power in W/m^2 has been calculated for each equipment.

Table 6 – Operation schedules for household appliances.

APPLIANCES	Room	W/m^2	n° of uses per week	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Usage hours
Cooking plate	Kitchen / Living room	0.95	3								18:30 - 20:30
Cooker	Kitchen / Living room	7.49	2								19:00 - 21:00
Dishwasher	Kitchen / Living room	3.82	2								20:00 - 23:00
Washing machine	Utility room	67.32	3								19:00 - 22:00
Dryer	Utility room	65.16	2								12:30 - 14:00 18:30 - 22:00

4. Results and discussion

4.1. Analysis of the monitored energy consumption

Figure 16 shows the monthly energy use recorded from 1st December 2017 to 31th May 2018. The total energy for the entire period amounted to 7213 kWh for heating and 1587 kWh for electricity uses.

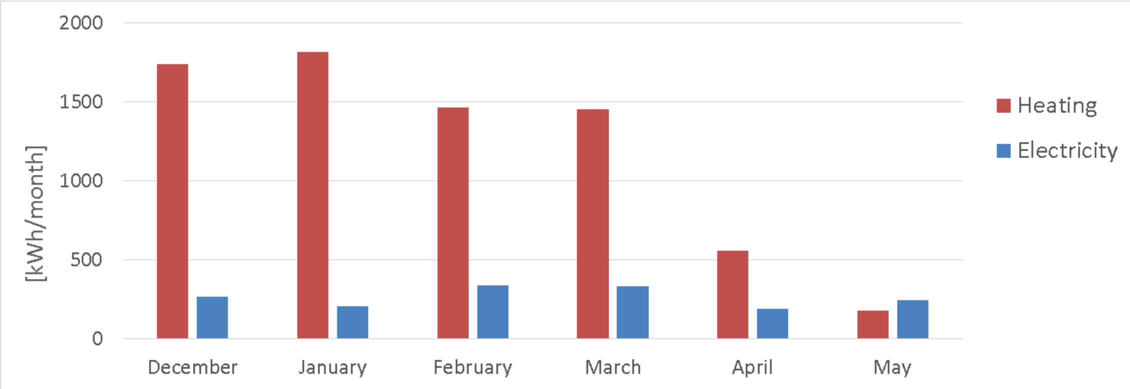

Figure 16. Monthly total energy use for heating and electricity, measured from 1st December 2017 to 31th May 2018.

The heating energy is connected with the use of district heating supplying the radiant floor. Electricity, instead, includes different uses due both to the systems operation (packaged unit for ventilation and DHW, floor circulation pump, control system) and to the occupants activity (use of household appliances and lighting). In figure 17 the total electricity energy measured is detailed according to the different uses.

The highest share is given by the packaged unit, providing ventilation and DHW, which is responsible for 51% of the total electricity use. A significant portion (about 35%) of electricity use is attributable to household appliances. This last item includes the use of electricity for different appliances, and can be further split according to the specific equipment used, since each home appliance is monitored with separate sensors (figure 18).

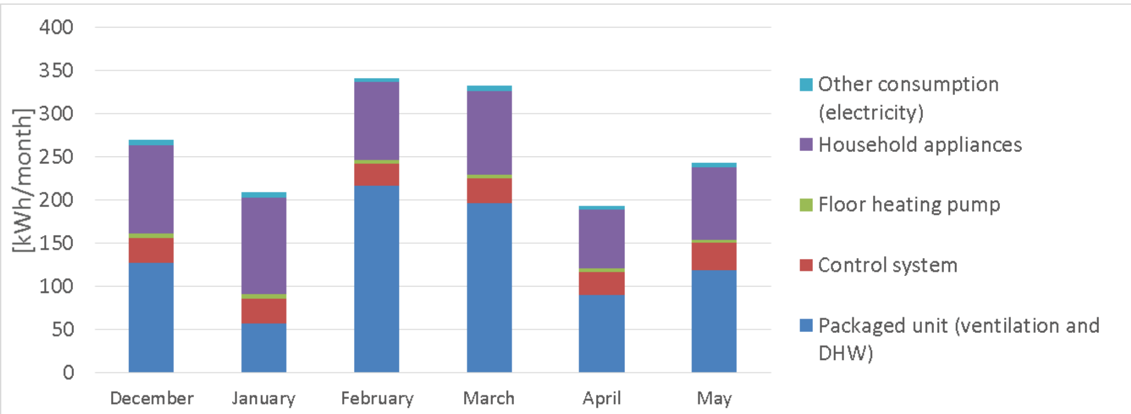

Figure 17 – Monthly measured electricity detailed according to the specific use in the dwelling.

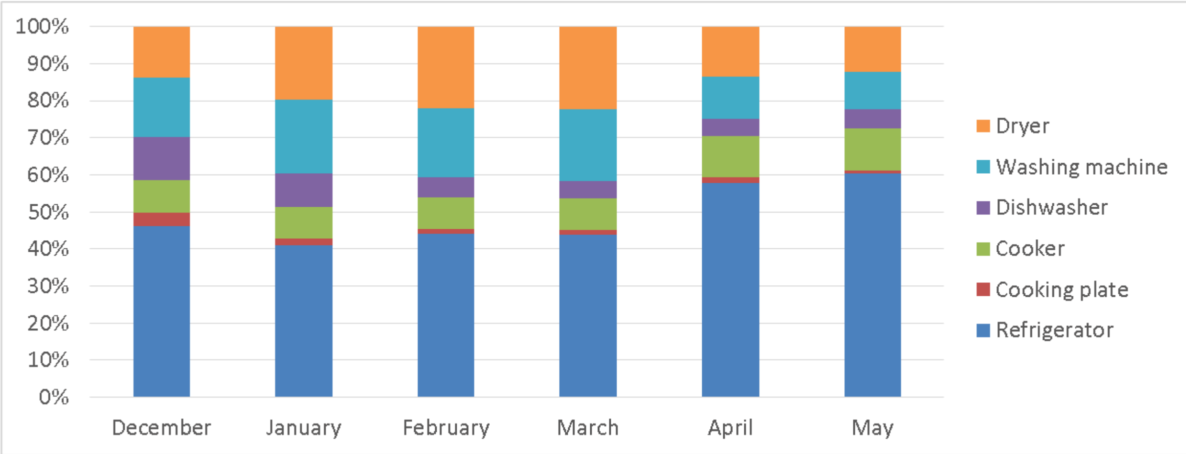

Figure 18 – Percentage breakdown of measured electricity use for “Household appliances” split for each specific equipment.

Figure 18 reveals that most of the energy is spent by the refrigerator, followed by washing machine and dryer. Some of the monitored equipment work with a continuous operation (refrigerator, heated floor circulation pump, control system, ventilation) while cooking plate, cooker, dishwasher, washing machine, and dryer are used according to the occupants’ habits, used to create the Actual profile as described in section 3.3.The item “Other consumption” includes the remaining electrical uses of the house, which account for 2% of the total electricity consumption. This quantity comprises for example the use of other appliances, such as vacuum cleaner, food processors, computers, TV. Furthermore, artificial lighting is also contained in the “Other consumption” and it is not monitored separately as the energy for lighting is very low compared to electricity spent for other uses.

4.2. Building model calibration and simulation effectiveness

This section is aimed at verifying the suitability of the simulation model in predicting energy uses. The capability and effectiveness of the simulation in describing the real use of the building and the actual behaviour of the occupants is also discussed, by highlighting some critical points.

The simulation of the building in the current state, obtained implementing the Actual occupancy profile, has shown very similar results to the monitored data. The comparison between registered and simulated energy use for both heating and electricity is shown in figure 19. The values refer to the total energy use measured over the six month period analysed. Analogously, the simulated values are obtained with reference to the same period. The heating energy is related to district heating while electricity is related to all the electrical uses occurring in the building, therefore due to the operation of the plants and also to the utilisation of equipment and lighting by the occupants.

Figure 20 displays the energy use on a monthly basis.

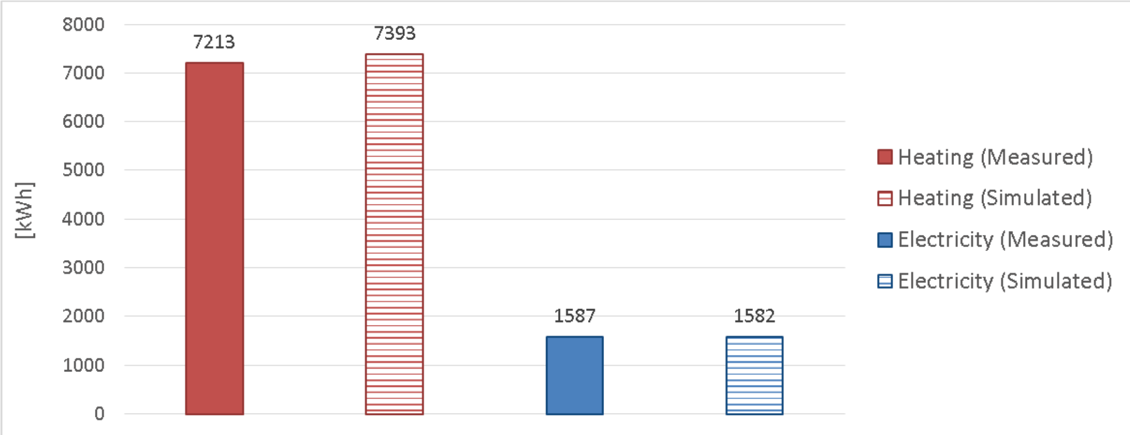

Figure 19 – Measured and simulated total energy use for the entire analysed period (six months).

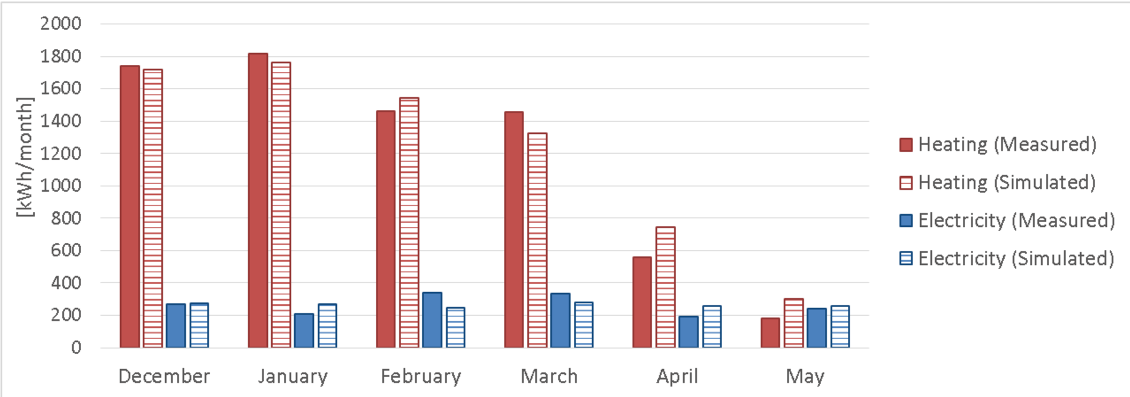

Figure 20 – Measured and simulated monthly energy use.

ASHRAE Guideline 14-2002 [54] was followed to calibrate the building model. Two dimensionless indicators of errors, the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CVRMSE) were calculated using the formulae (1) and (2), respectively:

$$MBE = \frac{\sum_{i=1}^{Ni}(M_i - S_i)}{\sum_{i=1}^{Ni}(M_i} \quad (1)$$

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{N_i}\frac{(M_i - S_i)^2}{N_i}}}{\frac{1}{N_i}\sum_{i=1}^{N_i}(M_i)} \quad (2)$$

Where M_i and S_i are respective measured and simulated data at instance i, and N_i is the count of the number of values used in the calculation.

The procedure was applied on a monthly scale and values lower than the acceptable limits were obtained for MBE (< ±5%). In particular MBE = -2,49 for heating use and MBE = 0,28 for electricity use. Values below 15% are, instead, required for CVRMSE. This constraint was satisfied by heating use, for which CVRMSE = 9,37 whereas for electricity use the Coefficient of Variation of the Root Mean Square Error is slightly higher than the suggested threshold, being equal to 21,59. This result allowed to develop considerations about the effectiveness of the simulation to adequately describe the actual use of the building. Therefore, on the whole, the mean bias error index returns reliable values, indicating that the overall estimated consumption is close to the real consumption. However, by deepening into a more specific detail, by considering the variability the consumption occurs, simulation exhibits some limits, as it is not able to reproduce exactly the irregularity of the electricity use. This is due to the high inconstancy characterizing the use of appliances by occupants and, even more, to the considerable instability related to the mechanical ventilation activation, which is controlled by the indoor air quality parameters. As previously illustrated, the simulation model was shaped by outlining a typical user profile, generated by the occupants' most frequent habits. This lead to average consumption, over the long term, comparable with the actual monitored consumption. By the contrary, if a shorter interval is considered, for example a weekly, daily or hourly time interval, the ability of the simulation to accurately reproduce the real use falls down. Consequently, the simulation is effective in estimating the total energy use over the entire period, but presents some criticalities in the description of the mutability of occupant behaviour in the short term. If the CVRMSE index is calculated by considering an average monthly electricity consumption, a value equal to 4,27 is obtained. Therefore, the model was considered calibrated for an "average" building operation and was subsequently used to simulate alternative occupancy profiles in order to assess their impact on the estimated final energy use.

Furthermore, an additional observation is needed pertaining to climatic data. The simulation is based on the climatic file generated for the specific locality using Meteonorm. However, it was not possible to check the accuracy of the calculated data in matching the actual weather data of the site, and this is of course an uncertainty in the investigation. Looking at the model calibration, a reasonable correspondence between measured and simulated performance is obtained. However, if actual weather data for the real monitored period had been used, a slightly higher certainty in the results would be achieved.

4.3. Comparison between different occupancy profiles

Detailed analyses for each occupancy profile were carried out in order to investigate the reasons for differences in energy use prediction.

Figure 21 discloses person loads associated with the three occupancy profiles, calculated for the six month analysed period.

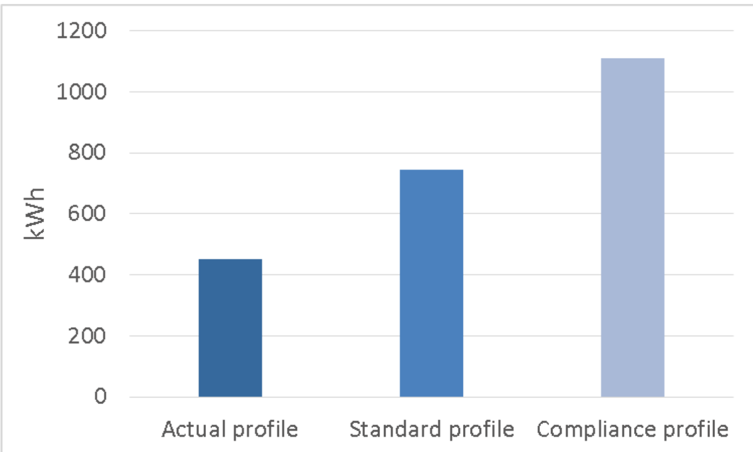

Figure 21 – Person loads related to different occupancy profiles for six months analysis period.

The figure shows that the Actual use determines the lowest value related to person loads. A 64% increase is achieved using the Standard profile while by modeling occupancy according to the Compliance procedure, an increment of 50% is obtained compared to the Standard profile and of 145% compared to the Actual one.

Figure 22 shows the electricity loads for household appliances and lighting in the three occupancy modes, for six months.

Figure 22 – Electricity loads for equipment related to different occupancy profiles for six months analysis period.

The lowest load for household appliances use is associated with the Actual profile. The modelling based on the Standard and Compliance profile produces a significant increment in electricity loads for appliances compared to the Actual case, quantifiable in a percentage increase of approximately 195% using the Standard profile and of around 240% using the Compliance profile. On the other hand, the loads predicted by using the standard and the Compliance profiles seem to be quite close (about 15% difference), indicating that the compliance calculation can adequately describe the appliances uses assumed as Standard, namely representative of a typical household. Whereas, considering a different household scenario from the representative one, such as the two-person family occurring in the analysed case, the loads due to equipment greatly shift from the values obtained with compliance or standard calculation.

Overall, the compliance calculation uses quite high loads and as a consequence the predicted heating energy will be lower than in the Actual and Standard cases.

Regarding DHW demand, the comparison between the three profiles is shown in figure 23.

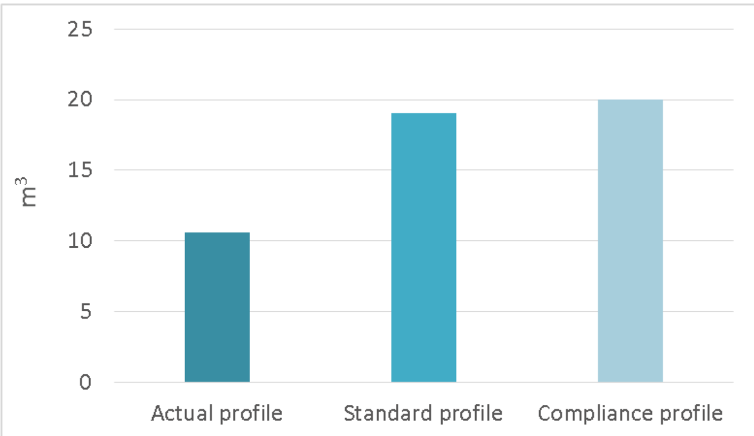

Figure 23 – DHW use for six months and for different occupancy profiles.

The DHW use for the Actual profile is almost halved with respect to the other two cases. Instead, the Standard and Compliance profiles are very similar (difference lower than 5%), thus regulations appropriately define DHW use for a representative family.

Based on these considerations, the calculation of the total electricity and heating use for the three occupancy profiles leads to the results displayed in figure 24, alongside the total use derived from measured data. The total electricity use includes all electrical uses in the building, hence appliances, lighting, packaged unit for ventilation and DHW, and control system.

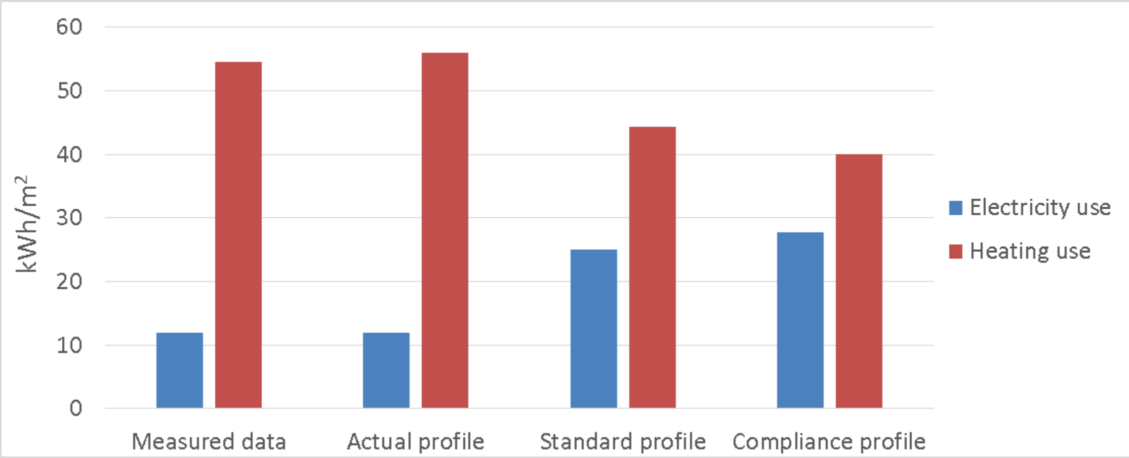

Figure 24 – The electricity and the heating use obtained for six months from measured data and simulation with three occupancy profiles. (The electricity use comprises all electrical uses in the building: equipment, ventilation, control,…).

The total electricity use and heating use resulting from the Actual profile are very close to the measured energy as the Actual profile was calibrated on the real data. Concerning the comparison with other occupancy modelling options, the Actual profile is characterised by the lowest total electricity use and the highest heating use. Conversely, the Compliance profile is characterised by the highest total electricity use and the lowest heating use. This is due to the fact that the higher electrical equipment use envisaged by the Compliance profile cause an increase in the internal gains with a consequent decrease in the energy use required for heating. The Standard profile occupies an intermediate position between these two extremes. The electricity use of the Compliance profile is 132% higher than the actual profile and 11% higher than the Standard profile. The heating use of the Compliance profile is 40% lower than actual profile and 10% lower than Standard profile. The Standard and Compliance profiles are quite similar. However, both are far from the measured data.

Therefore, the modelling according regulations is able to provide reliable results if the dwelling is occupied by households representing a standard use. If the actual occupancy model deviates from this reference, the consistency of the results is no longer guaranteed.

5. Conclusions

The paper presents the monitored data for a six-month period of a nearly Zero Energy Building built in the province of Aarhus, in Denmark, and currently occupied by a two-person family. A discrepancy was discovered between the expected energy use, calculated using the compliance model provided by the regulations, and the measured energy use. Based on the investigations conducted in this study, it was possible to find out that the difference in occupancy loads was actually the reason for this gap. The outcomes prove that ooccupancy profiles are particularly significant in the evaluation of the energy performance of nearly zero energy buildings and differences in loads are one of the most important reasons for the gap between the expected and the actual energy use.

In particular, the impact of three different occupancy profiles on the final energy use was explored. The first profile (Compliance profile) implements a simplified model, as dictated by the regulations, and it is used in the design of the building. The second profile (Standard profile), more detailed compared to the Compliance, is built on the "average" data obtained through surveys and it can be assumed as expression of a standard use of the building by a typical family. The third profile (Actual profile) is the most accurate, it is obtained from the actual data monitored and tries to reproduce the real habits of the occupants living in the house. The three different occupancy models lead to differences in the final energy use. In particular, in the Compliance calculation, higher occupancy loads are contemplated (both due to persons and electrical equipment) and this results in a lower energy demand for heating. By applying the Actual profile, indeed, a heating demand 40% higher than the Compliance model and of 26% higher than the Standard model, is obtained. Conversely, the Compliance profile generates the maximum electricity use, being 132% higher compared to the Actual profile and 11% higher with respect to the Standard profile. Differences are also obtained in the domestic hot water usage. The Actual profile is characterised by the lowest DHW use, with a difference of about 90% compared to the other two profiles, which are similar in the use of DHW.

Concerning simulation effectiveness, if the right estimation of the occupancy loads and occupancy profiles is available and in case that a good knowledge on systems operation is accessible, then a good fit between measured and predicted energy use can be reached. Thus, implementing the right assumptions and the proper conditions into the simulation model, a suitable correspondence between measurements and simulations is earned. Hence, the performance gap is not due to the unsatisfactory validity of the model, rather to the retrievable information on occupancy. Moreover, it was observed that the simulation model can effectively describe the average behaviour of the occupants derived from typical habits, but some criticalities emerged in the representation of unpredictable behaviours. This is the reason why the simulation is able to provide reliable results in the long term, whereas on limited time intervals a level of uncertainty has to be considered, due to the impossibility of exactly reproducing the users' changeable behaviour.

Acknowledgement

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Chapter 6
Occupancy profiles definition

Building simulation is often used for energy consumption estimation and optimization processes in the design phase. However, recent research has shown substantial differences between predicted and actual energy consumption. This significant disagreement is not imputable to deterministic factors such as building characteristics, HVAC systems, lighting, and appliances, which are usually well-defined. Instead, discrepancies arise from a lack of accurate quantitative description of energy-related occupant behaviour in buildings and the use of standard occupancy data. Occupancy profiles and occupant behaviour differ per household type but also can vary according to the socio-economic and cultural context. Regional responsive data allow for the achievement of better predictions. Therefore, the development of occupancy profiles for each specific analysed area is required in order to obtain more reliable predictions of energy performance.

As schematized in figure 1, four approaches can be adopted for the implementation of occupancy profiles in simulation software. Pre-defined occupancy patterns can be selected from default libraries provided by the software (fig. 1a). Time schedules can be pre-calculated by the user and entered in the software obtaining results that can be used to adjust the initial assumptions (fig. 1b). In more flexible configurations, occupancy is modelled through functions or customized code that allow the definition of building operation and controls (fig. 1c) or either generated by parallel simulations in software able to run multiple modules simultaneously (fig. 1d).

