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ESTIMATING THE BUILDINGS HOURLY ENERGY DEMAND FOR SMART ENERGY DISTRICT PLANNING.

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ABSTRACT

For planning smart energy districts in urban contexts, including the integration of the distributed energy supply, low-temperature district heating networks, possibly integrated with cooling, energy from renewable sources and storages, the assessment of hourly energy demand fluctuations of buildings, even undergone to energy retrofits, is relevant for optimising energy system related efficiency and costs. Accordingly, among commonly adopted tools for urban energy planning, the ones which are more detailed (e.g. EnergyPLAN, Homer, energyPRO, DER-CAM) base on hourly energy demand profiles. However, from the surveyed literature on related recent studies, often energy assessments are based on seasonally/annually buildings energy demands or measured consumptions so more robust methods are needed in case of data lack. Hence, in the frame of a research that has been developed during a Ph.D. at Politecnico di Milano – ABC Department, it has been defined a method for estimating the buildings hourly thermal and electric energy demand profiles, to be applied in urban areas within the Italian context. The method has been developed based on a georeferenced procedure which adopts available data on the national territory useful to define the volumetric consistency and characterize the built environment with reference to the period of construction and most widespread uses (residential and tertiary). For determining the hourly energy profiles, a set of dynamic energy simulations is foreseen. In particular, a set of building solutions, considering different envelopes representative of typical solutions in Italy across historical periods, has been defined. Such building solutions have been assessed as simplified building models, and the energy behaviour of selected zones, representative of the different boundary conditions options composing any building geometry, has been determined. The derived hourly energy density profiles [W/m^3] can be associated to the characterized building stock in order to derive the assessed urban/district hourly energy demand. Once validated the existing case data, by assigning the new physical properties regarding the envelope and the systems to the building models, it is possible deriving the updated profile for the defined energy improved scenario.

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Nell'ambito di scenari di riqualificazione energetica urbana di Smart Energy District, contemplando dunque generazione elettrica distribuita, reti di teleriscaldamento (a bassa temperatura) combinate a teleraffrescamento, integrazione di fonti rinnovabili, strategie di accumulo, ecc., una stima della variazione di domanda oraria di energia dovuta ad interventi di retrofit sui sistemi edificio-impianto a larga scala risulta indispensabile per ottimizzare l'efficienza e ridurre i costi associati ai diversi sistemi. Tra i software di calcolo più utilizzati nell'ambito della pianificazione energetica urbana, infatti, quelli rivolti ad analisi dettagliate (EnergyPLAN, Homer, energyPRO, DER-CAM, ecc.) si basano su profili orari di domanda di energia. Tuttavia, dalla ricerca di letteratura è emerso che spesso gli studi su esempi di pianificazione energetica sono basati su dati di domanda energetica stagionale/annuale o su consumi misurati, sottolineando la necessità di metodi solidi per la stima accurata dei profili orari. Con la presente ricerca, condotta nell'ambito di una Tesi di Dottorato presso il Dipartimento ABC del Politecnico di Milano, è stato dunque sviluppato un metodo di stima dei profili di domanda termica ed elettrica degli edifici applicabile ad insediamenti urbani nel contesto nazionale. Il metodo è stato sviluppato secondo una procedura geo-referenziata che si avvale di banche dati disponibili a livello nazionale al fine di definire la consistenza volumetrica e di caratterizzare il comparto edilizio sulla base delle diverse epoche di costruzione dei fabbricati distinti nelle destinazioni d'uso urbane più ricorrenti (residenziale e terziario/uffici). Per determinarne i profili energetici orari la procedura prevede simulazioni energetiche su base oraria di modelli edilizi. È stato infatti definito un set di soluzioni edilizie, differenziate secondo le tecnologie realizzative riconducibili alle principali epoche di costruzione, che sono state tradotte in modelli edilizi a semplice geometria parallelepipeda da cui sono stati desunti i comportamenti energetici di zone termiche-tipo identificate quali rappresentative delle diverse opzioni (condizioni al contorno) che possono concorrere a configurare qualsiasi geometria edilizia. I dati energetici orari delle zone termiche-tipo, ricondotti a profili di densità energetica [W/m^3], vengono dunque utilizzati per definire i dati energetici orari dell'intero parco edifici analizzato. Una volta calibrati i dati ottenuti per lo stato di fatto, relativi al caso in esame, ripetendo la procedura avendo assegnato nuove proprietà fisico-termiche e/o impiantistiche caratterizzanti i modelli edilizi, si possono ottenere dati di domanda energetica oraria previsionali per lo scenario considerato.

Keywords

Smart Energy System planning, Geographic Information System (GIS)-based procedure, building stock geo-database, urban district energy profiles modelling, buildings hourly energy demand estimation

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1. INTRODUCTION

From the 1973 when, as a consequence of the Yom Kippur War, the first oil crisis occurred involving a sharp rise of the related price and a rethinking of the energy sources exploitation, until today, the state of people consciousness and of accomplished pledges for contrasting the climate change, have significantly progressed, although the achieved results during these decades are not enough. Recently, the United Nations (UN) have recently approved a document, the Agenda 2030, calling for a coordinated worldwide effort towards a sustainable development and setting 17 goals [1]. Actually, the Agenda 2030 field of interest is quite broad, encompassing social, economic, environment and health issues, but dedicates a statement to the energy sector (7th, "Ensure access to affordable, reliable, sustainable and modern energy for all") while with another one remarks the role of the urban contexts (11th, "Make cities and human settlements inclusive, safe, resilient and sustainable"). In fact, the United Nations recently stated that cities are responsible for the 70% in the global energy demand [2] and that their relevance is expected to increase, in step with the urban population. Another prominent recent goal has been issued at the Conference of Parties (COP) in Paris, whose final declaration asked signatory Countries to maintain the global average temperature increment down to 2°C (or possibly 1.5°C) above the pre-industrial levels [3]. To achieve relevant results, great technical and economic efforts are needed and should be synergistically devoted to different sectors and measures. Considering the expected increase of the energy demand and the impossibility for a further exploitation of fossil resources, substantial changes in the energy production mix, largely integrating the renewable energy source (RES), are foreseen. Beside this, integrating RES allows to drastically abate the environmental impact of the energy sector, reduce existing energy imports, promote energy flexibility and increase the energy system capability, not least create job opportunities. In this framework, the European Union (EU) has put a lot of effort in acquiring relevant results in energy sector transition, doubling the share of energy from renewable sources in gross final consumption (Figure 1) but further pledges are recommended in order to dramatically increase the RES share in the future (in the Roadmap 2050 a set of scenarios, mainly based on solar and wind energy, for integrating RES into the energy supply mix from 40 up to 100% have been assessed [4]).

Among EU28, Italy is nowadays one of the lowest energy intensity Countries; in fact, it has overdone the fixed targets on RES share in advanced, achieving in 2014 a share of 17.1% on final gross consumptions. Thanks to efforts in promoting the energy efficiency (EE) and RES integration through mandatory requirements and considerable tax subsidies, the Italian renewable energy sector has witnessed a great expansion, mainly attributed to photovoltaic (PV) panels and wind turbines installation. This has clearly carried out positive effects, and impressively the grid parity has been reached in southern regions, as well as serious drawbacks, related to the grid reliability and to energy price increase [5]. In spite of such encouraging results, nowadays Italy is not one of the most RES-based EU Countries (Figure 1) and this aspect is quite challenging, considering the large potential due to diffuse availability of renewable resources on the territory (i.e. solar and wind ones mainly in the southern regions, biomass and hydro ones mainly in the northern ones) and the increasing role of the distributed generation (DG) [6]. Therefore, mid-term challenges to be pursued within 2030 have been recently defined within the National Energy Strategy

(SEN) [7], as required by the European Union. In the SEN it is also foreseen to: raise the share of energy from RES up to 28%, mainly in the electric sector, reduce the final energy consumption of 10 Mtoe per year, mainly thanks to measures in the building sector, whose responsibility in terms of energy consumptions and related greenhouse gas (GHG) emissions is relevant (40% and 36% on the total, respectively) [8]-[9], accomplish a whole electric sector decarbonisation by gradually expiring thermoelectrical plants. Notably, it is expected that a large part of the RES integration will be attributed to the enlargement of solar and wind energy plants capacity, whose installation will have to be governed consistently with urban planning concepts based on not increasing the land consumption and protecting the landscapes. For doing this, it will not be possible rely only on wide off-site fields, but other untapped sites in urban contexts will have to be identified for a large diffusion of RES (e.g. buildings roofs and vertical properly oriented surfaces are considered as optimal sites for implementation of building integrated PV panels). On the other side, for driving the decarbonization of the thermal energy in the civil sector (80% of heating and cooling energy is due to buildings [9]), a switch from conventional systems to heat pumps and biomass systems, which are already widespread among on the territory but must be converted into more performing ones for reducing the related emissions impact, is foreseen. It has been also investigated the possibility of developing in densely populated areas district heating/cooling (DH/C) networks, which are still a largely untapped technology in Italy (only the 7.7% of residing population is supplied by DH [10]). Additionally, it should not be neglected that in Italy, as a Mediterranean Country, it is expected a relevant role of space cooling demand, and consistently it has been recently consolidated the summer peak overtaking compared to the winter peak [5]. Furthermore, the SEN foresees: an increase in building or district level storages among the territory, along by the traditional hydro pumps, progresses in the transition to distributed energy generation, which additionally requires the overall refurbishment of the distribution system (both regarding the hardware part for dealing with bi-directional fluxes and the software one, mainly for exchanging energy data), not least, the promotion of demand response (DR) programmes, allowing active consumers (i.e. prosumers) to auto-produce the demanded energy, to possibly sell surplus energy to the grid, to shape the demand profile based on energy prices and availability changes.

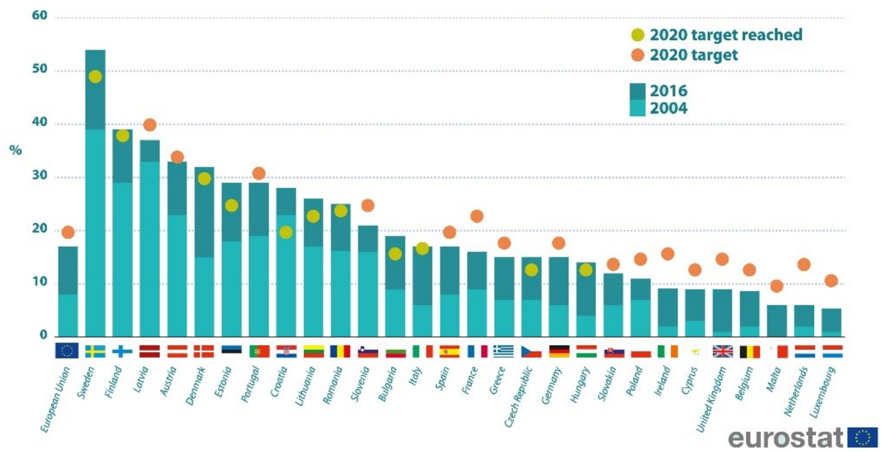

Figure 1. Comparison of the percentage of energy from RES on the gross final consumptions in 2004, 2016 and 2020 by each EU Member State [11].

1.1 Regulatory framework in the European Union and in Italy

1.1.1. The EU regulatory framework

The European Union is one of the leading areas through an energy transition, where most elements of a strong policy framework to support sustainable energy (i.e. solid legal and regulatory support, incentives and tax mechanism for renewables development, energy planning procedures, network connections, carbon pricing and monitoring) have been already implemented [12]. Moreover, in last decades, more and more ambitious targets for the reduction of the greenhouse gas emissions and the increment of both energy efficiency and penetration of renewables have been defined for the EU Member States (MSs); worthy of note in this regard are the 20-20-20 package [13], the 2030 horizon mid-term plan [14] and the long-term 2050 Roadmap [4].

One of the milestones of the EU regulatory framework has been the 2002/91/EC Directive (EPBD) [15], aimed at promoting the improvement of the energy performance of buildings within the Community MSs, taking into account different climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. It asked for establishing a general framework for a methodology of calculation of the integrated energy performance of buildings, minimum energy requirements of the newly built buildings as well as large existing buildings under major renovation, an energy certification of buildings and regular inspection of boilers and of air-conditioning systems as well as assessment of the old heating boilers installation. In the directive, some new concepts surged: the “energy performance of buildings”, i.e. the amount of energy actually consumed or estimated to meet the different needs associated with a standardised use of the building; the “energy performance certificate” (EPC) of a building, the “major renovation” of existing buildings.

Later, the purpose of the 2006/32/CE Directive [16] was to foster the cost-effective improvement of energy end-use efficiency and remove existing market barriers and imperfections in the MSs by providing indicative targets, financial mechanisms, legal support, as well as creating the conditions for the promotion of a market for energy services and delivery of other improvement measures to final consumers. A target of 9% energy savings to be reached within the nineth year of application of the directive with intermediate realistic targets had to be set by each MS and reported in the required Energy Efficiency Action Plans (EEAP).

The Directive 2009/28/EC on renewable energy [17] establishes a common framework for the promotion of energy from RES. Overall EU community targets of not less than 20% share from RES in gross energy final consumption and of 10% in the transport sector are set and then declined in mandatory national targets, which should be achieved by encouraging energy efficiency and energy saving measures. Assigned RES share in gross final energy consumption in 2005 and the target in 2020 is reported for each MS; in particular, a transition from 5.2% to 17% was set for Italy. Moreover, it is required to each MS to adopt a national action plan that establish pathways for the development of RES in transport, electricity and heating and cooling sectors and targets to be fulfilled within 2020 and defines the related structure and needed information.

The 2010/31/EU Directive (EPBD recast) represents the second directive on energy performance of buildings, updating the 2002/91/EC. It established a general framework for defining a methodology for calculating the integrated energy performance of buildings and building units; the application of minimum requirements to the energy performance of new buildings and building units as well as existing buildings, units and elements that are subject to major renovation. It also gave indication on building envelope elements under retrofit or replacement; newly installed, replaced or upgraded technical systems, energy certification, regular inspection of heating and air-conditioning systems, independent control for EPCs and inspection reports. Compared to the first EPBD, some definitions were updated, for instance "building energy performance" and "major renovation" while one of the novelties regarded the introduction of the "nearly zero-energy building" (nZEB) concept. Another novelty regards the definition of a general comparative methodology framework to determine the energy performance of buildings and elements and the economic aspects of measures relating to the energy performance, and to link them with a view to identify the cost-optimal level. According to the methodology, MSs were required to define "reference buildings", i.e. buildings characterised by/representative of their functionality and geographic location - including indoor and outdoor climate conditions - covering residential and non-residential, new and existing stocks, and a set of possible energy efficiency measures (EEMs) to be assessed with respect to the final and primary energy as well as the costs during the expected economic lifecycle.

The Energy Efficiency Directive (2012/27/EU) [18], which arose as a continuation of the EPBD, establishes a set of binding measures for the promotion of energy efficiency, in order to meet the 20% EE increase target in 2020 and to pave the way for further improvements. Main aspects regard recommendations and rules for: overcoming barriers and failures in the EE market, strengthening the exemplary role of public administration buildings by requiring a minimum annual rate of renovation equal to the 3% of floor area, increasing of 1.5% the energy savings in the energy distributors or retail energy sales companies, providing consumers with tools for improving their energy use, for instance free access to individually metered energy data, providing national incentives for energy audits in enterprises. High-efficiency cogeneration and DHC are remarked due to their significant untapped potential, therefore a comprehensive assessment on their potential is required to each MS. In the context of smart grids, mechanisms to promote the implementation of measures - e.g. for renovating the grid, allowing access and participation of DR or adopting high-efficiency cogeneration for balancing, reserve, etc. – are requested.

The Directive 2018/844/EU [9] has been recently enacted with the aim of amending the previous 2010/31/EU and 2012/27/EU ones. It asks each MS to establish a long-term renovation strategy, including definition of measures and proper indicators, for supporting the renovation of the national residential and non-residential public and private building stock, in order to reduce the Union GHG emissions by 80-95 % compared to 1990, and to facilitate the cost-effective transformation of existing buildings into NZEBs. Such strategy shall encompass an overview of the national building stock; the identification of cost-effective approaches relevant to the building type and climatic zone, an estimate of expected energy savings and wider benefits, etc. Among the discussed topics, the directive advocates the achievement of an average renovation rate of 3%, the improvement of the EPCs transparency by ensuring that all necessary parameters for calculations are applied consistently, the development of the infrastructure necessary for the electric mobility, the definition of a new indicator (i.e. the smart readiness indicator) in order to assess the capabilities of a building/unit to use information and communication technologies (ICTs) and electronic systems to adapt its operation, the assessment of the energy efficiency policies application in districts / neighbourhoods, the definition of measures to establish regular inspections of the accessible parts of heating/cooling/ventilation systems. Within the annex, it is also stated that the calculation of buildings energy performance for space heating/cooling, domestic hot water (DHW), ventilation, lighting and other technical systems should follow the standards ISO 52000-1, 52003-1, 52010-1, 52016-1, and 52018-1, developed under mandate M/480 given to the European Committee for Standardisation (CEN).

1.1.2. The Italian regulatory framework

In the past, Italy has been responsible for some pioneer regulations even before the Europe unification. In Seventies, as an immediate effect of the energy crisis, the Italian Parliament enacted the Law n. 373 of 1976 (L. 373/76) [19], which regarded three topics: features of building elements, installation and operation of new fossil fuels-based thermal systems, energy performance of buildings undergone to envelope or system renovation. Also, the definition of the coefficient of heat loss through the wall was defined in order to assess the energy use in buildings and to set related limited values, based on climate location. The Law n. 10 of 1991 (L. 10/91) [20] promoted the development of energy saving in buildings and set an assessing procedure of the energy balance, with details in the implementing acts, the use of energy certification, the regular maintenance of systems. The L.10/91 has been implemented with the Decree of President of the Republic n. 412 of 1993 (DPR 412/93) [21], which is still in force and gives rules for installing and operating thermal systems – for instance, calculation procedure for sizing and systems limited efficiencies - as well for energy saving in buildings. Among the treated aspects in the implementing decree, the most relevant ones are: the division of national territory in six climatic zones, based on heating degree days (HDDs) ranges, with related limit length of both heating season and heating hours per day, the provision of the number of heating degree days for Italian municipalities, classification of buildings based on use category with related limit indoor temperatures.

The Legislative Decree n.192 of 2005 (D.L.G. 192/05) [22], implementing the EU Directive 2010/91/CE (EPBD), established criteria, conditions and modalities to improve the energy performance in buildings, to foster RES and diverse energy mix, to contribute in achieving GHG emissions reduction targets and promoting technological progress. The decree established the calculation method of energy performance in buildings, by recommending considering: outside and inside conditions, building orientation, thermal properties of building, heating, ventilation and air conditioning (HVAC) systems, artificial lighting, natural ventilation, passive strategies, use of RES or other efficient technologies (e.g. cogeneration, DH). It defined the minimum requirements of buildings energy performance and three different levels of building energy renovation: entire refurbishment in large buildings, demolishing and rebuilding of large buildings and partial envelope renovation / new thermal system installation / supply unit replacement. It also implemented the EPBD for what concerned the energy performance certificate (in Italy named "Attestato di Certificazione Energetica (ACE)"), in terms of cases of application, criteria for drawing it up, criteria for certifiers qualification, validity length. Finally, other treated aspects regarded: thermal systems inspections, recommendations for integrating solar energy panels in buildings or connecting to a DH network, needed information for drawing up the report required in L.10/91 to verify energy standards accomplishment. The D.L.G. 192/05 has been soon updated with the D.L.G. 311/2006 [23], which fixed stricter building / building elements energy performance requirements and the compulsory installation of solar collector and PV panels on new buildings. Additionally, the D.L.G. 192/05 was also implemented with the D.P.R. 59/2009 [24], which made some changes in the field of energy performance in summer, for instance by introducing the periodic thermal transmittance. It also adopted the technical specifications UNI TS/11300 for the energy performance calculation.

At the national level, the EU Directive 2006/32/CE has been implemented by means of the decree D.L.G. 115/2008 [25], contributing to improve the safety in the energy supply, protection of environment with GHG emission reductions, defining a frame of measures for enhancing EEMs under cost-benefit perspective. The Energy Efficiency Action Plan (PAEE), indicating the national energy saving goals, and the Agency for New Technologies, Energy and Environment (ENEA), in charge to give technical support and carrying out actions related to energy monitoring and reporting, training and dissemination functions, were introduced. The standard promotes sustainable mobility, gives rules for fiscal incentives to energy efficiency, calculation procedure in case of energy audit. It also defined exceptions in the limited building volume and distances among buildings in case of new buildings and renovations with the goal of complying with energy saving requirements.

The Directive 2009/28/EC has been implemented in Italy through the so-called “decree on renewables” (D.L.G. 28/2011 [26]) that defined tools, mechanisms, incentives and regulatory framework for reaching RES targets on final gross energy consumptions and in transports in 2020. Some faster and simplified procedures for installing RES-based technologies as well as modalities and minimum requirements for accessing to incentives were set (such as in the case of solar panels mounted in adherence and within the roof surface according to Cultural Heritage requirements, transports using biomethane, heat pumps having a certain coefficient of performance, etc.). Additionally, the obligation of integrating RES is placed for meeting the space heating, DHW, space cooling and electric energy demand - with share ranging from 20% to 50% depending on the building construction/renovation date - of newly built and under renovation buildings. Also, for the buildings, where such needs are covered by RES of more than the 30% respect to the minimum requirements, an exception in terms of maximum allowed built volume is given. The standard also dedicates a part to smart grid and district heating/cooling networks by providing regulations, fiscal mechanisms and promoting measures, such as renovation measures on the transmission and distribution system; interestingly the DHC networks are referred as primary service infrastructures and related funds for their development was also set.

The European Directive EPBD recast has been implemented within the decree D.L. 63/2013 [27], promoting the improvement of energy performance in buildings by taking into account external and indoor conditions as well as costs impact. Energy performance improvement and integration of RES in buildings, energy mix diversity, national competitiveness, technological progress and construction industry promotion, respect of national targets and homogeneous application of the standards among the territory are claimed as main ambitions of this regulation. As key points: the energy performance certificate is renamed "Attestato di Prestazione Energetica (APE)", in contrast with the "Attestato di Qualificazione Energetica (AQE)", the concepts of "nearly-energy zero building", of "cost-optimal levels of energy performance in buildings" and of "reference building" are implemented from the EPBD recast, an extension of incentives to EEMs is also placed. The D.P.R. 74/2013 [28] is in the territory of implementing standards of the EPBD, too. As remarks, it recommends Regions to identify the proper modalities for operating thermal systems and related control procedures, by incrementing the number and type of systems to be compulsorily checked and fixing stricter efficiency requirements, making stringent criteria for the qualification and training of the technicians in charge of the systems inspection and the energy building performance certification. Notably, the Regions are also asked to create a Thermal Energy System Cadastre with accessible and exchangeable data among costumers and institutions.

More recently, the so called "Decreto Rinovabili" (D.M. 26/6/2015 [29]) intends boosting for a homogeneous and coordinate application of the EPC, by providing national guidelines and layouts, calculation procedure, new minimum requirements, including nZEBs, and regulative framework. It also announces the realization by ENEA of a national cadastre of energy performance certificate and thermal systems [30]. The calculation procedure is aimed at estimating the energy performance (i.e. the annual primary energy needed to meet space heating and cooling, ventilation, DHW and, in not residential sector, lighting and elevators demand of a building with a standard use) of a building, compared with a reference one in comply with the updated energy requirements. Four levels of renovation are foreseen: building new construction, demolishing and rebuilding, at least 15% extension, 1st level major renovation, 2nd level major renovation and energy retrofit.

1.2 EXPERIENCES OF SMART ENERGY URBAN SYSTEMS

Expertise from academic research, industrial and public ambits have been involved in last decades in order to realize the aforementioned vision and many heterogeneous experiences have been put in place. Hereinafter, some collected experiences of smart energy urban contexts, which mainly refer to the EU funded Horizon 2020 Programmes, are briefly described.

Some of them show a holistic perspective. The TRANSFORM programme [31], ended in 2015, dealt with the energy transition of cities under the umbrella of Smart Cities and Communities programme. It involved six European cities (i.e. Amsterdam, Copenhagen, Genoa, Hamburg, Vienna and Lyon) for which a plenty of measures (e.g. increase of energy supply capacity from solar and wind sources, increase of buildings connected to DH, promotion of buildings energy retrofit, smart waste management and mobility, transition to smart grid) was addressed. The READY (Resource Efficient cities implementing ADvanced smart city solutions) programme [32] will end in 2019 and aims to demonstrate the need for a holistic approach in smart city planning, promoting the retrofit of buildings at affordable prices, the district heating at low temperature, ICT systems, solutions to increase energy flexibility, recharging electric vehicles and so on. As demonstration case studies, the cities of Aarhus (Denmark), Växjö (Sweden) and Kaunas (Lithuania) have been selected for the application of solutions with different levels of impact. In particular, the following measures are planned in Aarhus: energy retrofitting of public/private residential and office buildings connected to a low-temperature district heating, reuse of the wasted heat from the hospital cooling system to feed the DH network, reuse of the wasted heat from buildings for DHW, the installation of PVs on buildings' roofs, smart metering and storages. In Växjö, besides residential and office buildings retrofit, the integration of information and communication technologies (ICTs) in the grid in order to smartly manage the fluxes is foreseen, integration of the DH network and the DC network with absorption cooling machines, reuse of industrial wasted heat into the DHC, existing DHC temperatures lowering, PVs installation. The Triangulum (The Three Point Project / Demonstrate Disseminate Replicate) programme [33], coordinated by the Fraunhofer Institute and planned to end in 2010, aims at deploying smart city solutions which integrate energy, mobility and ICTs in urban districts. The programme applies its principles on a set of cities in Europe but most of the pledges regard the implementation or strengthening of solutions in three cities: Eindhoven (Nederland), Manchester (UK) and Stavanger (Norway). With regard to the energy measures in buildings, it is foreseen to renovate the social housing stock in Eindhoven, to renovate the University district buildings and achieve the heat/electricity energy independence, thanks to integration of geothermal energy, district heating and a fuel cell, in Manchester, to design a sewer heat pump system for three public office buildings in Stavanger. Besides, ICTs for monitoring and/or managing the use of energy in buildings and public spaces as well for accessing the smart mobility is foreseen in all mentioned cities. The REPLICATE (REnaissance of Places with Innovative Citizenship and TEchnolgy) programme [34] (2016-21) aims to enhance the transition process to smart cities through integration of energy, mobility and ICT solutions in city districts. As case studies, the cities of San Sebastian (Spain), Bristol (UK) and Florence (Italy) have been chosen for carrying out campaigns of buildings envelope energy retrofit and their connection to DH networks (in particular biomass-based DH, in San Sebastian, integrated with solar thermal storage Florence and connected to a bio-gas cogenerator in Bristol).

The SCUOLA (Smart Campus as Urban Open LAbs) programme [35], concluded in 2014 and funded by Lombardy Region (Italy), had the aim to investigate the possibility of smartly managing the energy fluxes into a smart grid, integrating energy from renewables, ICTs and electric vehicles, and optimising them based on the economic saving issue. Finally, new systems for coordinating the energy generation from PVs with the electricity from grid and the demand profiles, as well as charge stations for electric vehicles, electricity storages and cooling systems have been implemented. Defined concepts have been applied in two University campuses in Milan and Brescia and a residential house in Brescia, too.