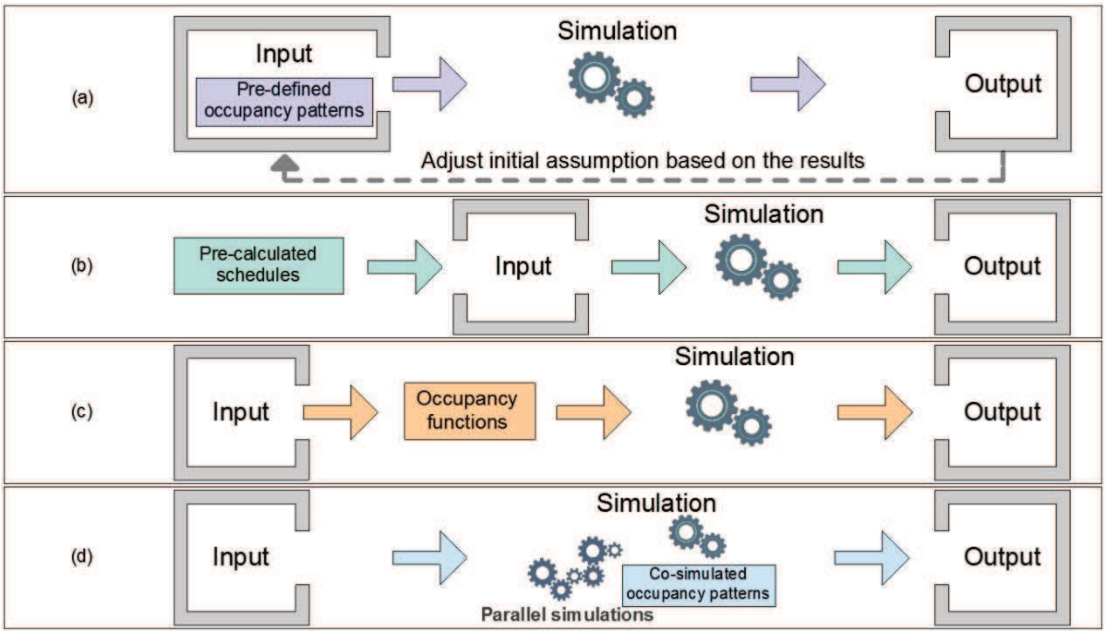

Figure 1. Different approaches for the implementation of occupancy models in simulation software

Regarding the definition of occupancy profiles, different methods can be used based on data collection and subsequent processing with distinct techniques. A comprehensive framework of reference procedures for obtaining occupancy profiles in residential buildings is provided in the report included in Section 6.1, developed within the IEA EBC Annex 66 “Definition and simulation of occupant behavior in buildings”. The paper presented in Section 6.2 illustrates the findings of a review aimed at exploring the use of the questionnaire as a data collection method for analyses carried out in residential buildings. Studies in Section 6.3 and 6.4 show the results of a survey conducted in the research area (southern Italy) using a questionnaire specifically designed for gathering information suitable to characterize occupancy and to define typical hourly profiles.

IEA EBC Annex 66 – Subtask A Deliverable

May 20, 2018

6.1 Reference procedures for obtaining occupancy profiles in residential buildings

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Contribution of the candidate: the candidate contributed to assemble the reference sample. She conceived the original classification of the variables characterizing an occupancy profile consisting of Presence variables, Comfort variables, and Tool variables, and outlined the framework reported at the end of the document. She wrote the sections 2.1 and 3 of the report.

1. Introduction

This report presents the main findings of the activity 4.4 "Reference procedures for obtaining occupancy profiles in residential building" belonging to IEA EBC Annex 66 Subtask A. The activity was conducted with the aim of providing methods to describe occupancy in residential buildings and technical approaches to define occupancy profiles for energy simulations. Occupancy data can be classified into four levels: presence status ("occupied" and "unoccupied"), number of occupants, place in the space and activity. Occupants' profiles can be defined by considering how people occupy the building, how they use the systems (heating, cooling, etc.), and how they interact with devices including windows, blinds, lights, appliances, etc. Occupancy profiles may differ significantly from each other and affect the energy performance of buildings. Their determination is essential as they are necessary inputs to energy building simulation. Based on these considerations, the report is focused on:

1. Investigating the procedures used to obtain occupancy profiles and their limitations;
2. Identifying the problems of data collection methods;
3. Characterizing different types of variables necessary to define representative occupancy profiles.

To achieve the aims above, the following steps were done:

1. Completing a literature review by considering different residential context and doing a classification (by continent, methodology, type of statistical analysis and other);
2. Providing information about methodologies for data collection and processing;
3. Define the variables to be considered in surveys to get occupancy profiles.

2. Review of case studies and methods

Identification of occupancy characteristics in residential buildings presents specific issues. Unlike in laboratory studies, researchers may have limited access to sensors and other equipment used for in situ monitoring. Adjustment or replacement of monitoring equipment can be invasive and time-consuming. Frequent visits may remind occupants that they are being monitored. Thus, occupants and their behavior can be significantly affected by knowledge that they are being monitored (Hawthorne effect). In consequence, in residential buildings, collecting data by applying social surveys is mostly preferred by researchers to reveal occupancy profiles and the reasoning for those.

2.1 Description of the sample of literature reviewed

A body of literature of fifty studies related to occupancy profiles was collected through systematic literature review and snow-ball approach. The selected documents were analyzed and classified according to geographic context, period, sample size, and methods used to collect information and analyze data. The review allowed also to identify which variables are taken into consideration, the sampling strategy, the study design. Most of the works were carried out in Europe (37), some examples were found in Asia (10) and only few works were identified in USA (3). Figure 1 details the countries where the investigations were conducted.

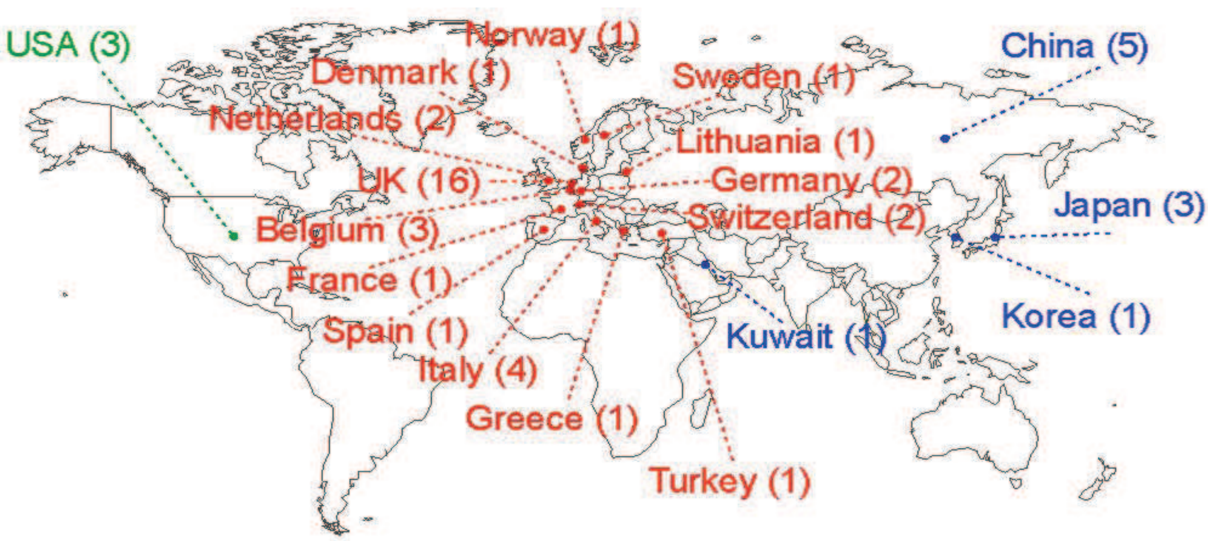

Figure 1. Countries of provenance of the analyzed studies on occupancy profiles.

The earliest study dates back to 1979 in USA, very recent investigations are also available. Most of the studies have been developed after 2000, on all continents. In particular an increasing attention to this topic is registered in latest years in Europe, where 60% of the studies are dated after 2010. In most of the analyzed cases (42.5%), data are collected through questionnaires administered in different ways (face-to-face, mailed, telephone, self-completed). In 34% of the cases, field measurements or time use data are employed. Some studies (15%) report mixed techniques for data collection, and about 8.5% refer to literature review for the definition of occupancy profiles. Data acquisition by field measurements is typically used for limited case studies while the application of time use data involves large samples. In the works elaborated before 2010s, the most commonly used analysis techniques are correlation, regression, and clustering. Markov models appear widely used after 2010s. Generally, cluster analysis is applied to large samples (hundreds or thousands investigated units), other statistical elaborations, such as regression or Markov chain, are used for diverse sample sizes (from less than ten to more thousands).

2.2 Methods of occupancy data collection

There are two main categories of data collection methods: social surveys and monitoring surveys. Social surveys collect subjective data and can capture causal inference (why and how people do things) and socio-demographic information. Monitoring surveys capture the actual type, duration and frequency of occupancy patterns. Reference studies for each data collection method can be found in [1] and [2].

a) Social Surveys

Method	Advantages	Limitations
Interview: private meeting to discuss a topic (face to face or not). Structured (fixed questions) to unstructured (guided interview)	Respondents are not limited in their answers Interviewers can confirm that respondents understand the questions and provide clarification when needed	Possible bias due to 'interviewer effect' Difficult to replicate
Focus group: group meeting between participants and moderator to discuss a topic	Flexible, content led by respondents	Possible bias due to 'moderator effect' and 'group effect' Difficult to replicate
Diary: self-completed questionnaires with structured entries, Time Use Survey (TUS)	Comparable and replicable when same diary structure is utilised (e.g. HETUS across Europe)	Requires commitment from participant Filling the diary may interfere with the activities
Questionnaire: structured questions and answers	High replicability Multiple means of communication: meeting, phone call, email, post Minimal interviewer intervention	No opportunity for follow-up questions Possible subsampling problems with post and email Limited answers
Observations: researcher observes participants on-site or passively through monitoring device, e.g. camera	Does not depend on people's report, activities are directly observed. High flexibility in the content captured	Possible bias due to 'Hawthorne effect' Relative to observer; two observers could consider the relevancy of events differently

b) Monitoring surveys

Method	Advantages	Limitations
Passive infra-red (PIR): detection of heat waves from warm objects. PIR sensors detect motion.	Affordable, available, easy to install and maintain Ease of data analysis	Does not allow differentiating between multiple occupants Can produce false negatives when occupant is still or false positives by pets

Method	Advantages	Limitations
Carbon dioxide sensor (CO2): capture of changes in carbon dioxide concentration levels	Affordable and easy to deploy	Requires mains power Measurements can be affected by ventilation practices and infiltration rates
Energy meters: inference of occupancy from electricity consumption	Non-intrusive Already installed technology	Limited to houses with smart meters only Requires high granularity
Device-free Localisation (DfL): detection of changes in a radio frequency signal environment due to absorption from occupants' bodies	Non-intrusive, no tag needed Allows tracking individual movement Not limited by structural elements	Requires precise positioning of components Possible interferences from other sources
Wearable loggers: geolocation sensing as GPS or inertial navigation	Already installed technology (e.g. occupant's mobile phone)	Possible bias due to 'Hawthorne effect' Privacy issues
Wearable loggers with stationary sensors: combination of wearable tags and beacons of Bluetooth, wireless or ultrasound networks	Precise detection	Participants have to wear/carry tags Requires challenging set-up and maintenance

2.3 Data analysis methods

Reference studies for each data analysis method can be found in [2].

Method		Common application
Descriptive statistics	Analysis of data, description and summary of main features	Energy meter data Monitored occupancy data from single sensors or networks
Inferential statistics	Generalisations about a population from a sample	Energy meter data Monitored occupancy data from single sensors or networks
Modelling	**Schedules** as binary daily occupancy profiles	Social surveys
	Deterministic models: to establish causal relationships to occupant behaviour	Monitored occupancy data from single sensors or networks Social surveys
	Non-probabilistic and stochastic models including Markov chain models based on a random transition between states	Extensively used with Time Use Surveys where state probabilities are derived from diaries
	Time series analysis: statistical analysis accounting for trends and seasonality. Forecasting model. Includes: Auto-Regression, Moving Averages, Hidden Markov Model	Energy meter data Monitored occupancy data from single sensors or networks Occupancy forecasting in BMS
	Agent-based: modelling of behaviour at individual level; each person is an autonomous agent with own behaviour, social norms, etc. that interacts with each other in a dynamic environment	Data from both monitoring and social surveys can be used for model calibration and validation
	Machine learning: algorithms that can learn from data without specific instructions. They can be supervised (Decision-tree, Support Vector Machine-SVM, k-nearest neighbours) or unsupervised (hierarchical clustering, neural networks)	Monitoring sensors networks Energy meter data Social surveys
Data mining	Identification of patterns in large datasets (factorial analysis, multidimensional scaling, cluster analysis, etc.)	Energy meter data Monitored occupancy data from single sensors or networks

2.4 How to define occupancy profiles

Social and monitoring surveys can be used to define or validate occupancy profiles. Occupancy profiles may be defined through Time-Use Survey (TUS) data. For example, Aerts et al. [3] described a methodology to obtain occupancy profiles based on the 2005 Belgian time-use survey with the aim of using it for user behavior modeling in building energy simulation. The authors of the study developed seven user profiles reflecting realistic user behavior in homes. Similarly, Richardson et al. [4] defined occupancy profiles for UK households by using TUS data describing people habits. The developed models indicate the number of occupants in the house at a given time to have information on the sharing of energy use. Wilke et al. [5] used French time-use survey data to calibrate stochastic models and to predict activity chains.

In [6] different procedures for obtaining occupancy profiles are reviewed focusing on residential building stock located in Italy. Three occupancy profiles are derived from different methods: (1) interview of residents, (2) national standards application and (3) Harmonised European Time Use Survey for Italy. Then, different modes of use of a representative dwelling are tested by varying density of occupancy, ventilation, lighting, domestic hot water and heating operation. Another study by [7] considers nZEB definition and national census information to determine a method for creating housing occupancy patterns by using free database. Finally, another study in Turkey [8] conducted social surveys in 4 residential complexes situated in 4 large cities of Turkey each of which is in a different climatic region but has similar design and construction system. In addition, monitoring survey was undertaken in one of the four residential complexes. The results showed that presence at home and window opening strategy are the most sensitive parameters on heating load and comfort levels both under winter and summer conditions.

3. Identification and classification of variables related to occupancy profiles

Occupancy profiles are determined by diverse driving factors such as household characteristics, cultural traditions, social and economic variables. On the other hand, occupant's preferences and attitudes affect the use of equipment and air conditioning systems and influence the building energy consumption. In general, it is possible to individuate two types of variables:

Variables Type_1 – Variables that influence occupancy profiles

• **Socio-demographic variables** are determinants of occupancy in dwellings as in 'when' people are in their homes [2]. Variables include household composition and employment status. Adults overs 60 years of age and families with small children tend to spend more time in their homes during weekdays and weekends. Regarding employment, work status (working full time, part-time, retired) and industry (working schedules) shape occupant's schedules throughout the week.

• **Environmental and physiological variables** influence occupancy patterns (time and/or space) and comfort level preferences [9]. Occupants' comfort depends on environmental characteristics (climate and building typology), psychological characteristics are related to age, gender and expectations derived from past experiences.

Variable Type_2 – Variables influenced by occupancy profiles

• **Presence variables**: energy consumption in households is heavily dependent on how the building is used. In particular, the type of activity, the hours of presence of the occupants in the different rooms and the density of occupancy should be considered for the estimation of sensible and latent heat associated with people and, consequently, in the convective/radiative loads that weights on the energy balance of the internal environment.

• **Comfort variables:** parameters that control the environmental conditions in homes (air temperature, heating and cooling systems operating, ventilation, etc.).

• **Tools variables:** use of the amenities in homes, including the use of electrical equipment, cooking and the demand for hot water.

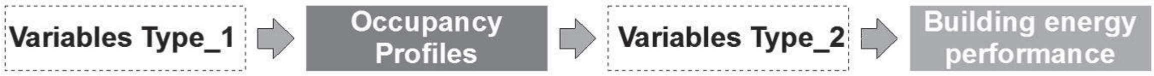

Figure 2. Variables categorization and reciprocal influences.

Both ‘comfort’ and ‘tools’ variables are strongly linked to the “type of user” and to the “management” of the house by the occupants. Heating/cooling demands are derived from set point temperature and occupancy profile, while ventilation is related to window operation. The figure below illustrates the framework of the variables in building simulation and modelling that are dependent upon occupancy profiles.

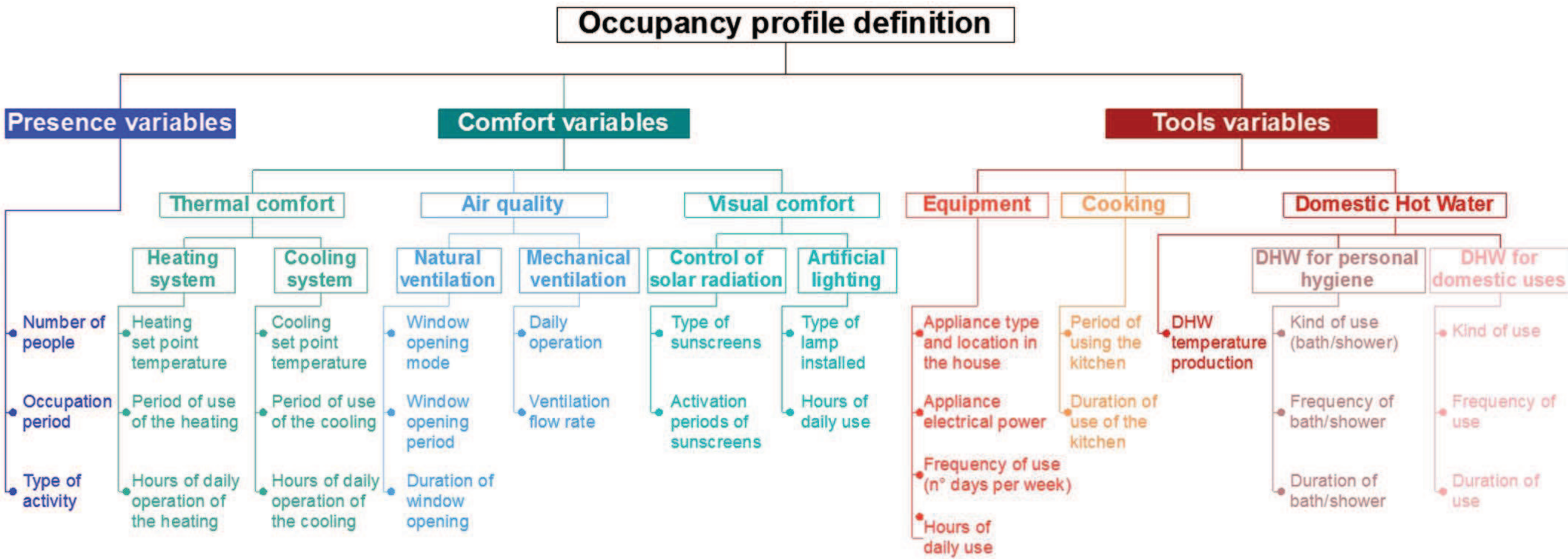

Figure 3. Variables categorization for input in energy building simulation and modeling.

4. Conclusions

This report draws out different methods for defining occupancy profiles and highlighted the advantages and disadvantages of each approach by considering an extensive literature review. Also, the variables related to occupancy, which are necessary input for energy simulation, are defined. In situ monitoring and social surveys are used as data collection methods, in some cases these are coupled. Monitoring sensors are able to track occupancy characteristics in real time but can be invasive and require an adequate observation period. The most common method is interview surveys, but this method can be time consuming and not replicable. A viable alternative might be the use of existing datasets; but most currently available datasets are not sufficiently detailed. Therefore, targeted surveys should be developed in order to create exploitable datasets for this specific purpose. Analyses at local level are needed since the habits and behaviors of users vary depending on the geographical area. Finally, this report underlines the necessity to include National survey questions about the occupancy and the use of houses. Generally, this information is poor and fragmented.

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6.2 On the use of questionnaire in residential buildings. A review of collected data, methodologies and objectives

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Abstract

The paper presents a review of the literature on the use of the questionnaire as a tool for collecting energy data in residential buildings. Numerous studies used the questionnaire to gather necessary information for different purposes. However, even using the same tool, the procedures differ in terms of distribution and compilation, contact with the interviewees and type of proposed questions. One hundred thirty-seven studies were considered in the review, including both scientific articles and surveys reports. The available works were analysed and classified according to the geographical origin, period, sample size, sample structure, data collection methods, response rate, data processing, and objectives of the investigation. In the 80% of the selected studies, the questionnaire is used as unique tool for data collection, albeit cases in which the questionnaire is coupled with other survey techniques, such as field measurements and time use surveys, have also been recorded. The in-person interview is the most common completion option in the sample and it is also the method that produces the highest response rate (77.6%). Generally, the collected data are subjected to statistical processing (over 80% of the cases). Regarding the objective of the surveys, the questionnaire is mainly employed for investigations on energy consumption and occupants' behaviour, but also other purposes were identified. Overall, the revised sample and the experiences reported are largely varied and heterogeneous. The lack of a homogeneous methodology appears in the use of an extremely diversified terminology. Therefore, the codification of a reference method and the standardisation of the nomenclature would be desirable. It would be useful to define general guidelines to be followed when designing surveys by using questionnaires. The review provides some suggestions and guidance on the use of questionnaire, highlighting strengths and weaknesses, and represents a source of information for future researches focused on the energy performance of buildings.

Keywords: Questionnaire; Survey; Residential buildings; Energy data; Data collection; Data analysis.

1. Introduction

Noticeable attention has been paid to research in the building sector due to its relevance for various stakeholders (designers, companies, vendors, industries, general public, energy consumers and suppliers, scientific community, and governments) in recent years. In particular, research activities have been directed on one side at exploring the way of constructing buildings and, on the other hand, at investigating the way in which buildings are used. Both routes converge towards the shared objective of identifying strategies and solutions able to give effect to the EU Directive [1] regarding energy containment, and seeking to guarantee improved environmental quality and livability of interior spaces at the same time.

However, this field of study seems to be highly complex because of the copious number of variables coming into play and their level of diversification. In fact, numerous factors are implied and cover different aspects, such as climatic conditions, constructive characteristics, building management and occupants' behaviour. All these elements have their own weight and have been discussed in numerous studies. Some authors were focused on the technical features, for example investigating buildings shape, materials, and system configurations [2-7]. Other authors have instead addressed the role of occupancy characteristics and social, demographic, economic and cultural variables [8-12]. Several studies have been directed to promoting energy efficiency and energy saving actions [13-15]. In many cases, the internal comfort and the level of satisfaction of the users have been investigated [16-19]. Moreover, some studies considered energy policies and proposals for minimizing environmental impact [20-23].

Whatever the objective of the study, nevertheless, a more or less extensive set of data is always required in order to perform modeling and analysis of buildings and to make assessments regarding the involved variables. In most cases, acquiring the necessary information to develop calculations is a challenging task. In addition, the accuracy and reliability of the collected data are crucial for the quality of the research results. Statistical database collected by public or private organizations are frequently used in order to make available the required information (energy consumption, buildings properties, households characteristics etc.) [24-26]. Methods and technical approaches to describe occupancy profiles in residential buildings have also been developed as a part of international research activities [27].

However, not always the needed data are retrievable and data collection for specific applications can result in a very demanding assignment. For public buildings, it can be quite simple to obtain information because some archives are usually held by institutions or offices responsible for storing data on the building characteristics and operation. On the contrary, gathering data and information in the sector of residential buildings is particularly hard due to the extreme variety of the building stock and the lack of unified and organic sources. Furthermore, an issue that arises in data collection is represented by the tool and the methodology that has to be adopted.

Extensive studies have been conducted concerning investigation methods [28-30], quality of the obtained data [31], and samples features [32-34]. Among survey methods, one of the most used tool is represented by the questionnaire, which can be administered in different ways [35]. Several and diversified experiences regarding data collection through questionnaire for applications in residential buildings emerged from the analysed literature. However, each individual study is focused on a specific case and data set, rather than on the collection procedures issues. Generally, researchers design the questionnaire by responding to their purposes, in accordance with general principles but still customizing it to suit precise scopes. This lead to a wide panorama in which it is worth noticing the dearth of a comprehensive and large-scale processing that can highlight how the questionnaire is used in different situations and what are the corresponding outcomes.

For this reason, an in-depth review was conducted by compiling a collection of more than one-hundred documents on research works that used questionnaires. In particular, source literature was identified from the late 1970s to the first half of 2017. The articles were reviewed and a table summarizing the key information was filled and reported in Appendix A.

The value and utility of the review consists in the fact that several sources using questionnaires in the residential area are collected, analysed, and compared for the first time according to different criteria. This work originated from the need of developing a systematic approach to understand how to adopt and improve suitable investigation methods under different conditions and contexts.

Based on these considerations, the review intends to:

- offer an overview of the studies that developed analyses in residential buildings by using data collected through questionnaires;
- highlight similarities and differences among the various experiences and outline some common practices;
- bridge the gap resulting from the paucity of an extended analysis on the use of questionnaires and define an homogeneous and coherent context from which glean information about benefits and drawbacks of the used tools.

To achieve these goals, the review evolved by means of the following steps:

- collection of the literature and classification of the works in a structured inventory;
- descriptive analysis of the collected sample;
- evaluations of the methods used for the questionnaire administration and associated response rate;
- examination of the data processing techniques applied in the considered studies;
- detailed exposition of the objectives for which the questionnaires have been used.

The main findings are debated in terms of assessment on the suitability of different methodologies, feedback on different procedures, and critical discussion of the outcomes. The review concludes by summarizing recommendations and addresses for future studies in this area. Moreover, some suggestions and proposals that could improve and facilitate research activities in this sector are provided.

2. Literature processing

A body of literature of one hundred and thirty-seven studies related to the use of questionnaires in residential buildings was collected through systematic literature review and snow-ball approach. The review primarily selected studies on questionnaire application included in peer-reviewed international journals indexed in Scopus (85.4% of the entire sample). Reports of official surveys administrated by statistical institutes and government agencies were also considered in the 6.6% of the cases and another 6.6% is represented by conference proceedings. Furthermore, 1.4% of the investigated sample consists of internal publications of departments or university journals.

Even using the same survey tool, each study pursues a specific goal. Questionnaires in the selected studies, on the whole, are used for investigations related to energy uses in housing, activities of the occupants within the home and experiences of living in it. Another category collects questionnaires aimed to provide guidelines and general addresses for authorities and practitioners.

The tracked documents were analysed and classified according to:

- geographical context
- period
- sample size
- data collection methods and response rate
- data processing techniques
- objectives of investigation

The review allowed also to identify which variables are taken into consideration, the sampling strategy, the study design.

2.1 Geographical distribution

Most of the works were carried out in Europe (56.2% of the total) and Asia (30.7%). A fair number of examples were also found in America (8%) while only a few cases were identified in Africa (1.5%) and Oceania (2.2%). Some of the detected studies involves more countries, in the same continent. In particular, four multinational studies in Europe and three in USA were listed. In detail, the survey illustrated in [36] was conducted in Spain and Netherlands; the [37] in Italy and Austria; the analysis presented by [38] included ten EU Countries (Germany, Denmark, Spain, Finland, France, Hungary, Italy, Netherlands, Poland, UK); [39] considered nine European Countries (Italy, Netherlands, Portugal, Denmark, Germany, Finland, UK, Czech Republic, Switzerland). The analyses showed in [40] and in [41] are extended to all USA, while the investigation in [42] is related to four states (Texas, California, New York and Texas). Two studies are transcontinental: [43] was developed across Europe and America, involving Italy, Spain, Finland and USA; while [44] pertained to Europe and Asia, throughout Norway and Japan.

Figure 1 details the Countries where the collected investigations were conducted.

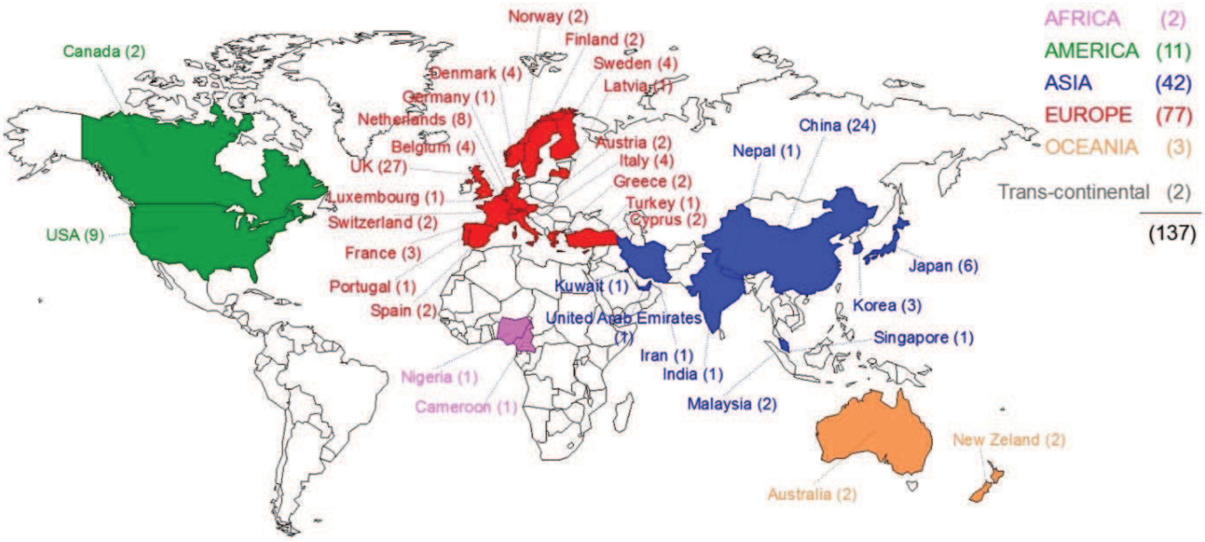

Figure 1. Countries of the analysed studies.

2.2 Time distribution

All the selected works were placed temporally by considering a subdivision per decades, starting since 1970 because no documents were identified prior to this period. The following time ranges were used for the classification:

- 1970-1980
- 1981-1990
- 1991-2000
- 2001-2010
- From 2011 onwards

For 15 studies out of the total, it was not possible to trace the year when the investigation was conducted, thus the year of publication of the article was taken as a reference, trusting this approximation is acceptable in a categorization for ten-year interval.

The earliest study dates back to 1979 in USA, very recent investigations are also available. The interest in this matter arose in Northern America and then spread in Europe in the 1980s and in Asia since the 1990s. In particular, most of the studies (over 80%) have been developed after 2000, and about 50% of these were carried out after 2011, proving that an increasing attention has been paid to this topic in the most recent years. About 11% of the cases fall in the 1990s and only a few applications were developed in the 1980s (3 cases). Five studies interested more periods and, for this reason, were classified as "straddling two or more decades". However, the majority of these studies belong to the 2000s and 2010s. The temporal distribution of the analysed studies is shown in figure 2.

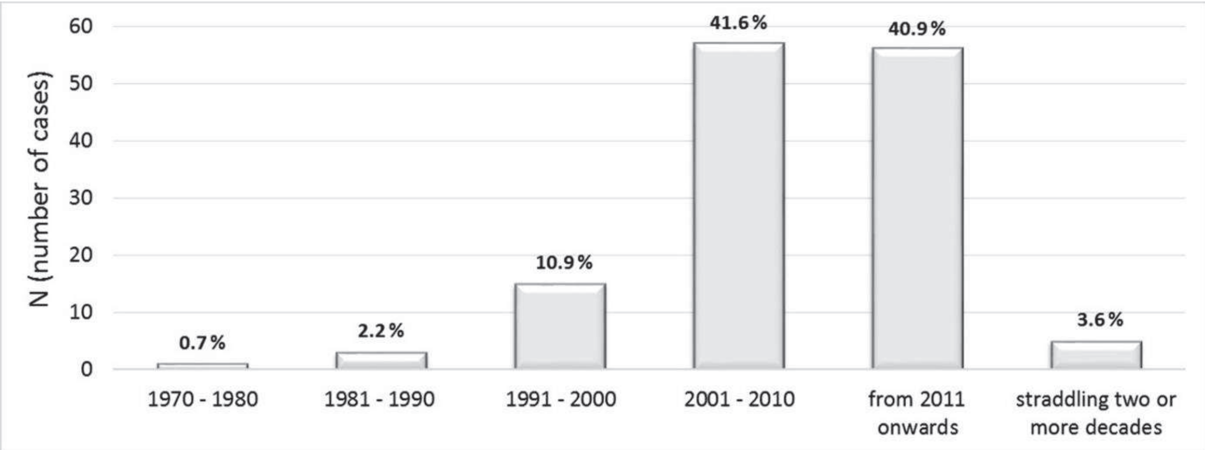

Figure 2. Time division of the collected works.

Deeping within the production period of the studies in each of individual continent, in America the number of analyses developed in the first ten years of 2000s is higher (45.5%) with respect to the other time slots, while in Asia the works carried out after 2011 (50.0%) prevail. In Europe, approximately the same number of cases (corresponding at about 40%) were collected for both the periods from 2001 to 2010 (33 cases) and from 2011 onwards (30 cases).

It is worth specifying the investigations involving more time intervals: [45] administered a questionnaire in two different times (2009 and 2013).The analysis in [46] refers to the Nepal Living Standard Survey (NLSS) conducted in the years 1995/1996, 2003/2004 and 2010/2011. [25] presents the results of two home energy use surveys driven in England in two different years, the first in 1984 and the latter in 2007. The empirical material used in [47] were collected during three different periods between 2002 and 2013. The investigation illustrated in [48] adopted a qualitative approach including three phases: netnography survey from 2009 to 2014, mailed questionnaire in 2013, and interview in 2014.

2.3 Sample size

The size of the survey samples considered by the various collected studies seems to be extremely diverse and complex. We provide some examples about the extent of the samples involved: the investigations range from States [49] and Countries [38], to Regions [50], Provinces [24], cities [51-53], small towns [54], and to districts [16,55], communities [56], villages [57], neighbourhoods [58], and parishes [59]. This short overview gives an idea of the enormous variety found in the set of the analysed works.

In addition to the extent of the context in which the investigations were developed, a multifarious and diversified nomenclature was discovered in defining the survey recipients. Figure 3 illustrates an overview of the terminology used to identify individuals, households, dwellings, and multi-family buildings. Moreover, the number of studies providing information on each typology of recipient is reported. However, 25 works (20% of the whole sample) give information about more than one category of recipients. For example, data used in [60] are given by 6400 individuals from 3474 families; [61] considered 20 households in 2 apartment complexes. For this reason, the number of cases reported in figure 3 exceeds the number of the analysed studies. Furthermore, in some articles, the identity of the recipients is not specified but just the number of the collected questionnaires or statistical observations is pointed out.

Figure 3. Overview of technical terms used to identify different categories of recipients and number of studies providing information about each class.

Within each category of recipients, the sample size varies widely, from some units of items to hundreds or thousands units. The graph in figure 4 summarizes the percentages of sample dimension for the various categories of recipients involved in the sample.

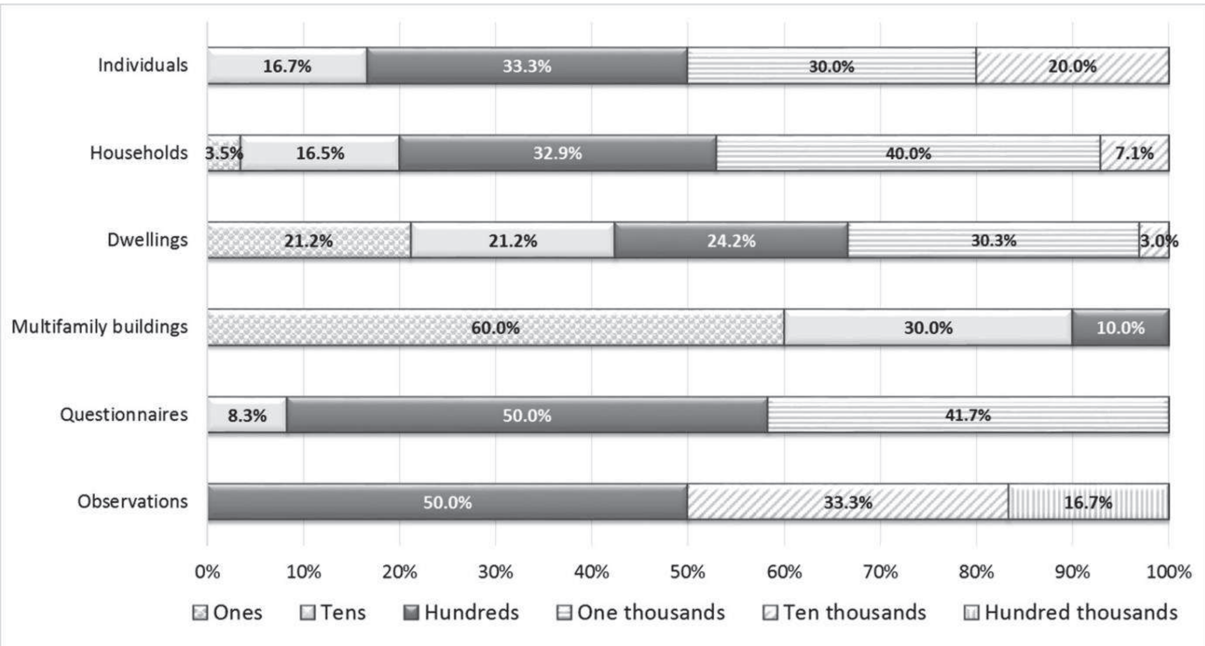

Figure 4. Percentage breakdown of the sample size for each category of recipients.

When data are collected singularly (for individuals), the minimum size of the sample considers tens of items. The administration of few units samples, less than ten elements, is not very frequent. In the only case of multifamily buildings a higher number of samples made by units is registered (60%). The more recurring size orders are hundreds and thousands of items, for all classes of recipients. The sample seems to be particularly conspicuous when the collection is reported in terms of Questionnaires or Observations, for which the size reaches tens of thousands and hundreds of thousands units.

In 27 cases (about 20% of the total) the samples are divided into sub-samples of equal or different size. In [62] no indication about the sample size is given.

A particular case is represented by [63] which has practically an open sample.

2.4 Sample structure

In 74.5% of the cases the sample selected for the survey is homogeneous, the survey is conducted at the same time and is addressed to recipients with the same characteristics. In the remaining 25.5% of cases, the samples can be defined as heterogeneous, undergoing a number of specific and different conditions. In particular, in some cases the sample is split because attributable to two or more separate investigations, conducted at different times. For example, in winter and summer [64,65], or in two successive winters [13], in different years [66,67] or decades [46], before and after the adoption of smart technologies [68] or the provision of energy-saving measures, in three distinct moments throughout the study (Preliminary Survey, Min Survey and Ending Survey) [69].

In other cases, although the survey is simultaneous, the heterogeneity of the sample is due to the fact that the study is undertaken in different places, for example 12 villages [70], different cities [36,44,52,57], two or more Countries [37-39], or considering a National sample and a Local sample [71]. Moreover, studies considering a branched sample have been found, meaning that the survey has the same space-time boundaries, but the sample is sectored according to certain parameters, distinguishing by gender [72], or building typology, or traditional and modern buildings [73], or public houses and private houses [74], villas and flat [75], apartments and detached houses [36,76].

In addition, certain analyses are addressed to samples with specific characteristics. For instance, regarding the peculiarity related to the categories of respondents, the following applications are registered: urban households [77], rural households [78], low-income households [16], indigenous [57], farmers [70], customers [79], consumers [80], students' families [81], employees [82,83]. Concerning particular typologies of buildings, investigations on social houses [84], green houses [85], and passive houses [86] are observed. Finally, the subdivision of the sample can be due to the nature of the investigation: pilot group and control group [87], different distribution methods of the questionnaire [48,88,89], creation of subsamples for monitoring and measures [13,56,82,90-92], quantitative questionnaire and qualitative interview [93], questionnaire about social problems and motivational questionnaire [94].

2.5 Data collection methods

Data collection took place by means of a questionnaire in over 80% of cases, while in 18.2% the questionnaire is used in combination with further investigation techniques consisting in field measurements and Time Use Survey. In figure 5 the various types of survey employed in the considered studied are displayed.

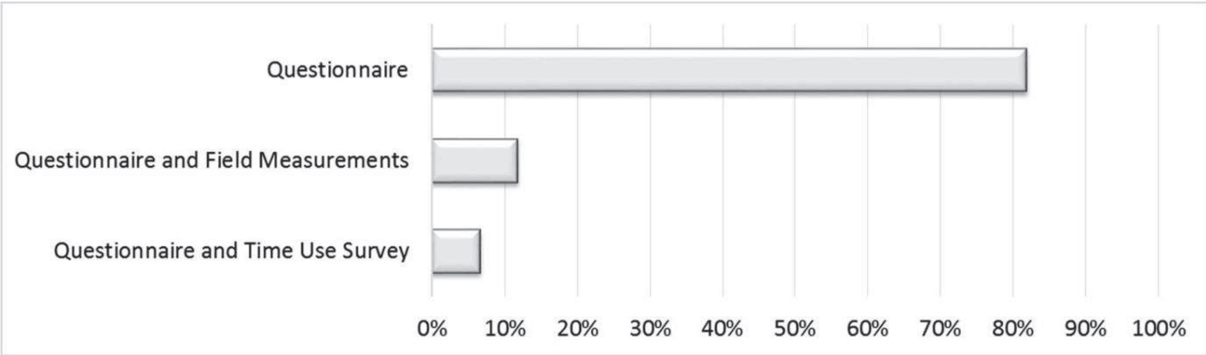

Figure 5. Types of investigation detected in the review sample.

13 cases report multiple investigations conducted at different times or at the same time interval but on different samples. Moreover, within the same survey, one or more data collection methods can be adopted. Not all the analysed works specify the method of data collection. In fact, in 12.4% of cases the methodology is not explicit. Instead, in 14.6% of cases different methods for collecting information are used. For example, in [95] in-person interview, telephone interview and mailed questionnaire were employed.

Different methods among the works that make known the modality applied for data collection were identified. In detail, various denominations of the used methods were traced. However, all these methodologies can flow into two main categories of techniques, characterized by the fact that data are reported by the respondents or, alternatively, acquired by persons appointed to pilot the survey. The subdivision shown in figure 6 is based on this discriminating factor. In 16.6% of cases mixed data acquisition methods are used.

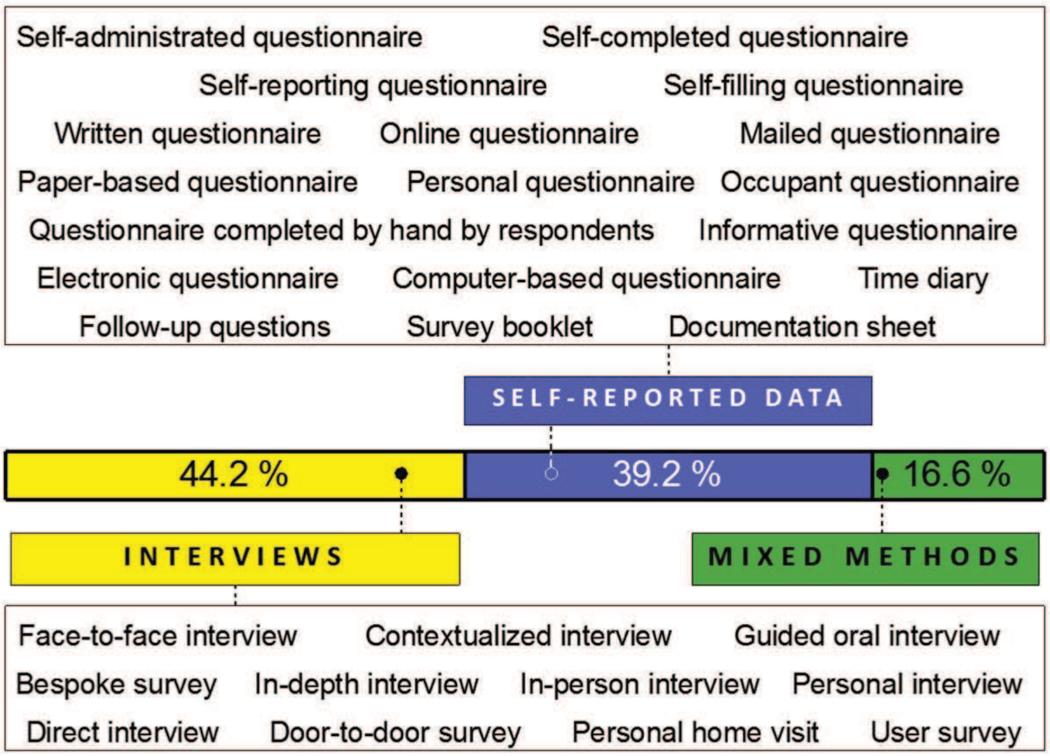

Figure 6. Sample classification according to the applied data collection method and adopted nomenclature in each case.

The interviews can be executed by personal meeting and direct conversation, by telephone or by using computer assisted systems. The supply of data autonomously from the participants includes options in which the questionnaire is compiled on paper, or through a link accessible from the email box, or even by filling an inquiry directly on the web, or by compiling diaries that record the activities carried out during the day and usually with very close time-steps.

Figure 7 shows the number of investigations conducted by using the described techniques. It is worth highlighting that not all the analysed studies specify the method used for data collection while in some articles performing more than one survey, different methods were detected.

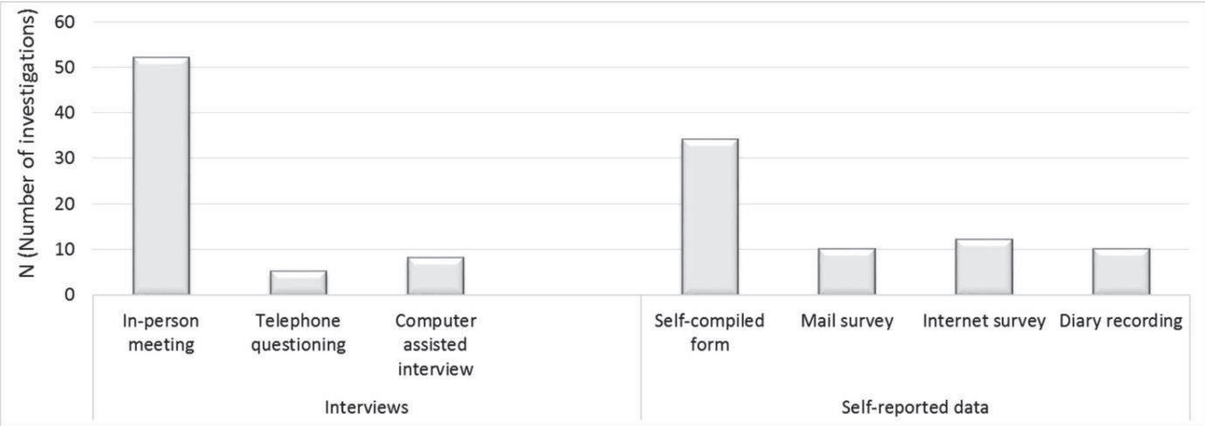

Figure 7. Survey completion options for interview and self-reported data.

Regarding interviews, the most widespread strategy consists in encountering the interviewee. In the case of information provided independently, the most common method is the self-compiled form.

No strict correlations were detected between data collection methods and size of the investigated sample, although a widespread use of email surveys, internet survey, and computer-assisted surveys can be observed in samples of thousands respondents. Instead, the interviews by in-person meeting and by self-filling questionnaires are widely used both for small and large samples.

In many cases, a large-scale questionnaire [45,52,67,96] or an extensive questionnaire [40,41,97,98] are used in the investigation. A micro level household survey is conducted by [99] for econometric estimation. The questionnaire can be administrated by trained surveyors [100], researchers [101] or students [24,78,81]. In some cases, data collection is handled by a specific market research company [38,68].

Special solutions are adopted by [63,102] and [48], which propose online interactive tools to get real-time information from respondents while in [103] an energy conservation through product-integrated feedback is experimented, by using specifically a computerized task consisting in a short list of questions carried out through electronic control panels on washing machine.

In certain research works, more than one questionnaire is issued to the interviewees. For example, in the survey reported by [94], regarding household energy requirement and value patterns, the respondents filled five different questionnaires: one for value patterns, two for the consumption patterns, one for the view on societal problems and one for the motivation to save energy. In [104] a brief pre-questionnaire and a more comprehensive post-questionnaire were sent to participants and, moreover, a post-experimental telephone interview was conducted on a part of the sample. Other investigations foresee diverse level of data acquisition, for example [105] and [106] required the completion of individual questionnaires, household questionnaires, daily diaries and weekly diaries. The authors of [71] used the CVM (Contingent Valuation Method) to design a questionnaire addressed to a National sample and the DCE (Discrete Choice Experiment) for a questionnaire directed to a Local sample.

In some studies, energy performance certificates [55,107,108] or building energy audits [75,84] are collected in addition to the questionnaire data, with the support of databases held by municipalities, or even energy bills and consumption data granted by energy providers [42].

When the completion and the return of the questionnaire are expected by the respondents, some examples of best practices have been identified and seem to be recommendable. It is useful to mention the strategy reported in [109] in this regard. In the investigation, for recruiting households, an information pack was mailed containing information on the study, a freepost reply envelope, and a free call centre was set up for occupants to reply or obtain further information on the research. In [84] a self-report, paper-based survey, accompanied by a letter, a one-page flyer about the project and a pre-paid returning envelope was sent by post to the households. Besides, delivery boxes located in public buildings and in post offices were provided to facilitate the return. Frequently, a prize draw is used as an incentive to encourage the participation in the survey.

2.6 Response rate

The response rate is declared in only 46.7% of the analysed cases. Consequently, in more than half of the reviewed papers, this information is not provided due to various reasons. In some cases, the answer ratio is not reported as considered unnecessary, because the sample is small and a direct interview method is used, and therefore it is implied that all the components of the sample participated. This circumstance also occurs when the sample is constituted by a few houses or a few households selected out of a total and directly involved in the study, and obviously all participants joined the survey.

Some authors report the number of collected questionnaires, but without specifying how many units have been distributed. Others claim the percentage of families or dwelling investigated over a total of apartment block, district or city without, however, clarifying the percentage of response obtained in the considered sample. It is very common that the rate of valid answers is provided. However, this information is different from the response rate because it does not consider the number of participants who provided incorrect replies but answered in any case.