Many programmes mainly refer to the improvement of district heating/cooling networks in urban neighbourhoods. The PITAGORAS (Sustainable urban planning with innovative and low energy thermal and power generation from residual and renewable sources) programme [36], which was completed in 2017, focused on efficient integration of city districts with industrial parks through smart thermal grids. In particular, two energy concepts were investigated: waste heat recovery and solar heat. A demonstrative case study for the former has been developed in Brescia and is now under monitoring. It includes the installation of a waste heat recovery unit to reuse the heat from a local steel mill, a steam accumulator, an Organic Rankine Cycle unit and a DH substation connected to the existing network. The system allows providing district heat in winter and power in summer to the city. The SmartReFlex programme [37], supported within the Intelligent Energy Europe programme and ended in 2017, aimed at facilitating the planning of smart, flexible and RES-integrated district heating and cooling networks. For this purpose, tools and assessments were developed to be shared with involved stakeholders. In particular, twenty case studies were selected among European Countries (i.e. Germany, Spain, Italy, Ireland) and the possibility of exploiting the integration in DHC of energy from renewables (e.g. biomass, geothermal source, waste heat recovery, solar thermal) based on the local conditions was investigated. The European Concerto programme GEOCOM (Geothermal Communities) [38] coordinated by a Hungarian company, was launched in 2010 for investigating heat applications of geothermal energy. Following three demonstration sites, respectively located in Italy, Hungary and Slovakia, were chosen as an application of the research purposes. The village of Montieri was regarded by a new geothermal DH, fully automated and remote controlled, complementary energy retrofit of selected public buildings and integration of new PVs, the town of Morahalom by the improvement of local geothermal DH cascade system, while the city of Galanta from an extension of the existing geothermal DH and a large buildings energy retrofit campaign. The FLEXINETS (Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS) programme [39], planned for the period 2015-18, is coordinated by the Italian research institute EURAC while involves partners from Germany, Denmark and Spain. It aims at the deployment of intelligent low-exergy district heating and cooling networks for reducing energy distribution losses. More in detail, main topics regard the analysis and simulation of possible substations, the analysis of possible network configurations, the development of proper control strategies and smart metering solutions and testing in two laboratories, in Spain and Italy. At the EURAC research centre, in Bolzano, a low-temperature network, with reversible heat pumps in buildings and a solar field as well as individual technologies such as boilers, absorption and compression refrigerators, cogenerating units, is under development. District heating and cooling is also the focus of the InDeal (Energy Efficient Optimised District Heating and Cooling) programme [40], planned for the period 2016-19, coordinated by the City University London and involving the participation of stakeholders from Spain, Greece, Finland, France, Poland and Slovene. It aims at improving the efficiency and cost-effectiveness in DHC networks through related automation. Main tasks regard the improvement of the heating/cooling demand analysis, of the weather prediction, as well as the development of pipes insulation material and of a tool for system monitoring. Within the project, an extension of the existing biomass-based DH system in Vransko (Slovenia), in order to meet the whole municipality demand, including mainly old residential multi/single family buildings as well as industrial, commercial and tertiary buildings, has been done. The entire centralized system consists of a DH network, which has been designed with adapted high supply-return temperatures for meeting also the DHW demand. The DH is fuelled by two biomass boilers, an oil fuel boiler as back-up, a small combined heat and power (CHP) plant based on wood gasification, a seasonal warehouse and a daily one for biomass storage, a control room, offices and external manipulation space, and flat solar collectors combined with storage tank. Another case study regards the extension of the DHC network in Montpellier (France) in order to cover the demand of a new mixed-use settlement area, including energivorous special buildings (e.g. an hospital, an aquarium, etc.). The system is made of CHP plants, power plants, cooling towers, gas boilers and a heat exchanger from biomass plant. The DHC network is designed with low supply-return temperatures and is controlled in real time.

Other programmes are targeted on the development of forecasting or controlling models. The INDIGO (New generation of Intelligent Efficient District Cooling systems) programme [41] (2016-19) aims at developing an efficient, intelligent and cheaper generation of district cooling systems. The defined controllers, including embedded self-learning algorithms, are to be developed at all DC system levels (building, generation and distribution level). A real application of the developed control system has been carried out for a sanitary district in Barcelona (Spain). The district is fed by a DHC network and, only regarding cooling supply, two absorption chillers and four conventional ones as well as cooling storages are installed. The goal of the control system was prioritizing the use of absorption chillers and storages in order to maximize the energy efficiency while minimizing the costs, by means of predictive algorithm, considering weather data, demand profiles and energy prices. Additionally, a virtual test for the control of integrated solar thermal systems coupled with storages has been done. STORM (Self-organising Thermal Operational Resource Management,) programme [42], planned for the period 2015-18 and involving partners from Sweden, Netherland and Belgium, aims at boosting energy efficiency at district level through the development of a DHC network controller based on self-learning algorithms. The developed controller will enable to maximize the use of waste heat and renewable energy sources and is based on three control strategies (peak shaving, market interaction and cell balancing). The controller is under testing in two locations, i.e. Rottne (Sweden), for reducing the oil usage and optimising the bio-fuel boilers in a high-temperature DH network, and Heerlen (Netherlands), for managing and balancing the different buildings clusters connected to a low-temperature DHC network. OPTi (Optimisation of DHC systems) programme [43], completed in 2017 and coordinated by Luleå University of Technology, aimed at the development of a methodology to control and optimise DHC systems through the use of predictive control, automated heat demand response strategies, passive heat storage. Two case studies were included, one urban mainly residential district in Sweden and a sanitary district in Spain. The recent expansion of the existing DHC network in Luleå (Sweden), which is fed by CHP plant and in peak periods by back-up units using wood pellets, electricity and oil, has offered the opportunity to be involved in the OPTi project with the aim of testing some optimising strategies (for instance, reduction of peak loads by moving the heat supply when tap water demand was lower, decrease of the DH supply temperature, valves optimisation etc.). The Energy Hub programme [44] aimed at deploying the possibility of providing on-site renewable energy within a district and developing a smart controller to allocate the energy efficiently and dynamically to the users. The control algorithm has first been demonstrated at the University of Genoa, where a sample of a small district heating system, including CHP plants, a microturbine and an absorption cooler, has been implemented. A real case study has been also implemented in a district in Leuven (Belgium) supplied by a biomass fired CHP.

1.3 Discussions

The EU is committed to develop a sustainable, competitive, secure and decarbonised energy system by including measures on the civil sector, considering its high responsibility. Indeed, significant efforts from academic research, industrial ambit and policies are devoted to the integration of buildings in smart energy systems, including the connection to (low-exergy) district heating and cooling networks and the integration of RES-based distributed energy generation sources and of flexibility solutions. Clearly, managing these energy systems is increasingly complex and an accurate knowledge of the related features and dynamic behaviour is essential for ensuring the optimal operation. In fact, the large integration of energy from RES implies a need of coordinating the related fluxes, considering their unpredictable and variable availability, with the demand side ones in order to reduce the energy wastes and costs. It also implies a need of governing the installation of such technologies on large scale avoiding irrational or unsuitable plants. The necessary integration of storages, to accumulate surplus produced energy and/or deferring the consumption, as well as of DR measures increases the level of complexity. European Countries generally boast a robust regulatory framework, but efforts should be made to obtain reliable detailed data on the energy sector.

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2. STATE OF THE ART

2.1. FRAMEWORK ON TOOLS FOR PLANNING DISTRIBUTED ENERGY SUPPLY

Distributed energy supply, involving energy integration from renewable sources, is acknowledged as one of the main opportunities for effectively reducing the energy sector impact. However, for dealing with RES intermittent and unpredictable behaviour and matching them with consumers demand (which in turn changes based on outdoor conditions, users' number and habits, energy costs, etc.), it is necessary accurately assessing the energy system operation. For supporting urban energy planners in this task, several computational tools and models have been developed. Previous studies in literature [1]-[5] have highlighted the abundantly heterogeneous characteristics of existing tools, tracing plenty of different goals and final users, calculation methods and typical applications, access modalities. Conversely, during this Ph.D. research, a study guided by a different purpose, compared to previous ones, was carried out on existing tools on urban/district energy planning. In particular, we searched a sufficiently detailed tool, i.e. able to assess the energy balance on hourly base, which was suitable for comprehensive energy planning on urban/districts scale. Additionally, our interest was oriented to easily accessible tools, both in terms of free download and graphical user interface (GUI), so liable to be used not only in academic research, e.g. in the context of public administrations which are one of the main actors in urban energy planning. The results of this research are also discussed in an article which has been presented at the Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES) held in Palermo in 2018 [6] (see also Appendix D).

From a methodological point of view, after collecting a large number of tools based on some related previous review studies [1]-[5] and online databases [7]-[11], the field of interest was first narrowed to seventeen tools that allow assessing energy projects also at the urban and/or district scale, include multiple diverse energy resources and supply technologies and for which both installation and/or detailed documentation are currently available. These selected tools have been classified according to three criteria: the time resolution of outputs (i.e. over-hourly based or sub/hourly based outputs), the type of download (i.e. subject to payment or not) and the easiness of use (i.e. advanced models or models with user-friendly GUI). Based on this classification, we saw that six tools of the seventeen ones both enable the visualization on a sub/hourly base of the energy outputs and are featured by a GUI, which makes them easy to use. The tools' collection, selection and classification are represented in Figure 2.

Following, we provided a brief description of the main features for 3 tools providing over-hourly based outputs (section 2.1.1.1) and for 11 advanced models providing sub/hourly based outputs (section 2.1.1.2). Then, a thorough description of the structure, the GUI, the required input data and level of detail, the constraints to implement an energy system analysis is provided for 3 commercial (section 2.1.1.3) and 3 freeware (section 2.1.1.4) user-friendly tools with sub/hourly-based outputs.

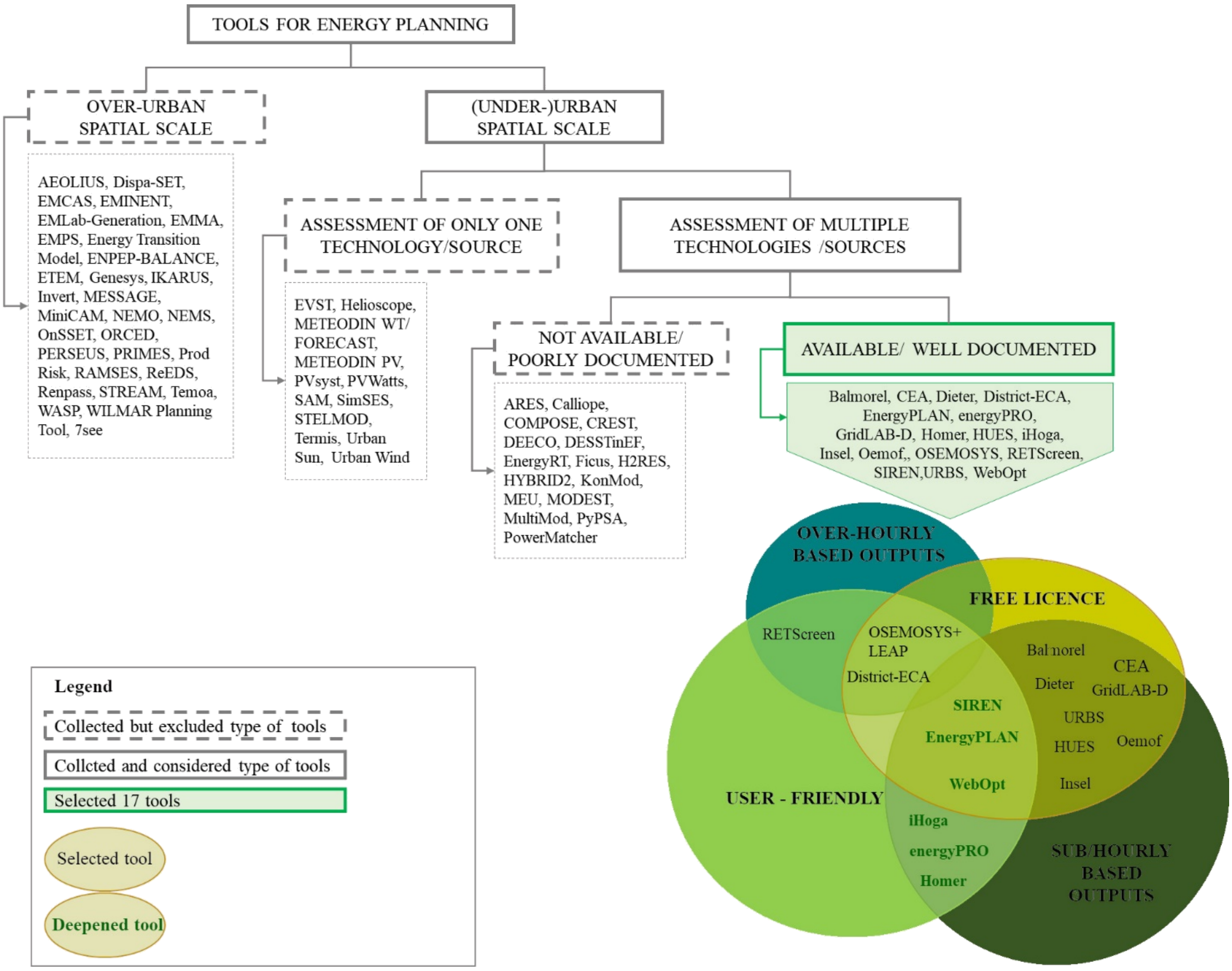

Figure 2. Diagram of the accomplished collection, selection and classification of tools.

2.1.1. Assessed tools

2.1.1.1. Tools with over-hourly based outputs

The District Energy Concept Advisor (District-ECA) was developed by the Fraunhofer Institute for Building Physics (IBP) with the partners from IEA-ECBCS Annex 51 "Guidelines and Case Studies for Energy Efficient Communities", for supporting actors in the first-stage of planning energy-efficient districts, for quickly evaluating the effects of both on supply and demand sides strategies. The software is freely downloadable through preliminary registration [12] and comprises a set of tools with miscellaneous scopes (e.g. benchmarks of national average districts energy consumptions, set of best practices of energy efficient districts; overview on common energy efficient solutions and so on). The actual main core is an easy-to-use tool, named Energy Assessment of Districts, for accomplishing a monthly based assessment of energy fluxes balance and related emissions of a district by modelling for each building the envelope and system. Provided technologies mainly refer to space heating while data-bases of weather data and typical solutions are constrained to IEA-ECBCS Annex 51 participating Countries [13],[14].

The Open Source Energy MOdeling SYStem (OSeMOSYS) is an open source modelling tool for long-term energy assessment and planning [15],[16]. It has been adopted for assessing diverse spatial scale, from the continent to the village ones, and ranges from many years to several decades' scenarios with a daily maximum resolution [17]-[19]. At least two graphical user interfaces exist, the open source browser-based Model Management Infrastructure (MoManI) and the most common, commercial software, LEAP. The latter, which is maintained by the Stockholm Environment Institute [20], is referred as a decision support software, not target for a particular energy system, but enabling users in extensive data management and reporting, assessing medium/long-term scenarios including changes in energy use, related emissions, resources deployment, for any economic sector. Most of its calculations occur on an annual time-step, while the time horizon is unlimited. Considering that it is a very general-purpose tool, required input data widely depend on the case study under assessment. For instance, it is possible either using top-down or bottom-up data-bases, accomplishing assessments from an economic, social, energy point of view. Concerning energy related data, following are usually required: energy balances, i.e. demand and production annual values, eventually broken down by sector and fuel, systems and energy costs, systems efficiencies and capacities, energy profiles, emission factors, interest and inflation rates. Also, OSeMOSYS and LEAP, even if can be used for district scale assessments, are more proper for macroeconomic ones due to their general-purpose structure.

RETScreen was developed at the Natural Resources Canada department of the Government of Canada as a clean energy management software system for energy efficiency, renewable energy and cogeneration project feasibility analysis as well as ongoing energy performance analysis [21]-[23]. It was defined as an accounting tool in previous review studies and accordingly, it is a decision-support tool useful to evaluate the energy production, life-cycle costs and GHG emission changes of several energy related projects types, including energy efficient measures and different energy supply technologies, by possibly comparing base and target scenarios. Currently, it consists of both the well-known Excel-based software package and a new Windows-based one. It is possible modelling systems at any scale, from a Nation to a building, by developing different scenarios (for assessing the effect of envelope and systems EEMs, the different impact of various electricity and thermal energy supply plants, including the integration of RES, etc.). Required set of information includes: general data and settings on calculation, climatic location, type of project, sector, systems' features such as capacity, delivered energy, efficiency; additionally, CO_2 emissions per each fuel and financial data (e.g. infiltration rate, lifetime, debt ratio range, initial costs, incentive and grants, annual O&M and fuel costs) can be added.

2.1.1.2. Advanced models with sub/hourly-based outputs

Balmorel [24],[25] supports users in modelling and analysing the energy systems with emphasis on the electricity and the CHP sectors. It allows to accomplish a linear optimisation of a defined energy system costs. It is a versatile tool, which allows assessing from under-regional up to national scale systems, developing both long-term scenarios and short-term ones and taking into account the hourly variations of energy fluxes. As an open-source model, the code can be modified according to specific purposes. It is formulated in the GAMS modelling language hence, although it is freely downloadable, it requires the GAMS license; additionally, it has a graphical user interface facilitating input data handling, output reporting etc.

The City Energy Analyst (CEA) is developed at the ETH Zurich and freely provided at website [26] as an open-source software, written in Python language and GIS-integrated for visualization purpose. It is conceived as an urban building simulation platform, made of a set of tools, for the design of low-carbon and highly efficient cities. Until now, the software has been used both for academic and real case studies [27],[28]. A library of prototyped buildings, described by envelope and installed systems characteristics, based on which hourly profiles are calculated, is included. However, since building prototypes data mainly refer to Swiss context, own building data should be imported. Some under development modules will include: multi-objective (economic/emissions) optimisation of one scenario at a time, library of energy supply technologies, described by systems' efficiency, capacity and possibly investment costs, input/output temperatures, heat losses in storage/network, performing a sensitivity analysis and a renewable energy assessment.

The Dispatch and Investment Evaluation Tool with Endogenous Renewables (Dieter) [29] has been developed to study the role of power storage and other flexibility options related to high RES penetration. The model determines cost-minimizing combinations of power generation, demand-side management and storage capacities and their respective dispatch. As an open source model, it can be freely used and modified by users, although paid license for GAMS is required to run it.

GridLAB-D [30] was developed by the Pacific Northwest National Laboratory as an open-source and free agent-based tool, which can be also integrated with other modules for enlarging its capabilities. It is conceived to model the power system and the overlying systems affecting electricity. In particular, it helps in assessing the distribution automation technologies, various peak-shaving strategies through consumer behaviour modelling, effects on consumers of new rate structures offer and cost effects of implementing distributed energy technologies, such as on-site generation, building CHP, storages.

The Holistic Urban Energy Simulation (HUES) Platform [31] is an open source platform (although it must be run on Matlab and Aimms which are not free) to support distributed energy system design and control. It includes databases of aggregated yearly heat demand and PV potential in Switzerland, technical and economic properties of distributed systems. The tool is quite versatile since it allows defining a plenty of carriers, demand and supply technologies, selecting the optimisation criteria accordingly to each studio purpose, assessing energy, environmental and economic effects of energy strategies.

The INtegrated Simulation Environment Language (INSEL) [32] has been developed at Faculty of Physics of Oldenburg University as a block-diagram simulation system for programming applications from the entire renewable energy sector. INSEL is not a simulation program but provides an integrated environment for the creation of simulation applications of energy projects involving RES.

Oemof [33] is a modular tool for energy system modelling and optimisation. It is based on the open-source Python programming language and additionally uses PostgreSQL and PostGIS for data processing. It is featured by a versatile structure since assessed energy sector, spatial scale and time-step can be user-defined based on specific purposes.

Urbs [34] is an open-source free model for cost optimisation of multi-commodity energy systems with a focus on storages. The energy demand and supply are modelled through time series datasets, as average power and normalized one respectively, related amount of GHG emissions, systems efficiency and costs as well as, for storages, the charging / discharging efficiency, capacity, investment, fixed and variable costs are required.

2.1.1.3. User-friendly commercial tools with sub/hourly-based outputs

2.1.1.3.1 energyPRO

energyPRO has been developed by the company EMD International A/S [35],[36], as a software for techno-economic analysis/optimisation of energy projects combining electricity and thermal energy supply and integrating multiple technologies. It is typically used for analysing DH, CHP and trigeneration but has been used for geothermal energy, solar collectors, PV, wind farms, hydro pumping stations, storage, too [37],[38].

In the input data structure, it is possible to navigate among six sections (Figure 3).

In the *Project identification* section, the user should choose the type of assessment: *Design*, with emphasis on energy conversion and operation payments and for one-year calculations, *Finance* for multi-years investment analysis, *Account*, which adds the calculation of income statements and balance, *Operation*, useful for optimising the operation in a daily period. Through the *Region* module it is possible defining more interconnected distributed production sites, as in a regional energy planning model, through the *Market* module, more than one market, through the *Interface* one, long-term calculations.

In *External conditions*, the user can provide information on the planning period by adding data, usually loads or energy prices, as time series (through online download, existing file upload, specific functions, etc.). In *Sites*, the project site/s (i.e. a location with demands, energy units and storages) is/are set. In *Transmission*, required data to describe the energy exchange among the sites are: start and end site, transmission direction, energy type, transmission capacity and loss. In *Fuel*, the used fuels calorific value is indicated.

In *Demands*, an unlimited number of demands per each type (heat, process heat, electricity and cooling) can be defined. If own data are chosen in place of arbitrary included energy demand profiles, it is possible specifying them both as annual or time-series (i.e. hourly or sub-hourly based) amounts, both as fixed or depending on weather data (i.e. average ambient temperatures) values and changed among the years.

In *Energy conversion units*, heat rejection and production units (i.e. CHP, electric boiler, absorption/electric chiller, heat pump, flat plate/evacuated tubs solar collector, PV, wind farms and storages) are foreseen. Required data, depending on the single technology, are: capacity, production, fuel, power curve, inlet and outlet temperatures, if the operation is dependent on another unit, charging/discharging power; hydro pumping storage reservoirs height difference, dimensions and technical features, etc.

The operation strategy is driven by net present cost (NPC) minimization through assigned priority level to production units or can be user-defined. Emissions of CO_2, NOx and SO_2 can be defined.

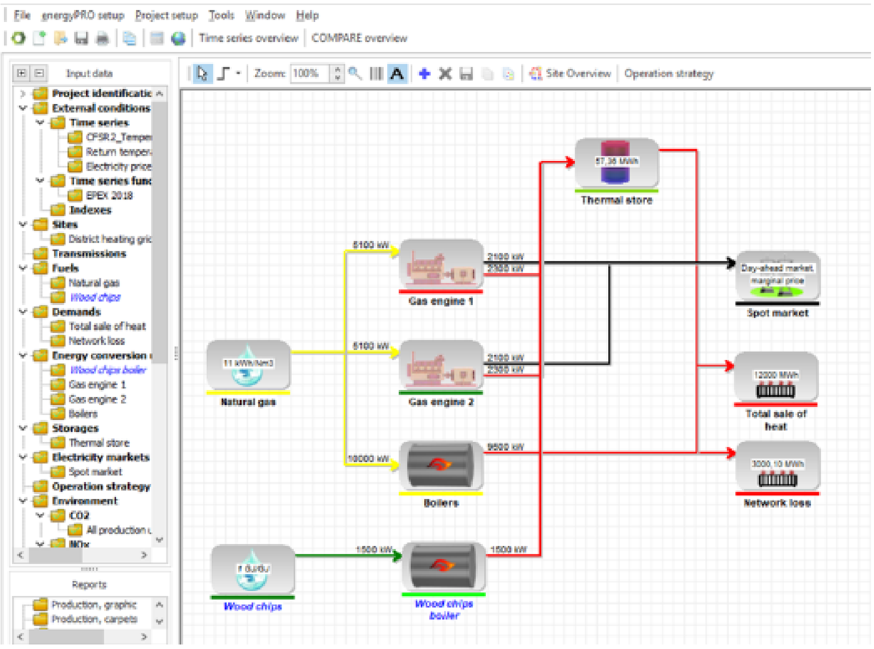

Figure 3. GUI of energyPRO (trial version).

2.1.1.3.2 HOMER

HOMER is a widely adopted optimisation software, developed at the U.S. National Renewable Energy Laboratory to assist in the design of micropower systems and facilitate in comparing many technologies [39]-[44]. Three subsequent analysis are performed: *simulation process*, to model the micropower system, *optimisation process*, to simulate different system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost, *sensitivity analysis process*, to evaluate the impact on the results from changes of input parameters.

Within the *Home* section, the climatic zone of the context under study must be specified to determine the RES availability.

The *Design* section is made of these subsections: *Load, Components, Resources, Project, System, Help* subsections (Figure 4).

In *Load*, four types of energy load are considered: *primary*, i.e. an electric demand, *deferrable*, i.e. electric demand that can be met at any time within a time interval (e.g. water pumps, ice makers, battery-charging stations), *thermal* and *hydrogen* ones. *Primary, thermal and hydrogen loads* must be featured by an average daily value of energy and power, a peak power and a daily hourly schedule in kW. The hourly profiles, which can alternatively be user-defined or predefined, can be also modified either introducing some weekly/monthly variations or adding a percentage of random disturbance. Predefined ones, namely *synthetic*, are arbitrary profiles and are different for energy sector (i.e. residential, commercial, community and industrial) but not for energy service (i.e. electricity or thermal), thus their use can be critical.

Components are the technologies to produce/convert/store energy and can be taken pre- or user-defined. Needed information includes: system capacity, plant lifetime, unit of investment, replacement and operation and management (O&M) costs. *Fuels* can be defined based on the library or defining the type, unit prices, calorific value, GHG emissions by each substance. In case of RES, required information includes: PVs derating factor, features of the tracking system, reflectance and effect of temperatures, wind turbines hub height, batteries percentages of state of charge, boilers efficiency, hydrothermal energy flow rate and pipe heat losses. In *Resources,* solar global horizontal and direct normal irradiance, wind speed, external average temperatures, water speed, stream flow, available biomass.

Once modelled the energy system, other data should be defined. In *Economics*, nominal discount rate, expected inflation rate, project lifetime, system fixed capital and O&M costs, capacity shortage penalty, currency. In *Constraints*, maximum annual capacity shortage, minimum RES fraction and operative reserve. In *Emissions*, possible economic penalties and annual limits of GHG emissions.

Outputs are: from simulation analysis, total and annually cash flows by component and NPC / annualized costs, electricity production and consumption per component and load, annually emitted pollutants, time series of systems operation and energy consumptions; from the optimisation, the ranking of defined scenarios based on NPC; from sensitivity analysis, the least-cost scenario.