In some cases, the response rate is not given because the questionnaire is coupled with data collection by monitoring, and hence part of the information comes from sensors installed in the houses and therefore a certain amount of data is always available in one hundred percent of the sample.

Sometimes, the number of individuals or families who completed a questionnaire within a certain survey is specified [110], but the size of the entire sample is undefined. In other cases, the number of residents who responded to an advertisement in local newspaper is expressed [103], but it is impossible to establish how many people the announcement came.

In addition, often the response ratio is not explicitly stated in the paper but easy to calculate because were revealed by one hand the number of questionnaires distributed, sent, issued or the total number of people contacted and, on the other hand, the number of collected, received, returned questionnaires or likewise the number of subjects who responded.

A particular case is represented by surveys using different data collection methods, which rarely provide a separate response rate obtained for each delivery method, and frequently only the overall achieved response rate is disclosed.

Complete information on both response rate and data collection method is only available for 61 articles within the reviewed sample, corresponding to 44.5% of the total. Focusing on this fraction, the answer ratio was analysed by distinguishing according to the questionnaire completion options. As shown in figure 8, the highest value is obtained through personal interview, allowing to reach even 100% of responses in some cases, while the lowest response rate is recorded for mail surveys (46.8%).

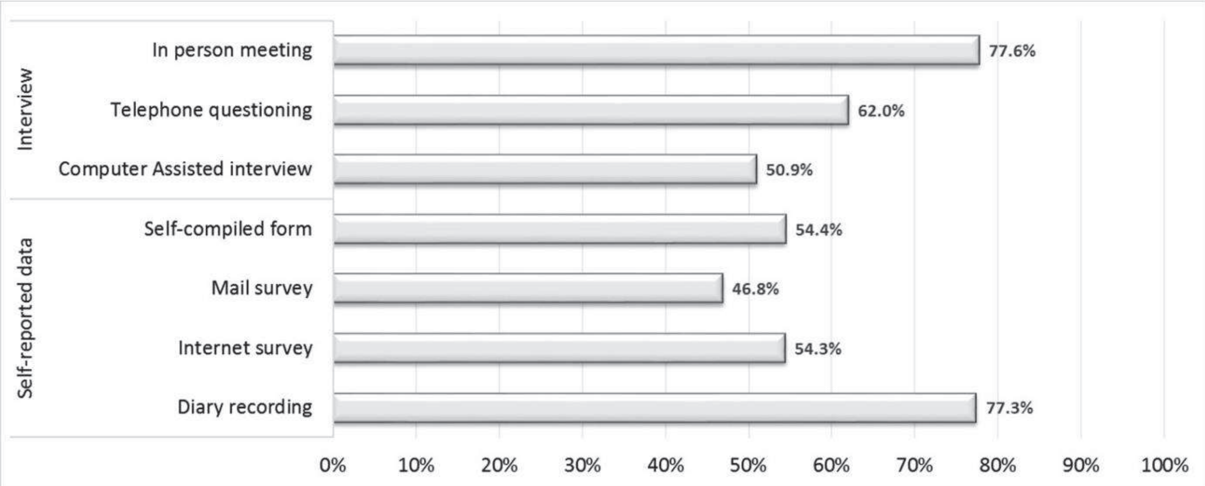

Figure 8. Response rate for data collection methods applied in form of interview and self-reported data approach.

2.7 Data processing

Among the 137 revised articles, 81.8% process the collected data through statistical analysis and about 32% of these use more than one statistical technique in data elaboration. Generally, studies that do not perform statistical calculations propose a straightforward presentation of the gathered information, aimed at explaining and describing the investigated reality. Some works collect both quantitative data, subjected to statistical analysis, and qualitative data, explored through thematic analyses [111]. Figure 9 contains the summary of the used statistics typologies. Descriptive statistic is the most widely used analysis method, followed by correlation and regression analysis. Clustering and Markov methods are less common.

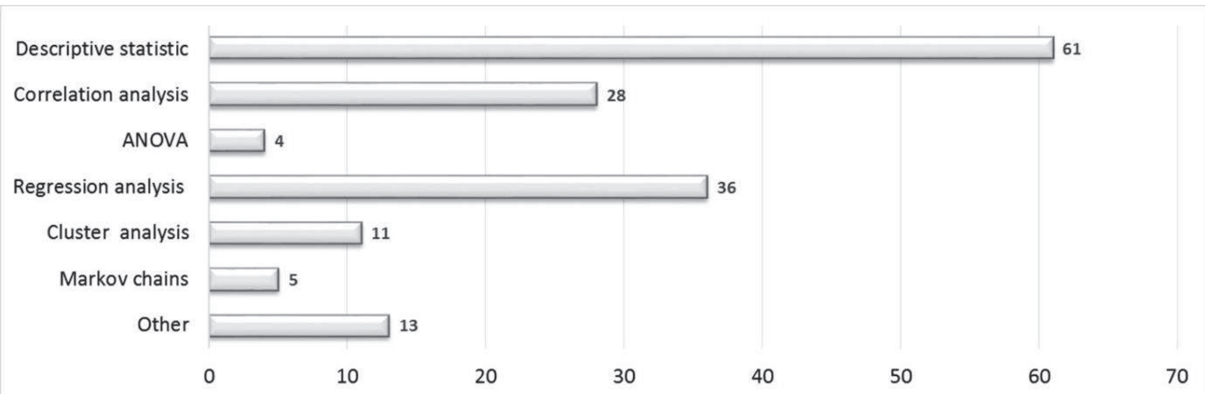

Figure 9. Data processing methods.

Frequencies statistics are calculated in [112] and [113]. Bivariate group comparisons are treated in [37] and, particularly, a two-way ANOVA is presented in [26]. Chi-squares statistics are applied by [83] and [111], while [100] examines data through tabulation and regression. Regression analysis include, in addition to the most widespread applications of simple and multiple linear regression models, also applications of quantile regression analysis [42], difference-in-differences models with a fuzzy regression discontinuity design [114], OLS (Ordinary Least-Squares) and PLS (Partial Least-Squares) regression methods [69,80,99]. Moreover, many studies use logistic regression: binary logit models are used in [71], multinomial logistic regression algorithms are implemented by [83] and [37], both multinomial and binomial logit models are considered in [46], and conditional logit and mixed logit models are used in [115]. The analysis presented in [116] combines OLS, probit, tobit and quantile regression techniques.

Regarding works using cluster analysis, different applications were detected: hierarchical clustering [60], Hierarchical Agglomerative Clustering analysis (HAC) [117], k-modes clustering method [50], multi-level latent class analysis [38], and clustering method based on the CHAID (Chi Square Automatic Interaction Detection) methodology [118]. Hidden Markov models are performed in [82] whereas [119] proposes a stochastic model based on Markov chain Monte Carlo techniques. Monte Carlo analysis is also employed in [86].

Furthermore, studies using more specific statistical techniques were found and they were grouped in the "Other" category illustrated in figure 9. To give some examples, Mann-Whitney U test is used in [68,72,111], Heckman two-steps selection strategy approach is faced by [120], confidence intervals and Matthews correlation coefficient (MCC) are employed in [95] and [121], respectively. In [122] time-series data are applied, whereas [58] performs exploratory factor analyses. Tree models and path analyses are developed by [94] and [41], while [62] deals with ANN (Artificial Neural Network) models and two Grey models.

Among the studies performing statistical analysis, only 44% indicate the software used in data processing, and six of these utilized more than one calculation tool. As illustrated in figure 10, SPSS [123] is the most widely used software.

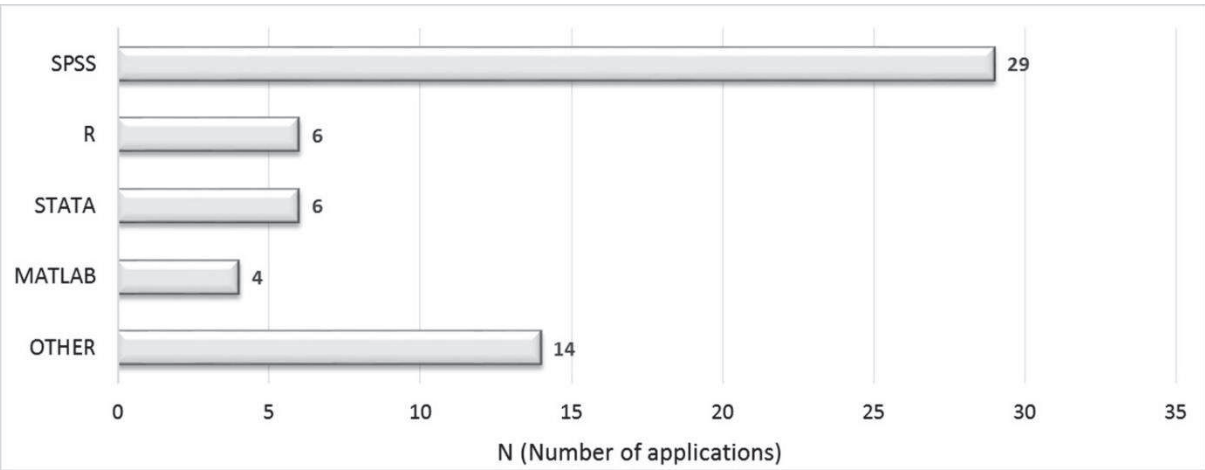

Figure 10. Software used for data analysis.

Other programs include R [124], WEKA [125], SAS [126], "Quantreg" package [127], NLOGIT [128], Biogeme [129], Spad [130], MS Access [131], S-PLUS [132], IBM PASW statistics package [133], Microsoft Excel [134], and Minitab [135].

The time evolution of statistical analysis techniques is represented in figure 11. As can be seen from the graph, the few cases found in the 1970s and 1980s only use regression analysis. Markov methods appear since 1990s, while cluster analysis is only used after the 2000s. More advanced techniques like Monte Carlo, Mann-Whitney U test, and artificial neural network have been found only in the last decade, from 2011 onwards.

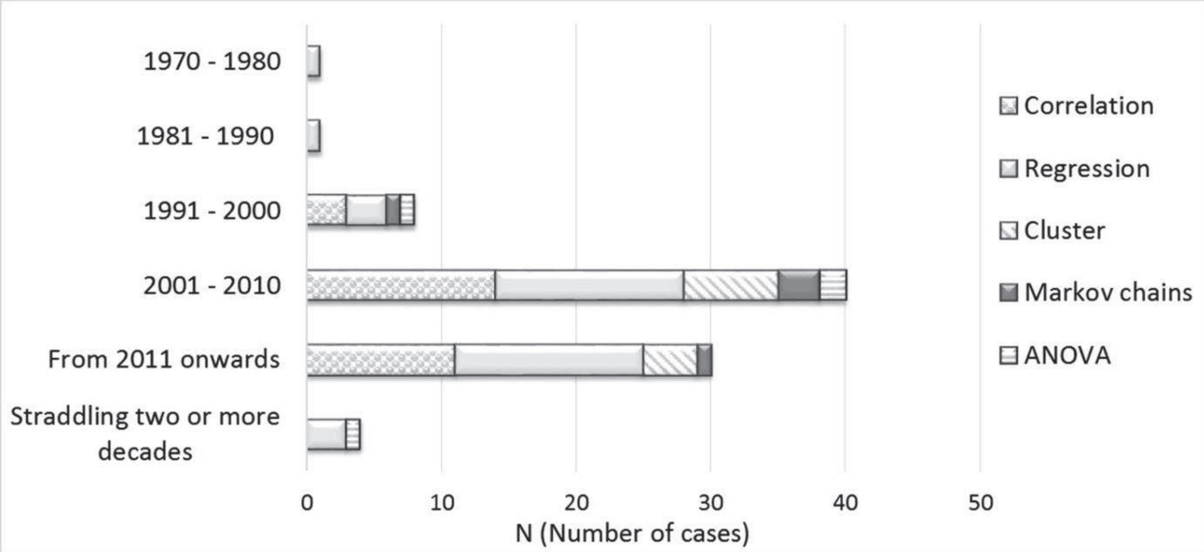

Figure 11. Methods of statistical analysis used over the years.

Figure 12 depicts the methods of statistical analysis used for different sample size. Correlation analysis is the technique utilised for different dimensions, as it is used for samples ranging from units to hundreds of thousands. However, correlation as well as ANOVA, are most widely used on samples of hundreds of items. Regression is mainly used with samples of thousands while for larger samples, of tens thousands, cluster analysis and Markov chain are applied.

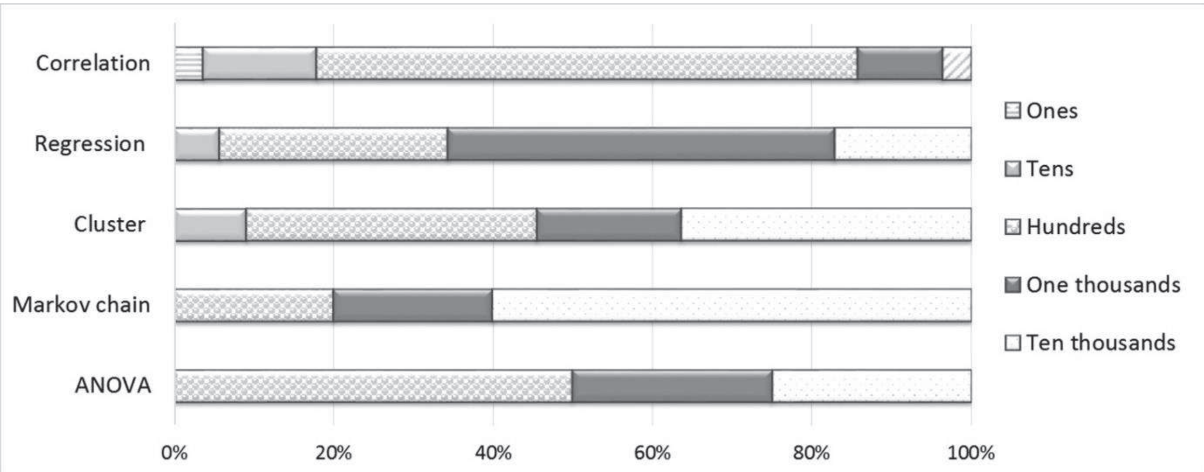

Figure 12. Methods of statistical analysis used for different sample size.

2.8 Objectives of the reviewed investigations

Figure 13 shows the three main categories of objectives identified in the reviewed sample and the sub-categories that can be recognized in each of them. These are listed and briefly described below.

Figure 13. Classification of the objectives covered in the reviewed articles.

Actually, each paper deals with more than one topic, as shown in table 1. The frequency table reported in figure 14 highlights that the most debated themes are energy consumption and occupant behaviour. Energy saving, energy policies, and occupancy profiles follow. Comfort, Occupants' preferences, time use, and simulation and design are considered in few cases.

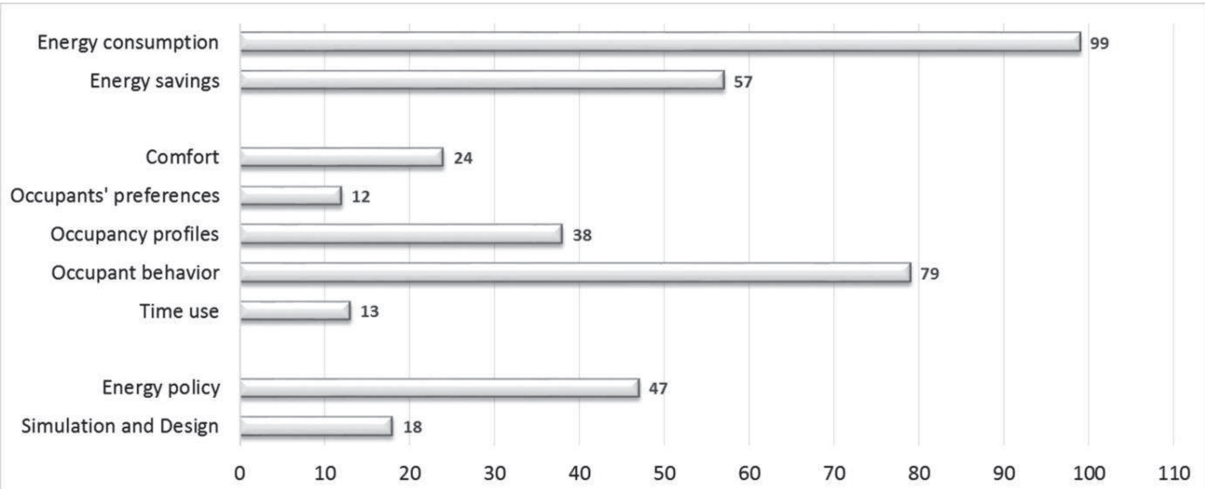

Figure 14. Frequency distribution of the objectives detected in the analysed sample.

Table 1. Chart of the targets tackled in the literature.

[Reference]	Energy consumption	Energy savings	Comfort	Occupants' preferences	Occupancy profiles	Occupant behaviour	Time use	Energy policy	Simulation and Design
[136]	■	■				■			■
[66]		■				■			
[137]		■				■		■	
[64]	■					■			
[138]	■				■	■			
[139]	■					■			
[45]	■	■				■		■	
[51]	■	■						■	
[95]	■	■						■	
[96]		■			■	■			■
[74]	■					■			
[56]	■		■			■			
[67]	■		■		■	■			
[81]	■	■			■	■			■
[61]	■	■							
[144]	■		■			■			
[145]								■	
[146]	■		■			■			
[148]	■	■			■				
[149]	■	■							
[62]	■								■
[54]	■							■	
[151]	■				■	■			
[152]	■				■	■			
[88]		■				■		■	
[154]	■	■			■	■			■
[78]	■								
[24]	■								
[157]	■					■			
[102]	■	■							
[99]	■					■		■	
[159]	■		■		■	■			
[73]			■						
[161]	■	■			■				■
[77]	■	■				■		■	
[75]	■	■				■			■
[46]	■			■				■	
[114]	■							■	
[57]	■			■				■	
[80]	■	■				■		■	
[70]	■	■						■	
[164]	■	■	■	■		■		■	
[49]	■					■		■	
[41]	■	■				■			
[167]	■					■			
[42]	■							■	
[170]	■					■		■	
[171]	■					■	■		
[97]	■		■		■	■		■	
[172]	■				■				
[173]		■				■			
[82]	■				■		■		
[79]	■	■				■			
[174]	■				■	■			
[175]	■			■		■			
[176]	■	■			■	■		■	
[89]			■			■			
[65]	■		■		■	■			■
[60]	■				■	■	■		■
[177]		■							
[178]		■				■		■	
[59]		■				■		■	
[179]		■						■	
[180]							■		
[43]	■	■			■	■			
[115]				■					
[36]		■	■		■	■			
[112]	■	■				■		■	
[107]	■					■			

[Reference]	Energy consumption	Energy savings	Comfort	Occupants' preferences	Occupancy profiles	Occupant behaviour	Time use	Energy policy	Simulation and Design
[84]	■	■		■	■	■			
[55]	■							■	
[122]	■				■		■		■
[110]					■		■		■
[105]					■		■		
[106]					■		■		
[140]	■					■			
[141]			■	■		■			
[108]	■				■	■			
[113]	■								■
[142]	■				■	■			
[143]	■								
[72]			■	■		■			
[44]	■					■		■	
[100]	■	■				■			
[116]	■					■		■	
[26]	■					■			
[147]	■	■							
[90]	■		■	■		■			
[104]	■								
[103]	■					■			
[150]	■	■				■			
[93]		■				■		■	
[153]	■	■				■			
[94]	■	■				■		■	
[155]	■					■		■	
[98]	■				■	■			
[156]	■	■						■	
[117]					■		■		■
[86]					■		■		■
[158]	■				■				
[121]	■				■				
[160]	■					■			
[91]	■				■				
[119]					■		■	■	■
[76]	■		■		■	■	■		■
[25]	■		■			■			
[13]		■							
[162]	■								
[163]						■		■	
[101]		■				■			
[165]		■	■			■			
[52]	■	■	■			■			
[166]			■						
[168]	■	■	■		■				■
[169]	■								
[63]	■	■							
[58]	■	■			■	■			
[16]	■								
[120]		■				■		■	
[69]	■	■						■	
[118]	■	■						■	
[47]	■	■				■	■	■	
[48]	■	■						■	
[83]	■	■				■		■	
[87]	■	■			■	■		■	
[71]				■				■	
[37]								■	
[38]		■			■	■		■	
[68]		■		■				■	
[111]			■					■	
[50]	■				■	■	■		■
[39]			■						
[181]	■		■						
[53]	■	■						■	
[85]		■	■						
[92]	■					■			
[109]	■					■		■	

2.8.1 Energy consumption

The theme of energy consumption is present in over 70% of the analysed works. In particular, this category embraces all those studies that examine the determinant factors associated with residential consumption. These investigations have the aim of individuating the aspects that have impact on energy needs, and of analysing energy consumption characteristics and their related issues in residential sector. Generally, the studies try to identify the potential driving forces of energy demand seeking to address the key problems and challenges in the different contexts. Also, the variation in the patterns and quantum of household energy requirements, both direct and indirect, and the factors causing such variation are analysed. Energy use is observed in terms of heating, cooling, lighting, appliances and ventilation. Not only the building design and physical variables are considered in the investigations, but also socio-economic variables affecting home energy performance are taken into account. In some cases, specific consumer behaviours are examined in depth, for example setting of thermostatic radiator valves and windows opening [157]. The influence of social variables is particularly evident in studies developed in different geographical contexts, for example in [44] the results of ethnographic investigations of energy use behaviour in Fukuoka (Japan) and Oslo (Norway) are compared. Moreover, the category includes studies that perform elaborations on actual consumptions obtained from energy invoices and bills. For example, in [90] the relationship between billing information and household energy consumption is investigated, while in [146] electricity and gas consumptions (acquired from the authority) are reviewed and analysed. Energy consumptions are used in certain cases to develop control and forecasting tools, for instance the aim of [95] is to find a national statistical system of energy consumption in the residential building sector of China, while the authors of [51] estimated how much electricity is currently used and would be used in the future in China urban household sector. And finally energy consumption can be inspected with the aim of checking the achievement of binding targets, such as those set by the EU directives [169] and to estimate emissions of greenhouse gases and air pollutants, from the environmental perspective of climate change and air pollution [78].

2.8.2 Energy savings

When energy consumption is considered, in most cases, the next step of the study concerns the analysis of the opportunities to limit it. Energy savings category groups all works that deal with energy efficiency measures, investigation on design characteristics and strategies implemented for conserving energy, estimation of potential energy saving. It is evident that the role of consumers is crucial in these analyses. Frequently this kind of investigations are addressed to evaluate the residents' awareness at energy conservation and the potential of reducing energy demand through energy-saving activities. Furthermore, the assessment of energy saving potential by improving occupants' behaviour in domestic life through energy-saving education is conducted. For example, in [93] the households were required to indicate whether they had taken any saving measures over the previous year and if they had intentions to take any measures in the future. Generally, research aims to identify changes in people's beliefs, attitudes, and values in relation to the environment, climate change and pro-environmental behaviour lifestyle that can lead to significant energy savings. Questionnaires on energy efficiency may also relate to specific aspects, such as household appliances [80] or innovative solutions for lighting [83]. Some studies go beyond the analysis of the energy saving actions, to discover the subsequent effect of perception of energy conservation results.

2.8.3 Comfort

Surveys on comfort aim at estimating residents' perception and comfort in indoor environment and at assessing the level of their satisfaction. The questionnaires used in this category are formulated with the scope of investigating the factors that influence users' thermal comfort, often by differentiating between summer and winter seasons, or by considering other distinguishing factors. For example, the study [72] found possible differences in thermal comfort between the genders in real-life situations while the authors of [73] explored a comparison of thermal comfort between traditional and modern buildings. A specific sector focuses on the linkage between comfort conditions inside the dwellings and health problems. In particular, the researchers of the study [111] investigated the association between cold and damp housing, as well as the role of energy affordability concerns in the relationship between the housing problems and health. As claimed in [25], comfort requirements increased over time. Consequently, the research, in addition to observing and analysing the indoor conditions, seeks to identify the solutions that can improve well-being within spaces. An emblematic example of this purpose is represented by [39], in which the authors examined the relations between the perceived health and comfort of occupants, the energy efficiency and characteristics of the building, and tried to give a better idea about the way to achieve a comfortable building, healthy and energy-efficient too. Furthermore, this category includes research works based on the outcomes of POE applications, namely Post Occupancy Evaluation [85,165,166].

2.8.4 Occupants' preferences

About 10% of articles that uses questionnaire were classified in this category. Occupants' preferences are intended as the aptitude of users to prefer certain solutions in the management of the house. For example, information regarding heating, ventilation and moisture production propensities is reported in the study [141], alongside preferences for airing rooms, cooking and laundry drying. Other questionnaires deal with more specific issues and collect data on particular respondents' inclinations. For instance, the objective in [57] is to understand households preferences for electricity services in two indigenous villages in Sarawak (Malaysia). The research presented in [46] is aimed at assessing the impact of various socioeconomic factors in cooking fuel choice in Nepal and motive for making a transition toward cleaner fuels. Other articles acquire data on user preferences with respect to the adoption of innovative systems attempting to identify advantages and obstacles on the implementation of new technologies. These contents are covered in the study [115] that investigates residential homeowner attitudes regarding innovative hybrid home heating systems with choice experiment and in the study [68] that aims to characterize through an online survey the perceived benefits and risks of Smart Home Technologies from multiple perspectives.

2.8.5 Occupancy profiles

The issue of occupancy profiles is debated in 30% of the collected cases. Generally, surveys conducted to investigate occupancy profiles are aimed at acquiring information on occupancy patterns and operating mode of home appliances. Questions are designed to discover the life-style of occupants, including the schedule of their presence and activities at home, type of plug-in appliances and the timetable of their use. Basically, three main strands can be found in this category. There are works dedicated to obtaining realistic occupancy data and defining standard behaviour patterns which can be used to make calculation of buildings energy consumption more accurate and reliable. An example is given by [38], where a new instrument for measuring housing-related lifestyle is introduced and used to identify national and cross-national housing-related lifestyle segments in ten European Countries. Part of the research is aimed at identifying patterns of electricity consumption or determining behavioural patterns associated with energy spent for heating. The questionnaires used for this purpose try to identify household and building characteristics that could contribute to the development of energy-user profiles and to investigate the interrelationships between home energy efficiency and household energy consumption patterns. And finally, a branch of research is addressed at extracting occupancy profiles in relation to the geographical context and to correlate household's patterns with social, cultural, economic variables and local features. For example, the study [142] is directed to present a more comprehensive picture of the heating patterns in UK homes and to identify where there are significant differences depending on the house (type, year of construction), the heating system (central or not) and the occupancy (tenure, employment status, age and size of household). The authors of [91] seek to identify patterns of internal temperatures, and link them to socio-demographic and building-demographic variables.

2.8.6 Occupants' behaviour

Occupants' behaviour is the most widely debated theme in the reviewed sample, after energy consumption. In fact, this topic is investigated in about 60% of the analysed studies. Papers using questionnaires addressed to collect highly detailed information about actual occupant behaviour were included in this category. This issue has attracted particular interest in recent years and is studied from different points of view. The main reason of this effort is to explore its impact and influence on building energy consumption. With this purpose, the administrated questions aim to find relationship between energy requirements and household lifestyle, and explain the variation in energy consumption due to different usage patterns. In particular, multiple aspects are examined, such as presence, thermostat regulation, heating and cooling system operation, windows opening, and further parameters related to the users actions on the management of indoor environment. Many studies are aimed at detecting or promoting behaviours that reduce energy consumption, or recording changes in behaviour resulting from energy efficiency measures. For example, in [178] a mailed questionnaire was administrated in order to individuate efficient and inefficient behaviours to improve energy efficiency. A personal interview was conducted in [41] in order to investigate the significance of behavioural, physical and socio-economic parameters on cooling energy with the aim of reducing energy consumption. The authors of [59] collected self-completed questionnaire to evaluate the impact of knowledge about environmental and energy issues on potential pro-environmental behaviour in households, specifically relating to behaviours, attitudes and habits towards energy use. The researchers in [182] used a paper-based questionnaire to determine how occupant behaviour affects energy consumption and what behavioural patterns can be observed in dwellings built after the introduction of new building regulations in the Netherlands. Finally, some researches focus on specific behavioural theories. For example, the effect of situational factors, the inconsistency between intention and actual behaviour, and the effect of perception of energy conservation results are examined in [88]. While the research carried out by [80] seeks to close the gap due to the lack of replacement of household appliances with more efficient ones, by applying the moral extension of the theory of planned behaviour.

2.8.7 Time use

Time use surveys provide detailed information on what people do, and on when and where they do it. The aim is to obtain precise time series data that can be used for extracting information on the activities carried out by the interviewees, their habits, their interaction with the house, spaces and equipment. Thus for instance, it is possible to describe the residents' behaviour in terms of when they are likely to be using household appliances, lighting and heating. In this case, each participant is asked to complete a questionnaire modelled as a diary, to be completed by reporting the activities and movements during the day, generally distinguishing between weekdays and weekends, with a fixed time slot, which can be defined in one hour, half an hour, fifteen minutes, ten minutes or lower. The more the investigation intends to be accurate, the more the fixed time slots are close. Time use surveys are conducted to generate realistic occupancy profiles, in most cases, or to define consumption patterns, and for reproducing the time-dependent activity probabilities in the investigated population. For example, an in-depth study is performed in [105] on the localisation of the daily activities, the simultaneity of different activities and the intensity of social interaction.

Everyday energy-related behaviour in homes is studied in [180] and common characteristics between different types of consumers are identified.

2.8.8 Energy policies

In the research works dealing with energy policies, surveys are frequently led to assess the effectiveness of the adopted measures and for monitoring the achieved results in relation to the established objectives. This class brings together works in which the questionnaire is used to provide important components for resource planning and conservation program development, to individuate policy measures for reducing residential consumption, to evaluate residents' attitude in energy saving policies, their motivation to save energy and perception of climate change. Investigations are also aimed at proposing feasible suggestions on energy policies to put forward sustainable development and make recommendations to support energy policy. Often surveys explore the role of energy performance regulations in lowering the energy consumption for space heating and quantify reductions in energy consumption after regulations. On the other hand, the proposed questions seek to identify households' problems with respect to information and energy savings and to estimate the influence of various actions on their future saving possibilities. The authors of [179] inspect why, when and how people do not renovate their homes; moreover, Danish policy measures aimed at encouraging people to energy renovation are presented and discussed in this paper. Instead, the authors of [114] are interested in estimating the causal effect of the introduction of an increasing block-pricing policy on electricity consumption for urban households in a Chinese province. An unusual study is illustrated in [120] where data from the Italian annual survey on "Aspects of daily life" are used to analyse the relationship between cultural capital, specifically individuals' participation in cultural activities, and pro-environmental behaviour. Some studies focus on more specific issues, like the [71] in which two economic nonmarket valuation techniques are applied to estimate the local environmental impacts of renewable energy systems in Portugal, targeting two stakeholders groups, local residents and national residents respectively. While the researchers of [37] piloted a mailed survey to enhance the understanding of crowding effects of photovoltaic policies.

2.8.9 Simulation and design

The questionnaire is also used to acquire information needed during the building design and in the simulation process. This category includes studies in which investigations are conducted with the purpose of establishing an approach to inform the design phase by addressing the complexity of project variables, like occupant behaviour. Generally, these studies are directed to explain the difference between actual and predicted energy consumptions. Therefore, the results of different demand models are compared with the actual energy consumption acquired by questionnaires, to improve the prediction of future energy demand. With this aim, a bottom-up residential activity model to support predictions of individual members of statistically significant demographic sub-populations is formulated in [110]. The authors of [113] report key findings of two official surveys in UK, primarily of interest for energy modelling and the development and use of energy models such as SAP [183] and BREDEM [184].

2.9 Questionnaire's contents

Questions vary according to the objective of the survey and the specific aspects that are investigated. However, even if the questionnaire is used for surveys with different purposes, some unavoidable contents and queries are commonly asked. Figure 15 outlines the main categories of questions that are frequently proposed by considering the objectives of the study. The level of detail and the number of questions within each section certainly may vary according to the deepening required by the analysis. However, maintaining a reasonable degree of flexibility, categories of questions are described below in order to provide a reference architecture for the questionnaire design. Successively, the most commonly asked questions are summarised for each category and examples of questions selected from the reviewed literature are quoted.

Survey objectives		CATEGORIES OF QUESTIONS: Household information	Building characteristics	Technical installations	Energy expenses	Energy efficiency	Users/house interaction	Users' patterns	Indoor conditions	Pro-environmental attitude
Energy	Energy consumption	Needful	Needful	Needful	Needful	Recommended	Recommended	Recommended	Needful	Optional
Energy	Energy savings	Needful	Needful	Needful	Recommended	Needful	Recommended	Optional	Recommended	Needful
Occupants	Comfort	Needful	Needful	Needful	Optional	Optional	Recommended	Optional	Needful	Optional
Occupants	Occupants' preferences	Needful	Needful	Needful	Optional	Recommended	Needful	Recommended	Recommended	Optional
Occupants	Occupancy profiles	Needful	Recommended	Recommended	Optional	Optional	Recommended	Needful	Recommended	Optional
Occupants	Occupant's behaviour	Needful	Needful	Needful	Recommended	Optional	Needful	Recommended	Needful	Recommended
Occupants	Time use	Needful	Recommended	Needful	Recommended	Recommended	Recommended	Needful	Recommended	Optional
Guidelines	Energy policy	Recommended	Recommended	Recommended	Needful	Needful	Recommended	Optional	Optional	Needful
Guidelines	Simulation and design	Needful	Needful	Needful	Recommended	Optional	Recommended	Needful	Recommended	Optional

● Needful ● Recommended ○ Optional

Figure 15. Shaping of the questionnaire structure considering the categories of questions according to the objectives of the study.

Questions on **household information** may include: number of family members, age, gender, level of education, employment status, year of moving into the house, presence of elderly persons, presence of children, presence of smokers, presence of pets at home, annual income, durable goods, expenditures on goods and services. Level of affinity for technology of the respondents, social, economic, and health problems can also be investigated.

An exhaustive example is available in [185] where the authors also used questions to characterise the *national statistics socio-economic classification of household representative person (managerial or professional occupation, lower supervisory or technical occupation, small employers or own account workers…).*

Generally, questions about family composition and description of individual components are widely answered, whether asked in the form of open questions or in the form of multiple choice questions. In this section, the most critical item is represented by income because it is a confidential information and people can be unwilling to reveal these data. Questions about income should consequently be designed with particular attention by the appropriate choice of the applicable classes or by proposing a less stringent classification, such as the one used by [149], which adopted three general income levels (low, medium and high).

Questions on **building characteristics** involve: location, property, type of dwelling, number of floor, year of construction, number of rooms, net surface area, thermal insulation of the envelope, renovation works, type of window frame and glazed surfaces, type of external and internal shadings, weatherproofing.

For instance, detailed questions were proposed in [75] with respect to the building. Constructive features are not always easily identifiable by the residents. It is therefore advisable to use multi-choice structured questions that can facilitate the respondents.

Questions on **technical installations** usually comprise: presence of heating/cooling/ventilation systems, autonomous or centralized systems, type of generator installed, energy sources for heating/cooling, type of heat emitters, cooling units, type of DHW production, energy source for the DHW production, presence of dehumidifiers, mechanical ventilation flow rate, control and automation systems for smart management, type of lamps, ownership of equipment, type of equipment, energy label of appliances and their location in the house, presence of renewable systems as photovoltaic and solar thermal collectors.

Information on the systems installed in the investigated houses was obtained in [186] through the questions:

Q: What is your dwelling's main type of heating equipment? Is it …?

A: A forced air furnace (hot air vents) / Electric baseboards / A heating stove / A boiler with hot water or steam radiators / Electric radiant heating / A heat pump / Other / Don't know

Q: What source of energy does your heating equipment use?
A: Electricity / Natural gas / Heating oil / Wood or wood pellets / Propane / Other

Q: Does your dwelling have an air conditioner?
A: Yes / No / Don't know

If yes, is it: A central air system / A stand-alone unit in a window or elsewhere / Other
Q: Do you have a thermostat?
A: Yes / No / Don't know

Q: Do you have any of the following types of energy-saving bulbs?
A: Compact fluorescent lights (for example corkscrew or spiral) / Fluorescent tubes / Halogen lights / LED holiday lights / Other types of LED lights / None of the above – household does not have any energy-saving lights

Questions on **energy expenses** cover annual costs for electricity use, heating use, cooking and hot water supply, and costs of each type of energy. Moreover, water consumption can also be inquired. The questionnaire administered by [113] included in this regard a section on methods of payment and tariffs, containing the question:

In the letter you were sent about this interview, you will have been asked to have ready some information on your electricity/gas supplier and tariff. Were you able to do this?

The affordability of energy bills was asked in [84] by proposing the options: *Very easy / Fairly easy / Neither easy nor difficult / Fairly difficult / Very difficult.*

Questions on **energy efficiency** incorporate the issues: energy-conservation behaviour, use of technology in energy saving, perception of energy-conservation results, practices and awareness related to energy conservation and consciousness of energy sources and energy-saving equipment, design characteristics and strategies implemented for conserving energy in buildings, environmental quality of housing and neighbourhood.

For example, in the survey conducted by [66], ten questions about energy savings and environmental problems were asked to evaluate occupants' awareness and willingness for energy savings in domestic life. The submitted questions included items like:

Do you care about the problem of global warming and/or greenhouse effect?
Do you think that the current electricity price is expensive?
Do you like to do something to save electricity if possible?
Will you try not to turn on air-conditioning if not too hot?
Will you try not to turn on air-conditioning or other heating machine if not too cold?

The respondents assigned to each question a consciousness mark based on a 5-grade-scale ranging from 1 to 5 (1, very positive; 2, positive; 3, neutral; 4, negative; 5, very negative).

In addition, the researchers evaluated the potential energy savings resulting from users' energy-conscious behavior. For this purpose, the questionnaire contained a sequence of statements concerning energy saving measures in the use of the main electrical appliances. For instance, and regarding *washing machine*:

Wash more clothes once if possible
Choose fast-washing mode if clothes are not too contaminative.

Every measure was evaluated by the respondents based on how they implemented the actions in their daily domestic life. A mark from 1 to 5 was required (1, did thoroughly; 2, did; 3, neutral; 4, undid; 5, undid thoroughly).

Questions about motivations and perception of energy use were submitted by [84], for instance:

I am worried about my energy bills
I don’t understand how my home uses energy
I often think about how I could save energy
I have control over how much energy is used in my home
I am not able to save any more energy
The choices provided for the answers were:
Strongly agree / Tend to agree / Neither agree nor disagree / Tend to disagree /Strongly disagree.

Questions on **user/house interaction** contain the subjects: activation mode of the heating/cooling/ventilation systems, heating/cooling period, thermostat management strategy, use of artificial lighting in winter and summer, use of electrical equipment, use of DHW, DHW temperature, window/door opening habits in winter and summer, use of sunscreens and curtains in winter and summer, moisture production habits, bathing habits, laundry and drying habits, habits in dishwashing, sleeping habits.

For example, regarding the management of the air-conditioning system, the questionnaire developed by [96] contains a list of options describing under what occasion users would switch on or off the air-conditioning in their living-rooms and bedrooms.

Regarding domestic hot water usage, as suggested in [138], the following questions can be posed:

Water heater is turned on full time or part time
Temperature at which water heater is maintained
For each season: the mean hours per day or the number of times used per day/week and mean minutes per use.

When analysing ventilation, questions regarding the window opening strategies adopted by users to control indoor temperature, tendency to open window during the heating season and general habits for airing rooms can be included in the survey. A specific questionnaire on mechanical ventilation was used by [166] containing, among others, the questions:

Do you open the window after: Cooking/Having used the bathroom/Sleeping/Never

How often and how long do you open the windows during the day?
What do you think about the ventilation system and why?
Would you like to have more influence and control over the ventilation system?
Do you have more comments on the quality of the air and the ventilation system?

The authors in [89] investigated the importance of being able to open windows or having mechanical ventilation system at home through the questions:

How important is it to have the possibility of opening a window?
How important is it to always have fresh air supplied by a mechanical ventilation system?

Answers on a scale of four options were required (Very important, Important, Not very important, Not at all important).

Within the **users' patterns** category, questions aimed at investigating hours of presence at home, working hours and typical habits of the occupants in carrying out their activities can be grouped. For example, presence patterns were explored by [84], which required the interviewed person to specify dwelling occupancy patterns during the heating season.

Questions on users' patterns may also involve habits in using home appliances. Queries on the use of electrical equipment can be expressed as open-ended questions asking how many times per day/week/month and for how many minutes the specific appliance is used [138] or, alternatively, in the form of tables that allow obtaining operation schedules, which can also be used as input data in simulation software. A diary on the use of the washing machine is presented in [158]. The diary needs to be completed by recording the information displayed in figure 16, every time the washing machine is used.

	Date	Programme *e.g. Cotton, Easy Care etc.*	Temperature (°C) *e.g. 40 etc.*	Spin Speed (RPM) *e.g. 1200 etc.*	Other Programme Options *e.g. intensive, extra spin etc.*	Fullness of drum *e.g. ¼, ½, ¾ or full*
	EXAMPLE 5/5/2018	Cottons	30	1400	N/A	Full
1						
2						
3						
4						
5						

Figure 16. Example of washing machine usage diary provided in [158].

Knowledge about "at home" and "awake" family members and their hourly behavior can be earned with close intervals questions. Generally, interviewees are asked to fill a diary indicating, with a frequency of 10 minutes, the activities performed during the day and the location, and whether they are accompanied by someone. A typical example is shown in figure 17 that presents an extract of the survey conducted by [106].

DAY DIARY – SAMPLE (From 07.00 to 08.00 am)

Time, am	**What were you doing?** Record your main activity for each 10 minute period from 07.00 to 10.00 am! Only one main activity on each line! Do not forget travels and mode of transportation. Distinguish between first and second job, if any.	*(For whom?)* **Was this helping somebody outside your own household?** Mark "yes" by crossing here ↓	**What else were you doing?** Record the most important parallel activity.	*(With whom?)* **Were you alone or together with somebody you know?** Mark "yes" by crossing here: Alone	Children up to 9 living in your household	Other household members	Other persons that you know	
07.00–07.10		☐		☐	☐	☐	☐	|_|_|
07.10–07.20		☐		☐	☐	☐	☐	|_|_|
07.20–07.30		☐		☐	☐	☐	☐	|_|_|
07.30–07.40		☐		☐	☐	☐	☐	|_|_|
07.40–07.50		☐		☐	☐	☐	☐	|_|_|
07.50–08.00		☐		☐	☐	☐	☐	|_|_|

Figure 17. Example of daily diary for Time Use Survey extracted from [106].

Questionnaires on **indoor conditions** include questions related to the following aspects: indoor temperature, relative humidity, clothing habits in winter and in summer, temperature preferences, indoor air quality in winter and in summer, subjective assessment and satisfaction on indoor thermal environment, use of air cleaner during heating season, odour elimination, noise control in summer and in winter. The use of sensors for measuring environmental parameters is expected alongside questions on thermal comfort that are generally proposed in the form of scales (from satisfactory to unsatisfactory) both for thermal and air movement sensation.

The questionnaire administered by [73] evaluates the indoor environment of a stock of traditional and modern houses. The following questions about thermal comfort parameters and overall thermal comfort were presented:

1. *How would you describe the following indoor conditions of your traditional/modern house in summer season?*

   a) *Temperature (please tick one)*
   Cold, Cool, Slightly cool, Neutral, Slightly warm, Warm, Hot

   b) *Humidity – Moisture in the atmosphere (please tick one)*
   Very dry, Moderately dry, Slightly dry, Neutral, Slightly humid, Moderately humid, Very humid

   c) *Air movement (please tick one)*
   Very still, Moderately still, Slightly still, Acceptable, Slightly draughty, Moderately draughty, Very draughty

2. *How do you rate the overall thermal comfort your house in summer season based on the following scale (please tick one)*
   Very comfortable, Comfortable, Slightly uncomfortable, Uncomfortable, Very uncomfortable

The respondents were required to evaluate the environment in the condition when they were not using any support (fan, cooler, air conditioning, etc.) to improve or modify thermal comfort of indoor environment and wearing normal clothing.

The authors of [89] asked questions in the form of comparison between two parameters and as evaluation of the importance of different factors. Specifically:

What in your opinion is more important for a good indoor environment?

Thus, several couples of parameters are compared (*Temperature/Air quality, Temperature/Acoustics, Lighting/Acoustics…).*

Questions on **pro-environmental attitude** usually come from interrogatives regarding respondents' beliefs towards the environment, knowledge of climate change and of environmental terms, energy use within the home and tendency to use energy efficient appliances and light bulbs.

The questionnaire administrated by [83] asked the respondents to specify the time when they recall last changing a light bulb, indicate what type of light bulb was changed, and select the three most important guiding factors used in order to select the replacement. A list of ten factors was included in the survey: *(1) manufacturer or brand of light bulb; (2) service time of the light bulb; (3) rating in the test reports; (4) possibility to change light intensity; (5) electricity consumption of light bulb; (6) price of light bulb; (7) impact to the environment; (8) light intensity of light bulb; (9) shape of light bulb; and (10) quality of light coming from the light bulb*.

In [137] attitudes of respondents on changing their behaviours in buying and using energy-saving household appliances were evaluated through questions like the following:

What changes would you be prepared to make today under present conditions in order to reduce your use of electricity by household appliances?

What factors could persuade you to make a bigger change in order to reduce your use of electricity by household appliances?

Numerous studies are aimed at collecting data to assess the health status of inhabitants inside their home and to register recent experiences of sick building syndrome (SBS), as in [39]. Therefore, questions directed at detecting perceived problems with condensation, damp, or mould, and perceived affordability of energy, health and well-being are used, as in the survey administrated by [111].

Following the example provided by [166], questions submitted to detect SBS can be:

Q:Do you feel any of these symptoms?
A:Dry eyes / Dry throat / Irritated skin / Lethargy, tiredness / Blocked nose / Watery eyes / Runny nose / Sneezing / Headache

Q: These symptoms disappear when you leave the building?
A: *Yes / No / Sometimes*

Finally, very specific questions were identified in studies with unique objectives. For example, the relationship between cultural capital and pro-environmental behaviour is analysed in [120], and questions related to the participation in cultural and in social activities and other attitudes, cultural consumption and social capital were used. In particular, the frequency of attendance at archaeological sites, cinema, music concerts, and theatres over the last 12 months was asked in order to explore the participation in cultural activities. The number of book read and the frequency of reading newspapers were also asked.

In the interview conducted in the study [70], questions on personality traits (neuroticism, extraversion, openness, agreeableness, conscientiousness, external locus of control) were posed with the aim of examining the role played by personality on the decision of renewable energy technologies adoption. The authors of [80] applied a moral extension of the theory of planned behaviour to examine the determinants of consumers' purchase of energy efficient appliances. For this purpose, they distributed a questionnaire containing questions on attitudinal factors that affect respondents' attitude towards energy-efficient household appliances, subjective norms, perceived behavioural control of the respondents, moral norms, respondents' perceptions of affordability, and to purchase intention for energy-efficient household appliances.

Generally, questionnaire items are formulated as closed ended questions. Likert scale with 5, 7 or 9 points is used for questions concerning the level of agreement, ranging from "strongly disagree" to "strongly agree".

Examples of survey, in the form of complete questionnaire or parts/sections/portions or questions excerpts are reported in 61% of the reviewed literature. The presence of questionnaire examples in the analysed articles is marked in Appendix A.

3. Discussion

As emerged from the presented analysis, the sample of reviewed literature seems broad and diversified, as well as rich in information and knowledge to be discussed for drawing interesting considerations. The first aspect that can be underlined is the nature of the conducted investigations. In fact, interdisciplinary and multiple fields of study are considered in most cases, by involving more than one science.

Frequently, investigations are identified as social surveys [25] or socio-technical surveys [142], because they are aimed at acquiring information not only on technical-practical issues, but also on social, demographic, economic, political, cultural, and behavioural characteristics of the inspected reality. These aspects in fact are indispensable for explaining and correctly interpreting the investigated phenomena. Consequently, all the traced questionnaires include an unavoidable section dedicated to the description of social context, which is the essential key to a comprehensive reading of any faced issue.

And this is the reason why the concepts of ethnography or ethnographic analysis, or even netnography and digital ethnography, are frequently used in the analysed articles. Ethnography constitutes indeed the method to represent, describe, interpret and understand the phenomena, the dynamics, and the socio-cultural contexts by means of various tools. Therefore, ethnographic analysis is the foundation to build a solid reasoning and to develop studies with robust bases, any aspect you want to explore.

Generally, the collected data are cross-sectional data, and collected by observing many subjects at the same point of time. Furthermore, works that process data collected at different times, namely time series data, were found in the review.

Other frequently cited concepts are those of structured survey [62] and semi-structured survey [141].Questionnaires include only pre-categorized response options and closed-ended questions in the former case, and open-ended questions in the latter.

Important considerations can also be extrapolated by looking at the literature process from two points of view: HOW data are collected and WHY data are collected, respectively. The continuation of the discussion is focused on these two perspectives, and the authors analyse the results of the elaborations previously presented, by highlighting the main findings.

Regarding the first aspect, HOW data are collected, preliminary observations concern the extent of the investigations. Generally, large-scale questionnaires [45] and extensive surveys data [40] are used more often than restricted investigations.