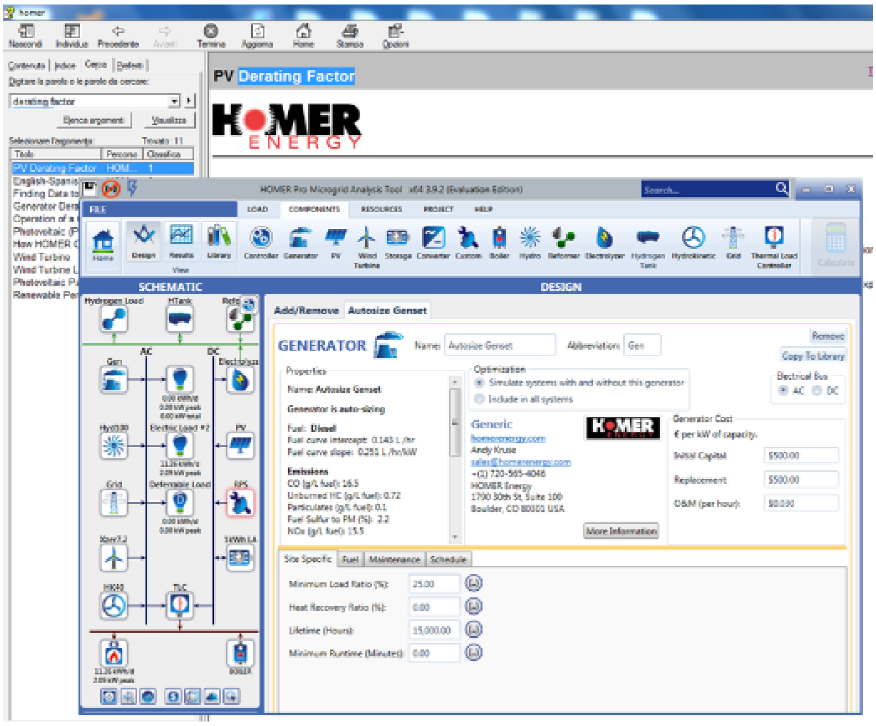

Figure 4. GUI of HOMER (trial version).

2.1.1.3.3 iHOGA

The Improved Hybrid Optimization by Genetic Algorithm (iHoga), has been developed at the University of Zaragoza for the simulation and optimisation of hybrid stand-alone systems of electric power generation based on RES [45],[46], which has also been used to model solar, wind and hydraulic energy [47],[48]. An educational version can be freely downloaded, although lack of several functionalities but also computer related requirements (i.e. internet connection and Windows version up to 8) widely limit its use, therefore it has not taken into account for this review.

The main screen consists of five sections (Figure 5): *General Data, Optimization, Control Strategies, Financial Data, Results Chart*.

Within the former, following described six sub-sections are included. In *Components*, the supply technologies to be assessed must be chosen among: PV panels, wind turbines, hydro turbines, battery bank, AC generator, inverter, hydrogen tank. In *Min. and Max. No Components in Parallel*, the allowed range of batteries, PV panels, wind turbines and AC generators in parallel must be provided. In *Constraints*, the allowed maximum unmet load as a percentage of the annual required energy must be specified. In *Optimization Parameter Selected by*, it is possible defining the time of execution which affects the performance of the optimisation algorithm. In *Simulation*, the time steps, between a minute and an hour, and the starting date of the yearly simulation must be defined. In *Compare with Worth Month Method (PV-bat)*, an only PV-based system can be assessed by inserting the battery autonomy in number of days.

In *Option*, time horizon and optimisation type must be defined. If a time horizon of the whole system life is chosen, either mono-objective or multi-objective optimisations can be done. In the former, the simulation objective is minimizing the NPC, while, in latter NPC, equivalent CO_2 emissions or unmet energy load are minimized; otherwise, more advanced user-defined alternatives can be defined. The time horizon can be lower than a year only in the case of a system based on PV, diesel and/or battery, and optimisation analysis aims to minimize the weight to be transported or the total cost of operation and maintenance, transport, degradation.

In *Control Strategies*, the overall control strategy and the variables to be optimised are defined. In *Global strategy*, it is possible choosing to cover the unmet demand from RES by using batteries or generator without power limits (load following option) and/or according to the nominal power, allowing to charge the batteries with extra power (cycle charging option). In *Financial data*, the following parameters must be entered: nominal interest rate, expected annual inflation rate, system lifetime / assessment period, currency, installation and variable initial cost.

Besides, in *Load* section, the expected load consumption of electricity, hydrogen and /or water has to be defined. It is possible adopting monthly average values or selecting default profiles to which eventually applying a percentage of random variation. Otherwise, own time-step based profiles can be adopted by importing files with rows of data referring to hourly power, hydrogen mass flow rate and water volume flow rate. Regarding energy resources, it is possible indicating data on solar irradiation, wind and hydrogen either as average monthly values from NASA or as own time-step-based files.

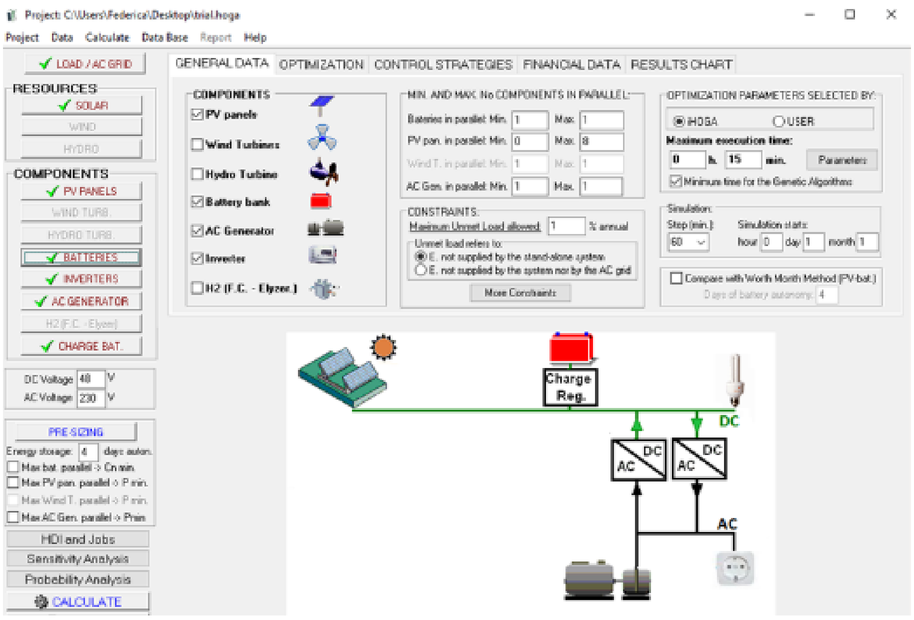

Figure 5. GUI of iHOGA (educational version).

2.1.1.4. User-friendly freeware tools with sub/hourly-based outputs

2.1.1.4.1 EnergyPLAN

EnergyPLAN is a deterministic software developed at Department of Development and Planning at Aalborg University, for assisting the design of national energy planning strategies on the basis of technical and economic analyses [49],[50], which has been used in several researches and real case studies [51]-[55].

Two alternative analysis can be performed: *technical simulation*, for balancing either thermal or electric energy fluxes, and *market-economic simulation*, for assessing the system feasibility on the basis of annual costs.

With reference to the 12.0 release, EnergyPLAN comprises following sections (Figure 6): *Demand, Supply, Balancing and Storage, Cost, Simulation, Output*.

The *Demand* section includes *Electricity, Heating, Cooling, Industry and Fuel, Transport, Water subsections*. For all of them, needed input data are the total annual energy requirements and related hourly "distributions" for a leap year. The distribution is here intended as the energy consumption profile, where each hourly value is normalized to the maximum hourly one. In the library, energy demand distributions, usually coming from utility companies or previous research programmes, are included both for cities and Countries. Additionally, in *Electricity*, the user can model a flexible share for the related demand; in *Heating and Cooling*, the production units' efficiency must be specified, the solar thermal storage capacity, in days of mean heat demand, and related share of consumers as well as annual production and hourly distribution can be entered.

The *Supply* section is made of *Heat and Electricity, Electricity Only, Heat Only, Thermal Plant Fuel Distribution, Waste, Liquid and Gas Fuels,* CO_2 subsections. Except for some cases, required data for each plant, classified by type and fuel, are annual production and/or capacity, operation efficiencies and supply hourly distribution; in the case of more than one DH demand, the data must be reported for each group. In CO_2, the carbon dioxide content by kilogram of fuel can be inserted.

For performing a market-economic analysis, in the *Cost* section the interest rate and each plant investment cost, lifetime and fixed O&M costs percentage share are required. In the *Additional* subsection, other costs which are not explicitly included in the previous ones can be indicated, for instance, costs for building retrofitting campaigns. Hourly energy balances, annual/monthly fuel consumptions, CO_2 emissions and costs of the defined system are provided as outputs, which can be exported in excel sheets and charts (some bugs still are in the charts plotting).

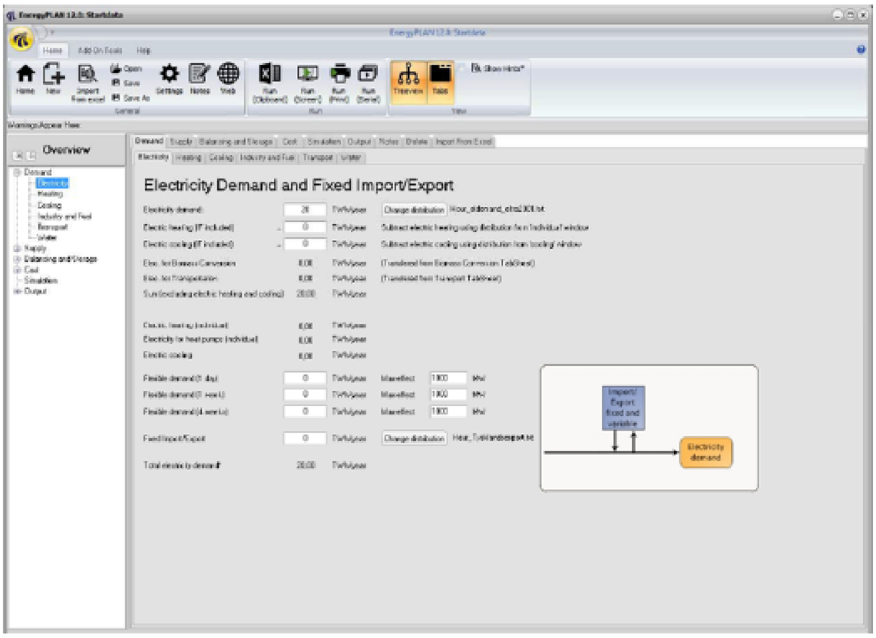

Figure 6. GUI of EnergyPLAN.

2.1.1.4.2 SIREN

The SEN Integrated Renewable Energy Network (SIREN) Modelling Toolkit is an under-development tool at the Australian not-for-profit organisation called Sustainable Energy Now team (SEN), which is currently distributed as a beta version [56]. The software's goal is used to calculate RES electricity generation and developing long-term scenarios. In detail, it aims to determine the optimal locations to access RES, minimise grid connection costs and meet the varying demand on the grid, while achieving the best in terms of efficiency, cost-effectiveness and energy security.

The whole software is made of a georeferenced tool (SIREN, Figure 7), an energy calculation tool (SAM Power Models), provided by the National Renewable Energy Laboratory (NREL), and a set of Excel worksheets for the energy system optimisation (Power Balance tool). The main window consists of a menu bar including following sections: *Scenario, Power, View, Preferences, Windows, Tools*.

In *Tools*, the project area based on coordinates and the related satellite image are imported, then the hourly weather and electricity loads data and, possibly, the existing georeferenced electric network layout. The satellite maps are used for visualizing, locating and modelling both the existing electricity network and the new RES plants. Then, the size and place of the new stations must be created by referring to one of the following technologies: biomass, PV (fixed, tracking or rooftop), geothermal, solar thermal, wind, hydro and wave. Required parameters are: power capacity, area, capital, operation and maintenance costs, hourly power production and, in the specific cases of wind farm and PV, the type, the rotor diameter, the number of turbines and the panels orientation, respectively. Connecting lines must be specified with regard to type, cost and maximum carrying capacity.

By means of the SAM Power Models, hourly electricity balance is reported and exported to the Power Balance tool, which quantifies and cost-optimises the various amounts of storage and generation technologies for completely balancing the system; finally, CO_2 emissions can be calculated as outputs.

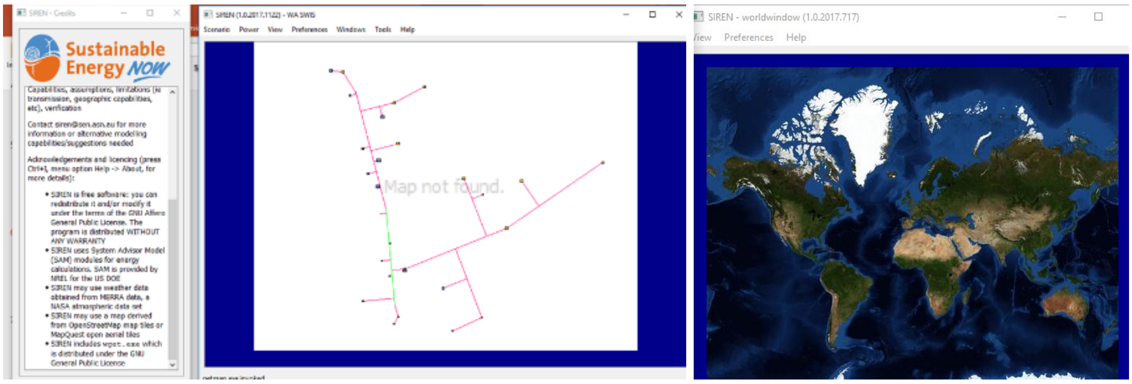

Figure 7. GUI of SIREN (Beta version).

2.1.1.4.3 WebOpt

The Distributed Energy Resources Web Optimization Service (WebOpt) [57],[58] is an optimisation software that allows modelling energy scenarios under the criteria of economic costs and/or carbon dioxide emissions. It is the limited and web version of the Distributed Energy Resources Customer Adoption Model (DER-CAM) software, developed at the Berkeley Lab. Even if WebOpt is featured by some limitations (e.g. it is not easy copying and pasting data and is not possible using shortcuts; some components, like electric vehicles, and functions, like 5-minute time-step optimisation, are not included) and has seldom been used in research, it can be considered to all intents as a complete tool, able to assess an integrated energy system, therefore it has been assessed within this research.

The interface is made of the following sections (Figure 8): *Overview/Optimization Settings, Load Profiles, Utility Tariffs, Technologies, Demand Response, Solar Radiation, Marginal CO_2 Microgrid, Results*.

In *Overview/Optimization Settings*, the technologies can be selected among the several ones provided by the software for the supply of electric, heating and cooling energy. Three alternative optimisation strategies can be accomplished: a cost minimization; a CO_2 emissions minimization or a multi-objective analysis.

In the *Load Profiles* section, the hourly energy loads for electricity, electric cooling, electric refrigeration, space heating, water heating and/or natural gas should be imported as "distributions", intended here as normalized profiles to 1 GWh. They can be inserted either using one of the default profiles (suggested for fast and easy investigations to get a first estimate) or copying and pasting in each cell the user-defined data; another alternative would consider selecting one profile from a database, although referring to US context. While, if the user-defined load data are entered, a monthly average hourly value, the typical hourly based weekly profile, differing if possible, between working and weekend days, and the peak are required. Specifically, the cooling and the refrigeration load are always expressed in consumed electricity of an electric chiller with a COP of 4.5.

In *Utility Tariffs*, it is possible modelling in detail the energy costs of electricity and natural gas, possibly indicating: differences of cost on a seasonal/monthly base, costs fixed and variable part, different time of use. In *Technologies*, systems' investment and O&M costs, lifetime and maintenance period, efficiencies and capacity must be defined. In *Demand Response*, the percentage of schedulable load, in *Solar Radiation*, the daily profile, in *Marginal CO_2 Microgrid*, the carbon dioxide emissions per energy unit can be defined while, in *Results*, information on total annual costs, payback time, installed plants capacities, the detailed hourly energy profile should be provided.

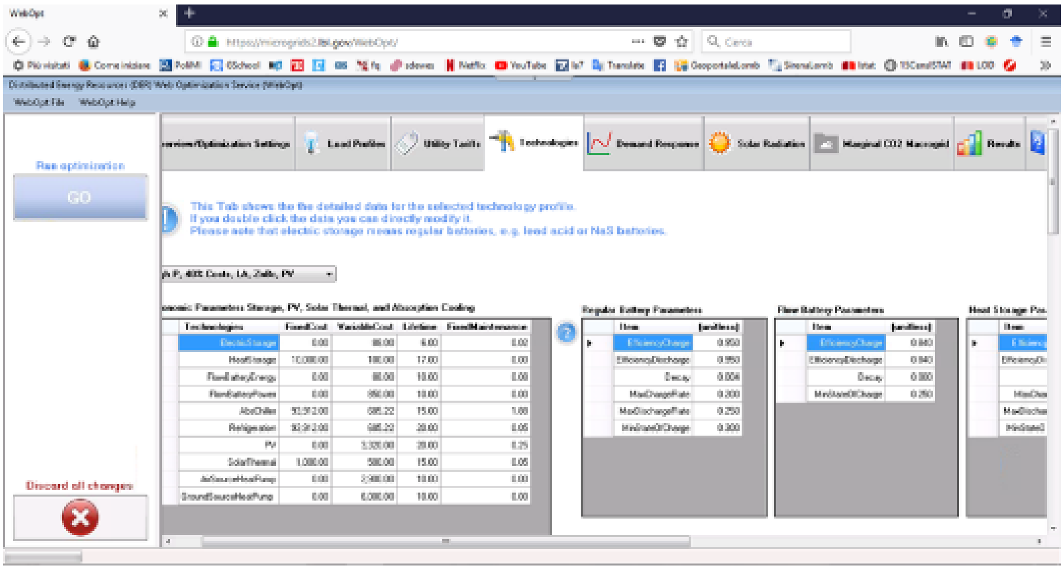

Figure 8. GUI of WebOpt.

2.1.2. Results

Seventeen tools for urban energy planning have been described and six of them deeply treated. For these six tools, which are considered as the more proper ones for widespread urban smart energy planning, since able to assess the energy balance with at least hourly resolution and because user-friendly, the main features and identified strengths are reported in Table 1. In particular, we indicated the type of analysis, distinguishing between:

- "simulation" (SIM), if the analysis is aimed at modelling the operation of a given energy system both on supply and demand sides;
- "optimisation", if the analysis is aimed at selecting the better system operation/ configuration according to only economic criterion (CostOPT) or more criteria such as costs, polluting emissions, etc. (MultiOPT).

We indicated the optimal spatial scale for which they were conceived, although applications on other scales are viable. For instance, Energy-PLAN, whose optimal application is the national or rather regional one, has been used even by the same developers at urban level [53].

Regarding the time scale of provided outputs, we reported the time horizon, for distinguishing between tools modelling short (1 Year) or long-terms (N Years) scenarios, and the time resolution, for identifying those even able to run with time-steps until 1 minute.

Considering the data type and source of the energy demand profiles, all tools foresee the possibility of importing time series from own case studies (user-defined), which is also the most suggested option, otherwise, default ones can be used, but they are often arbitrary or constrained to specific contexts, aspect that calls for further developments in research. In this frame, we also distinguished between demand profiles expressed as:

- "distributions", i.e. energy hourly values relative to an absolute one;
- "loads", i.e. energy hourly absolute values.

All tools have been selected since easy to use, although the online tool WebOpt is featured by slowness and limited basic functions, while SIREN lacks a good support platform, also because under development. Three tools are also freeware, fact that boosts for a greater diffusion.

Regarding the energy sector liable to be modelled, we can highlight that HOMER, iHoga and SIREN are more proper for assessing the electric sector. Accordingly, in HOMER, modelling thermal energy depends on preliminary modelling the electric one, although it is able to consider up to two thermal loads. Also, some heating supply components are included, while no plant is specifically included for space cooling. The energy sectors that can be modelled are deepened in Table 2 with reference to the supply technologies provided in the six tools libraries.

The possibility of modelling and comparing more than one scenario at time is possible only with Homer, SIREN and WebOpt.

As an additional value, the integration with spatial representation, i.e. georeferenced satellite maps in SIREN or network graphical representation in energyPRO and iHOGA, could allow to spatially analyse the energy fluxes, optimal locating RES plants, estimating distributed network losses, etc.

Table 1. Main features of the surveyed 6 user-friendly tools with sub/hourly-based outputs.

	Energy-PLAN	**energyPRO**	**HOMER**	**iHOGA**	**SIREN**	**WebOpt**
Type of analysis	SIM	CostOPT	CostOPT	MultiOPT	CostOPT	MultiOPT
Optimal spatial scale	Nation to Region	Region to District	District	District	District	District
Outputs time horizon	1 year (leap)	N years	1 year	1 year	N years	N years
Outputs time resolution	hourly	sub-hourly	hourly	sub-hourly	hourly	hourly
Energy demand profiles type and source	Distributions · user-defined · case-studies	Loads · user-defined · arbitrary · standards from Germany	Loads · user-defined · arbitrary from US	Loads · user-defined · literature · case-studies	Loads · user-defined · from Australia	Distributions · user-defined · from US
Good support platform	yes	yes	yes	yes	no	yes
Freeware download	yes	no	no	no	yes	yes
Several energy sectors analysis	yes	yes	≈	no	no	yes
Simultaneous scenarios comparison	no	no	yes	no	yes	yes
Data spatial representation	no	yes	no	yes	yes	no

Table 2. Default energy supply technologies by tool and energy sector of the surveyed 6 user-friendly tools with sub/hourly-based outputs.

Energy sector	Energy supply technology	EnergyPLAN	energyPRO	HOMER	iHOGA	SIREN	WebOpt
ELECTRICITY	Power plant/grid	x		x		x	
	CHP/CCHP	x	x			x	x
	Hydroelectric	x		x	x	x	
	PV	x	x	x	x	x	x
	Wind turbine	x	x	x	x	x	
	Biomasses	x				x	
	Electric Storage	x	x	x	x	x	x
	Others	x		x	x		
HEATING	District heating	x	x				x
	Boiler	x	x	x			
	HP	x	x				x
	Solar thermal	x	x				x
	Heat storage	x	x				x
	Others	x		x			
COOLING	District cooling	x					
	HP/chiller	x	x				x
	Dessicant cooling						
	Solar cooling						

2.1.3. Discussions

Summarizing, for each one of the surveyed six accurate and user-friendly tools, we could appreciate the following aspects:

- energyPRO is an accurate tool, which allows assessing DES scenarios, although it is mainly conceived for CHP and DHC, and related NOx, SO_2 and CO_2 emissions, so it is suitable for more overall environmental assessments;
- Homer is a mature and widespread tool, more proper for electricity-based systems, that allows to quickly model defined scenarios and compare the effects of several configurations towards a more comprehensive perspective;
- iHoga bases on a powerful probabilistic algorithm and an abundant set of supply technologies, which make it accurate and easy-to-use tool for local energy planning, although its application is limited to power systems;
- EnergyPLAN is a tool free of charge, quite user-friendly and well-documented, allowing to easily model all sectors and energy services from energy, environmental and economic point of view. Also, as it is a deterministic software, it can be fully controlled by the user, but an uncertainty analysis is not included while, as it is a simulation software, a true integrated multi-criteria optimisation is not included;
- SIREN could be a promising tool since the ability of both adopting spatial data visualization and reliable calculation engine, although its application is limited to power grids assessment;
- WebOpt can be considered as a powerful tool due to both its completeness, in terms of several energy uses and technologies, and implementable improving strategies, although it is worth mentioning that a time-consuming procedure depending on

internet connection quality is detected and also, the whole transition to the commercial version is foreseen in the future.

Concluding, several tools are available for supporting the decision-makers in the urban distributed energy planning while differ for calculation method, required data, users' skills and possible applications. Even if identifying the optimal one is not straightforward, some considerations can be done. As already highlighted in previous review studies [1]-[5], tools able to model different sectors and/or able to consider costs and energy related emissions for doing overall and multi-criteria assessments are most interesting.

In addition, thanks to this research, it can be said that detailed tools, able to model the hourly energy balance during a time horizon and evaluate the effects of concurrent energy supply units and increase of intermittent and unpredictable sources, should be adopted. However, this requires the availability of detailed energy profiles. In this regard, even if they include arbitrary or case-specific profiles, they are hardly adoptable in other contexts, thus importing own hourly load profiles, whose availability is not a widespread condition yet, is definitively the most proper choice.

2.2. LITERATURE REVIEW ON METHODS FOR LOCAL ENERGY PLANNING

Notoriously, urban contexts play a crucial role for significantly reducing the global energy consumptions and related GHG emissions [59]-[61] while districts and neighbourhoods are considered an effective scale for acquiring relevant results since some strategies can be accomplished (e.g. connection to DHC networks, implementation of smart grids, cascade processes, etc.) or can more easily pursued than at the single building one due the economy of scale (e.g. promotion of large envelope/systems retrofit campaigns, implementation of seasonal storages, etc.). For managing such complexity, an accurate knowledge of the hourly energy profiles is essential for ensuring a proper energy balance and, consequently, an efficient and least-cost systems operation. Also, in paragraph 2.1, it emerged that for using existing energy planning tools, detailed energy profiles to be used as input data are needed. At the same time, it is a quite challenging task, since the availability of actual energy profiles is not widespread, yet.

Starting from this framework, at the beginning of the Ph.D., an overall survey was carried out on selected studies in literature regarding methods for urban energy planning, with a focus on the methods adopted to estimate the building stock energy demand. The contents of this latter focus have been treated within an article presented at the Conference SDEWES 2018 [62] (see also Appendix D).

2.2.1. Review methodology

From a methodological perspective, this survey has been performed by searching in Sciencedirect, IEEE Xplore, Scopus, Google Scholar bibliographic databases [63]-[66] the terms "urban / local / district / neighbourhood energy plan, renewable / distributed energy system". In order to identify a manageable subset of papers, the found articles were initially filtered based on the recent publication and high number of citations, then the ones not consistent with this research topic were further manually excluded. First-desk selected contributions regarded the definition of scenarios for improvement of the local energy systems. We observed that a large number of them underlined lacks in the definition of the hourly profile of the energy demands. In order to explore this critical point, studies dedicated to the methods of assessing the hourly demand for various end-uses were further investigated. Therefore, by a second desk research, accomplished by typing the terms "typical urban / building energy demand / load profiles modelling", other scientific contributions were selected and analysed.

Consistently, this paragraph is structured in two sections regarding studies on applications of urban energy planning (section 2.2.2) and a deepening into the methods adopted for estimating the energy demand of buildings (section 2.2.3).

2.2.2.Approaches for defining urban smart energy scenarios

The development of smart energy supply strategies at local level is a widely treated topic in literature, reasonably leading to a set of heterogeneous approaches and outcomes. Therefore, collected studies have been assessed according to three topics:

- Application case, i.e. the case study (in terms of spatial scale and energy service) to which the defined energy scenario was applied;

- Scenario objective, i.e. the main (technical, economic, other) goal driving the defined energy scenario;
- Tool, i.e. the software or the model which has been adopted for assessing the energy scenario;
- Demand data, i.e. the time resolution of the buildings' energy demand used as input data.

2.2.2.1. Application case

Articles reporting researches on alternative energy scenarios for small communities comprise a wide variety of applications for contexts featured by different size. Also, previous related review articles have highlighted that even a shared definition of the application contexts is hardly adopted. In [59], the authors dealt with the concept of *urban energy system model*, defined as a formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area. In [61], the concept of *multi-energy system* was defined as a whole system approach to optimisation and evaluation of a specific case-study, explicitly expanding the boundary beyond one specific sector of interest. In [67], the concept of *smart energy system* has been defined as an approach in which electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system. In [68] the *energy district* was defined as a settlement featured by different use (i.e. residential, not residential or industrial) where it is possible both implementing a mix of technologies - thanks to which optimising the interaction between local consumption and production, reducing consumptions and increasing RES - and establishing new relationships throughout the supply chains, involving users, producers, management and funding roles, public offices and researchers. Since this research is in the frame of urban energy systems, integrating technologies for increasing flexibility and distributed resources, exploiting renewable sources, we here refer to *urban smart energy systems*.

Additionally, we hereinafter consider a neighbourhood as a group of less than a hundred buildings, a district as a group of at least a hundred buildings [44], while a city as defined by the administrative boundary. Based on this, among studies which referred to the still defined neighbourhood scale, some of them were applied to groups of a few buildings [77],[83],[86],[88],[102],[103] or to larger groups [27],[28],[41],[44],[82],[85],[94],[95] or University campuses [98],[101]. The applications on city scale vary from small cities with a population not more than 5 thousands inhabitants [75],[76] (or urban areas in island [159]) to medium cities [53],[54],[92],[93],[97],[100], large cities or even megalopolis [135]. In the middle, there are applications at district level, in particular regarding historical city centres [89],[91] or several different districts [70], mainly residential [69],[84],[92] or mixed use areas [74],[78],[81], connected to DH networks [90],[99], having high energy performance buildings [72].

Regarding the investigated energy service, only electricity has been studied in [70],[71], [77],[78],[82],[97],[159], only thermal energy in [79],[81],[83],[85],[88]-[90],[92],[99]-[101], while the other half of studies regarded at least both of them.

2.2.2.2. Scenario objective

Some studies adopted a purely technical perspective. The increase of the RES share into the energy supply mix is one of the most pursued strategies in order to effectively decarbonizing the energy sector and reducing the fossil fuels exploitation. Some studies carried out approximated estimations of the potential annual energy production from RES-based technologies, regarding mainly PVs [69]-[72] but also biomass, wind, geothermal energy and hydropower [73]-[75], since data on yearly availability of natural resources and seasonal efficiencies of foreseen systems. However, more accurate approaches can be even found in [94]-[98],[102],[103],[135]. In the study of Ostergaard and Lund [53], an urban scenario featured by a drastic increase in the RES penetration (i.e. geothermal energy in combination with absorption heat pumps) was developed for the Danish city of Frederikshavn. Brandoni et al. [76] assessed the possibility of integrating alternative types of μCHP for covering up to 50% of the thermal demand of an assumed retrofitted building stock in Italy. The authors concluded that operating μCHP for balancing both heat and electricity demand in place of giving to thermal loads the priority returned in worse environmental results, and that space cooling demand could be almost completely covered by PV whose possible excess generation could be useful in balancing the grid. Smart energy means also integration of demand response measures: in the study of Guelpa et al. [79] it was observed that, due to peak shaving, a primary energy consumption's decrease up to 8% can be obtained.

In the frequent case of not only technical assessments, the most adopted perspective is obviously the economic one as in [54],[77],[78],[81],[84],[89],[99]-[101]. The net present cost is one of the most adopted indicators. Goodbody et al. [41], by means of Homer tool, compared electrical and heating systems with or without RES while grid-connected and stand-alone based on the NPC but later also the cost of energy (COE) and the CO_2 emissions were considered. It was observed that integrating RES and connecting the system to the grid respectively lead to lower NPC and COE. Similar conclusions were carried out in [42] for diesel generator-based microgrids. In [84] the configuration based on PVs returned in lower NPV than the one with wind turbines. Abdilahi et al. [82] have investigated the possibility of integrating the existing diesel generators with alternative RES-based technologies and returned in a more convenience of wind turbines compared to the PV, due to their higher capital cost. NPV was the optimisation criterion also in the study of Comodi et al. [92] even if assessment of related emissions and exergy was carried out. Other driving indicators have been also used, such as the levelized cost of energy (LCOE) in [83] for comparing three electric thermal scenarios for a residential neighbourhood in California; the net present value in [85] for the optimisation of thermal energy systems retrofitting in residential sector and the costs present value-based in [86]. Weber et al. [87] developed a mixed integer linear optimisation method either based on costs or GHG emissions while, for the case study, accomplished a total annual cost-driven optimisation. Conversely, a mono-objective optimisation aiming at reducing carbon dioxide emissions was accomplished in [80].

Considering that assuming a solely economic perspective could lead to critical conclusions, the assessment of related environmental effects is often integrated into multi-criteria optimisation analysis [28],[44],[92],[94]. In [88],[89] two methods for accomplishing multi-objective optimisation analysis, by considering energy, costs and emissions of defined urban energy systems scenarios were developed. In [90] the economic and environmental effects of three energy efficiency measures (i.e. heat load control, attic insulation and electricity saving) in residential buildings have been analysed. In [159] several scenarios for the case study of a Turkish island under the lens of NPC, energy cost and carbon emissions, in [91] the technical and environmental effects of an energy supply scenario, based on DH connected to CHP and electric/adsorption heat pumps, were assessed.

2.2.2.3. Adopted tool

We previously outlined available, accurate and easy tools: Homer has been used in [41],[82],[159] while EnergyPLAN in [53],[54],[76],[93],[100]. However, in academic environment the adoption of more advanced [90],[120] or customized models seems to be prevalent [77],[78],[83],[85],[86]. The Geographic Information System (GIS) has been adopted in several experiences [28],[70],[75],[91],[96]. The use of GIS allows collecting, storing, analysing and correlating georeferenced data hence it is promising in the energy planning field. In fact, it enables accomplishing spatial analysis useful to calculate and monitor the spatial energy intensity and performance of an area as well as to identify potential sites. This can be useful for instance for the provision of funding programs of EEMs, for the implementation of new energy supply plants, for the extension of existing DHC networks, etc. [5],[91].

2.2.2.4.Demand data

Different sources or methods have been adopted for estimating the buildings energy demand data. Seasonal or annual data were used in [69]-[75],[83], scaled hourly profiles referring to larger spatial areas in [76],[93],[135] or from temporally aggregated data [74],[81],[84],[89],[90], approximated profiles, assuming similar behaviour in groups of hours in [42],[82],[85]-[87],[159]. Conversely, in some cases real hourly measured data were available [53],[54],[78]-[80],[92],[93],[97]-[101]. In few cases, detailed hourly profiles were determined by means of differently accurate methods [28],[77],[88], [94],[102],[103]. The lack of accurate data, often leading to the adoption of methods whose estimates reliability could be controversy, clearly emerges in Figure 9.

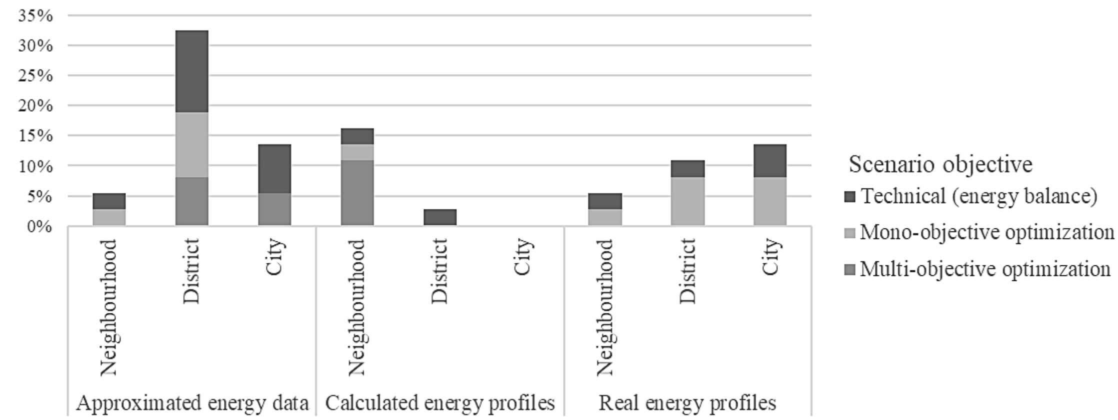

Figure 9. Consistence of assessed studies in terms of goal, type of energy demand data and spatial scale.

2.2.3. Approaches for defining urban building stock energy demand profiles

From the survey on detailed and user-friendly tools for local energy planning (paragraph 2.1), the need of standardized hourly energy demand profiles, as needed input data, was highlighted. However, from the survey on adopted approaches in scientific literature for defining urban smart energy scenarios, it emerged that a large share of studies relied on aggregated energy data or on real measurements. In order to investigate methods for buildings energy profiles estimation, a second-desk literature research on adopted methods for determining the urban buildings hourly demand was carried out. This research outcomes are more extensively reported in an article presented at the SDEWES [62] (see also Appendix D), while main results are hereinafter reported.

Within the abundant related scientific literature, the study of Swan and Ugursal [104] is generally considered as one of the most exhaustive. The authors reported a first broad distinction of methods for energy demand estimation between *top-down*, where outputs are estimated through econometric or technological correlations from more aggregated input data, and *bottom-up* ones, where from used inputs subordinated data and more detailed and reliable evaluations can be provided. Bottom-up methods were in turn divided into *engineering* and *statistical* methods. The *engineering* methods explicitly account for the energy consumption of end-uses, based on equipment power ratings and heat transfer laws and can be fully controlled across all calculation steps. They were divided into: *archetypes*, which allow to model the energy demand of a given building stock based on its clustering through representative fictitious buildings, *samples*, similar to archetypes but using real selected buildings, and *distributions*, allowing to calculate the energy consumption of each end-use based on statistical information of the different appliances and related usage. In *statistical* methods, outcomes come from identified statistical correlations among considered variables (e.g. energy use, weather data, occupancy behaviour, buildings' features, etc). They were divided into: *regression*, determining the coefficient of the model corresponding to the input parameters which are considered as affecting energy demand, *conditional demand analysis*, regressing energy demand onto the list of appliances indicated with binary or count variable, *neural networks*, inspired to the biological neural networks.

Conversely, investigated studies within this Ph.D. research have been classified (Figure 10):

- first, according to the time resolution of used energy demand data between *studies adopting time-aggregated energy data* (A) and *studies adopting detailed energy profiles* (B)
- and then, according to the adopted data source/estimation method, into *studies adopting over-monthly energy data* (A1) or *approximated profiles* (A2), *actual consumption profiles* (B1), energy profiles *estimated through Engineering Methods* (B2) or *Statistical Methods* (B3). Studies based on engineering methods are in turn divided into: *Representative buildings* (B2.1), where archetypes and samples have been grouped into one category, given their similarity as also suggested in [105], and *Distributions* (B2.2). Studies based on statistical methods are in turn divided into: *Statistical correlations* (B3.1), comprising simpler models such as the regression, and *Machine Learning* (B3.2), comprising more advances models including the artificial neural networks (ANN).

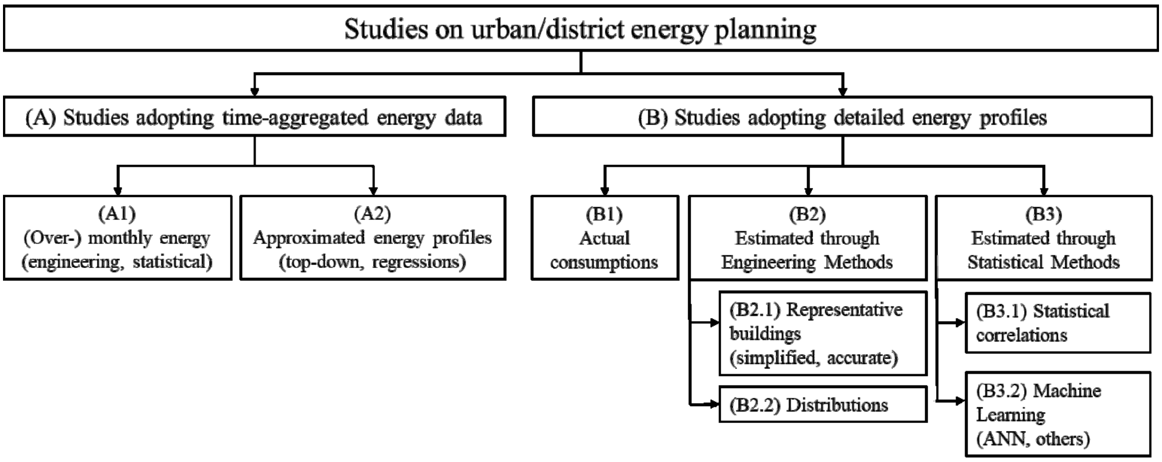

Figure 10. Diagram of the adopted classification.

2.2.3.1. Studies adopting time-aggregated energy data (A)

2.1.1.4.4 Studies adopting (over-)monthly energy data (A1)

In some studies, the annual or monthly energy demand was calculated, either based on engineering or statistical methods, for assessing the balance of the potential energy supply with the energy loads. Such approach is typical of early stage first analysis and returns in highly approximated outcomes which can be largely far from more detailed results. Paiho et al. [72] studied several thermal and electric alternative scenarios for a new residential district development in Helsinki. The annual space heating/cooling and electricity consumptions of the considered high energy performance buildings, including the heat distribution losses in the DH network, were calculated according to local monthly based calculation procedure for the new buildings. Brum et al. [83] assessed an electricity-based scenario for a residential neighbourhood in California. The buildings annual electricity consumption has been calculated by energy simulations, assuming single thermal zones and retrieving properties from direct survey, statistical and commercial data and software libraries. Campana et al. [84] calculated the monthly electricity consumptions, including space heating/cooling energy. Vettorato et al. [75] presented a GIS-based method for the RES energy balance for the mountain town of Roncegno Terme, in Italy. For determining the buildings annual space heating energy needs, a simplified steady–state procedure was adopted. Marique and Reiter [69] studied the concept of “net zero energy neighbourhood” for a residential district in Belgium by assessing the annual energy supply-consumption balance; the monthly energy consumption for space heating, cooling and ventilation were dynamically simulated.

Statistical methods are largely adopted for seasonal building energy assessment. In [69], the annual energy consumptions for DHW and electricity were estimated based on the number of people and statistical data. Lizana et al. [73] analysed the application of solar and biomass energy in district heating in a Spanish town. When buildings actual annual consumptions were not available, a constant DHW consumption was calculated based on typological features, the monthly space heating based on a corrected energy signature and the electricity based on building use and literature. Becchio et al. [89] from the annual space heating energy consumptions in TABULA project database, derived the thermal profiles based on the distribution of the HDDs on a fortnight basis. Amado and Poggi [70] developed a GIS-based model for assessing solar energy potential in districts in the city of Oeira, Portugal. The annual electricity consumption was assumed as proportional to the resident population. Cellura et al. [71] assessed the roof-top photovoltaic production potential for a district in Palermo, Italy. The annual electricity consumption of buildings was calculated based on statistical data.

2.1.1.4.5 Studies adopting approximated energy profiles

In order to provide more accurate energy assessments while coping with serious lack of data, some studies adopted procedures for deriving approximated profiles, thanks to correlations with weather data, building use category or typology, from top-level data.

In some studies, spatially aggregated data were used. Brandoni et al. [76], have derived the electric and thermal energy demand hourly profiles for a small Italian town by scaling-down the previously determined national hourly profiles to the consumptions reported in the municipal energy balance, and adjusting it for considering the local climate conditions and a future scenario. Similarly, Prina et al. [93] scaled-down the national electricity profile to the annual energy consumptions of a small mountain city in Italy. In the study of Niemi et al. [135] starting from the available overall urban hourly energy data, profiles at a lower scale, based on the distance from the urban centre (i.e. urban texture) and on the different end-use energy sector, were determined.

In other studies, energy profiles were derived from temporally aggregated data. Ascione et al. [91] calculated per each building, with a simplified quasi-steady state procedure, the seasonal space heating and cooling energy consumption, from which determined the thermal profiles per each month and day type. In Jennings et al. [85], a corrected steady state procedure for the calculation of required energy for space heating was adopted while DHW was assumed as constant. Another commonly adopted method is the energy signature, where the average heating/cooling power is plotted versus the average external temperature or degree-days. Henchoz et al. [81] regressed into daily energy demand the annual energy requirements per space heating, space cooling and DHW calculated for each considered building use category based on a Swiss standard and previous research. In Girardin et al. [74] the annual consumptions of electricity, space heating/cooling and DHW for defined archetypes were determined based on statistical analysis on measurements from about nine thousand buildings. Pagliarini et al. [112] presented a steady-state inverse method to derive hourly space heating and cooling loads by regressing the simulated monthly loads with test reference year (TRY) climatic hourly data.

In other studies, the defined daily energy demand was stochastically regressed in hourly profiles by means of the Homer software library of scalable and randomizable “synthetic” energy profiles (see details in section 2.1.1.3.2). Abdilahi et al. [82] defined for a residential building the typical appliances equipment, including devices for artificial lighting, entertainment and refrigeration uses. Kalinci defined a winter daily consumption for one dwelling and then scaled-up it to a neighbourhood [159].

In other studies, realistic daily patterns for scheduling temporally aggregated energy demand were assumed. In Goodbody et al. [41] energy profiles have been estimated by scheduling during the occupancy hours the annual and daily estimated amounts: the residential buildings’ annual space heating and DHW energy were calculated based on a monthly calculation procedure; the tertiary thermal energy consumption and all buildings electric consumptions from statistical correlations in previous studies. Akbari et al. [86] adopted energy profiles from a previous study whose authors, starting from statistical correlations among recorded consumption data and weather variables, had in turn determined 4-hours based energy profiles of typical days representing summer, winter and intermediate seasons. Weber et al. [87] for each considered building use and for six periods per day the energy consumptions of space heating, assuming two seasonal typical days, DHW and electricity.

2.2.3.2. Studies adopting detailed energy profiles (B)

2.2.5.1.1 Studies adopting actual energy consumption profiles (B1)

For the accurate estimation of energy fluxes, the availability of actual hourly-based energy consumptions for the investigated case study is of course the optimal condition. Hourly data can be generally retrieved by monitoring campaigns in delimited areas, such as University campuses, or provided by electricity distribution utilities or district heating networks ones. In the studies of Comodi et al. [92] and Difs et al. [90], the hourly consumption profiles provided by the local DH utilities for the small Italian town of Osimo and the Swedish city of Linköping respectively, in Kayo et al. [98] the electricity and DH ones from a Finnish University campus, in Kaldellis et al. [97] the electricity one for the Greek island of Lesbos, in Faria et al. [78] the hourly-based electricity consumptions, measured among domestic, commercial and industrial users in Portugal over a day, were used.

In the following cases, the EnergyPLAN software was used and, as explained in section 2.1.1.4.1 the annual energy consumptions combined with the hourly distributions for one leap year are compulsorily required. Local DH hourly profiles were available for the Danish cities of Frederikshavn [53],[100] and Aalborg [54] and for the Italian city of Bressanone [93]. In the study of Ostergaard [134] the Aalborg profile from [54] was adjusted on foreseen energy efficiency measures while the built environment electricity profile was deducted by local utility measurements. In [101], the heating profiles measured in a Norwegian University campus was adjusted based on different simulated scenarios, including either a higher occupancy level or upgraded envelope energy performance; in [153] the used DH profiles for the cities of Torino and Stockholm were taken from existing networks data and correlated with building archetypes annual consumptions; in [99] the DH profile from Zagreb was adjusted to the Croatian city of Pokupsko consumption.

2.2.5.1.2 Buildings energy profiles estimated through Engineering Methods (B2)

Engineering methods are also named *physical*, since are founded on the detailed assessment of processes through physical laws, merely the building's thermal energy balance and the electric appliances consumption, *deterministic*, since from given inputs certain outputs are derived, or *white-box* methods, since the user is able to fully control their execution. Their application relies on a deep knowledge of each system component, although this requires particularly accurate input data and subsequently great work effort and time consumption, although does not account for diversity and stochastic effects.

2.2.5.1.2.1 Representative buildings (B2.1)

Duanmu et al. [114] developed a simplified method for the prediction of buildings hourly cooling loads, to be applied on large-scale urban planning, which bases on linear correlation between cooling load components of the thermal balance and environmental parameters such as temperature and enthalpy differences. He et al. [113] developed a simplified method for HVAC load estimation, assuming only one thermal zone building, neglecting internal gains, considering average solar radiation among exposures. An application of the method to a group of ten archetype buildings was reported. Fonseca et al. [27]-[28] developed a GIS-based tool where, with a hybrid procedure, the space heating/cooling profiles of building archetypes defined for the Swiss context were calculated by means of the simplified hourly method in EN ISO 13790, and then calibrated with the statistical procedure outputs. The same simplified hourly method was also adopted in the study of Quan et al. [96], corrected for considering buildings shadowing, urban heat island effects and occupancy and modelling the electricity and gas consumption of buildings archetypes defined based on the DOE Commercial Prototype Buildings dataset, and of Fischer [156].

For more accurate estimates of the hourly energy demand of buildings, detailed dynamic energy simulation tools, such as TRNSYS [106], EnergyPlus [107], ESP-r [108], etc., have often been used. Kazas et al. [109] presented a method to generate buildings hourly thermal energy demand profiles for district energy assessment, consisting in: real buildings clustering according to age, typology, etc., for finding the more representative building samples; dynamic simulation of them; stochastic-random association of provided energy profiles to the real buildings and aggregation on the district scale. An application was presented for a real district in Turin. Korolijia et al. [110] assessed the annual space heating and cooling profiles of a parametrized office building representative of the UK building stock; Best et al. [44], modelled the heating profiles of archetype buildings, according to the DOE Commercial Prototype Buildings dataset, in mixed-use district in California; Morvaj et al. [88] modelled the thermal and electric hourly profiles for one day per month of a mixed-use neighbourhood in Zurich, and Orehounig et al. [94],[95] simulated the space heating profiles of real buildings in a mixed-use Swiss town. Ziegler and Benard [115],[116] simulated representative multi-thermal zones archetypes for both residential and office use, based on different building sizes, envelopes, occupancy patterns and HVAC technologies, for the Austrian context. The simulated hourly space heating consumptions were converted into percentage of hourly density profiles, i.e. ratio between hourly power and annual energy consumption. Ahmed et al. [117] generated typical occupancy and appliances profiles, according to new prEN 16798-1 and ISO 17772-1 standards [118]-[119], for the dynamic simulations of the space heating and cooling need for a set of residential and tertiary building archetypes placed in Finland. Regarding the hourly electricity consumptions, Caputo et al. [131] developed a procedure for synthetizing standard electricity profiles for residential and office building archetypes in Italy, based on usage profiles from the Swiss standard. The same standard was also used by Orehounig et al. [94]-[95] for real buildings and Fonseca and Schluter for archetypes [27]-[28]. Hayn et al. [128] modelled a typical single-family building electricity consumption profile according to a German standard reporting reference load profiles of houses for the use of CHP plants, and then compared different supply units. Hourly electricity loads of small communities in U.S.A. were simulated by defining the kind of appliances based on real case study data in the study of Brooer et al. [120] and statistical data in the study of Adika and Wang [77].

2.2.5.1.2.2 Distributions (B2.2)

Detailed data on the occupancy patterns, the kind of electric equipment and use and the energy consumptions, can be retrieved from comprehensive time of use surveys, statistical information or actual measurements. Richardson et al. [127],[139] have developed a model for generating electricity profiles for dwellings in UK which integrated a previous model for 1-minute resolution artificial lighting profiles, based on irradiance actual measurements, industrial product data and considering daylight, co-use of lighting and frequency of use. Taniguchi et al. [140]-[141] first defined occupancy and activity profiles based on statistical information and time of use survey across Japan population and then, by crossing them with information on appliances type and usage, generated household electricity profiles. The model included the space heating and cooling consumptions dynamic simulation. Other similar examples of these approaches can be found in the studies of Marszal-Pomianowska et al. for Denmark context [142], Widén et al. for households' electricity and DHW in Sweden [143], Ortiz et al. for neighbourhood level application in Spain [144], Yao and Steemers for household electricity and DHW daily profiles in UK [133], Fischer et al. for the German residential sector [157] and Gruber and Prodanovic for residential buildings in UK [132].

2.2.5.1.3 Buildings energy profiles estimated through Statistical Methods (B3)

Statistical methods are also named *data-driven* or *black-box* methods, since the correlation among inputs and outputs is not always straightforward and is derived by assuming weights and bias. Despite for the single data it is required a level of detail lower than in the engineering methods, their use allows coping with data uncertainty, randomness and lack, therefore their application is suitable for prediction of stochastic phenomena, like renewable energy or consumers behaviour. Since the recent increasing diffusion of statistical methods in building physics related research and applications, several methods nowadays exist: linear regression, artificial neural network (ANN), genetic algorithm (GA), probability function, Monte Carlo, support vector machine (SVM), etc.

2.2.5.1.3.1 Statistical correlations (B3.1)

Chung et al. estimated typical space heating, DHW, space cooling and electricity consumption profiles for department stores [145], hotels, hospitals and office buildings [130] based on statistical analysis on data from direct survey and measurements overall Korea. Gadd et al. [146] assessed one-year hourly measured consumptions from more than a hundred residential, tertiary and industrial buildings connected to two DHs in Sweden and average hourly profiles per season were determined. Velik and Nicolay [102]-[103] for the six single-family houses case study, adopted electricity load hourly profiles based on the ADRES-CONCEPT Austrian database [147], whose profiles have been determined for a set of building typologies and day-types since direct survey and measurements. Pedersen et al. [122] for Norwegian building archetypes, and Jardini et al. [120] for the Sao Paulo end-use sectors, determined electricity profiles with probability distribution. Pedersen et al. [122] also provided a set of typical hourly space heating profiles, for different building archetypes, defined in terms of period of construction and use category, based on regression analyses of measured outdoor temperatures. Lundström and Wallin [148] based on historical data of DH consumption and weather data for a Swedish town, computed regression coefficients to be applied to a TRY in order to define a normalized heat load profile. Then, for testing effects of a set of EEMs, heat demand profiles were dynamically simulated, and the daily difference was computed. Dotzauer [129] presented a piecewise linear function between consumptions and outdoor temperatures plus a component dependent on consumers behaviour. The algorithm was applied to predict the hourly heat load for two DH networks in Stockholm.

2.2.5.1.3.2 Machine learning (B3.2)

Al-Shammari et al. [149] developed a Support Vector Machine for short-term predicting the heat loads of DH connected consumers based on collecting the real data from a heating substation in the Serbian city of Novi Sad. Shamshirband et al. [124] presented an adaptive neuro-fuzzy inferences system model to forecast DH single consumers, based on real consumptions from the DH station in the Kviri vir town, in Serbia. Kato et al. [150] presented a method for forecasting district heating and cooling loads, with the aim of improving previous tested ANN-based method predictions in periods affected by high fluctuations. Past heat loads, as well as the day-type, the highest and lowest air temperatures of the predicted day were used as input data. Powell et al. [151] proposed a method for estimation of day-ahead space heating, space cooling and electricity loads for a University campus in Austin, Texas. They compared some linear and non-linear models, using as input data, past recorded weather data, occupancy data, hourly average measured energy consumptions. Beccali et al. [123] proposed an unsupervised and supervised ANN-based method for the electric energy demand forecasting with a prediction time of one day. Input data were dry bulb temperature, relative humidity, global solar radiation, recorded electricity consumptions for a district in Palermo, Italy. Monfet et al. [152] proposed a so-called Case-Based Reasoning based method to predict the short-term hourly energy demand of tertiary buildings. Disaggregated electricity loads, both from real and simulated data of an office building in the Canadian city of Varennes, as well as outdoor air temperature and relative humidity were used.

2.2.4. Discussions

Existing studies on urban energy planning, including RES and storage systems integration, are characterized by a wide variety of approaches, regarding application case study, objective of the defined scenario, adopted tool and level of used energy demand data.

For dealing with this issue, a survey of the most commonly adopted methods for estimating the energy demand has been accomplished and the related classification is summarized in Table 3.