The most widely used method is the self-reporting questionnaire issued via direct distribution or face-to-face interview that can take place in different places: at home, or in public locations, such as shopping centres, squares, parks, etc. However, in addition to the direct contact method that involves data collection through person, online methods are also widely used, especially in recent years. These methods exploit the potential of new technologies and allow to reach a greater number of respondents. Therefore, web surveys and online surveys are also reported among data collection methods. Consequently, paper-based questionnaires or electronic questionnaires can be used as support, depending on whether direct or indirect contact is implemented. Even in the case of direct contact, paper-based questionnaire is not widespread today, as it is obsolete. On the other hand, computer-assisted interview techniques are expanding, including CAPI (Computer Assisted Personal Interview), CATI (Computer Assisted Telephone Interview), and CAWI (Computer Assisted Web Interview). These techniques exhibit an average response rate comparable to other collection methods (around 50%), but they facilitate and accelerate data collection and elaboration. The use of advanced techniques seems to do not solve the problem of lack of interest or unavailability of respondents to participate in the survey. In addition, innovative techniques consisting in the provision of interactive tools are applied, such as the online interactive tool showed in [63] and the iMeasure online energy feedback tool described in [48].

It is useful to understand, on the other hand, WHY data are collected. The answer to this question is partially provided by the elaborations presented in section 2.8. In particular, this analysis showed that the main objectives consist of obtaining information on energy consumption in ninety-nine cases, and occupants' behaviour is a matter addressed seventy-nine times in the reviewed literature. The investigated energy consumption can be related to the house management, thus energy demanded for heating, cooling, hot water production, use of appliances, and lighting. In addition, data on energy bills or invoices and energy certificates or energy audits are often required in surveys on consumption. Many of these surveys are official and promoted by public institutions, and aimed at gathering data on energy demand in order to plan energy saving policies. Questionnaires on energy consumption are also used in the sector of energy efficient buildings, green buildings, passive houses and zero energy buildings with the target of limiting consumption. Some studies present the results obtained after the introduction of advanced systems in houses and analyse the effects and opinions produced in the occupants involved in the questionnaire. For example, the study [43] investigates the capability of an automated home to automatically and timely inform users about energy consumption, by harvesting opinions from inhabitants on energy feedback interfaces. While the authors of [63] intend to encourage positive changes in the energy efficiency of the building stock, by providing an online interactive tool that will help citizens and local stakeholders to assess energy uses in their houses and neighbourhoods, starting from individual scale.

Energy consumption is often analysed in correlation with occupants' behaviour. Questionnaires formulated to investigate occupant behaviour contain questions that seek to obtain information on user activities within the home, their habits and preferences.

The interest in this matter arises to cope with the so-called prebound effect that is the gap between predicted and actual energy consumption due to the impact of variables difficult to be foreseen, such as occupancy. Usually, a questionnaire created for this purpose should be directed to characterize occupancy under three fundamental aspects: magnitude, duration and variability [82].

Time use surveys can be very useful to this goal, as aimed at reconstructing user actions throughout the day, with time steps of ten minutes or lower. Asking what occupants are doing, where, how and when allows to obtain typical occupancy profiles which represent an essential input for energy rating procedure, like SAP (Standard Assessment Procedure) and energy models as BREDEM (BRE Domestic Energy Model) used for the calculation of annual energy requirements of dwellings.

Occupancy features are closely linked to the socio-cultural context. In this regard, transnational studies are particularly significant. For example, the studies [44] and [39] compare surveys on occupancy carried out in different Countries, and in particular the work [38] uses data collected through a computer assisted web interview in order to define house related lifestyle across ten European Countries.

Those described above are the main objectives came out from the analysed studies. However, it is also worth mentioning other more specific areas of investigation in which the questionnaire is used for data collection and that can represent a reference for researchers working in this sector. In particular, questionnaires have been used for: examine the role played by personality traits on the adoption decision of renewable energy technologies [70]; evaluate the local impact of photovoltaic [71]; assess household preferences for cooking fuels [46]; explore energy saving resulting from the application of washing machine control panels [103]; study householders' water-use routine [47].

4. Conclusions

The review presents a sample of studies that use questionnaire for investigations in the residential sector.

It is recognised that questionnaire is a valid and widely medium for the acquisition of information, and the revised literature shows that works using this tool have grown progressively in recent years. Furthermore, questionnaires are used in combination with other techniques, such as monitoring and time use survey. However, some problems were detected in the set of the analysed papers. For example, a huge diversification in the use of terms, which are not uniquely coded, was disclosed. Each study consequently uses the terminology most familiar to his field and concerning the specific type of study.

The homogenisation of the nomenclature is therefore recommendable in order to unambiguously identify the objects of surveys. Detailed sample description and wording inspired to a common codification can help in making the research results comparable and earning higher validity for the study since it would be possible to compare results obtained at different times and in different places. Another essential aspect is the identity of recipients. Some studies, in fact, report in the sample description the number of collected questionnaires, observations or N, without specifying whether the survey is addressed at individuals, families or buildings. Consequently, it is essential to specify clearly whether the number of questionnaires corresponds to the number of interviewed people or to surveys addressed at households, avoiding generic expressions like "observations" or "N" that do not allow to understand the nature of the questioned subjects. The basic measurement unit can be the "individual" or the "family", according to the objective of the survey. For example, comfort surveys require questionnaires administrated independently for each individual while investigations on energy consumption can be directed to household as the basic unit. Once explained the identity of the recipients, it can be useful to provide information on the typology of the examined buildings. By considering that the most elementary housing unit is the apartment or the single family house, the survey can be extended to multifamily buildings, neighbourhoods, and cities. Furthermore, the location needs to be pointed out, as it provides indications on climatic conditions and on the socio-economic-cultural context. Interview through personal meeting is the data collection method that offers the highest response rate (mean response rate of 77.6%). In recent years, more advanced data collection techniques have been developed, such as computer-assisted interviews which on average offer 50% response rate. Moreover, dedicated applications working online can be utilised.

A further issue, shared by all data collection methods, consists of the mischievous respondents which can provide incorrect information. A strategy to solve this problem could be to involve previously respondents in the survey, and besides, to guarantee assistance and support, for example through free call centres, clear informative packages, details and instructions, specific smartphone apps, etc. In addition, some rewards and prizes may be offered to incentivise respondents to join the study and encourage them to provide reliable information. Another problem to be considered is the preparation of the contacts list. Different options can be adopted: apart from personal knowledge, which allows to reach a limited number of users, contacts provided by students, employees of firms or institutions, energy suppliers, customers of companies, national databases of buildings, and advertisements on local newspapers were used to recruit participants in the analysed articles.

With regard to the type of questionnaire, it varies according to the field of investigation. Quantitative questionnaires and qualitative interviews can be administrated.

Time is another important variable to be considered, time intended, firstly, as the period chosen to carry out the survey. In fact, it could be appropriate to conduct studies in specific periods over the year (winter season and summer season, for instance), or in a period before or after the introduction of certain energy measures and policies. However, the time factor operates also in another way which is the temporal split established to pilot the survey and the time phases in which it is organized and technically divided. For example, surveys by questionnaire can be subdivided into three phases (Preliminary survey – Min Survey – Ending Survey), and this decision depends on the sample handled and the objectives pursued. As a rule, it is advisable to run a first study on a pilot group suitable to detect critical issues and improve the procedure, and a second study on the entire sample.

In conclusion, the preparation and management of a survey through questionnaire is a very complex and articulate process whereby experience and competence are indispensable requirements.

The action field is very wide and the questionnaire has to be planned and well-structured a priori, seeking to have clear when, where, how and what to ask.

In some cases, where the catchment area is very wide, the designation of a proper market research company could be recommended because should be able to face the needs posed by complex studies by means of structured apparatus and precise organization.

In any case, the following elements need to be clearly explicated when managing surveys based on questionnaire:

- methods for recruiting participants;
- participants typology (families or individuals);
- delivery method (in person distribution, sending by post, sending by e-mail, …);
- electronic questionnaire or paper-based questionnaire;
- data collection method (self-reported data or interview. In the last case, specify whether the interview is performed face-to-face or via different channels, e.g. telephone, VoIP, …);
- sample size;

- time and duration of the survey;
- response rate.

The provision of this key information is critical to comprehensively characterise the sample and lead to an effortless and definite interpretation of the results.

The outcomes of this review are addressed to researchers aimed at implementing surveys that use questionnaire to investigate any aspect related to residential buildings. Moreover, the findings could represent orientation and guidelines for public institutions and practitioners interested in investigating residential stocks from the energy quality point of view.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.enbuild.2018.12.021.

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6.3 Application of survey on energy consumption and occupancy in residential buildings. An experience in Southern Italy

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Abstract

The aim of the study was to create and administer a questionnaire to collect data and obtain typical occupancy profiles of residential buildings. The survey was developed by considering previous experiences conducted in the University of Calabria since 2012, and it was distributed among 80 families via email, face-to-face and through social network. Different levels of occupancy (high, medium and low) and different sub-categories of high occupancy (morning, afternoon, and intermediate) were individuated by processing the gathered data. Buildings energy consumption was investigated with regard to occupancy categories, and correlations were found.

1. Introduction

To address the challenges of climate changes, the three main sectors (buildings, transport and industry) need to develop effective strategies to reduce their share of fossil fuel use for energy supply. The built environment consumes a great amount of the produced energy, 40% of total final energy consumption, in Europe, comes from buildings [1]. In the last decades, governments worldwide have implemented energy requirements in their building regulations to reduce levels of energy consumed by buildings and to promote more energy-efficient edifices [2]. Improvements have been registered due to the development of new materials, more efficient heating systems (e.g. boilers and heat pumps) and low energy appliances (e.g. labels A+ and A++). In parallel, the use of advanced simulation tools is encouraged. On the other hand, the recent literature demonstrates that frequently the expected building performance does not meet real consumption, and the gap is due to the influence of human factors [3].

Table 1. Summary of the literature review about the use of questionnaire in residential buildings.

Location	Survey Distributed	Distribution	Valid data sets	% response	Data Analysis
Hokkaido, Tohoku, Hokuriku, Kanto, Kansai, and Kyushu District. Japan [4]	80 buildings	Not specified	67	83%	Correlation analysis
Hangzhou. China [5]	124 households	Reports	71	57%	Correlation analysis
Chongqing. China [6]	201	Interviews face to face	182	90%	Descriptive
Hangzhou. China [7]	2000	Not specified	642 winter surveys 838 summer surveys	74%	Not specified
Changsha. China [8]	73	Face to face	73	100%	Descriptive
Seoul. Korea [9]	200	Self-administered questionnaire	139	69%	Correlation analysis
Suita. Japan [10]	10000 in 2009 4000 in 2013	Mailed	4448 in 2009 1245 in 2013	40%	Regression Analysis
China [11]	75 families	Reports for 1 year	60	80%	Confidence intervals
Chengdu. China [12]	Large scale 287 districts	Non- specified	1426		Descriptive
Shanghai, Chongqing and Changsha. China [13]	27 households	Selected sample for time recording of heating operation	27	100%	Descriptive
Sichuan, Chongqing, Hunan, Hubei, Jiangxi, Anhui, Jiangsu, Shanghai, and Zhejiang. China [14]	1800 households	Online questionnaire	1625	90%	Descriptive
Northern Ireland [15]	27 households	Non - Specified	27	100%	Correlation analysis
Netherlands [16]	7000 households	Mail	313	(5%)	Correlation analysis
Cameroon [17]	1750	Distributed twice a day: from 8:00 to 12:00 PM and from 14:00 to 18:00.	1750		Descriptive (time reports)

Generally, standardized occupant behavior is used as input into most common Building Simulation Software (BSS) but, the complex nature of occupant behavior makes the results far from reality. Hence, contextual occupancy schedules instead of standardized schedule are needed with the end to bridge the gap between theoretical models and real building performance. Several studies, such as [18,19], analysed the influence of occupant behavior on Thermal Activated Building System (TABS) and showed that the knowledge of real occupancy profiles also let to develop an efficient control of thermal storage technologies in terms of operation time. The occupant monitoring approaches can be divided into three categories [20]: surveys and interviews, observational studies, laboratory studies. The first one is the most common technique used for residential buildings. The value of surveys is not immediately apparent upon the availability of a rich dataset, but they can be used to develop a greater understanding of the predominant behavioral characteristics or motivating factors for interacting with building systems [21]. A review of previous experiences is presented in Table 1 with the aim of understanding the common ways to distribute the questionnaire, the samples size, the response rate and the techniques for data elaboration. The aim of this work is to create and deliver a questionnaire to collect data for obtaining typical occupancy profiles trends to be compared with related buildings energy consumption. Occupancy profiles can be individuated through some regularities in occupant actions and lifestyle. In fact, occupancy includes features of time and space, and occupants usually maintain a specific schedule in each room of the house.

2. Methodology

2.1 Survey preparation

The survey comes out by considering previous experiences. The first work is a Chinese study made in the Tsinghua University [22]. This study was conducted in two times: first in 2006 and 2007 and then in 2015, covering in total a sample size of more than 7000 households. The questionnaire translation process from Chinese to English and then to Italian language took a long time, because it was necessary to adapt the questionnaire to the Italian context, including habits and heating/cooling/DHW systems used in the considered Mediterranean region. The new questionnaire was used in researches conducted in the University of Calabria, from 2012 to 2018 [23–26]. The results showed that the questions with the lowest answer ratio were those regarding total annual income, presence of air-conditioning systems and thermal sensation (especially in cooling). The authors conducted further research about Italian experiences, and the collected information is summarised in Figure 1.

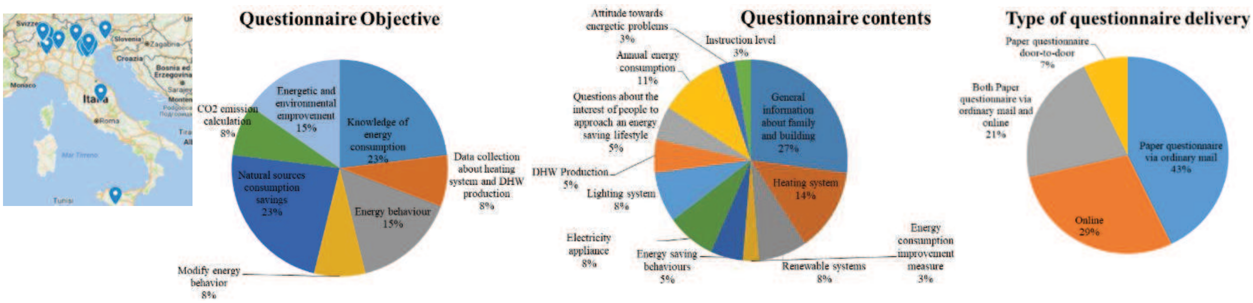

Figure 1. Location, objective, contents and type of questionnaire delivery.

The questionnaire proposed in this work is obtained by combining the previous Chinese and Italian models. An intermediate step, however, consisted of a further improvement by means of comparison with Mediterranean [27] and Northern European [1] investigations. The long process of elaboration of previous experiences in the world led to the definitive version of the questionnaire. The survey consists of 80 questions grouped into four sections (see Figure 2). The repartition in sections was dictated by the aim of collecting information about physical, socio-demographic and behavioral variables. Physical parameters allow to define the climatic context, the construction typology, the heating/cooling/DHW systems, and equipment. Socio-demographic parameters are collected in order to describe composition, education, and income of families. Occupant's behavior is detected by means of detailed schedules in which people indicate, for every hour of the day, the presence in each room of the house. Similar schedules are applied to collect the operation of heating, cooling, lighting, DHW, and electrical devices. Furthermore, windows opening and curtains usage are detected both for winter and summer.

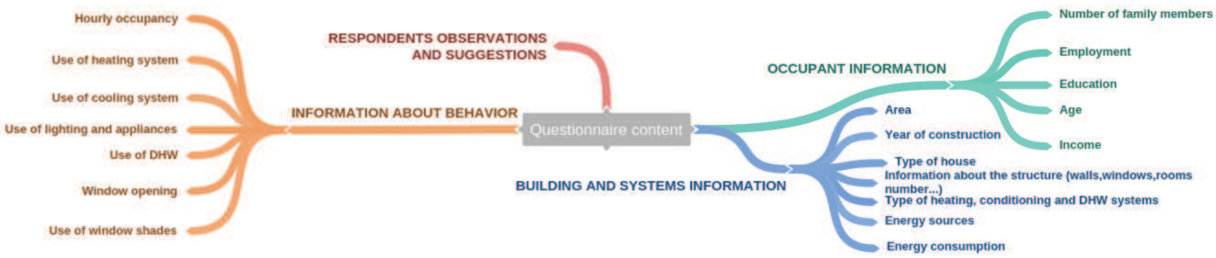

Figure 2. Questionnaire content grouped into four sections.

2.2 Survey distribution

The questionnaire was distributed between September 19th and October 3rd, 2017 to a sample of 80 families residing in Calabria (Southern Italy). The distribution took place in three different ways: via email, face-to-face and through social network. Among the 80 questionnaires distributed, the percentage of valid answers used in the study was 65%.

3. Results

The different distribution methods were analyzed in order to understand which one was the most efficient. The comparison is shown in Figure 3.

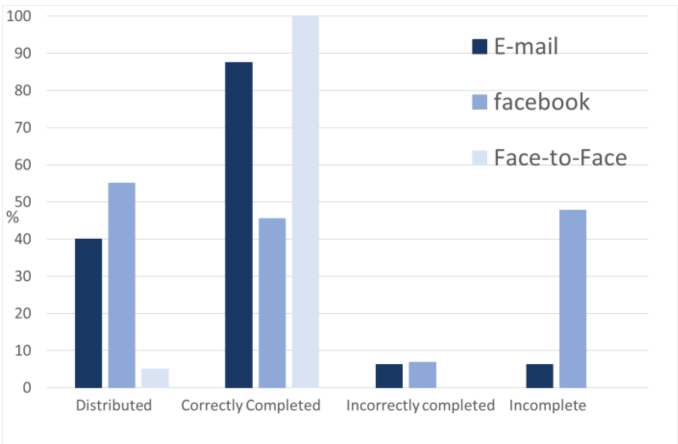

Figure 3. Breakdown of the methods used for the questionnaire distribution and their effectiveness.

Only four questionnaires (5%) were completed through face-to-face interview. Even if this sample is smaller than the others, it is immediate understanding that this method is the most effective. By contrast, it is also the most time consuming, requiring 45 minutes per interview. Facebook guarantees a greater number of respondents, but most of the returned questionnaires were not fully completed (48%). E-mail delivering is probably the best compromise, because most of the respondents fully completed the questionnaire (88%).

3.1 Description of the sample and energy consumption

The first section of the questionnaire is aimed at gathering information to characterize the respondents' families and their houses. On average, the sample consists of 44% of men and 56% of women, and 50% of people belong to the age group between 18 and 40 years old. About 35% of households have average annual income less than € 15000. 53.8% of the respondents live in apartments and the majority of the investigated buildings were built between 1973 and 1991. The type of heating system was widely investigated by considering several options. Almost 86% of respondents have a heating system and, among them, 89% have an independent system. 60% of respondents use traditional gas boilers and the most common energy source is methane (44.2%). Among households not provided with a heating system, 42.9% use fireplace and electric heaters. 61.5% of respondents use the same system for heating and DHW production, and electricity is the most used energy source in the remaining part. 48.1% of the investigated dwellings are equipped with a cooling system. Regarding artificial lighting, 90.4% of respondents use low energy consumption bulbs. About electric appliances, 80% of respondents own high efficiency appliances. Only 7.7% of respondents have a photovoltaic system, while solar thermal collectors are present in 5.8% of the analyzed cases. Energy consumption data are collected by bills: the range of variation of electricity consumption is wide (from 475 to 4775 kWh/year), and has average annual value of 2139 kWh; annual consumption of primary energy for heating and DHW varies from 7 to 375 kWh/m^2 with an average value of 99.07 kWh/m^2. Higher consumption is registered when wood is used as a fuel. In fact, fireplaces are commonly applied in cold area (climatic zones D and E [28]) and present low thermal efficiency [29].

3.2 Occupancy profiles

Data gathered through questions aimed at exploring the presence of the occupants at home are used to obtain occupancy trends. In the first phase, the percentage of daily hours in which at least one person is present in the house is calculated for each surveyed family. This allows obtaining of three occupancy classes characterized by high occupancy, medium occupancy and low occupancy, as described in Table 2.

Table 2. Occupancy classes.

	Low occupancy	**Medium occupancy**	**High occupancy**
Occupancy hours range (%)	0-60	60-80	80-100
Buildings in the class (%)	7.7	7.7	84.6

In the second phase of the analysis, for each family in the sample, a specific occupancy profile was built by calculating the percentage of people present at home compared to the total number of family members, for each hour of the day. Typical profiles for each class were successively determined by calculating the average of all the profiles of the households belonging to the same occupancy class. Figure 4 shows how the percentage values of people in the house as well as the extent of the time intervals in which people are present at home, progressively increase moving from the low to the high occupancy class.

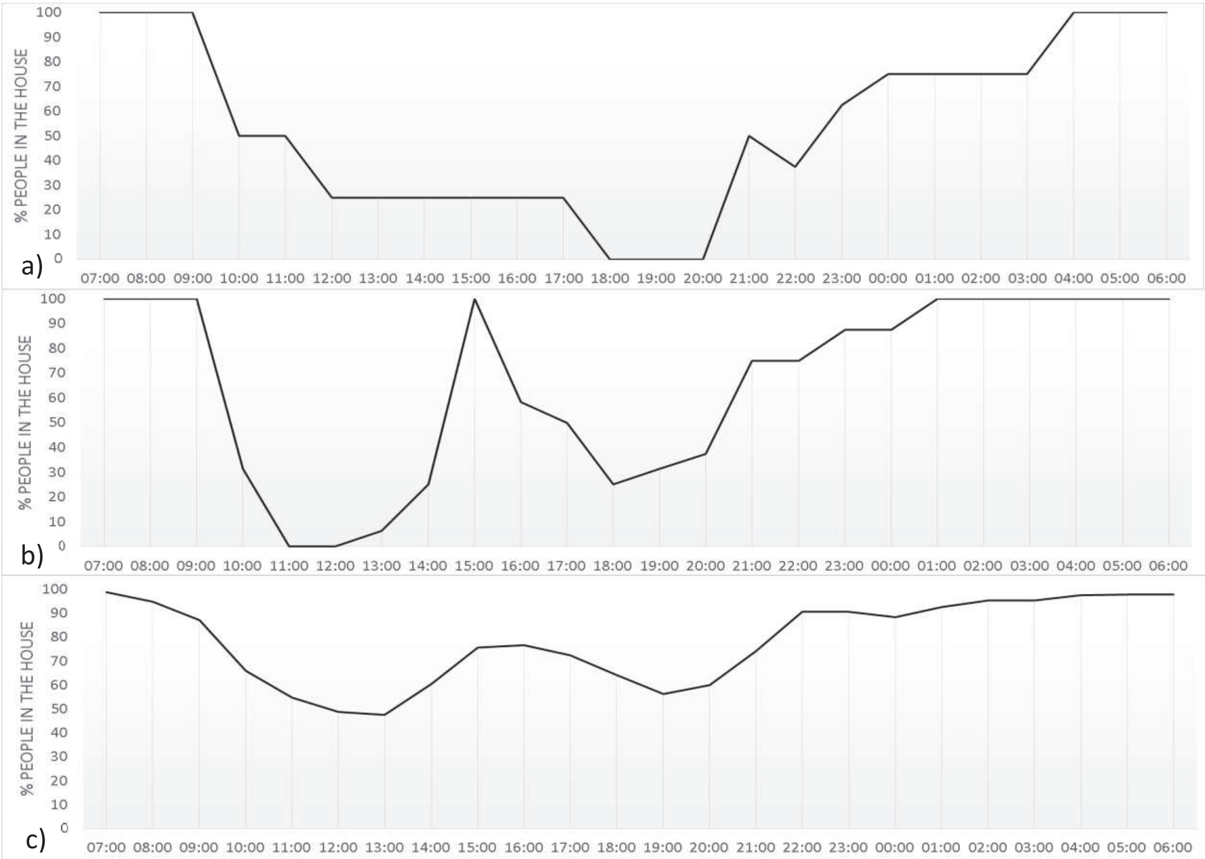

Figure 4. Average profile for a) low occupancy class, b) medium occupancy class and c) high occupancy class.

In particular, the low occupancy class (Figure 4 a) is characterized by 100% occupancy only during the night hours. For the medium occupancy average trend (Figure 4 b), 100% occupancy appears also during lunch hours. For the high occupancy class, a continuous presence throughout the day is highlighted (Figure 4 c), with two minimum levels in the morning and afternoon. It is immediately clear that the house is always occupied in the latter case. Moreover, the percentage of people at home never drops down 50% in the high occupancy profile, while wide time ranges in which the percentage of people at home is lower than 50% are displayed in low and medium occupancy profiles. For example, only a fraction of 20% of the family is on average present at home between 12:00 and 17:00 in the low occupancy profile.

Within the high occupancy class, due to the large number of families ranked in this category, a further classification was done, in order to explore in more detail how the percentage of people present at home during the day evolves. The classification criterion is based on the distinction between the category of families characterized by a prevalent occupancy during the morning, and the families class with a predominant occupancy in the afternoon hours. An intermediate category is represented by the buildings in which the difference, between the occupancy in the morning and in the afternoon, is lower than 10%. The resulting average trends are illustrated in Figure 5.