Based on this survey we saw that the studies relying on time aggregated energy data (A) often lead to the accomplishment of truly approximated estimations. In fact, the adoption of seasonal energy data (A1) is responsible for neglecting energy fluctuations which are relevant when planning smart and RES integrated energy systems, including storage systems assessment. Moreover, approximated energy profiles (A2) derived from spatially aggregated data through top-down approaches, by putting on the same level a small community and a Country, or from temporally aggregated data through regressions based on the outdoor temperatures, neglecting other weather parameters, such as the solar radiation [154] or building usage patterns, which are usually responsible for a more variable profile, can be also critical.

Regarding the studies adopting detailed energy profiles (B), apart from those cases where actual consumption profiles are available (B1), robust methods for the estimation of reliable profiles, engineering (B2) or statistical based (B3), must be chosen.

For reducing the computational effort of engineering modelling, the clustering of a building stock in a series of representative buildings (B2.1) is a well-established approach that allows, if combined with accurate dynamic energy simulations, maintaining an acceptable approximation of the energy evaluations; however, a critical point of these studies could be the assumption of standard values of the building usage patterns instead of an accurate assessment [155]. Studies adopting distributions (B2.2), which are based on statistical approaches but detailed as the engineering ones, could be a way to overcome this issue.

Among the statistical methods, the machine learning based ones (B3.2) enable to reliably estimate uncertain data and even reduce computational effort, overcoming the limitations of the basic statistical correlations (B3.1). However, statistical methods adoption relies on measured/ simulated data which are not everywhere accessible.

Table 3. Characteristics of the adopted energy demand data among investigated studies.

Sub-class	Energy Calculation Method	Output Time Resolution	References
(A1)	(Over-)monthly (engineering)	Annually	[75],[83]
		Monthly	[69],[72],[84]
	(Over-)monthly (statistical)	Annual	[69]-[71],[73]
		Fortnight	[89]
(A2)	Approximated profiles (top-down)	Hourly	[76],[93],[135]
	Approximated profiles (regression)	Daily	[81],[91]
		(Over-)hourly	[74],[85]-[87],[112]
		Hourly	[41] ,[82],[159]
(B1)	Actual consumptions	Hourly	[53],[54],[90],[92],[93], [97]-[101], [134],[153]
(B2.1)	Representative buildings (simplified)	Hourly	[27],[28],[96],[113],[114], [156]
	Representative buildings (accurate)	Hourly	[44],[77],[88],[94],[95], [109],[110], [115]-[117], [120],[128],[131], [158]
(B2.2)	Distributions	Hourly	[127] ,[132] [133], [139]-[144],[157]
(B3.1)	Statistical correlations	Hourly	[102],[103],[121],[122], [130],[145],[146]
		(sub-)Hourly	[122], [129],[148]
(B3.2)	Machine Learning (ANN)	(sub-)Hourly	[123],[150],[151]
	Machine Learning (Others)		[124],[149],[151],[152]

Concluding, for appreciating the complexity of smart energy systems, accurate energy data at the proper time scale are needed. However, not all studies adopted suitable energy demand data or methods for energy demand estimations, thus leading to very approximated evaluations. Also, for modelling the effects of implemented energy scenarios (e.g. envelope/systems retrofit measures, RES-based technologies integration, etc.), it is necessary updating the developed energy profiles. That is feasible with both methods but in the case of engineering methods, it is necessary knowing quality and intensity of new describing parameters (e.g. thermal transmittance, system efficiency, shading factor, etc.) while in the case of statistical methods, besides the knowledge of new parameters, it must be verified that the statistical correlation among exogenous and endogenous data still remains.

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3. METHOD FOR ESTIMATING THE BUILDINGS HOURLY ENERGY PROFILES

3.1. PREMISES AND RESEARCH AIM

For planning the improvement of energy supply within smart urban districts, including the connection to DHC networks, the integration of non-programmable RES (e.g. solar, wind) and flexibility solutions (e.g. smart grid, DR strategies, storages), in order to correctly size the supply systems and estimate the related costs and possibly optimise its operation, as well as for assess the variation of the energy demand due to measures upgrading the existing buildings envelope and systems, it is fundamental having reliable buildings hourly energy demand profiles (chapter 1), even more when using one of the assessed targeted tools (paragraph 2.1). In paragraph 2.2, in particular, it has been noted that the lack of energy demand profiles for the given context has in some cases lead to adopt approximated energy data that cannot be considered adequate. In contrast, real energy profiles are currently available for a few cases, such as buildings that are specifically monitored or when the local energy companies can provide sufficiently disaggregated data. Therefore, the topic of the estimation, through accurate methods, of existing building stock hourly energy demand, for multiple contexts, deserves further insights. Furthermore, when the ongoing implementation process of smart meters in buildings throughout the EU MSs [1] will be completed, measured energy profiles will be available both to be directly used in energy planning and to validate accurate energy profiles estimation models. Hence, it will be necessary defining a method able to consider the effects on urban energy profiles of variations in buildings energy behaviour (due, for instance, to implementation of envelope energy efficiency measures, retrofit of HVAC systems, integration of RES-based systems, etc. [2],[3]).

The energy planning of urban building stock has been also the topic of previous Ph.D. researches within the same research group. In particular, in [4] a model for the assessment of distributed energy generation, in [5] a methodology for collecting information and providing assessments of the annual energy performance of a large building stock, in [6] a set of tools for stimulating the energy renovation of the building stock contrasting data fragmentariness and existing not-technical barriers were developed.

Starting from outlined premises and as a continuation of mentioned previous Ph.D. researches, the aim of this Ph.D. research has been to provide a method for the accurate estimation of the energy demand profiles of a building stock with reference to the Italian urban contexts based on available data overall the national territory. The research question regards how outlining a method which could be easily updated, widespread adoptable and targeted on bodies involved in the energy planning and building stock energy at municipality level.

3.2. METHODOLOGY

In order to address the research question on an updatable and widely spreadable methodology for the accurate estimation of Italian urban building stocks energy demand profiles, we decided to integrate spatial data both on geometry and typological information on existing buildings, available on the whole national territory, with hourly energy profiles determined with an engineering method.

The defined methodology foresees the implementation of a geodatabase of an urban building stock in GIS platform, namely in the open-source QGIS software [8]. In particular, considering that the energy demand of a building is also influenced by the geometry, the technological solutions physical properties and the usage profile, and given the currently and almost uniformly available spatial geometric and statistical data throughout the Country, we have coded a procedure enabling to calculate the building stock volume, differently characterized on the basis of mostly diffuse buildings use categories (i.e. residential and common tertiary-office), main construction periods (from old with traditional buildings to recent with buildings complying with energy saving requirements) and different geometric portions of buildings, referring to different boundary conditions.

While, for determining buildings energy profiles, we approached as following outlined. In paragraph 2.2, we could appreciate the differences among methods for the estimation of the energy demand. Among the most accurate engineering and statistical ones, as highlighted in [9], the latter ones, since relying on historical data of both input and outputs in order to derive the model describing their relationship, are more proper for existing systems, which have been already mathematically described. Therefore, also considering the kind of available data in Italy, we defined a methodology that refers to the subclass of Bottom-up Engineering Methods with Representative buildings (B2.1). So, we defined a set of Building Energy Models, considering the main periods of construction and use categories, carried out from a Building Concept, intended as conceptual buildings having a simple parallelepiped geometry, which we modelled in TRNSYS software [10]. Then, by simulating the hourly energy behaviour of selected thermal zones, representative of the different boundary conditions options composing any building geometry, (namely "typical thermal zones") the profiles of sensible energy need for space heating and space cooling can be obtained. Along by this, based on standards in force, the profiles of energy demand of electricity from electric appliances and artificial lighting for a generic thermal zone can be also obtained.

Once done these, the energy density hourly values [W/m^3] can be associated to the considered total built volume calculated in GIS in order to derive the urban building stock thermal and electric energy profiles. By associating typical heating and cooling systems efficiencies based on the installed thermal system in buildings from the local databases, it could be also possible carrying out the urban energy consumption profiles. Additionally, once calibrated the simulated Building Energy Models' hourly energy profiles with the real measured ones, by changing the properties of them thus referring to improved building envelopes and/or new building systems, by rerunning the dynamic energy simulations and associating the new obtained profiles to the built volume, it is possible to determine the hourly energy demand profiles for the considered urban energy scenario. Finally, as an application case study, the city of Milan was adopted to test and validate the defined method.

3.3. Framework on spatial data on buildings in Italy

The European Directive n.2 of 2007 [11] established general rules for implementing the INfrastructure for SPatial InfoRmation in the European Community (INSPIRE) in each Member State to assist policy-making towards environment protection. “An infrastructure for spatial information means metadata, spatial data sets and spatial data services; network services and technologies; agreements on sharing, access and use; and coordination and monitoring mechanisms, processes and procedures, established, operated or made available in accordance with this Directive”[1]. In Italy, the digitization process of public data begun even in 2005 [12], but carried out few concrete initiatives [13]. In 2010 the INSPIRE Directive has been implemented with the D.L.G. n.32/2010 [14], setting regulations for realizing the infrastructure for spatial information and environmental monitoring and defining the services for consulting geodata. In this frame, the national inventory of spatial data (in Italian, *Repertorio Nazionale dei Dati Territoriali*, shortened in RNDT) [15], introduced with [12] and standardized with [16], is a continuously updated national open catalogue of the metadata of spatial datasets and related services available at public administrations. In particular, a plenty of data regards the built environment, divided in cadastral data, buildings addresses and generic buildings data (Figure 11), which are mainly held by Municipal bodies (Figure 12).

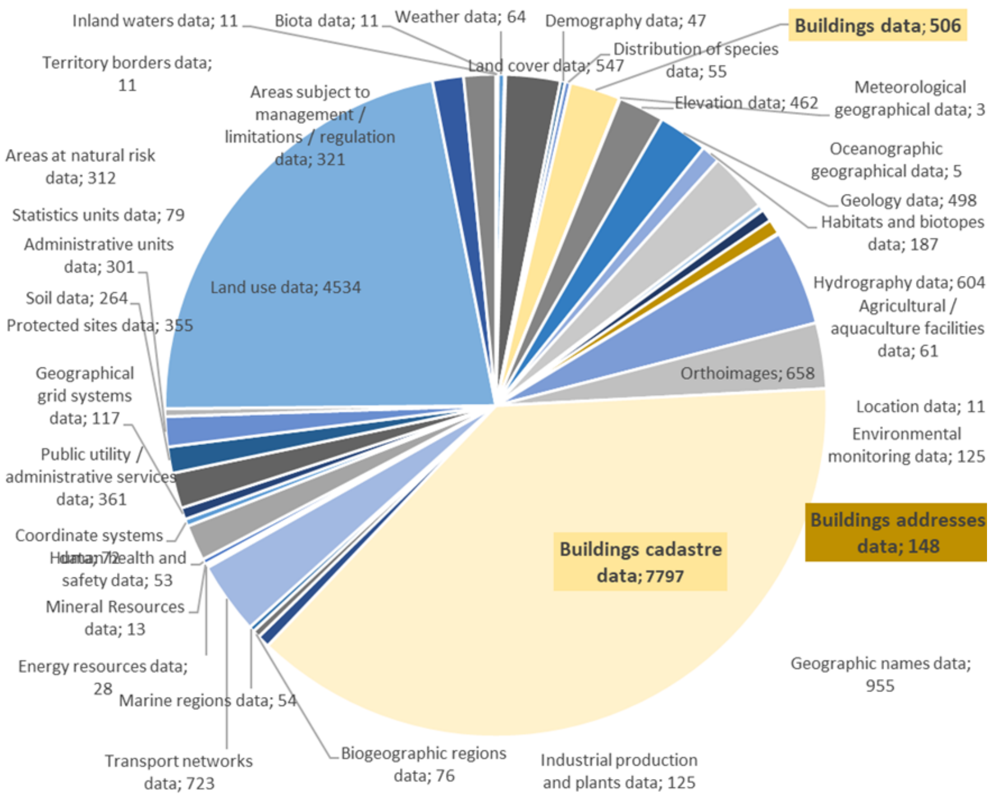

Figure 11. Chart on the number of spatial datasets by each INSPIRE Theme (from [15]).

[1] From the EU 2007/2/CE [11], following definitions are reported: “spatial data” are defined as any data with direct or indirect reference to a specific location or geographical area; “metadata” refer to the information describing “spatial data sets” (i.e. collection of spatial data) and “spatial data services” (i.e. computer operations performed either on spatial data or metadata) and making it possible to discover, inventory and use them.

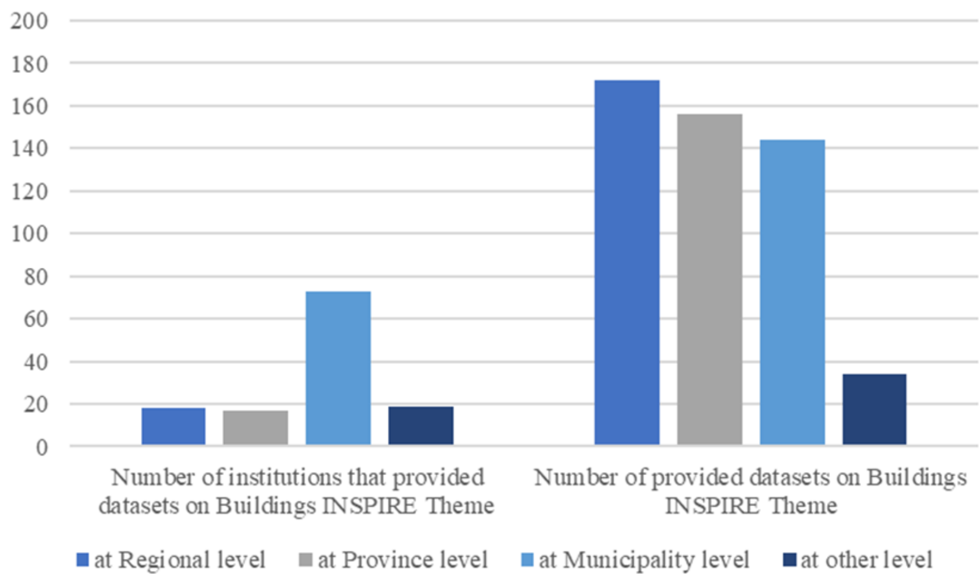

Figure 12. Statistics from the RNDT [15].

2.2.6 The Topographic Database

Among uploaded spatial datasets on buildings, a fundamental one is the Topographic Database (TDb), in Italian *Database Topografico*, introduced with the Ministerial Decree D.M. 10/11/2011 [16]. The TDb is a relational database of georeferenced and continuously updatable data, which is gradually replacing the traditional raster cartography, encompassing all fundamental information for describing the built and natural environment.

The TDb standardization state of progress is still variable among the national territory: some Regions have implemented it before the D.M. 10/11/2011 so updates are ongoing, while in other Regions the situation is more critical. In detail[2], controversy situations regard the Regions of Sardinia and Lazio where the updating process is ongoing, Lombardy that implemented several changes respect to the official specifications, Umbria and Tuscany where the TDbs partially cover the regional territory, Calabria e Sicily having quite lacking and not consistent TDbs, Marche, Molise and Valle d'Aosta still relying on the digitized traditional cartography. Furthermore, the TDb is less easily provided on geo-portals so the access modality and the quantity/quality of provided information vary and are hardly traceable through direct survey of each regional web sources. Main contributions standardizing the TDb are reported in the GeoUML Model [17] and the updated IntesaGIS document [3] [18], which list the possible objects and formally define the content specifications and constraints.

The TDb is based on a hierarchical structure, which consists of following decreasing levels:

– **Layers** (e.g. mobility, human settlements, streets and addresses, hydrography, orography, vegetation, infrastructures, significant locations and administrative

2 Information from contact with RNDT staff in february 2018.

3 The IntesaGIS agreement was signed in 1996 by the State, Regions and Local Bodies and was aimed at boosting for a coordinated development of spatial information systems among the territory (https://inspire.ec.europa.eu/SDICS/intesagis).

boundaries). Consistently with the field of this research, the layer Real estate and human settlements (in Italian, *Immobili ed antropizzazioni*) has been used since it comprises all objects carried out by human activities except for mobility facilities;

- **Themes**. Within the selected layer Real estate and human settlements, five themes are included: Built Environment, Inhabitable Constructions, Constructions for Transports, for Soil Containment and for Water Containment. For the scope of this research, we referred to the Built Environment theme (in Italian, *Edificato*), which refers to constructions which are stable, built with masonry, wood, prefabricated materials, etc., covered with a roof, usually hosting residences otherwise either work or leisure activities;
- **Classes**, which is the unique mandatory level, are the basic units of a TDb and correspond to sets of objects with homogenous geometries associated to topological and informative data (named Attributes). In the selected Built Environment theme, six classes are included: Volumetric Unit (in Italian, *Unità Volumetrica*), Building (in Italian, *Edificio*), Building Group (in Italian, *Cassone Edilizio*), Roof Element (in Italian, *Elemento di Copertura*), Architectural Detail (in Italian, Particolare Architettonico), Minor Building (in Italian, *Edificio Minore*).

  Following, for these six classes definitions and included information are reported (see also Table 4):

  - **Volumetric Unit**, a built elementary solid embedded as portion of a building, covered by a real or ideal flat surface, whose height is usually detected at the eaves level, and represented through a polygon which outlines the basement surface; main attributes regard its height and type;
  - **Building**, a continuous built volume, featured by only one typology, use category, status of maintenance; at the same time, it encloses one or more associated Volumetric Unit(s) and is a portion of a Building Group; main attributes regard the definition of its typology, use, status of maintenance, age;
  - **Building Group**, the envelope of all adjacent Buildings without interruption, up to their largest boundary. Clearly, each Building Group is disjointed by the other objects in the same class and is defined entirely by perimetric walls. Main attributes regard its spatial definition;
  - **Roof Element**, a portion of a roof (e.g. slopes, terraces, domes, etc.) or an element which overlaps and holes the roof surface; it is described by means of typological and geometric information;
  - **Architectural Detail**, i.e. the set of elements belonging to a building, which are not characterized by relevant spatial volume and are not taken into account in the volume calculation, such as: chimney pots, bow-windows, columns, pillars, etc. They are an optional class in low resolution maps; related attributes refer to typological and geometric data;
  - **Minor Building**, which collects all built volumes that complete the building definition but namely are not real buildings, because unstable, small or used in a discontinuous way; constituting attributes describe its typological features.

Table 4. TDb dataset: foreseen Classes on buildings.

Class: Volumetric Unit (UN-VOL 0201 01)

	Class attributes		Spatial component	Spatial component Attributes	
Name	0201 01 02 UN_VOL_AV	0201 01 03 UN_VOL_PORZ	0201 01 101 UN_VOL_SUP	0201 01 07 UN_VOL_QE	0201 01 08 UN_VOL_EX
Description	height	portion type	surface	extrusion height	extrusion measurement
Possible values	n° of meters	On the ground, overhanging, ceiling of gallery/ subway/ loggia, intermediate or overhead, attic, underground, archivolt or covered corridor	-	n° of meters	absolute, relative

Class: Building (EDIFC 0201 02)

	Class attributes				Spatial components		Spatial component Attributes	
Name	0201 02 01 EDIFC_TY	0201 02 02 EDIFC_USO	0201 02 03 EDIFC_SOT	0201 02 04 EDIFC_STAT	0201 02 101 EDIFC_IS	0201 02 102 EDIFC_ME	0201 02 20 EDIFC_CONT	0201 02 05 EDIFC-PORZ
Description	typology	use category	location	maintenance status	ground floor	largest extension	surface boundary type	portion type
Possible values	terraced house, block of flats, church, etc.	residential, public service, transports, industrial, etc.	not underground, underground	under-construction, ruined, used	-	-	real, fictitious	footprint, overhanging, gallery, subway

Class: Building Group (CS_EDI 0201 03)

	Spatial components		Spatial components Attributes
Name	0201 03 101 CS_EDI_IS	0201 03 102 CS_EDI_ME	0201 03 01 CS_EDI_CONT
Description	ground floor surface	largest extension	surface type
Possible values	-	-	real, fictitious

Class: Roof Element (ELE_CP 0201 04)

	Class attribute	Spatial component	Spatial component Attributes		
Name	0201 04 01 ELE_CP_TY	0201 04 101 ELE_CP_SUP	0201 04 03 ELE_CP_QE	0201 04 04 ELE_CP_EX	0201 04 20 ELE_CP_CONT
Description	type	surface	extrusion height	extrusion measurement	surface type
Possible values	flat, slope, terrace, skylight, etc.	-	n° of meters	absolute, relative	real, fictitious

Class: Architectural Detail (PAR_AR 0201 05)

	Class attribute	Spatial component	Spatial component Attributes		
Name	0201 05 01 PAR_AR_TY	0201 05 101 PAR_AR_SUP	0201 05 02 PAR_AR_QE	0201 05 03 PAR_AR_EX	0201 05 20 PAR_AR_CONT
Description	type	surface	extrusion height	extrusion measurement	surface type
Possible values	chimney pot, balcony, bow-window, pillar, etc.	-	n° of meters	absolute, relative	real, fictitious

Class: Minor Building (EDI_MIN 0201 06)

	Class attribute			Spatial components		Spatial components Attribute
Name	0201 06 01 EDI_MIN_TY	0201 06 02 EDI_MIN_PREC	0201 06 03 EDI_MIN_STATO	0201 03 101 CS_EDI_IS	0201 06 102 EDI_MIN_ME	0201 06 04 CS_EDI_CONT
Description	type	status	status of maintenance	ground floor surface	largest extension	surface type
Possible values	stand, garage/ box, highway exit, etc.	temporary, permanent	under-construction, ruined, used	-	-	real, fictitious

2.2.7 The 15th General Census of Population and Houses

For characterizing a building stock from the point of view of the period of construction and use category, the related information contained in the TDb are not sufficiently available and homogeneous overall national territory yet. Hence, another resource has been considered, i.e. the the National Institution of Statistics (Istat) whose provided data are collected through the ten-years census of population and buildings.

Since 2001, the census has been made of two parts: the population survey, which is carried out by means of questionnaires filled by respondents, and the survey on the consistence of the existing buildings, accomplished on-site by Istat technicians. Last Census [19], namely the 15th General Census of Population and Houses (GCPH), has been accomplished in 2010 and related data were first published in 2011. It has been characterized by some methodological novelties respect to the past one [20], regarding: increase in the accuracy, for instance by using municipal residing people registers for identifying with more precision the recipient people, introduction and dissemination of related data of the Census Area, as an additional spatial scale, and collection of more detailed data, without implying unsustainable time consumption, with the submission of two different questionnaires. In particular, a long-form was sent to a sample of people, consisting in the whole population residing in cities with less than 20 thousand inhabitants on January the 1st in 2008 and, both in cases of cities with a population above the set threshold and in chief towns, to one-third of the people, selected among the so-called Census Areas. Besides, a short-form was given to the most people and included all data that are at least required by the European Statistical Office (Eurostat). Among the information collected through the short-form, the ones that are useful for this study are the number, type and surface of dwellings. Some information collected through the long-form could be interesting for this study purpose too (i.e. presence and type of space heating system, presence of system for generating electricity since renewable energy source and type of RES, presence of a space cooling system, availability of DHW and if it is combined with the space heating system as well as the used fuel) although they are not publicly provided.

For using the data from the survey on the existing building stock consistency, the main adopted assumptions by Istat technicians [21] are following summarized. A “building” is defined as a built volume, due to unitary design and construction processes, with autonomous structure, hosting frequently used spaces, be they residential or services, bounded by walls and roofs, with at least one external access. While a “group of buildings” is defined as a set of not-residential buildings and/or infrastructures, usually located in a clearly defined small area and intended for one/main activity. The building use category can alternatively be: **residential**, if the building was conceived or is mainly used for housing scope; **industrial**, if it hosts factories, crafts, agriculture, manufacture, etc.; **commercial**, if it hosts spaces for retail, wholesale, etc.; **tertiary**, if it hosts public/private offices for administrative, finance, assurance, institutional activities; **touristic**, if it hosts hotels, conference centres, spas, camping areas; **services**, if it hosts spaces for cultural, social, health activities, hospitals, sport facilities, parking areas, exhibit areas, parks, defence related facilities; **other**, if it hosts spaces for religious activities. The definition of the period of construction only refers to the year when construction process ended, so excluding subsequent renovation measures. As "building units"[4], it is referred to real estate units (residential, office, commercial, etc.) within a building, to be entered from collective distribution areas (e.g. staircases, courtyards, etc.) and residential estate units which are entered from outside and with own address.

After the statistical survey and subsequent post-processing procedures were finalized, the Istat publicly disseminated data by means of two main datasets: Spatial Bases and Statistical Variables (a list of collected data on buildings compared with the open provided data is reported in Table 5).

The **Spatial Bases** (in Italian, *Basi Territoriali*), which are provided as shapefiles[5] for GIS, comprise the geographic representation of the following geographic scales (from the smaller to the larger one):

- **Census Unit** (in Italian, *Sezione di Censimento*), the smallest spatial unit for the survey accomplishment; the sum of Census Units must correspond to the city edge;
- **Census Area** (in Italian, *Area di Censimento*, shortened as ACE), a group of contiguous Census Units, with an intermediate extension between the Census Unit and the Location and belonging to main urban centres; its boundary has been defined with regard to the existing administrative divisions, infrastructures and natural elements and population density, in order to range between 13-18 thousand inhabitants;
- **Sub-municipal Area** (in Italian, *Area Subcomunale*, shortened as ASC), one of the administrative territories that a municipality, having more than 100 thousand inhabitants, is divided in (e.g. districts);
- **Location** (in Italian, *Località*), a large territory with own name, made of a group of at least 15 buildings, featured by a main residential or productive use;
- **Administrative Boundary** (in Italian, *Confine amministrativo*), with reference to the edge of Regions, Provinces, Municipalities.

Besides, the **Statistical Variables** (in Italian, *Variabili Censuarie*), which are provided as comma-separated values (CSV) files per each mentioned spatial scale (i.e. Census Unit, Census Area, etc.), contain an extrapolation of gathered statistical data, covering five topics: population, foreign population, families and the two ones used for this research, i.e. dwellings and buildings.

[4] In the EPBD recast [22], a *building unit* is defined as a section, floor or apartment within a building which is designed or altered to be used separately.
[5] A shapefile is a format for storing vector data Esri in order to archive the location, shape and attributes of geographic features (https://www.esri.com/en-us/home).

Table 5. GCPH dataset: Surveyed and publicly provided data on building units and buildings.