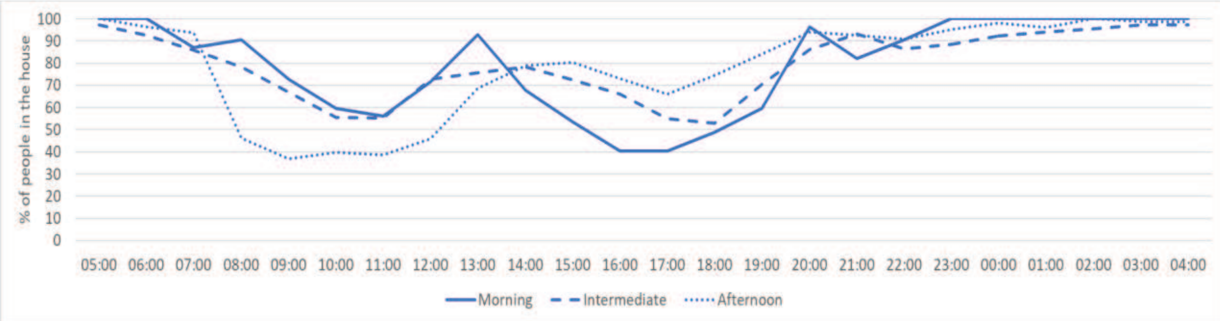

Figure 5. Average profiles for the three sub-categories of families within the high occupancy class: prevalent occupancy in the morning, in the afternoon and intermediate.

The profile with prevalent occupancy in the morning shows higher occupancy rates (ranging from 55% to 93%) between 8:00 and 14:00 and exhibits a minimum corresponding to 40% of occupancy in the afternoon hours. By contrast, the profile with predominant occupancy in the afternoon reports higher occupancy rates (varying from 66% to 94%) between 14:00 and 20:00 and shows a decrease in the morning hours, reaching a minimum at 9:00, equal to 37% occupancy rate. In the intermediate sub-category, it was not possible to identify a strong difference in house occupancy between morning and afternoon. The obtained average profile reveals a symmetrical trend, with occupancy rates never below 50% and maximum occupancy during the night.

Further analyses were carried out with the aim of identifying possible relations between occupancy classes and the variables investigated in the questionnaire. In particular, a significant relationship was found for both households' income and energy consumption, which present a diverse distribution among the different occupancy classes.

Data presented in Figure 6 and Figure 7 disclose that high occupancy class is characterized by the lowest income families and by the highest average value of electricity (generally equipment and cooling) and primary energy consumption for heating and DHW. Instead, within the low occupancy class, 40% of the families have an income between € 15000 and 28000 and show the lowest average value of energy consumption. Information about income and heating/DHW energy consumption were not provided by 50% of the households classified in the medium occupancy class.

With regard to sub-classes of high occupancy class, it can be inferred that the families in this class have almost the same annual income. On the other hand, some differences can be highlighted among the values of primary energy consumption. The highest value was found in the class “afternoon”, this is reasonable because the most used fuel in this class is wood that, as already said, is the fuel for which the highest primary energy values are registered.

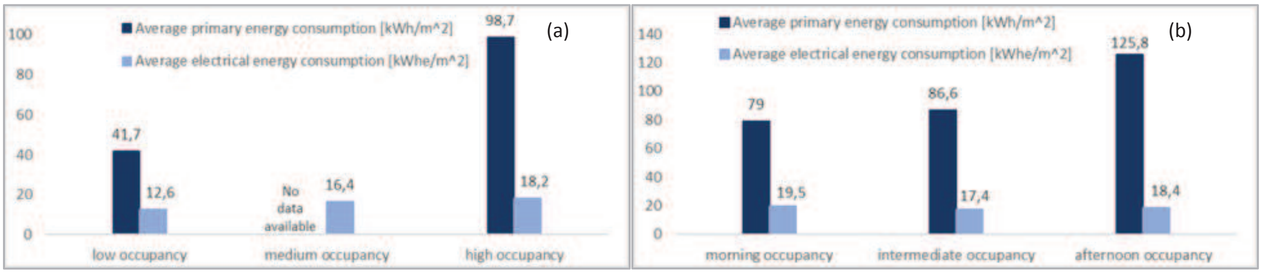

Figure 6. Annual values of average energy consumption as a function of occupancy classes (a) and of high occupancy sub-categories (b).

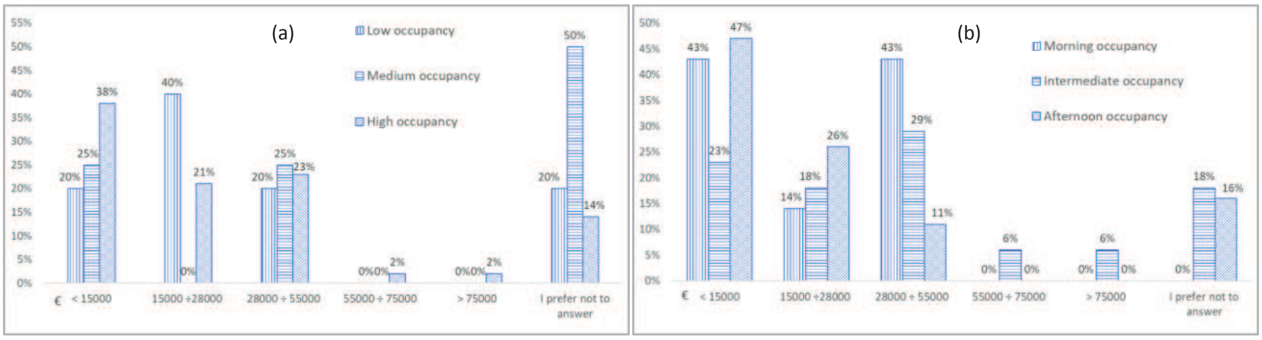

Figure 7. Income distribution for each occupancy class (a) and for each high occupancy sub-category (b).

4. Conclusions

This work is a pilot study. For this reason, the first aim was to understand how much efficient is the use of the questionnaire and what are the most critical issues in using this investigation method. Moreover, it has been a useful experience to understand what kind of data can be gained. In fact, it has to be considered that in order to make energy consumption forecast the most possible precise, a lot of information is needed. When this information involves occupant behavior it is almost impossible to establish standard values. The possibility to have an average trend of occupancy profiles makes easier and more precise working on energy simulations. Only using as average occupancy trends as starting point in energy simulation, it is possible to obtain reliable building energy consumption estimation usable in thermal storage systems dimensioning and renewable energy applications.

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6.4 Activity and occupancy profiling based on data collected by questionnaire. Pilot study on a residential buildings sample

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Abstract

The present study summarizes the results of a survey conducted by questionnaire in order to gather informative data on the occupancy characteristics in residential buildings. The questionnaire was distributed to a pilot sample by using different methods (online, face-to-face interview, social network). In particular, data on presence at home and occupants' behavior were collected with the aim of profiling occupancy and typical activities by statistical approach. Moreover, the effectiveness of the proposed tool was evaluated in order to understand its capability in achieving the required information, and underline critical issues to be resolved in order to optimize future research experiences in this sector. The study provides average hourly profiles of presence at home, heating/DHW usage, cooling and lighting usage, ventilation and blinds control.

Keywords: Residential buildings; Survey; Profiling; Occupancy; Systems operation.

1. Introduction

Energy calculations require both building and occupants' data in input. While building characteristics and physical properties are easily retrievable, considerable difficulties are generally faced in the description of occupancy. Information like presence of people at home, activities carried out in the house, habits in opening windows, use of household appliances, heating/cooling activation, are source of uncertainty in energy assessment. In the absence of definite data, generalized occupancy models are adopted, leading frequently to deviations in results. Especially for those applications in which a high level of detail is required, such as dynamic simulation. Three levels of definition of behavioral parameters (simple, intermediate and complex) addressing different research purposes are discussed in (Chen et al., 2015). For example, for simulation purposes, a detailed understanding of occupancy is needed and it can be achieved only with the "complex" level, which allows for the definition of accurate schedules of presence, appliances, window/shading, and air conditioning operation.

As can be deduced from existing literature, different sources can be used for occupancy modelling and profiling, including data collected through targeted surveys, data measured during monitoring campaigns, and data derived from national Time Use Surveys (TUS).

(Feng et al., 2016) presented typical occupant air-conditioning behavior patterns use in Chengdu (China) extracted from a large-scale questionnaire survey based on the energy consumption levels. A building simulation model was successively employed in order to assess the difference of energy consumption among various behavior patterns and the effect of occupants' control on air-conditioning. Occupancy patterns and operation schedules of electrical appliances used in Kuwaiti residences were surveyed in (Al-Mumin et al., 2003) and then used as input data for simulation. The authors demonstrated that the software default schedules based on the Western lifestyle were not adequate in describing the behavior of the local residents. Therefore, they claimed that more regional responsive data should be used in energy simulation software in order to achieve better-informed predictions. (Iwashita and Akasaka, 1997) investigated habits in occupancy, window/door opening, and air conditioning operation in eight Japanese dwellings in order to measure the ventilation rate and to explore the relationship between occupants' behavior and air conditioning energy consumption. They found that 87% of the total air change rate is due to occupants' habits. Data on the lifestyle from an eight unit apartment building in Tehran (Iran) were collected by (Yousefi et al., 2017) with the aim of obtaining detailed schedules of occupancy, usage of electric and gas appliances, lighting, heating, and cooling devices for different times and days of the year. The implementation of the real data in simulation and the sensitivity analysis showed that occupants' behavior can impact heating and cooling loads up to 90%. (Papakostas and Sotiropoulos, 1997) gathered data from 158 families in Greece through interview. In particular, occupants were asked by a trained person and filled an extensive questionnaire concerning their presence at home, the use of domestic appliances, and the performance of energy-related activities. The percentage of occupants at home throughout the day, distinguishing between employed men, employed women, housewives, children (5 – 15 years), and youth (15 – 20 years) was calculated on hourly intervals. Occupational patterns of three typical Greek families and activities patterns (watching TV, house cleaning, cooking, taking meals, clothes washing, dish washing, and taking bath-shower) were delineated. (Barbosa et al., 2016) proposed a methodology to develop accurate occupancy profiles for Portuguese residential buildings. In particular, profiling was detailed at room level and based on questionnaires. It was proved that an accurate occupancy modelling allows a more grounded assessment of buildings performance.

Measured data are frequently used for defining occupancy profiles, either alone or in combination with occupant surveys. For example, (Kleiminger et al., 2013) proposed to derive occupancy information from the electrical load curve. With this purpose, the identification of features that may be indicative of occupants' presence is necessary. A clear indicator of occupancy is represented by switch events in the load curve that require the interaction of occupant with appliances (e.g. television, stove or cooker). Instead, the electricity consumption of appliances such as fridges, freezers or standby consumption of electric devices does not give any indication about the occupancy state of the household. (Guerra-Santin et al., 2016) presented the results of two monitoring campaigns focused on two owner-inhabited apartments in Spain and three social rental dwellings in The Netherlands. The study adopted the Mixed Methods Research integrating qualitative and quantitative data to develop occupancy and heating patterns. A mixed methodology was furthermore used in the research conducted by (Escandón et al., 2017) to capture technical and social aspects of user practices. Real use and occupancy patterns were defined based on qualitative data of user surveys and quantitative measured data obtained from the monitoring of representative case studies located in Southern Spain. Data collection lead to the development of energy simulation models better suited to the real behavior of the examined social housing stock. 48 households were assumed as case studies in the analysis carried out by (Guo et al., 2015). Energy consumption of each heating device was measured and the temperature and CO_2 concentrations in each room were monitored over one heating season. Thus, temperature profiles and use of air conditioners for heating in the studied households were shaped.

Several studies drawn from national Time Use Survey (TUS) databases to define occupancy and consumption patterns. For example, the authors of (Widén and Wäckelgård, 2010) used data from Swedish TUS (2007) along with electricity use survey and measurements of household electricity in order to develop a stochastic model that can be used for generating realistic activities patterns and power demand patterns. A bottom-up stochastic model validated by using French TUS (1998-1999) is presented in (Wilke et al., 2013) to accurately predict residential building occupants' time-dependent activities. (Aerts et al., 2014) report on the methodology used to obtain realistic occupancy profiles based on the 2005 Belgian TUS by using hierarchical clustering. The analysis resulted in seven profiles differentiated on the basis of occupancy level. Furthermore, the relationship between employment status and occupancy level during weekdays was detected. Realistic and quasi-empirical profiles for occupancy, lighting, and appliance usage based on 2000 UK TUS were defined in (Blight and Coley, 2013) and applied in a dynamic simulation program, in order to evaluate the energy performance of a set of passive houses. The authors showed that it is possible to generate varied and representative models of typical UK occupancy patterns and appliance-use behavior in homes, and to successfully use these in simulation tools. An hybrid method, combining both engineering and statistical methods for identifying household energy consumption was developed by (Shiraki et al., 2016). The proposed method, developed on the basis of 2010 Japanese TUS and direct metering, can adequately estimate hourly electricity consumption, and it also decomposes the contribution of the major appliances.

Some studies focused on the development of end-use energy consumption models to provide a basis for the design and evaluation of Demand Side Management solutions. For example, (Richardson et al., 2008) and (Buttitta et al., 2017) used 2000 UK TUS to define high time-resolution occupancy profiles able to reproduce when occupants likely use home appliances, lighting, and heating. (López-Rodríguez et al., 2013) used 2009-2010 Spanish TUS to determine occupancy patterns and peaks in active occupancy, coinciding with morning, noon and evening.

The present study reports the results of a questionnaire survey designed to investigate occupancy characteristics and occupants' behavior in residential buildings located in Mediterranean climatic conditions. A pilot sample was surveyed in order to verify the validity and suitability of the items included in the questionnaire and to test the possibility of deriving typical occupancy and activities profiles from the collected data. The description of the survey content and of its administration is provided and the response rate of each query is analyzed and discussed. Some of the variables related to occupants' habits are examined in depth in order to obtain hourly profiles to be used as input in simulation software.

2. Methodology

The questionnaire used in the investigation was designed on the basis of several previous experiences and through comparison with other studies. The first version of the questionnaire was developed at Tsinghua University, in China (Building Energy Research Center of Tsinghua University, 2016). It was translated by a research group of the University of Calabria and adjusted to the new social and environmental scenario. The questionnaire was used for a study performed in the years 2012 – 2018 (Bevilacqua et al., 2015; Mora et al., 2015; Carpino et al., 2017; Mora et al., 2018). Successively, by considering other investigations conducted in Italy, an updated version was created and it was administrated to a few respondents in order to gather information on possible hurdles in answering questions. Thanks to the feedback gathered from this test and by analyzing two further studies conducted in the Netherlands (Guerra-Santin, 2010) and in Turkey (Harputlugil and Harputlugil, 2016), the final version of the questionnaire was obtained (Carpino et al., 2018).

The questionnaire is divided into four main sections, as illustrated in Figure 1. The structure was dictated by the aim of collecting information about physical, socio-demographic, and behavioral variables. The respondents were asked to share their lifestyle by completing timetables of their presence and activities at home.

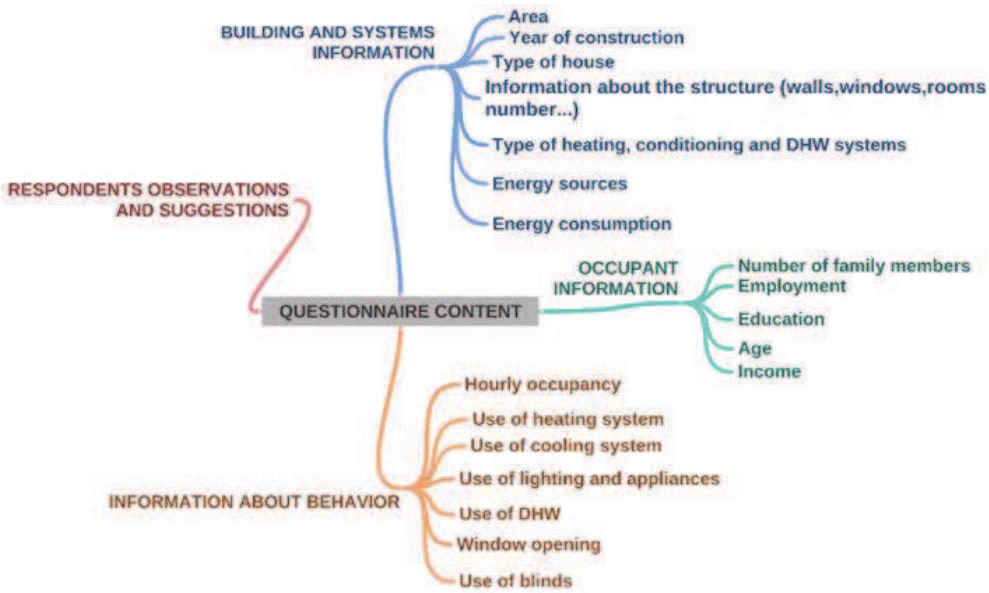

Figure 1 – Questionnaire content grouped into four sections.

In particular, for every hour of the day, detailed schedules were filled with information regarding the presence in each room of the house, the operation of heating, cooling, DHW and electrical devices. Furthermore, lighting, window opening, and blinds usage were detected both for winter and summer seasons.

The survey was conducted in the autumn of 2017 on a pilot sample of 80 families, resident in the Calabria region (Southern Italy). Three methods were used for its administration: direct interview, e-mail distribution, and social network. The most effective method is the interview since it guarantees 100% complete and correct answers. By contrast, this is also the most time consuming. Distribution via social network allows to reach the greatest number of people, but it is the method that presents the highest number of incomplete answers (48%). Among the questionnaires sent via e-mail, 88% were fully completed. Overall, the percentage of valid responses throughout the whole sample was of 65%.

3. Results and discussion

3.1 Questionnaire effectiveness and sample characterization

Figure 2 presents the response rate of questions grouped into six categories: building information, systems information, consumption, family information, occupancy, and usage. What is clear is that there is not deep knowledge about building characteristics among the interviewees. In fact, the questions regarding specific aspects, such as thermal insulation of walls, energy renovation works, and year of construction are those ones with the lowest response rate in the first group. The response rate of questions about total annual income reaches 83% and it can be considered a rather satisfactory share, as people usually do not answer this question willingly. The lowest response rate is obtained for the lighting usage in summer (10%).

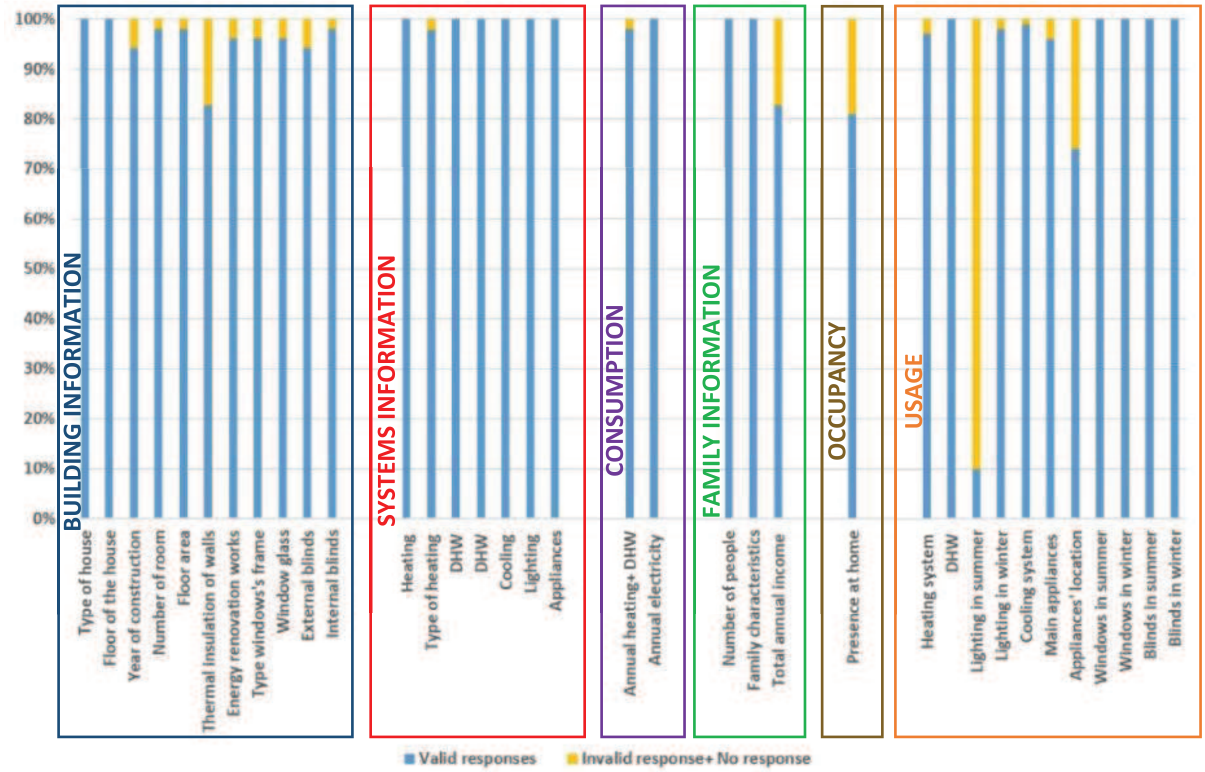

Figure 2 – Response rate for each section of questionnaire.

Data provided by the National Institute of Statistics (Istat, 2017) were used to verify the sample representativeness. The average age of respondents was 41.7 years, comparable with the average age of the analyzed population (44.2 years). In particular, 46% of the interviewees were males and 54% females, in accordance with the gender distribution in the region (49% males and 51% females). The average annual household electricity consumption was 2140 kWh, and consistent with the average regional value of 2283 kWh.

Furthermore, some of the detected features are reported in order to provide a general description of the investigated sample. Regarding building characteristics, the majority of the constructions were built between 1973 and 1991 and apartments are the most common dwelling type. About 90% of the respondents own an independent heating system consisting in a gas boiler supplied by natural gas. 43% of respondents use fireplace and electrical heaters. Generally, a combined system both for heating and domestic hot water is installed, and an average primary energy consumption of about 100 kWh/m2 is observed. Cooling system is present in 48% of the houses. Regarding appliances, 80% of the households declared to have low-consumption appliances while energy efficient light bulbs are used by 90% of the respondents. Renewable energy systems are actually not widespread, photovoltaic and solar thermal collectors are installed in less than 10% of the analyzed cases. Concerning occupants' habits, the collected information is analyzed in detail in the following paragraphs in order to provide typical profiles.

3.2 Occupancy profiles

Occupancy profiles are intended as timetables of presence at home during the day and are the basis for further data processing because of presence is the necessary condition for the implementation of the activities at home. Questions about occupancy required the filling of a table with hourly time interval for each room of the house. This question reached a response rate of 81%. Within the valid sample, data were processed by grouping the rooms of the house in three macro areas with common characteristics, namely living space (including kitchen, dining room, and living room), bedroom area, and bathroom area. This subdivision was suggested by simulation software that usually requires separate presence schedules for each zone of the house with different activity type.

The occupancy profile was built by calculating, for each hour of the day and for each zone, the percentage of households that reported the presence of at least one person compared to the total number of households. The resulting occupancy profiles are shown in figure 3. As expected, bedrooms are occupied mainly during the night. The percentage of occupancy for bathrooms is higher in the morning hours. Continuous occupation during the day is registered for the living space, with peaks arising at meal times.

In line with the lifestyle of the families in the surveyed area, there are not hours with high percentage of non-occupancy. Differences emerge by comparing the graph with occupancy profiles obtained in different scenarios. For example, in the study conducted by (Barbosa et al., 2016), occupancy profiles outlined for weekdays show that Portuguese homes are often unoccupied during the day, as highlighted in figure 4(a). Similarly, the occupancy patterns developed by (Aerts et al., 2014) for Belgian households show that the probability that people are outside home from 8:00 to about 19:00 is high, as displayed in figure 4(b).