Surveyed data based on questionnaire per each building unit		**Publicly provided data per each census unit**
Question	**Possible answers**	
Type of residential accommodation	Dwelling, other type (shack, caravan, etc.), at diplomatic place, collective accommodation (hotel, retirement, etc.)	Number of dwellings with at least one residing person (A2) Sum of dwellings which are empty or inhabited by only domiciled people (A3) Number of other accommodation (A5) Number of empty dwellings (A6) Number of dwellings with only domiciled people (A7) Total net surface (A44) of dwellings with at least one residing person Number of families in rented accommodation (A46) Number of families in owned accommodation (A47) Number of families in other purpose accommodation (A48)
Number of living families	1, 2 or more	
Type of living people	Ownership, rental, other	
Owner	Person, company, Public body, other	
Net surface	Number of m^2	
Number of rooms	Number	
Number of rooms with professional use	Number	
Presence of spaces for cooking use	Number and type	

Surveyed data based on on-site audit per each building		**Publicly provided data per each census unit**
Question	**Possible answers**	
Type of building	Building, group of buildings	Number of buildings and group of buildings (E1)
Status of use	Used, not used because under refurbishment/ construction, not used because ruined / under demolishment	Number of used buildings (E2)
Building use category	Residential, industrial, commercial, tertiary, touristic, public services, other (religious)	Number of residential buildings (E3) Number of not residential buildings (E4)
Residential building status attachment/contiguity	No adjacent walls, one adjacent wall, more than one adjacent wall	Not provided
Residential building construction material	Structure of masonry, of reinforced concrete, of reinforced concrete and on pilotis, on other material (mixed, steel, wood, etc.)	Number of residential buildings and per each technology (masonry, reinforced concrete, other material) (E5 to E7)
Residential building period of construction	<1919, 1919-45, 1945-60, 1961-70, 1971-80, 1981-90, 1991-2000, 2001-2005, >2005	Number of residential buildings and per each period (<1919, 1919-45, 1945-60, 1961-70, 1971-80, 1981-90, 1991-2000, 2001-2005, >2005) (E8 to E16)
Residential building status of maintenance	Excellent, good, scarce, worst	Number of residential buildings and per status (excellent, good, scarce, worst) (E28 to E31)
Residential building number of building units	Number split by residential and not residential	Number of residential buildings and per each range of building unit (1, 2, 3 to 4, 5 to 8, 9 to 15, 16 or more) (E21 to E26) – Total number of building units (E27)
Residential building lift	Present/absent	Not provided
Residential building underground floors	Present/absent	Not provided
Residential building staircases	Number	Not provided
Residential building over ground floors	Number	Number of residential buildings and per each range of floors (1, 2, 3, 4 or more) (E17 to E20)

2.2.8 The Spatial Cadastre of Thermal Energy Systems

As mentioned in section 1.1.1.2, the D.P.R. 74/2013 [23] required Regional bodies to develop a cadastre of installed thermal energy systems. Currently, its state of progress is still ongoing and the quality and quantity of provided data largely varies among Italian Regions. Therefore, the description of possible data on thermal systems is referred to only one and in particular, since the case study application regards the city of Milan, to the Lombardy Region one. The Unique Regional Cadastre of Thermal Systems (in Italian, *Catasto Unico Regionale degli Impianti Termici*, shortened as CURIT) [24] is elected to gather data regarding the maintenance, control and inspection of thermal systems within the Lombardy Region. From the database, space heating systems with a total capacity lower than 5 kW (such as stoves, fireplaces, etc.), as well as heat pumps and/or solar collectors for space heating systems, space cooling systems with a total capacity lower than 12 kW are excluded. Data are provided per each installed individual or centralized thermal system for supplying energy for space heating and/or cooling, possibly including the combination with domestic hot water (Table 6).

Table 6. CURIT dataset: Surveyed and publicly provided data.

Surveyed data per thermal system		Publicly provided data per thermal system
Question	**Possible answers**	
Type of the accomplished measure on the thermal system	Installation, Refurbishment, replacement, Booklet filling	Not provided
Location of the thermal system	Address, building unit, floor, Province, City, Building Cadastre data	Province, City, Building Cadastre data
Single Building Unit	yes/no	Not provided
Building use category	E1, E2, E3, E4, E5, E6, E7, E8 according to the DPR 412/93	Building use category
Gross heated volume	Number of m^3	Gross heated volume [m^3]
Gross cooled volume	Number of m^3	Gross cooled volume [m^3]
Presence of building energy performance certificate	yes/no	Presence of building energy performance certificate
Fuel meter point reference number	ID Code	Not provided
Electricity meter point reference number	ID Code	Not provided
Supplied energy services	DHW, space heating, space cooling, other	Supplied energy services
System capacity by energy service	kW for DHW, space heating, space cooling, other	System capacity by energy service
Heat transfer fluid	water, air, other	Not provided
Type of thermal supply sub-system	Generator, Heat pump, Chiller, District heating, District cooling, Cogeneration/ trigeneration, other	Thermal supply system category
Gross surface of possibly integrated solar thermal collectors	Number of m^2	Not provided
Capacity of possibly integrated systems by service	kW for DHW, space heating, space cooling, other	Not provided
Thermal system responsible	Surname, Name, Fiscal code, etc.	Not provided
Generator data	Data of installation and disposal, producer, model, reference number, fuel, heat transfer fluid, capacity, efficiency	Data of installation, producer, fuel, capacity, efficiency
Generator characteristics	Single generator, modular generator and number of foreseen fumes analysis, radiant tube, hot air generator, traditional, condensing, other,	Generator typology
	DHW, space heating, space cooling, other	Generator service
Burner characteristics	Data of installation and disposal, producer, model, reference number, typology, fuel, maximum and minimum capacity [kW]	Burner typology and fuel
Fumes recovery/condenser characteristics	Data of installation and disposal, producer, model, reference number, typology, fuel, total capacity [kW]	Not provided
Chillers / Heat pumps characteristics	Data of installation and disposal, producer, model, reference number, heat transfer fluid, typology, fuel, total capacity [kW]	Data of installation, producer
	External source (water, air, soil)	Not provided
	fFluid (water, air, brine)	Not provided
	Heat recovery absorption, Direct flame absorption, compression cycle with electric motor, compression cycle with endothermic engine	Chillers / Heat pumps typology
	Number of circuits, system number from geothermal pipelines register	Not provided
	DHW, space heating, space cooling, other	Chillers / Heat pumps service
	EER (GUE), cooling capacity [kW], electric power [kW] for space cooling	EER (GUE), cooling capacity [kW]
	COP, heating capacity [kW], electric power [kW] for space heating	COP, heating capacity [kW]

3.4. Procedure for implementing a geodatabase of an urban building stock

The defined procedure to implement a geodatabase in GIS environment for characterizing a building stock with energy related features and then estimate the related energy profile, by considering the minimum level of data which is available among the National territory, is hereinafter outlined. The whole procedure has been implemented in QGIS 2.18.14 [8] and includes some routines for more complex calculations (Python console 2.7). The chapter traces the main procedure structure and related assumptions, while details and related scripts are reported in the Appendices A-C.

3.4.1. Base-map preparation (A)

First, some pre-processing actions are required, which can be easily performed through the standard toolbox within the GIS platform and are explained in detail in the Appendix B.

3.4.1.1. Download and import of spatial datasets in GIS environment (A1)

With reference to the spatial datasets previously treated, the essential spatial data to be downloaded in order to implement the geodatabase are: from the TDb, the Classes included into the Built Environment Theme, while from the GCPH the Spatial Bases and Statistical Variables for the proper Region. Then, the Buildings and Volumetric Units Classes as well as the Spatial Bases and Statistical Variables are to be imported in the GIS map canvas[6]. Table 7 lists the spatial data to be used for the accomplishment of the method with related attributes and includes some additional data to be required, as explained later.

Table 7. Adopted datasets.

from the Topographic Database								
Dataset	**Volumetric Unit (UN_VOL-020101)**							
Attributes name	UUID	0201 01 02 UN-VOL-AV		0201 01 03 UN-VOL-PORZ				
Attributes description	ID code	height		portion type				
Dataset	**Building (EDIFC_020102)**							
Attributes name	CR_EDF_UUID	0201_02_01 EDIFC_TY	0201_02_02 EDIFC_USO	0201_02_04 CR_EDF_ST				
Attributes description	ID code	typology	use category	maintenance status				
from the 15th General Census of Population and Houses								
Dataset	**Spatial Bases**							
Attributes name	NSEZ		ACE					
Attributes description	Census Unit ID code		Census Area ID code					
Dataset	**Statistical Variables (open-data)**							
Attributes name	A2	A6	A7	A44	E1	E2	E3	E4
Attributes description	N° of flats inhabited at least by 1 residing person	N° of empty flats	N° of flats inhabited by not residing people	Net surface of flats inhabited by at least 1 residing person	N° of buildings	N° of used buildings	N° of residential buildings	N° of not residential buildings and groups of buildings
Dataset	**Statistical Variables (to be required)**							
Attributes description	N° of building units per each period of construction (<1919, 1919-45, 1945-60, 1961-70, 1971-80, 1981-90, 1991-2000, 2001-2005, >2005)		N° of tertiary buildings and groups of buildings					

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[6] The "Map canvas" widget is the space where the map is composed from overlaid and interacting layers (http://docs.qgis.org/testing/en/docs/pyqgis_developer_cookbook/canvas.html).

3.4.1.2. Selection of the municipal area to be assessed (A2)

It should be noted that the two datasets from the GCPH are provided for the whole Region while the ones from the TDb for variable scales down to the entire city, depending on the assessed case study. Hence, the area of interest, be it a city or a district, must be selected. For selecting a whole city, the Spatial Bases can be selected based on the Istat code given for each municipality and then the corresponding Statistical Variables can be associated. In this way, a unique dataset with all spatial and statistical information on the Census Units is derived. Also, an auxiliary dataset, where census units are grouped into Census Areas, based on the related ACE code, is created. Selected Spatial Bases are grouped in order to define the city boundary thanks to which the overlapping objects from the other datasets, i.e. the Buildings and the Volumetric Unit, are selected and can be later associated to statistical data. Figure 13 shows the adopted datasets imported in GIS canvas.

Figure 13. Import of adopted spatial datasets in GIS map canvas.

3.4.1.3. Datasets cleaning (A3)

The used datasets provide several kinds of information on the overall built environment, hence in order to use only data which are relevant for an energy assessment of buildings, some filtering actions are necessary.

Census Units for which the associated Statistical Variables are not provided, report a null value of number of buildings or are identified with a numeric code greater than 8888880, which refers to homeless, are removed.

Buildings classified as ruined or under construction, since are not liable to cause energy consumptions, are removed.

The Volumetric Unit class can comprise constructions that are not actually inhabited buildings. For removing this source of error, Volumetric Units referring to balconies, galleries, loggias, underground volumes etc., or with a height lower than 3.00 meters, which is a typical floor gross height in Italy, depending on the typical net one (i.e. 2.70 m), and logically, not overlapping Buildings are removed.

3.4.1.4. Correlation of spatial datasets (A4)

For correlating information among the used spatial data, they are associated based on spatial relations. In particular, the Buildings are associated with the enclosing Census Units. However, it can occur that some buildings overlap more than one Census Unit, hence each Building centroid is determined and associated to the enclosing Census Unit. Since the Centroids maintain all the features of the original Buildings, including the identification code, the latter can be associated to the Census Unit too. An example of some Buildings overlapping more than one Census Unit is highlighted within a red rectangle in Figure 14. Also, since Volumetric Units are associated to Buildings through the identification code, they can be associated to the Census Unit too.

Figure 14. Determination of Buildings centroids.

3.4.2. Building stock characterization (B)

The procedure for characterizing the building stock by age, geometry and use is made of a series of operations which are described in related next three sections, while listed in a series of tables accompanied by Python codes, reported in the Appendices B-C, respectively.

3.4.2.1. Assessment of the prevailing period of construction (B1)

For defining the period of construction of buildings, so that assigning them a typical technological solution with related thermophysical properties, the use of TDb is still controversy because the given information on buildings age is currently rarely held. Otherwise, within the 15th GCPH, Istat technicians were committed to detect the number of buildings and related features. Publicly available related data regard the number per each Census Unit of residential buildings per each one of the defined nine periods of construction (i.e. before 1919, from 1919 to 1945, from 1946 to 1960, from 1961 to 1970, from 1971 to 1980, from 1981 to 1990, from 1991 to 2000, from 2001 to 2005, after 2005) and the number of residential buildings per each one of the defined six ranges of building units number (from 1 to over 16 units), as previously shown in Table 5. From these data and as already pointed out in [25], it is not possible appreciating the actual consistence in terms of built volume by age thus, in order to overcome this gap, the data on the number of building units, including the not-residential ones (e.g. professional studios, private offices, etc.), within only residential buildings, per each period of construction and aggregated per each Census Unit, has been required.

Hence, for each Census Unit, the period of construction with the highest number of building units is assumed as its prevailing age. Additionally, in case of missing data (e.g. fully tertiary Census Units), the Census Area spatial scale is recalled. Based on this, per each ACE, the prevailing period of construction that is mostly occurrent among the enclosed Census Units, is calculated and adopted as its prevailing period of construction. Thanks to the previous spatial correlations among datasets, the determined prevailing period of construction is given to the all included buildings. In Figure 15, the described three steps are clearly visualized.

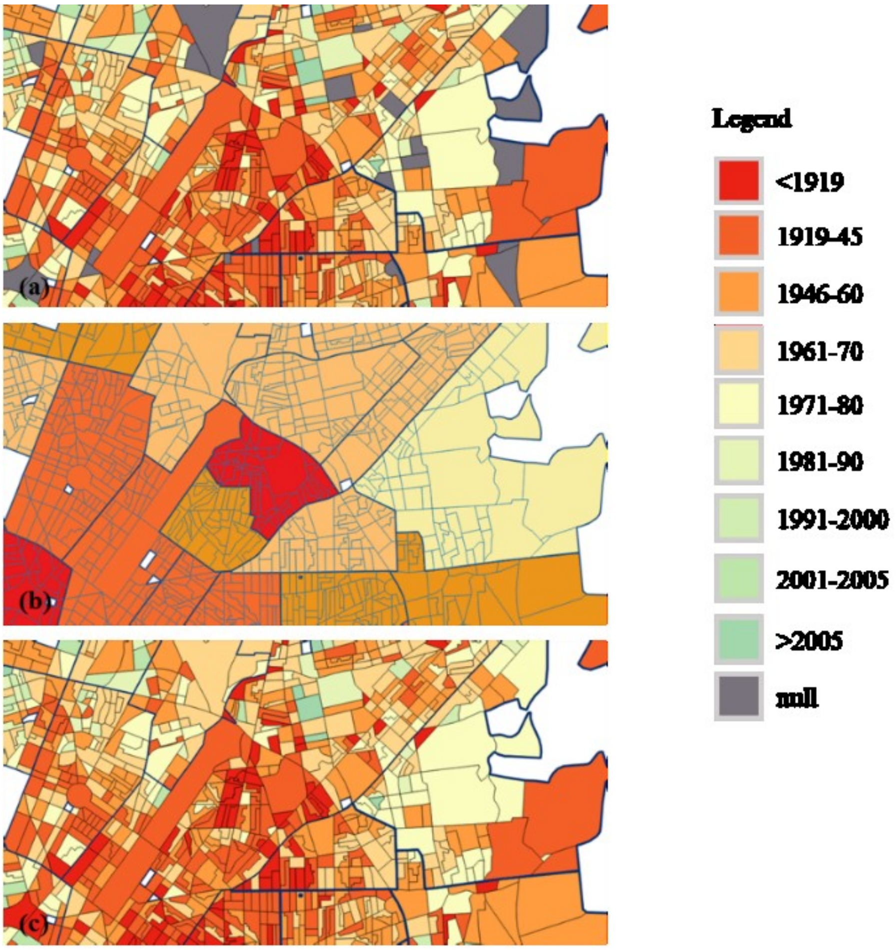


Figure 15. Determination of the prevailing period of construction of each Census Unit (with residential buildings) (a) and of the most occurrent prevailing period of construction of each Census Area (b) for assigning it to each non-residential Census Unit (c).

Additionally, an information directly correlated to the construction period and that is used in following calculations is the definition of the ratio net-to-gross volume. According to common practice[7], gross volume is obtained by considering a share of net volume equal to 60% or 70%, in case of buildings built before or after 1960, respectively.

3.4.2.2. Assessment of the conditioned volumes (B2)

3.4.2.2.1. Deletion of the unconditioned built volume (B2.1)

For properly estimating the conditioned volume of buildings, we decided to preliminarily identify not conditioned spaces, such as distribution spaces. Considering that non-conditioned staircases volumes are often small volumes slightly taller than the building average height, a reference height per each Building is determined as the one corresponding to the Volumetric Unit with the largest floor surface. Based on this reference height, all Volumetric Units which have both a height no more than 6 meters of the reference one and a floor area lower than 50 m^2, which has been considered as realistic for the assessed case study, are excluded by the next calculations (Figure 16a).

3.4.2.2.2. Definition of the Buildings Groups (B2.2)

Since the Buildings class includes also buildings having adjacent walls (i.e. not exchanging heat with outside), we decided to group these buildings into an overall one. For this purpose, the elected spatial class in TDb (namely, Building Group / Cassone Edilizio) should be used, although it is currently rarely available at public spatial databases, so we decided to aggregate the Volumetric Units into groups with all external perimeter walls, but within the same Census Unit, in order to assign only one prevailing period of construction (Figure 16b).

Moreover, each real Buildings Group will be considered, for the assessments described in the next sections, in terms of its equivalent parallelepiped volume. In fact, for each Buildings Group, the sums of volumes and areas of the enclosed Volumetric Units are calculated and based on their ratio, a weighted mean height is given. Additionally, on the basis of the weighted mean height, the number of floors and the gross floor height, variable but not lower than 3 meters, are calculated.

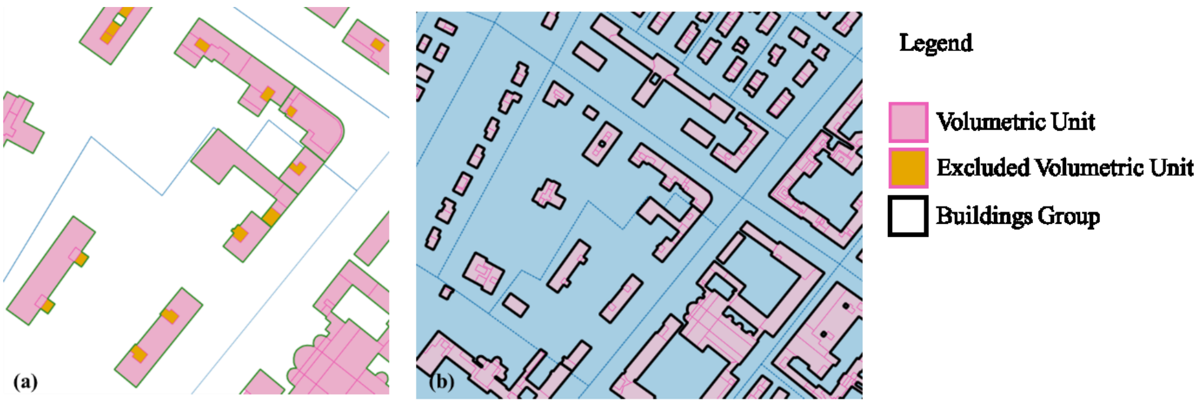


Figure 16. Staircase volumes deletion (a) and Unit Volumes grouping into Buildings Groups (b).

[7] In the no longer in force standard UNI 10379:1994 [26], factors were recommended for converting gross volume into net one according to building typology, precisely equal to: in case of residential, office, health and educational uses, 0.6 for old buildings and 0.7 for new ones; otherwise 0..8 and 0.9, based on presence or lack of partitions inside the building, respectively.

3.4.2.2.3. Assessment of the typical thermal zones composing each Buildings Group (B2.3)

For determining the hourly energy profiles of the considered building stock, a set of dynamic energy simulations is foreseen (see details in paragraph 3.5) based on a simplified Building Concept, in which typical thermal zones, representative of the different boundary conditions options composing any building geometry, have been considered. The typical thermal zones energy simulations results can then be assigned to the considered building stock once its consistency, in terms of typical thermal zones volume, is determined (see next section).

The Building Concept, which has been defined based on a previous study [27], is assumed as an isolated building with a rectangular plan and 5 conditioned floors above an unconditioned basement (i.e. garages, cellars, technical rooms, etc.). The conditioned floors are divided into a central unconditioned distribution space and two side volumes, containing the rooms. For each floor and side volume, 5 square conditioned thermal zones, having openings on the main façade, have been assumed.

For this Building Concept, we identified the 9 thermal zones of the façade representative of the different boundary conditions of heat exchange that compose any building geometry. Analysing the building storeys, in fact, differently from the intermediate floors, the first conditioned one has a horizontal boundary facing the unconditioned basement and the last conditioned one facing the sky. As a result, 3 different types of floors can be assumed: ground, intermediate and top. Then, by considering also the different vertical boundary conditions of the thermal zones composing the building, 3 typical thermal zones have been assumed for each floor: 2 located on the corners, thus having two vertical walls towards outside, and 1 placed at intermediate position, thus having just one vertical wall facing outside. Totally, by coupling horizontal and vertical conditions, we obtained 9 different typical thermal zones.

Also, assuming with good approximation the buildings random orientations in urban context, average energy performance, from the simulations results, among the 4 main orientations (i.e. north, south, east and west) can be adopted to be applied to the considered building stock. Therefore, with good approximation, only 3 of the 6 symmetric corner thermal zones have been assumed, thus reducing the number of the typical thermal zones from 9 to 6 (Figure 17).

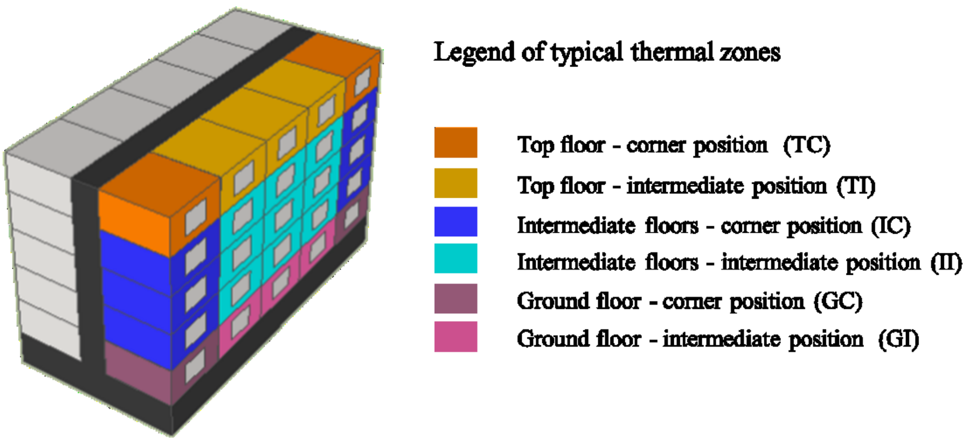


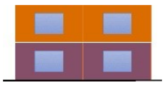
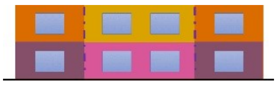
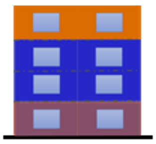
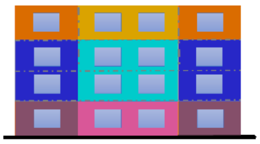
Figure 17. Building Concept typical thermal zones.

For determining the built volume by each typical thermal zone composing the built volume on urban scale, following calculations are performed.

Per each parallelepiped volume, representative of a Buildings Group, the thermal zones dimension is defined, whose variable gross floor surface is calculated from the volume, by considering a fixed net floor area, a net height of 2.70 meters, as mostly diffuse in Italy from 60s, and the previously calculated conversion ratio net-to-gross volume according to the prevailing period of construction. Hence, based on the ratio between the calculated Building Group floor surface and the assumed typical thermal zone one, the number of thermal zones per each floor is calculated.

Then, the total volume referred to each typical thermal zone condition is calculated for the Buildings Group according to the assumptions explained below. In detail, four possible configurations of Buildings Group, in terms of number of floors (i.e. not more or more than two) and number of thermal zones per floor (i.e. four or more) are defined. Table 8 lists the equations implemented to calculate the volume per each thermal zone position considering four possible configurations of Buildings Group, in terms of number of floors and of thermal zones per floor.

Table 8. Equations for calculating the typical thermal zones gross volume based on position and Building Group's configuration.

		Buildings' Group configuration			
		Up to 2 floors		**More than 2 floors**	
		4 typical thermal zones per floor	**more than 4 typical thermal zones per floor**	**4 typical thermal zones per floor**	**more than 4 typical thermal zones per floor**
					
Typical thermal zone	**TC**	$\frac{V_{BG}}{2}$	$\frac{4 \cdot A_{tz} \cdot h_{wm}}{2}$	$\frac{V_{BG}}{N_f}$	$4 \cdot A_{tz} \cdot h_f$
	TI	0	$\frac{V_{BG}}{2} - TC$	0	$A_f \cdot h_f - TC$
	IC	0	0	$V_{BG} - 2 \cdot TC$	$4 \cdot A_{tz} \cdot h_{wm} - 2 \cdot TC$
	II	0	0	0	$V_{BG} - (2 \cdot TC + +2 \cdot TI + IC)$
	GC	$= TC$	$= TC$	$= TC$	$= TC$
	GI	$= TI$	$= TI$	$= TI$	$= TI$

Legend:

V_{BG}= total gross volume of the Buildings Group
h_{wm} = gross weighted mean height of the Buildings Group
A_{tz} = gross floor surface of a thermal zone of the Buildings Group
N_f = number of floors of the Buildings Group
h_f = gross floor height of the Buildings Group
A_f = gross floor surface of the Buildings Group

Calculation of the gross volume of the corner thermal zones placed on the ground and top floors (i.e. GC and TC)

If the Buildings Group is made of four thermal zones per floor, it is conceived as only made of corner thermal zones. Then, if the Buildings Group has up to two floors, the volume of the thermal zones is equally shared between ground and top levels; while, if it has more than two floors, the volumes of ground and top levels' thermal zones are calculated based on the multiplication between the floor area and the previously calculated floor height.

If the Buildings Group is made of several thermal zones per floor, since it is assumed that the Buildings Group is a parallelepiped, four corner thermal zones per floor are determined. Each corner thermal zone has a floor surface equal to the previously calculated for the typical one. Then, if the Buildings Group has up to two floors, the thermal zone height is considered as equal to half of the weighted mean one; while, if it has more than two floors, it is considered as equal to the previously calculated for each floor one.

Calculation of the gross volume of the corner thermal zones placed on the intermediate floors (IC)

If the Buildings Group is made of four thermal zones per floor, the volume of thermal zones on the intermediate floors is calculated as deduction of the ground and top levels' ones from the total one.

If the Buildings Group is made of several thermal zones per floor, each corner thermal zone has a floor surface equal to the previously calculated for the typical one and a height that is derived by deduction of the ground and upper level heights from the weighted mean one.

Calculation of the gross volume of the intermediate thermal zones placed on the ground and top floors (GI and TI)

If the Buildings Group has more than four thermal zones per floor, other thermal zones in intermediate position on the façade on ground and top floors are supposed. Then, if the Buildings Group has up to two floors, the volume of the thermal zones placed in intermediate position on ground and top floor is calculated by deducting the corner thermal zones volume on ground and top floor from the total volume; in case of more floors by deducting them from the floor volume.

Calculation of the gross volume of the intermediate thermal zones placed on the intermediate floors (II)

If the Buildings Group has more than four thermal zones per floor and at least three floors, some thermal zones in intermediate position, both from vertical and horizontal point of view, are also supposed. Their volume is calculated as deduction from the previously calculated volume of the other thermal zones by the total one.

In Figure 18, it is reported an example of the characterization of Buildings Groups by typical thermal zone.

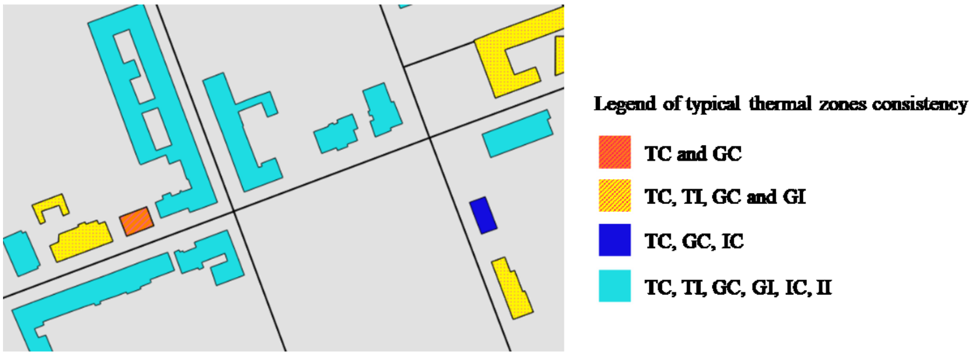


Figure 18. Typical thermal zones consistency per each Buildings' Group.

3.4.2.3.Assessment of the volume by use category (B3)

Once calculated for each Buildings Group the total volume referred to each typical thermal zone condition, the total volume by each condition as well as the sum are calculated at the level of the enclosing Census Unit in order to be correlated with the statistical information on period of construction and use category.

The building stock is characterized also from the point of view of diffuse use categories, in particular with reference to residential and common tertiary (office) buildings. The association of these uses to real buildings by means of the foreseen attribute in the TDb is still controversy due to current scarce availability and reliability of the data among the local public administrations. Thus, the data provided by Istat per each Census Unit can be alternatively used although cannot be directly attributed to the single building or Buildings Group, leading to determine a percentage of use category per each census unit.

First, the residential use net floor area per each Census Unit is calculated based on the sum of the floor area of the buildings' units with residing people and the floor area of the other buildings' units (i.e. occupied by domiciled and unoccupied), which is in turn calculated based on the average surface in the former case. Based on this, the residential gross volume is calculated by assuming a typical height of 2.70 meters and the mentioned ratio gross-to-net volume based on the Census Unit prevailing period of construction.

By subtracting the calculated residential gross volume from the total built volume, the gross volume of not-residential use buildings is derived. For extracting the share attributable only to tertiary buildings, it is again possible to benefit from data gathered within the GCPH, i.e. the number of not-residential buildings and groups of buildings alternatively categorized as commercial, office, service, touristic, religious, industrial. Thus, the weighted percentage of buildings and groups of buildings occupied by offices to the built volume is calculated. Finally, the two shares are applied to the volume calculated per each condition. Therefore, per each Census Unit, which is in turn featured by a prevailing period of construction, the gross volume per each one of the considered use categories and typical thermal zones is derived. In Figure 19, an exemplary representation of the prevailing use for each Census Unit is reported.

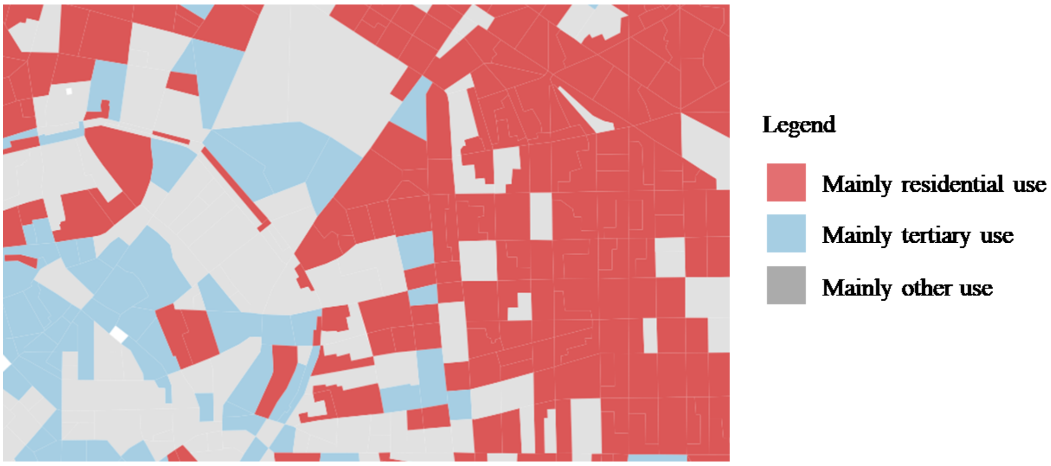


Figure 19. Characterization of each Census Unit by prevailing use.

3.4.3. Association of thermal systems (B4)

From the Thermal System Energy Cadastre, it is possible deriving information on the installed thermal systems. Thermal systems are associated to the building address and not to the building fabric, so it is first necessary to acquire the related coordinates for georeferencing and associating the systems to the overlapped buildings. Within the dataset, information on the typology of each subsystem (i.e. supply, distribution, regulation, emission) should be provided; additionally, the seasonal efficiency of the boiler is provided based on actual measurements while the efficiencies of the other subsystems could be assumed based on national standards. Possibly, more than one thermal system is associated to one Buildings Group, so it could be defined to adopt one prevailing thermal system or averaging the related effects. Based on these assumptions, it could be possible assigning a seasonal efficiency to the entire thermal system.

3.4.4. Determination of the building stock energy profiles

Once calculated the built volume [m^3] per each prevailing period of construction, use category and typical thermal zone condition for the whole district/city, it can be multiplied for the hourly values of energy density [W/m^3] of space heating, cooling or electricity demand, for the same thermal zone of the Building Energy Model with same period of construction and use resulting from the simulations in paragraph 3.5, in order to obtain the urban energy profiles [W]. Then, thermal energy profiles could be divided for the assessed heating and cooling systems efficiencies in order to derive the related hourly energy consumption profiles for a year. As a result, the estimated building stock energy profiles can be imported in an urban energy simulation/optimisation tool among the ones which have been discussed in paragraph 2.1, with the purpose of developing energy scenarios regarding the improvement of the local energy mix supply.

Summarizing, a diagram of the whole procedure for implementing a georeferenced database of a building stock is next reported (Figure 20).

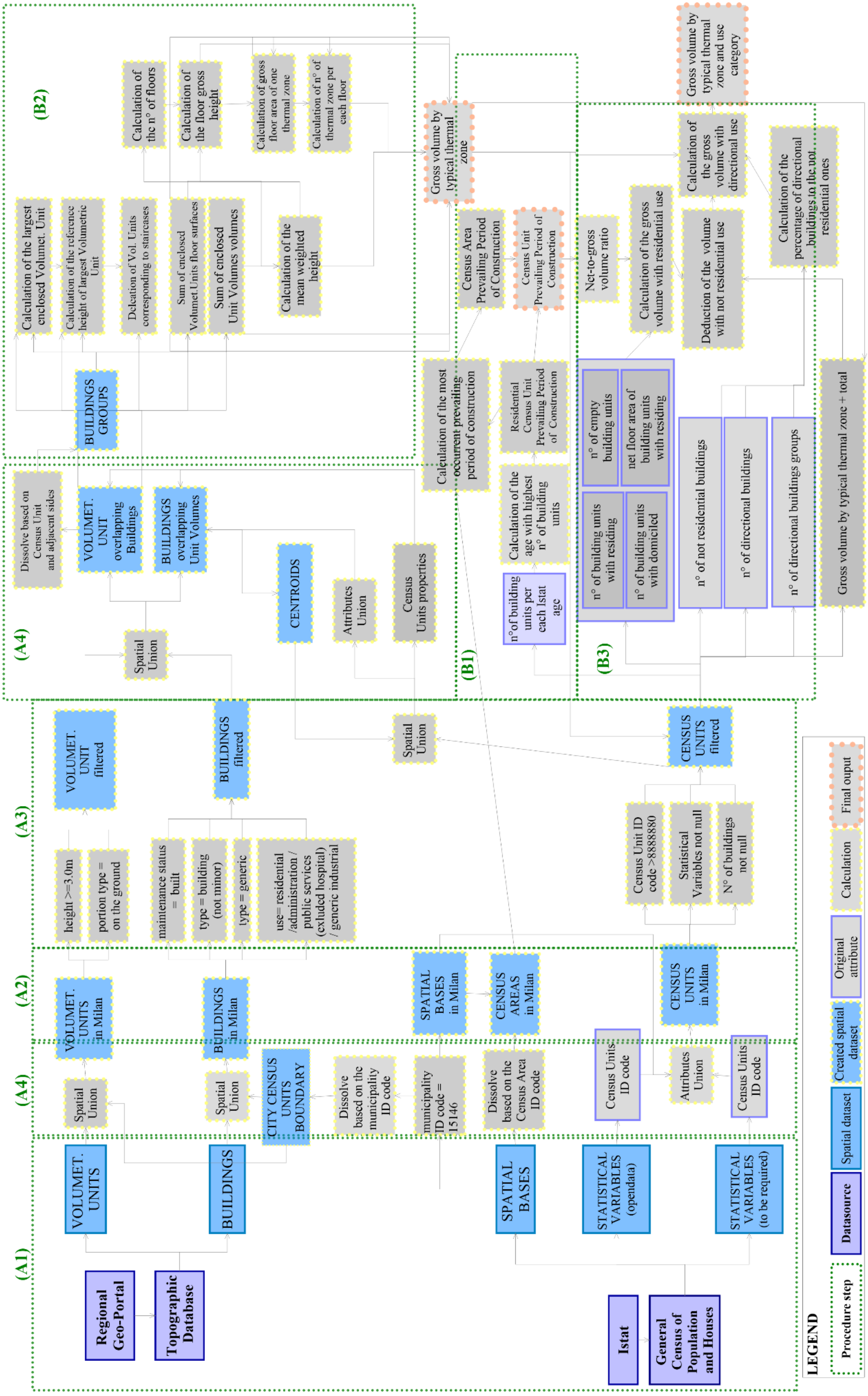
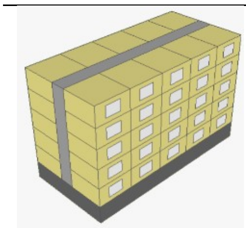


Figure 20. Diagram of the GIS-based procedure for implementing a geodatabase of an urban building stock.

3.5. Definition of typical energy profiles for the Building Energy Models

As previously mentioned, in order to determine dynamically simulated hourly energy profiles for a building stock, we decided to adopt a Bottom-up Engineering Method with Representative buildings, since it is featured by estimates accuracy, easy update in case of new energy scenarios and sustainable computational effort. Therefore, considering the level of detail that can be achieved through the previously described procedure for implementing the building stock geodatabase, based on a previous study [27] we have defined a Building Concept, assumed as isolated from the urban context and having a simplified geometry (related dimensions are provided in Table 9), while assessing in detail different technological solutions related to the main construction periods and different usage patterns uses related to the use category. The hourly thermal energy needs for sensible space heating and cooling of typical thermal zones, selected according to their different position, have been dynamically simulated by means of the TRNSYS 17 calculation engine [10], while the electricity demand for electric appliances and artificial lighting has been calculated based on the regulation in force giving data on the typically installed power.

Table 9. 3D model and geometric features of the Building Concept.

3D Model		Thermal zone	Conditioned volume	Unconditioned middle space	Unconditioned basement
	Net length [m]	5.0	25.0	25.0	25.0
	Net width [m]	5.0	10.0	2.0	12.0
	Net height [m]	2.7	13.5	13.5	2.4
	Floors number [-]	1.0	5.0	5.0	1.0
	Net floor area [m^2]	25.0	1250.0	250.0	300.0
	Net volume [m^3]	67.5	3375.0	1250.0	720.0

3.5.1. Building Concepts envelope technological solutions for the defined periods of construction

The set of Building Energy Models has been defined by assigning to the Building Concept different envelope characteristics and window percentages with reference to three main periods of construction (i.e. old, 60s-80s and recent) based on a previous research [27] where, for limiting the number of variables, main differences regarded the definition of the vertical elements. In detail, for every period of construction and use category, a conventional envelope solution is taken into account: traditional heavyweight masonry walls for the old buildings, air cavity walls for the 60s-80s ones and, in order to comply with the most recent limit in force (valid for buildings built/renovated since 2010) reported in the Italian D.L.G. 311/06 [28], insulated cavity walls for the contemporary ones. In case of conventional envelopes, a window surface equal to 1/8 of the floor area, based on the diffuse Italian praxis to provide natural ventilation and lighting, is considered. Additionally, alternative more glazed and lighter solutions have been considered for the office buildings: in particular, walls made of sandwich panels and more than 30% glazed surface for the 60s-80s building, while walls made of insulated sandwich panels and a glazed curtain wall on the main façades for the recently built one. Features of adopted solutions are shown in Table 10 and 11.

Table 10. Adopted vertical opaque envelope solutions (table based on [27]).

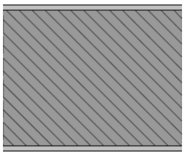
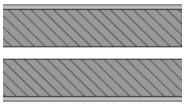
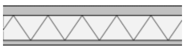
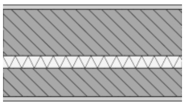
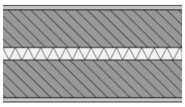
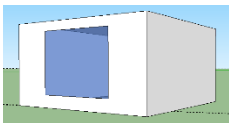
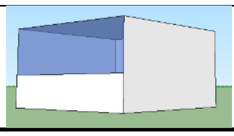
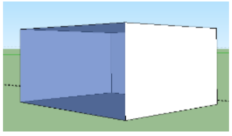
Envelope solution	Building use category	2D Scheme	Layers (from inside to outside)	Thickness [cm]	U-value [W/(m² K)]	Heat Capacity [kJ/(m² K)]
Old Conventional	Residential, Common Tertiary (Office)		1 Gypsum plaster 2 Full bricks 3 Cement plaster	2.0 50.0 2.0	1.08	818
60s-80s Conventional	Residential, Common Tertiary (Office)		1 Gypsum plaster 2 Hollow bricks 3 Air 4 Hollow bricks 5 Cement plaster	2.0 12.0 6.0 12.0 2.0	0.98	263
60s-80s Sandwich Largely Glazed	Common Tertiary (Office)		1 Gypsum board 2 Insulation (mineral wool) 3 Fiber cement board	2.5 10.0 1.5	0.36	53
Recent Conventional	Residential, Common Tertiary (Office)		1 Gypsum plaster 2 High density hollow bricks 3 Insulation (mineral wool) 4 High density hollow bricks 5 Cement plaster	1.5 17.0 7.0 8.0 1.5	0.33	~260
Recent Glazed	Common Tertiary (Office)		1 Gypsum plaster 2 Hollow bricks 3 Insulation (mineral wool) 4 Hollow bricks 5 Cement plaster	1.5 12.0 8.5 12.0 1.5	0.33	~251

Table 11. Adopted vertical glazed envelope solutions (table based on [27]).

Envelope solution	Building use category	3D Model	Glazed area [m²]	Glass type	Frame type	Window U-value [W/(m² K)]	Solar heat gain coefficient
Old Conventional	Residential, Common Tertiary (Office)		3.15	Double	Wood	2.73	0.76
60s-80s Conventional				Double	Aluminium	2.91	0.76
Recent Conventional				Low-e double	Aluminium, Thermal break	1.77	0.60
60s-80s Sandwich Largely Glazed	Common Tertiary (Office)		8.0	Double	Aluminium	2.91	0.76

Recent Glazed	Common Tertiary (Office)		13.50	Low-e double	Aluminium, Thermal break	1.28	0.39

3.5.2. Buildings Concept use categories

In the implemented geodatabase, the determined built volume refers to two diffuse uses, i.e. residential and common tertiary (office) ones, with regard to both private and public buildings as well as large directional complexes.

Analogously, the modelled Building Concept has been alternatively referred to the residential and office use. For this purpose, since the occupants' activities and electric devices usage are affecting aspects of the thermal energy balance and electricity consumptions [28], the hourly profiles of internal loads per occupants, equipment and artificial lighting, as well as of air change rates, and of thermal systems activation have been accurately determined for a residential and a tertiary Building Concept.

Since in some standards the useful data are given for single rooms, it was needed defining the buildings floor plan. Therefore, based on previous research, where typical thermal energy need profiles for representative buildings in Italy were developed and whose contents have been published in an article presented at the World Multidisciplinary Civil Engineering - Architecture - Urban Planning Symposium in 2016 in Prague [30] (see also appendix D), conceptual floors plans for each building use have been considered (Figure 21). In particular, a typical floor plan of a multi-family residential building has been assumed as made of 15 square thermal zones (16 m^2 each), three different size flats (48, 80 and 96 m^2, respectively), corresponding to a total of 96 m^2 for both bedrooms and bathrooms, of 128 m^2 for living rooms and kitchens, and of 16 m^2 of unconditioned vertical distribution space (i.e. stair and lift). While, for the office building, a plan made of 10 square (25 m^2 each) office rooms per floor with a distribution area (50 m^2) in the middle has been considered.

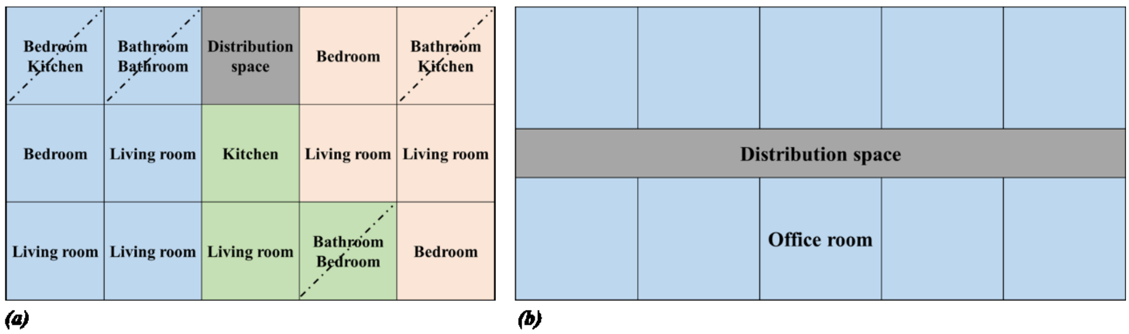


Figure 21. Concept of the typical floor plan of the residential building (a), with differently coloured flats, and of the office building (b).

3.5.2.1.Internal heat loads

For defining the building usage profiles, during the Ph.D. course some available standards providing nominal values and related hourly schedules of internal heat loads were assessed in order to define the one to be adopted for this study, namely the Italian technical specification UNI/TS 11300:2014 [31], the Swiss technical worksheet SIA 2024:2015 [32], the standards ASHRAE 90.1:2013 [33], and, only for the office, ISO 18523:2016 [34]. Subsequently, the standard ISO 17772:2017 [35]-[36] was enacted and, considering that is the most recent one and carries out comparable values with the other standards, as shown next, has been adopted for modelling the Building Concepts hourly usage schedules. As a result of the firs-desk study, we compare hereinafter the internal heat loads and air change rates, determined according to the mentioned standards for the defined Building Concept, both in case of residential and tertiary use.

The Italian National Unification Body (UNI) issued and periodically revises the technical specification series **UNI TS/11300 (UNI/TS)** for the evaluation of the building energy performance based on the implementation of the European standard EN ISO 13790:2008 [37]. Last version of UNI TS/11300 is made of seven parts, the first of which (UNI TS/11300-1:2014) [31] regards the calculation of space heating and cooling energy needs. Suggested applications are: assessing the compliance with energy targets in related regulations, comparing the energy performance of a set of designed measures, estimating conventional buildings energy performance and forecasting future energy demand through the energy performance estimation for representative buildings of a large building stock. Three types of evaluation are foreseen: the "design rating", the "asset rating" and the "tailored rating". The former two enable to calculate a conventional energy demand and can be useful when comparing buildings, regardless their real usage pattern. Conversely, the tailored rating bases on accurate, customized and variable data, so that enables to realistically estimate the buildings energy use. In this case, typical values of global hourly internal heat loads, due to occupants, wasted DHW, electric appliances, artificial lighting and cooking, implemented from the EN 13790 [37], are provided as well as a set of profiles for different rooms within residential and office buildings and varying between workday and weekend day (Table 12).

Table 12. UNI/TS 11300-1:2014: Default specific global internal loads in residential and office buildings.

		Specific global internal loads [W/m^2]			
		in residential buildings		in office buildings	
Day type	**Hours**	**Living room and kitchen**	**Other rooms**	**Offices rooms**	**Other rooms**
Working day	7-17	8.0	1.0	20.0	8.0
	17-23	20.0	1.0	2.0	1.0
	23-7	2.0	6.0	2.0	1.0
Weekend day	7-17	8.0	2.0	2.0	1.0
	17-23	20.0	4.0	2.0	1.0
	23-7	2.0	6.0	2.0	1.0

Based on the defined typical floors, the global internal load hourly peak densities for a thermal zone in residential and tertiary Building Concepts were calculated (Figure 22, Figure 23) and then referred to the single thermal zone surface, as equal to 11.78 W/m^2 and 22.0 W/m^2, respectively.

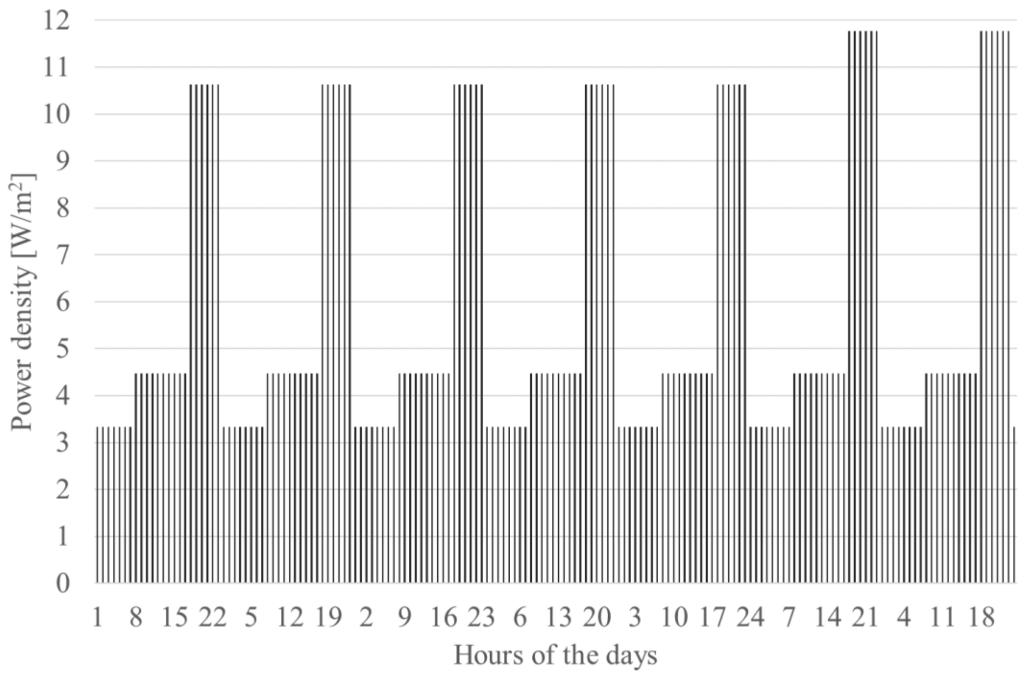


Figure 22. Internal heat load density profile of a residential Building Concept thermal zone during a week according to UNI/TS 11300:2014.

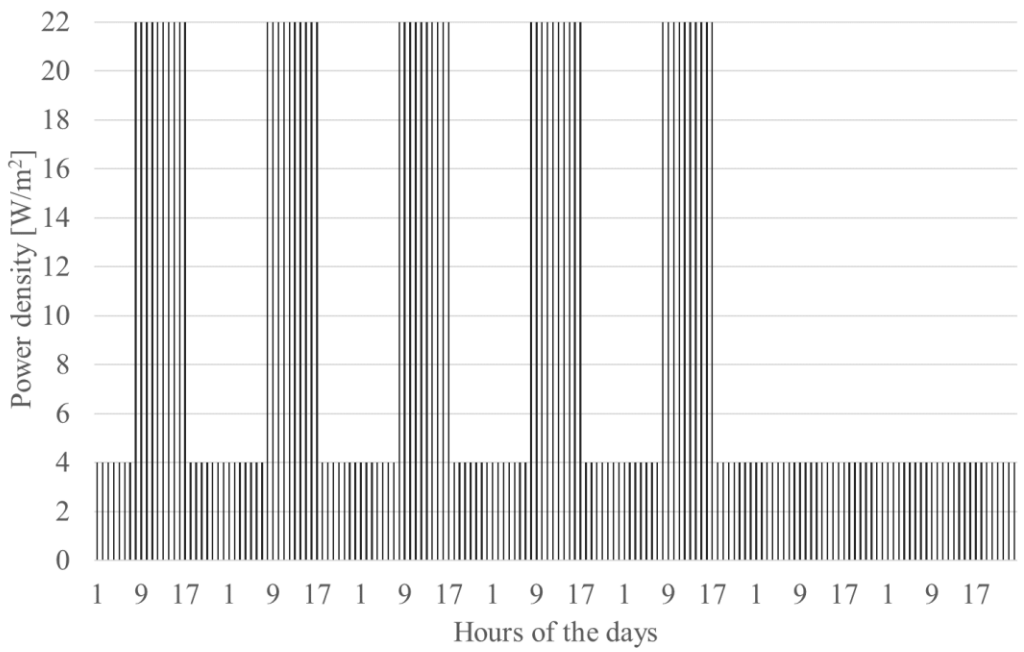


Figure 23. Internal heat load density profile of an office Building Concept thermal zone during a week according to UNI/TS 11300:2014.

The Swiss Society of Engineers and Architects (SIA) issued and periodically revises the technical worksheet SIA 2024, which aims at harmonizing the assumptions on spaces to be adopted in energy calculations when more precise data are missed. The standard can be applied for ensuring the thermal, acoustic and lighting comfort and sizing buildings systems in first analysis. In the last version, the **SIA 2024:2015 (SIA 2024)** [32] the needed assumptions for building energy-use calculations are provided in terms of detailed occupancy and appliance use data (e.g. people per floor area, installation power density, etc.) and hourly schedules that modulate the occupancy as well as the loads of the installations, which do not operate at their nominal power all the time. The usage patterns were derived by surveys on buildings in Switzerland, in order to cover most of the possible building use categories. Hence, data are provided for 45 rooms with reference to different building use categories (i.e. single-family house, multi-family house, administration, educational, commercial, restaurants, leisure, hospital, industrial, storage, sport, ancillary spaces). Peak values of equipment and artificial lighting are reported for three levels, namely "default" and "target", which are typical and optimal values, respectively, both to be adopted for new and largely renovated buildings, and "standard", for existing buildings data back before Eighties. In particular, the standard provides for the occupancy and equipment use proper hourly schedules for a typical day (i.e. generic or working one), while for the artificial lighting, the number of daytime and night-time usage hours, different by winter and summer; also, a monthly average simultaneity factor, equal to 80%, is provided (Table 13).

Table 13. SIA 2024:2015: Default specific internal loads in residential and office buildings.