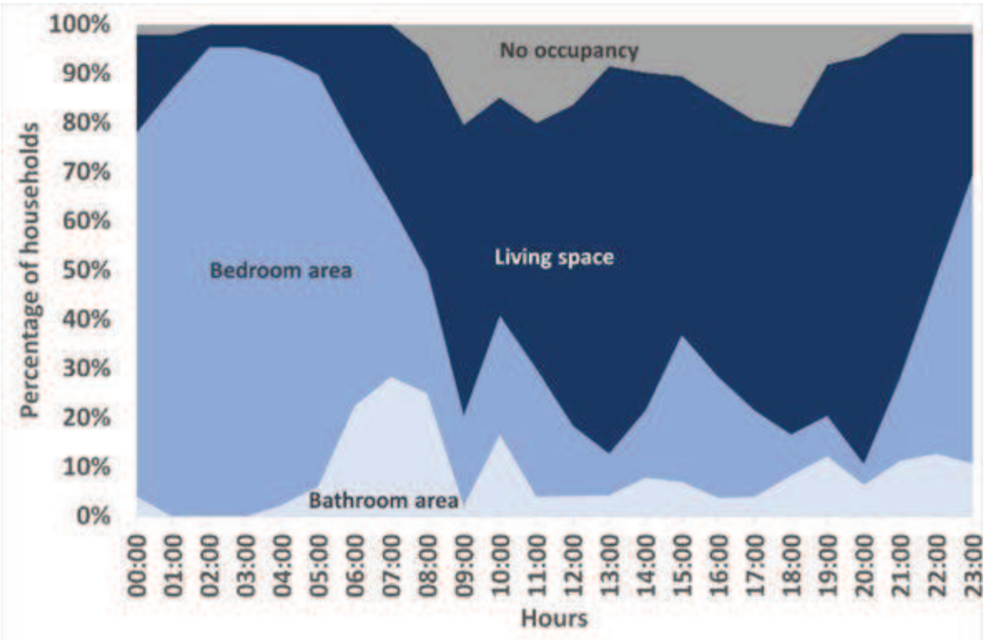

Figure 3 – Hourly average occupancy in the different zones of the house.

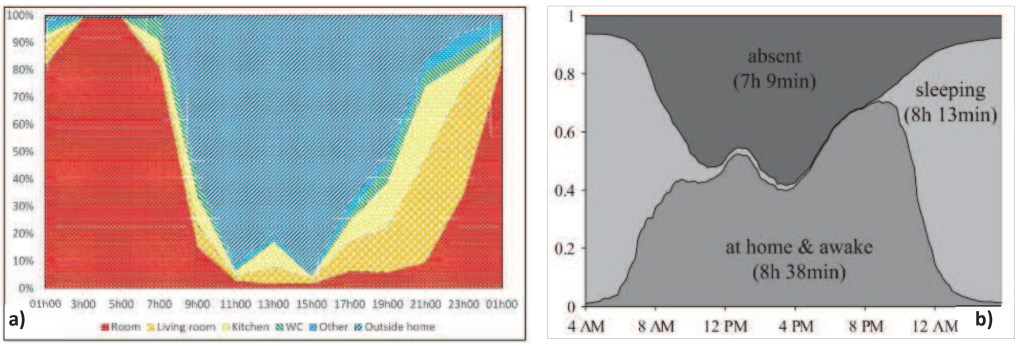

Figure 4 – a) Occupancy profile of Portuguese buildings in week days (Barbosa et al., 2016); b) Average occupancy profile for Belgian households (Aerts et al., 2014).

3.3 Heating operation and DHW usage profiles

Figure 5 shows the hourly average usage of heating system for two different operating modalities declared by the respondents: activation in every room (Figure 5(a)) and activation only in the occupied rooms (Figure 5(b)). In particular, 63% of interviewees are in the habit of heating all the house zones, and 37% are used to heating only the occupied rooms. The heating system is mainly used in the early hours of the day and close to dinnertime, for both profiles. In particular, when the heating system is switched on in the entire house two usage peaks (45% and 85%) are registered at 7:00 and at 20:00, respectively. Regarding the use of the heating system in the different rooms, it can be seen that people prefer heating bedroom and bathroom areas more in the early morning (41% around 6:00) and the living space in the rest of the day. The maximum percentage of heating usage in the living space is 65% from 19:00 to 20:00. After dinner, there is a slight percentage increase in the bedroom area and a decrease in the living space.

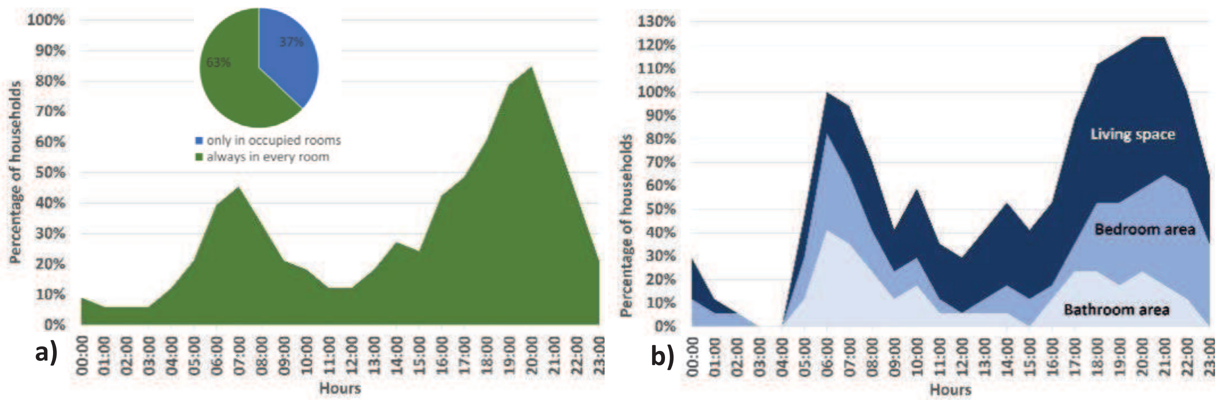

Figure 5 – Hourly average usage of heating system a) in every room and b) only in occupied rooms.

Furthermore, the time interval in which houses are less occupied is characterized by a lower usage of heating system. In these hours, the most heated area is the living space.

The hourly average use of domestic hot water (DHW) is presented in Figure 6, by differentiating between kitchen and bathroom area. As expected, hot water demand in each room varies according to the considered time range. DHW is mainly required in the bathroom area in the morning, reaching a peak of 67% at 7:00. For lunchtime and dinnertime, instead, the main consumption of DHW is registered in the kitchen.

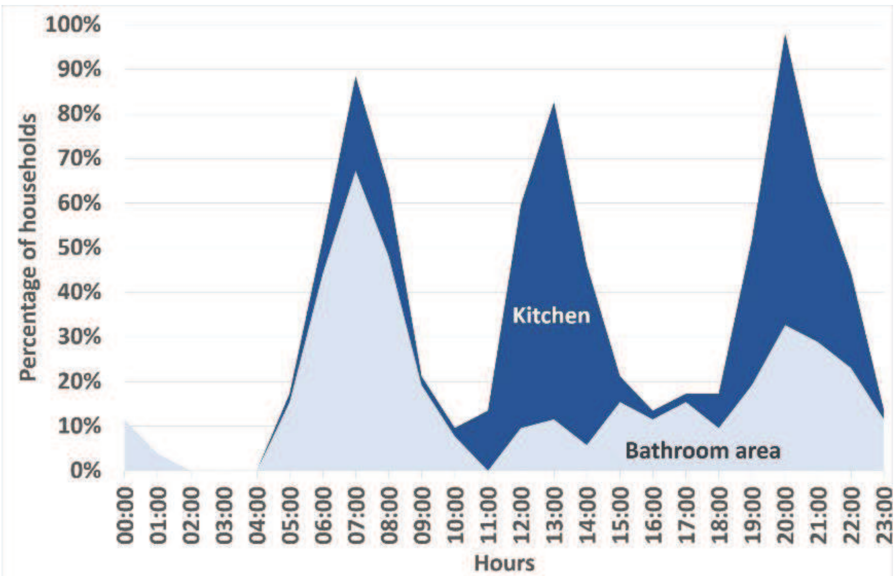

Figure 6 – Hourly average use of DHW.

3.4 *Lighting and cooling operation profiling*

Lighting and cooling system, in addition to domestic appliances, are responsible of electricity consumption. The survey revealed that the most common appliances in the analyzed houses are: fridge (98%), hoven (77%), washing machine (65%), and dishwasher (40%). On average, there are more than one computer and television for every house.

Figure 7 shows the hourly average functioning of lighting system in summer (Figure 7(a)) and in winter (Figure 7(b)). In both the trends, there is more intense artificial lighting usage in the first hours of the day and in the late afternoon. Differences in some hours of the day are noticed: in summertime, there is not usage of lighting around noon while it can be seen a reduction in usage in wintertime. In summer, the same percentage of households (40%) stated to use the lighting around 6:00 in bathroom area and in the living space. This percentage increases in the late afternoon: for the living space the lighting usage is 100% at 22:00, and 80% at 23:00. Similar percentages were found in winter.

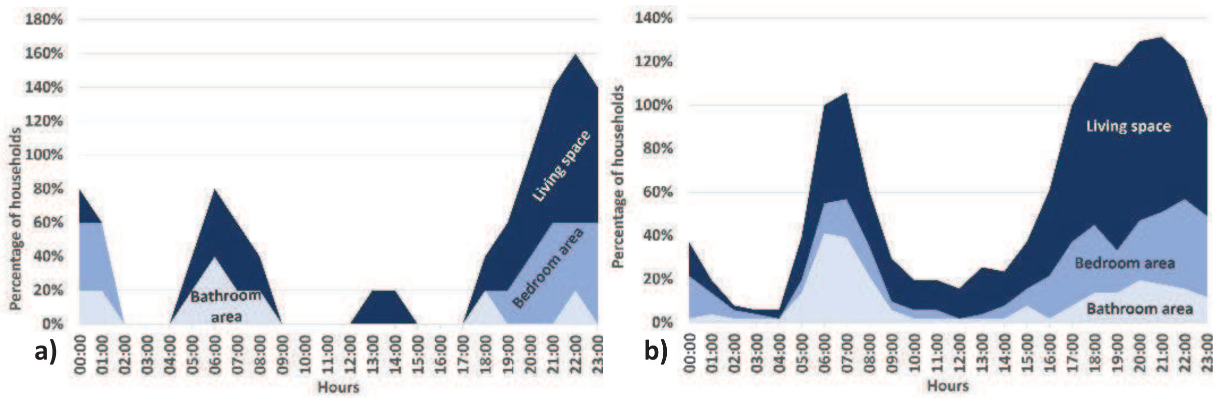

Figure 7 – Hourly average operation of lighting system in a) summer and b) in winter.

Only 48% of respondents declared to have a cooling system. Figure 8 presents the hourly average operating of cooling system during the day. As expected, cooling system is mostly used in the warmest hours, with the highest percentage during lunchtime. A typical behavior emerges from the graph, revealing that people prefer to cool the bedroom area before going to bed and turn off the system during the sleeping hours.

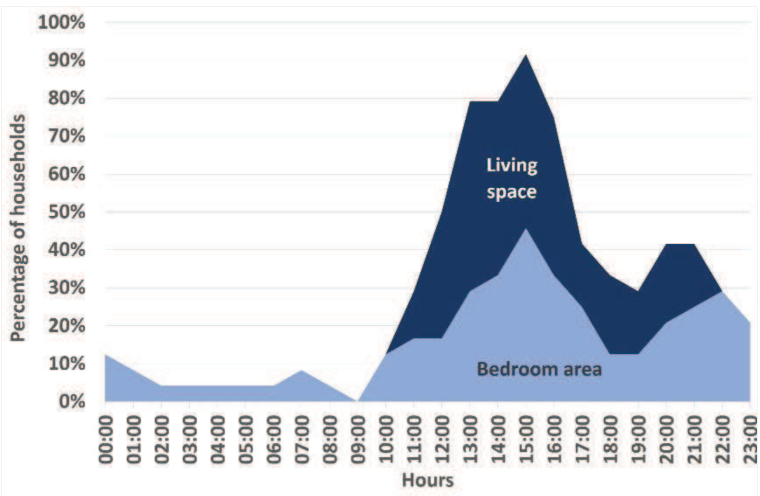

Figure 8 – Hourly average operation of cooling system.

3.5 Ventilation and blinds profiling

Natural ventilation and usage of internal and external blinds indirectly affect energy consumption because they modify, positively or negatively depending on the season, the external thermal loads of buildings. An adequate use of natural ventilation and internal/external blinds usage are the main strategies of passive design for energy saving.

The following Figures present the hourly average profiles of ventilation and blinds usage both for summer and winter. In summer, the percentage of natural ventilation ranges from a minimum of 40% (bedroom area at 15:00) in the warmest hours of the day to a maximum of 79% in the living space at 21:00. Different profiles were found for winter ventilation.

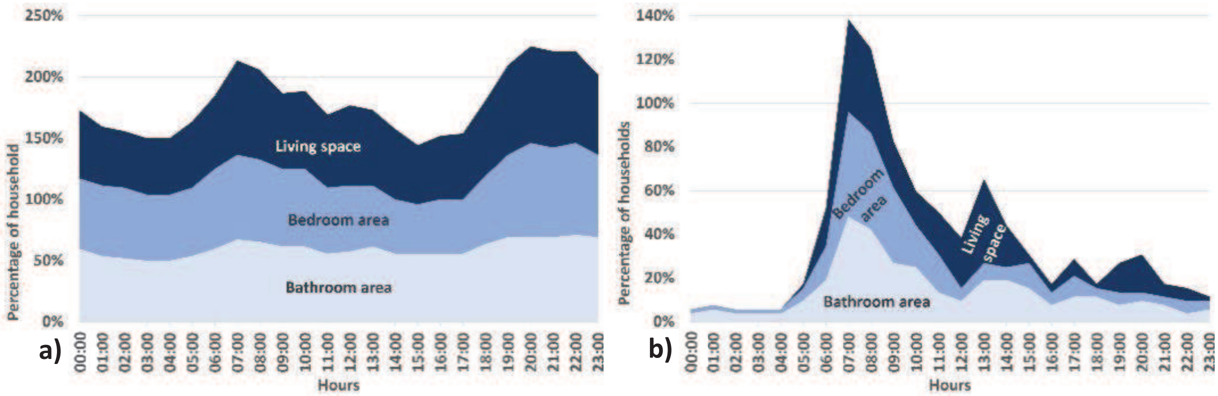

Figure 9 – Hourly average ventilation profile in a) summer and b) in winter.

It seems that people, despite the low external air temperatures, do not renounce to have fresh air for hygienic reasons. In fact, natural ventilation is mainly preferred during the first hours of the day with a maximum at 7:00 in every area (48% in the bedroom and bathroom areas, and 42% in the living space). With regard to the hourly average usage of blinds in summer and in winter, Figure 10 includes both internal and external blinds usage. In summertime, the high percentage of blinds usage is during the daily hours, probably due to the need of blocking solar radiation. During the late afternoon and for all the night, the percentage is lower and the usage is likely associate to privacy. A different profile is obtained for winter (see Figure 10(b)). In fact, the main usage of blinds is from the late afternoon and for all the night. In this case, blinds usage is more imputable to the intention of saving energy by reducing thermal dispersions through the glazed surfaces.

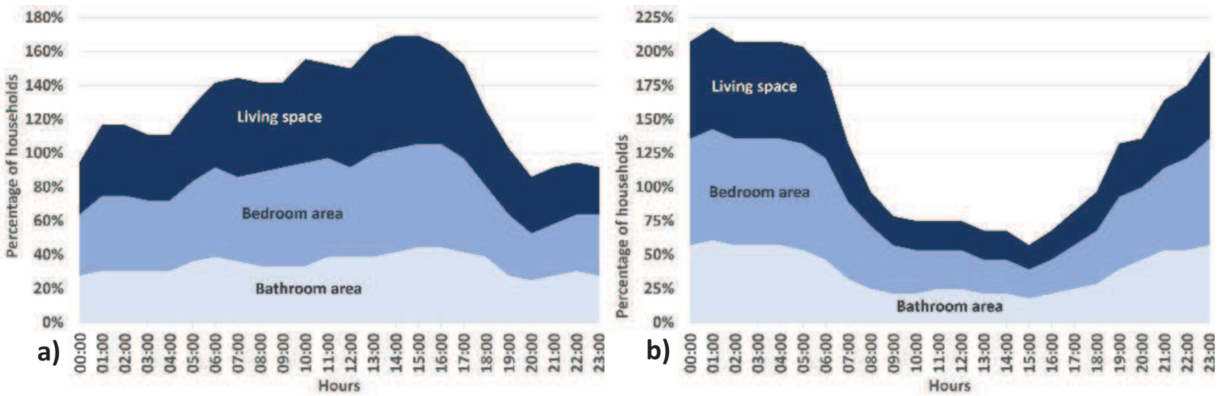

Figure 10 – Hourly average usage of internal and external blinds a) in summer and b) in winter.

4. Conclusions

A questionnaire survey was delivered to a sample of 80 families residing in Southern Italy. Respondents were asked to fill timetables reporting presence and systems usage in every room with hourly interval. These data were processed to obtain hourly occupancy and systems operating (heating, lighting and cooling systems, DHW, ventilation and blinds) profiling for three homogeneous areas: living space, bedroom area, and bathroom area. In the analyzed dwellings, the hours of no occupancy are limited reaching a maximum of 24% at 9:00 and in the late afternoon. This trend appears to be very different from those found in other socio-climatic contexts wherein the middle hours of the day have higher values of no occupancy. The respondents declared to use the heating system following two modalities: in every room or only in the occupied rooms. Despite the different operating modalities, the hourly profiles are similar. DHW usage was obtained for kitchen and bathrooms separately. The highest DHW demand is early in the morning, at lunchtime and between 20:00 and 21:00. With regard to lighting operation, seasonal differences were found from 9:00 to 17:00. In fact, in this time interval there is no lighting usage in summer and a reduction in winter. Less than half of the surveyed houses have a cooling system and the time when there is a greater use is around 15.00. During the night, the usage of cooling system is unusual.

Seasonal analysis was also conducted for ventilation and blinds. In summertime, the usage is persistent during the day in the three considered area. In winter, the trends are different. In particular, people are in the habits to ventilate the houses only in the early morning and to use blinds at the beginning and at the end of the day.

These findings can be useful in energy simulation because the energy performance of residential buildings depends both on the characteristics of the building-plant system and on the ways in which it is used by the occupants. Generally, operation schedules obtained by statistical data or provided by standards are assumed in energy calculations. However, the use of generalized information can result in significant uncertainty in energy consumption prediction. Whereas, much more reliable energy consumption estimations can be obtained if occupancy and systems usage are accurately described.

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Conclusions

The research has sought to address the following topics:

- Analysis of strategies for the construction of nearly Zero Energy Buildings in the Mediterranean climate, with a focus on thermal inertia and the thermal storage capacity of the building envelope;

- Refurbishment of existing buildings into nZEBs, by also considering cost-effectiveness and economic optimization;

- Influence of occupancy and occupant behaviour on the final energy use of the building and impact on the theoretical "nearly-Zero Energy" balance;

- Development of reference procedures for the definition of occupancy profiles and their application in the research area.

Concerning the first aspect, two construction systems were analysed, namely the dry assembly technique and Insulated Concrete Forms, with the aim of verifying their suitability for applications in warm climates.

The results highlight the significant role of thermal inertia and dynamic properties of opaque components. Therefore, in the case of dry construction, it is necessary to adapt the light structures typical of this system, in order to increase their thermal capacity. In the specific case, the possibility of including a layer of dry sand on the inner side of the walls and floor was studied. This solution, coupled with nightly free-cooling, has been proved to be successful according to the evaluations conducted. In the case of ICF structures, these are already equipped with an adequate thermal inertia. However, the internal insulation layer of the formwork can limit the full exploitation of the fabric storage capacity. Therefore, the possibility of replacing the thermal insulation layer on the inner side of the form with a material characterized by a higher thermal transmittance was analysed in order to favour the activation of the thermal mass of the envelope.

Detailed analyses have shown that the thermal mass layer which can be activated in a 24-hour charge/discharge cycle does not exceed 10 cm and that the interaction between thermal mass and heat/cool emitters should be considered to make the best use of the storage capacity. In fact, based on the same amount of thermal mass, the storage capacity is increased if radiant systems are used for air-conditioning. By using these systems, indeed, the surface temperatures of the construction components reach values close to the air temperature, thus storing a greater quantity of energy. Therefore, the use of the building structures for thermal storage can facilitate the attainment of nZEB status. In particular, the thermal mass of the building can be used to accumulate surplus energy produced from renewable sources. In this regard, experimental data measured on a smart air-conditioning plant using a PV driven heat pump, demonstrate that a considerable increase of the self-consumed PV electricity can be achieved by better exploiting the storage capacity of thermal energy inside the building fabric. In fact, by means of overheating and undercooling strategies, applicable when free sources are available, the electricity surplus can be transferred to the conditioned building and used later, allowing a reduction of energy taken from the grid.

Concerning the renovation of existing buildings, the study was conducted on two levels. First, an investigation was carried out on the building stock. Information collected through questionnaires and energy certificates allowed for the outlining of an overview of the energy performances of residential buildings in the research area and to identify variables that most influence energy consumption. Multivariate regression analysis was performed in order to obtain a forecasting model to be used for the prediction of heating and DHW energy consumption of residential existing buildings, by distinguishing between apartments and detached houses. The proposed simplified procedure, requiring a few immediately available data, can be easily used to envisage different redevelopment scenarios and evaluate the effects of interventions on the most significant variables, supporting decision makers in identifying the most favourable measures.

Secondly, following the instructions provided by the European Union, which encourages the cost-effective transformation of existing buildings into nearly zero-energy buildings, a procedure aimed at determining the cost-optimal level for the refurbishment of a social housing was applied. From the economic point of view, it was found that the most effective solutions consist of the upgrading of the heating/cooling system combined with the integration of renewable energy production. The thermal insulation of the envelope improves the building energy performance. However, it seems economically less advantageous compared to the interventions on HVAC systems and needs to be supported by financial incentives. In addition, the insulation thickness must be carefully sized in order to optimize the energy performance on an annual level, considering both heating and cooling needs.

Finally, the influence of occupancy on the building energy use was investigated highlighting how, due to occupancy variables, the actual energy consumption may significantly deviate from the estimated one. This discrepancy is more evident in low-energy buildings and can sometimes undermine the real achievement of the zero-energy goal. The research both considered evaluations on simulation models and analysis of measured data collected by means of monitoring campaigns. The study has shown that different occupancy modes lead to different final energy uses. In particular, the results revealed that the evaluation of the performance based only on the heating, cooling, and ventilation uses can be inappropriate, because the whole consumption of the house should be taken into account for a comprehensive assessment. It is worth providing a special warning in this regard, because what the research is focusing on, in the building area, is to reduce energy consumption in buildings, and to achieve this goal it seems essential to focus more on the energy use for appliances and the occupant related energy use. This is because, as confirmed by the research findings, currently, the primary energy use of electricity for household equipment is considerably high. Consequently, it is advisable to involve electricity used by appliances in the calculation of the energy performance to obtain results that are both more realistic and more reliable. Moreover, since for this type of buildings, i.e. nZEBs, the building related energy use has already been fairly optimised and actually it represents only a minor part of the total household energy use, a greater focus is needed on the occupant related energy use. Therefore, in the future, more attention should be paid to the use of equipment in households in order to fully decrease the energy demand.

Regarding occupancy modelling in simulation processes, the forecasting reliability can be enhanced by a more accurate description of the occupancy characteristics. To this end, the research aimed to provide reference procedures for obtaining detailed occupancy profiles that can be used for energy consumption calculations. Specifically, three categories of variables were introduced in order to comprehensively characterize the occupancy profile: presence variables, comfort variables, and tool variables. In particular, the analysis focused on the definition of occupancy profiles based on data collected by administration of a questionnaire. A thorough review of the literature concerning the application of the questionnaire in the residential sector allowed a better insight regarding the potentiality of this survey tool and of its way of use. Based on the outcomes of this analysis, a questionnaire was designed to gather information on occupant habits and energy consumption. The questionnaire was administered to a pilot sample and the procedure for creating presence and behaviour patterns from the collected data were reported.

Future lines of research

The evolution of the building process is leading to the establishment of more sustainable building systems able to reduce construction times and costs and to decrease environmental footprint, through the limited utilization of raw materials and the reuse of components. However, the constructive flexibility characterizing these systems does not reflect design flexibility in terms of possible effective use in different climatic conditions.

The results of the research showed that specific adjustments are needed to make these systems usable also in climatic zones different from those in which they were originated and diffused, and that pose different performance requirements.

Based on the obtained results, future research will be oriented towards the optimization of new construction systems, through the exploration of innovative materials and advanced design strategies, which can facilitate the widespread implementation of Zero Energy Buildings. In particular, future studies will be directed to deepen the thermal storage in the building structures to take the best advantage of the energy provided by renewable sources.

Besides the optimization of the building characteristics, the research findings highlighted the crucial role of the occupants. Concerning this aspect, future research will be aimed at two objectives. On the one hand, standardized reference procedures will be codified for the definition of realistic occupancy profiles, which can be used for energy simulations in the design phase, in order to make energy use prediction more reliable. The questionnaire previously submitted to a pilot sample will be used for a wider survey, in order to obtain occupancy profiles representative of different geographical, social and cultural contexts. In addition, general guidelines will be drafted, to inform statistical offices and local authorities in charge of investigations, so that periodic surveys could also include, among other collected data, questions about occupancy and occupants habits, which can be useful to define typical patterns.

On the other hand, the research will focus on innovative control and management technologies, which allow to decouple the house operation from users. In particular, future studies will be aimed at developing a prototype of “cognitive building”, envisaging a building able to learn the habits of the occupants and independently implement all the actions required to meet the needs of users, while ensuring energy conservation and internal comfort.