Use category		**Occupancy (sensible)**			**Equipment**			**Artificial lighting**		
MULTI-FAMILY HOUSE	Usage hours per day [h]		17.0			24.0		4 (day-time) + 3 (night-time)		
	Full usage hours per day [h]		14.0			1.0				
	Peak heat load density (target/ default/ standard) [W/m^2]	2.3	2.3	2.3	4.0	8.0	10.0	1.7	2.7	2.7
OFFICE ROOM	Usage hours per day [h]		11.0			24.0		11 (day-time) + 0 (night-time)		
	Full usage hours per day [h]		7.2			2.0				
	Peak heat load density (target/ default/ standard) [W/m^2]	5.0	5.0	5.0	3.0	7.0	15.0	11.6	15.9	15.9
CORRIDOR	Usage hours per day [h]		13.0			0.0		11 (day-time) + 2 (night-time)		
	Full usage hours per day [h]		4.8			0.0				
	Peak heat load density (target/ default/ standard) [W/m^2]	1.0	1.0	1.0	0.0	0.0	0.0	4.6	7.0	7.0

Settings and profiles provided for a multi-family building were adopted for the residential case while, the ones for an office room (for up to 6 people) in a business day were combined with the ones for a corridor in any day for the office case. For considering the electric demand of electric appliances in stand-by mode is reported in the SIA 2024 as the 10% compared to the peak load, which has been adopted during the non-occupancy hours and weekend days. The calculated total hourly peak heat load, according to the three levels and referred to the thermal zone area, to be modelled according to provided schedules, are 6.55 W/m^2, 11.42 W/m^2 and 13.34 W/m^{2,} in the residential Building Concept, and 8.92 W/m^2, 17.60 W/m^2 and 24.00 W/m^2, in the tertiary one. Since the seasonal variation regards only the artificial lighting contribution and, additionally, with a not relevant reduction in summer (in fact only 2 hours less per day of lighting use are recommended), hereinafter an example of the weekly charts for an existing (i.e. standard level) residential and office Building Concept thermal zone uses in winter is reported (Figure 24, Figure 25).

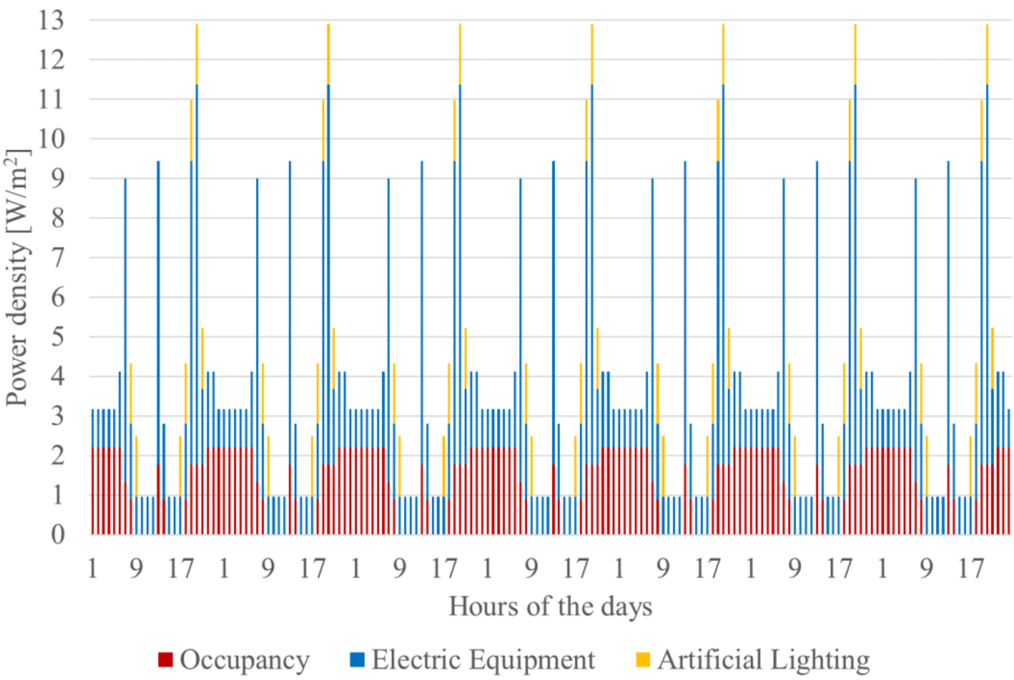


Figure 24. Internal heat load density profile of a residential Building Concept thermal zone during a winter week according to SIA 2024:2015 standard level.

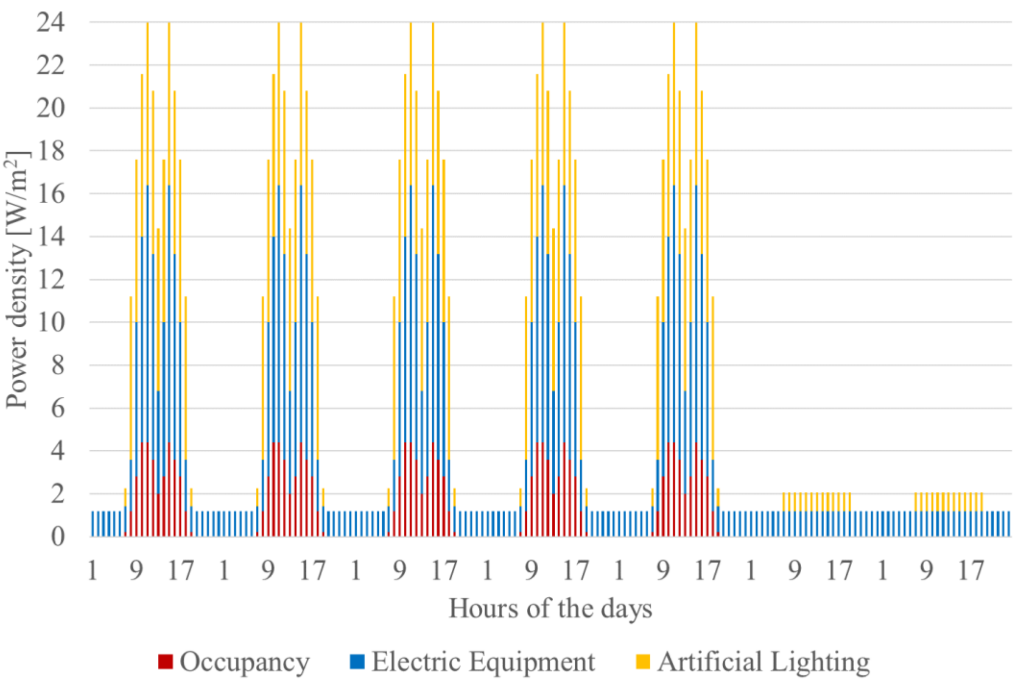


Figure 25. Internal heat load density profile of an office Building Concept thermal zone during a winter week according to SIA 2024:2015 standard level.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) issued and periodically revises the ANSI/ASHRAE/IES Standard 90.1 "Energy Standard for Buildings Except Low-Rise Residential Buildings", which establishes the minimum energy efficiency requirements and the criteria for determining the related compliance for buildings with more than three floors. In Appendix G, the Performance

Rating Method is outlined for quantifying the energy performance of buildings exceeding the fixed requirements, which is useful to define a baseline building performance to be compared with the one after the implementation of energy efficiency measures. In 2013, the **ASHRAE 2013 addendum to Standard 90.1 (ASHRAE 90.1:2013)** [33] has been issued with the scope to modify the Appendix G providing parameters that reflect the conditions of an existing not retrofitted building. The addendum provides the link to an external resource[8], where data, expressed in the United States customary units, are provided on heat loads per floor area due to electric appliances (namely the miscellaneous loads) and sensible and latent occupancy, natural ventilation and infiltration change rate and occupants' density as well as hourly schedules of occupants, artificial lighting, equipment, infiltration, cooling and heating set-point temperatures for three day-types (working day, Saturday and Sunday). Besides, two methods for assessing the internal heat loads due to artificial lighting are foreseen, one based on whole building use (e.g. hotel, multifamily houses, office, retail, sports, school /university, warehouse, etc.) and one based on room use (Table 14).

Table 14. ASHRAE 90.1:2013: Default specific internal loads in residential and office buildings.

Use category		Occupancy (sensible)	Equipment	Artificial Lighting
MULTI FAMILY HOUSE	Heat load density [W/m^2]	2.07	6.67	5.5
	Number of hours per day [h]	24	24	24
	Number of full hours per day [h]	10	2	2
OFFICE BUILDING	Heat load density [W/m^2]	3.94	8.07	8.8
	Number of hours per day [h]	18.0	24.0	24.0
	Number of full hours per day [h]	8.0	0.0	0.0

Provided settings and profiles for whole multifamily and office buildings as well as the lighting power provided for the whole buildings by use have been used for this study (Figure 26, Figure 27). The resulting peak values of internal loads for the Building Concept thermal zone to be modelled according to provided schedules are 10.50 W/m^2 for the residential case and 22.72 W/m^2 for the office one.

[8] http://sspc901.ashraepcs.org/documents.php

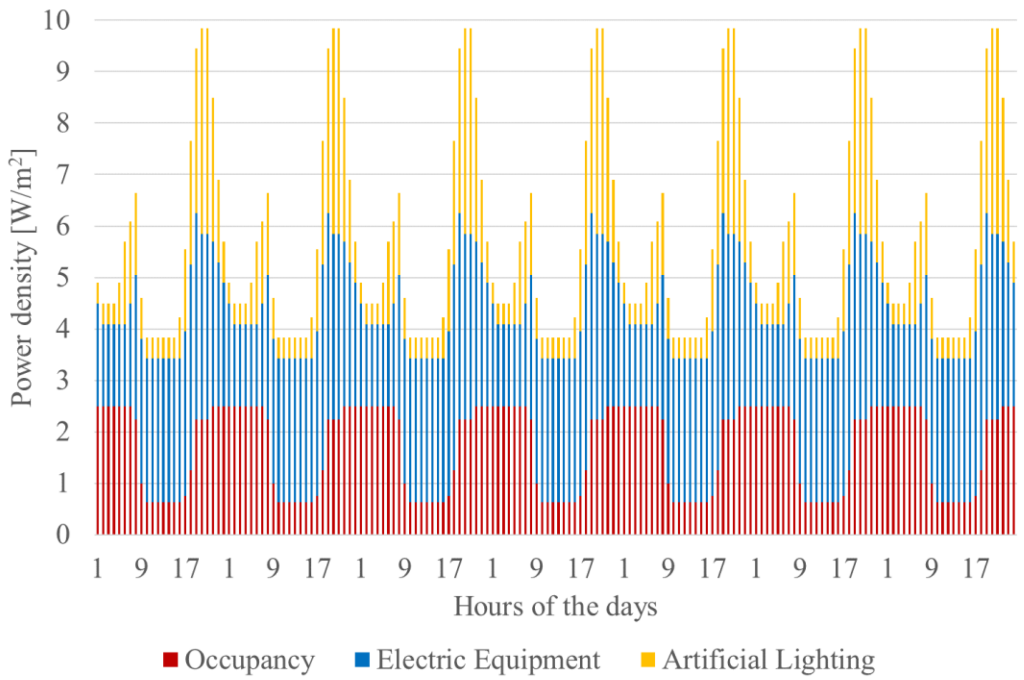


Figure 26. Internal heat load density profile of a residential Building Concept thermal zone during a week according to ASHRAE 90.1:2013.

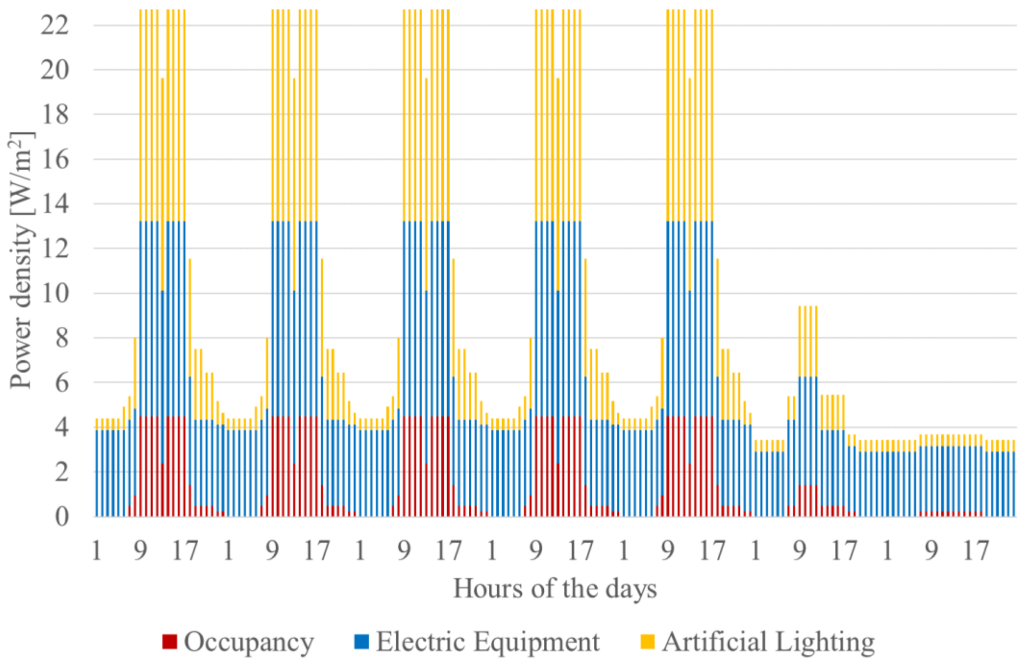


Figure 27. Internal heat load density profile of an office Building Concept thermal zone during a week according to ASHRAE 90.1:2013.

The International Organization for Standardization (ISO) has issued the standard **ISO 18523** – Energy performance of building – Schedule and condition of building, zone and space usage for energy calculation with regard to different building categories with the aim of specifying the formats to present the necessary schedules and conditions of buildings / zones / space usages) as input data of energy calculations.

In the part 1 of the ISO 18523 [34], which regards the non-residential buildings, for some rooms according to the building use category (i.e. office, hotel, hospital, commercial, educational, restaurant, library, museum, sport and leisure, theatre, religious), a set of informative data, developed between 2011 and 2012 on the basis of interviews to building technical systems designers and electricity consumption measurements, are reported in the Annex D. In particular, provided data (Table 15) regard: number of operation hours per year, peak densities per floor area of heat loads due to occupants (sensible and latent contributes), electric appliances and artificial lighting, occupancy density, required volume flow rate of mechanical ventilation in both conditioned and unconditioned spaces, average illuminance and working-plane height, daily demand per person and number of usage days of DHW, hourly schedules of heat loads disaggregated per occupants, appliances and artificial lighting as well as simultaneity factor for typical days. Considering that the ventilation requirement refers to mechanical ventilation, only internal heat loads have been following assessed.

For assessing the residential buildings, the second part of the standard has been later enacted [38]. Differently from part 1, in the standard part 2 the heat loads profiles have to be determined taking into account the family structure and activities and, as an example, a daily activity schedule for each person of a four-member family is attached. However, defining heat load profiles based on a particular family can be critical while assessing different families' structure and lifestyles is quite hard. Therefore, for this study, only the office building has been considered.

Table 15. ISO 18523-1:2016: Default specific internal loads in office building.

Use category		**Occupancy (latent + sensible)**	**Equipment**	**Artificial Lighting**
OFFICE ROOM	Heat load density [W/m^2]	11.9	12.0	12.0
	Number of hours per day [h]	13	24	13
	Number of full hours per day [h]	9	10	11
CORRIDOR	Heat load density [W/m^2]	3.6	0.0	15.0
	Number of hours per day [h]	13	0	13
	Number of full hours per day [h]	13	0	13

Since the provided value of the specific heat load due to occupancy considers the sum of sensible and latent heat, we adopted the share between sensible and latent heat from the ASHRAE 90.1:2013 in order to approximate the sensible heat load in the ISO 18523. The settings and profiles for the single office rooms and the corridor, in a workday and weekend day, have been combined to define the internal loads for the office Building Concept and referred to a single thermal zone (Figure 28), returning a total internal load of 34.01 W/m^2.

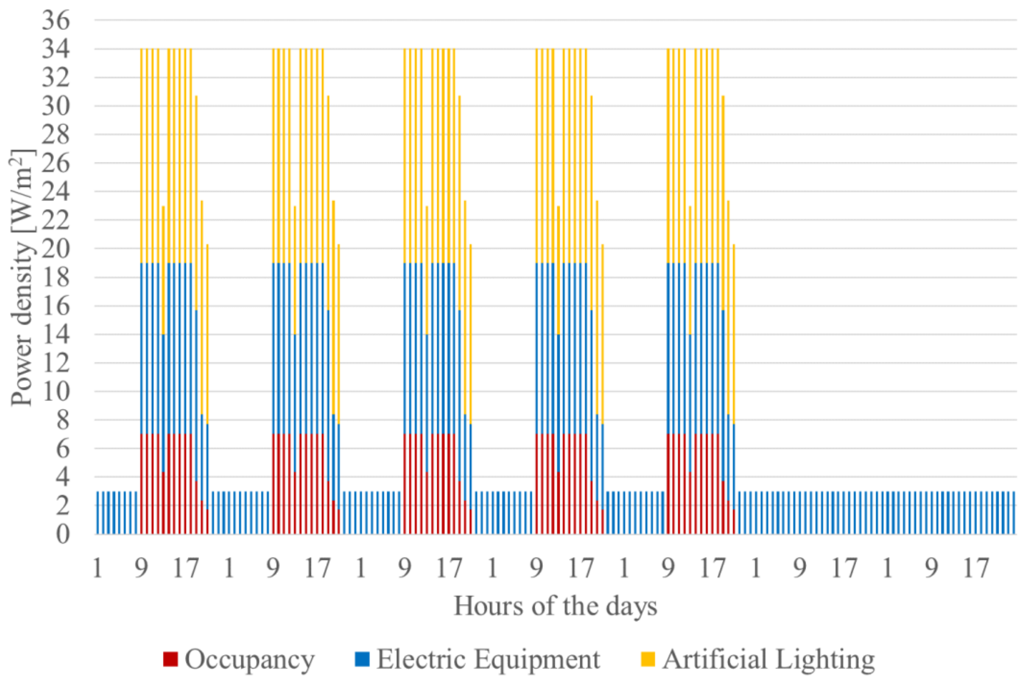


Figure 28. Internal heat load density profile of an office Building Concept thermal zone during a week according to ISO 18523:2016.

The European Commission has mandated to the European Committee for the Standardization (CEN), the European Committee for the Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI) to elaborate harmonized standards for the application of the Energy Performance Building Directive (EPBD recast). As a result, a modular package of 91 technical standards and workbooks has been enacted with the purpose to be both liable of immediate adoption as well as adaptation according to national contexts needs. The standard 52000-1:2017 [39] is the over-arching one since provides the general framework and procedure for the building energy performance calculation, recalling the subordinated standards. Among the latter, within the frame of overarching and building related modules and sixth and seventh sub-modules (namely the "Building occupancy and operating conditions and "Ways to express indoor comfort", respectively), it is referred to the **ISO 17772** (part 1 and 2, [35]-[36]), which indicates the requirements for indoor environmental parameters of thermal environment, indoor air quality (IAQ), lighting and acoustics and how establishing them for building energy calculation and systems dimensioning. In detail, within the Annex O - Occupants schedules for energy calculations, a set of informative default input values, such as occupancy and internal heat gains densities, set-point temperatures, ventilation rate, DHW demand and related schedules for a working and a weekend day, are reported for several building and rooms uses (e.g. educational, residential, office, commercial, etc.).

Among the offices related categories (i.e. single office, landscaped office and meeting room), the data of the landscaped office are used, since referring to an office building with more functions. The recommended load densities of 8.0 W/m^2 due to occupancy and of 12.0 W/m^2 due to equipment are adopted. Regarding the contribution of artificial lighting, the standard recommends referring to the EN 15193:2017 [40], which allows calculating the total installed power in offices based on room characteristics, so a value of 10.73 W/m^2

has been determined. While, within the residential buildings related categories (i.e. retired apartment, apartment and detached house), the data referring to the single apartment were combined at the building level. The recommended load densities of 2.8 W/m^2 due to occupancy and of 3.0 W/m^2 due to equipment are adopted. Conversely, the calculation of the internal load for artificial lighting is based on use and size of single rooms. Based on this, the total installed power for artificial lighting is calculated as equal to 8.24 W/m^2. The set load densities have been modulated according to the provided profiles for a typical working day and a weekend day and, in order to consider the stand-by consumption of electric appliances, the lowest load density due to equipment has been added during the not occupancy hours (Figure 29, Figure 30). The values elaborated for a thermal zone are: 6.85 W/m^2 (residential) and 19.20 W/m^2 (office).

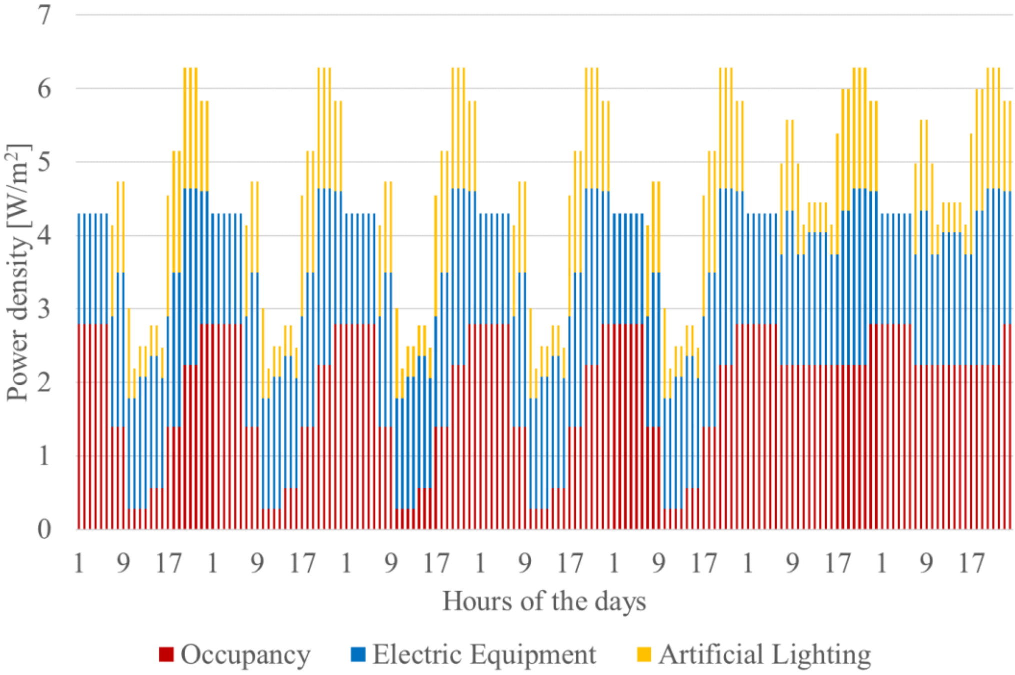


Figure 29. Internal heat load density profile of a residential Building Concept thermal zone during a week according to ISO 17772-1:2017.

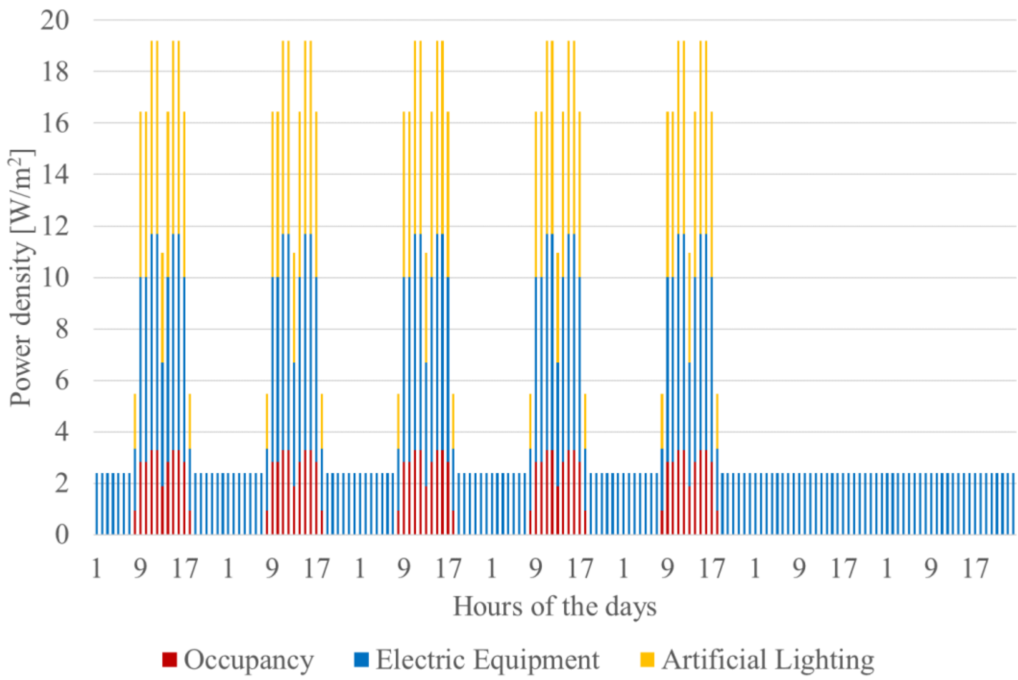


Figure 30. Internal heat load density profile of an office Building Concept thermal zone during a week according to ISO 17772-1:2017.

Discussions

In Figure 31 the hourly profiles of the internal heat load single contributions, determined according to the SIA 2024:2015 levels (SIA-STANDARD, SIA-DEFAULT, SIA-TARGET), ASHRAE 19.1:2013 (ASHRAE), ISO 17772:2017 (ISO 17772) and ISO 18523:2016 (ISO 18523) for both uses during a working day, are compared.

Regarding the residential building profiles, the SIA 2024:2015 foresees a peak in lunchtime for occupancy, three peaks in meal times for equipment and two, in morning and evening, for artificial lighting. Also, in the other hours the heat load profile is null, thus not considering different cases from the one with full-time working people. The ASHRAE and ISO 17772 provide less stepped profiles, with increasing occupancy towards the evening and a share of usage during day-time hours (e.g. students, elder people, part-time working people, etc.), artificial lighting use in the morning and evening. For the equipment, the ASHRAE foresees an increasing use towards evening, while the ISO 17772 foresees a higher share during meal-times.

Regarding the office building profiles, the SIA 2024 and the ISO 17772 foresee a more modular pattern for even eleven hours from 7:00 to 18:00 and a flexible lunchtime break too from 12:00 to 14:00. Regarding artificial lighting, the SIA contribution can assume only null or maximum values, as mentioned. The ASHRAE foresees a period with full occupancy of nine hours from 8:00 to 17:00 but a reduced usage is reported in the range 6:00-24:00 and during weekend days (actually, the occupancy during Sunday seems to be attributable to service workers since no equipment are used). Regarding artificial lighting, it does not foresee a reduction in lunchtime. The ISO 18523 foresees a full occupancy period of ten hours from 8:00 to 18:00 while a reduced occupancy up to 21:00. The lunchtime break is assumed in both ASHRAE an ISO 18523 between 12:00 and 13:00.

Figure 31. Profiles of internal heat loads density due to occupancy, equipment and winter artificial lighting of a residential and an office Building Concept thermal zone in a working day.

In Figure 32 and Figure 33, the annual heat loads, determined according to the SIA 2024:2015 levels, ASHRAE, ISO 17772 and ISO 18523 are compared.

Regarding the residential building case, the total peak heat load density of SIA-STANDARD (13.34 W/m^2) is the highest value together with the UNI/TS one (11.78 W/m^2), although the annual demand from SIA is 27% lower than the UNI/TS one (36.41 and 49.92 kWh/m^2_{year}, respectively) thanks to a profile which takes more into account the variability of occupancy and electricity consumptions as well as a lower artificial lighting demand in summer. The ASHRAE returns in a high annual internal heat load (49.84 kWh/m^2_{year}), which is closed to UNI/TS value and can be justified by a more continuous use of the building, compared to SIA levels and ISO 17772. The SIA-DEFAULT has a value of total peak heat load density closed to UNI/TS too (11.42 W/m^2) but carries out an annual demand that is largely lower (i.e. the 36%) than the UNI/TS one. More discontinuous use, more efficient devices and seasonal difference in lighting consumption feature the internal loads based on the SIA as the lowest ones. The total peak heat load density from SIA-TARGET and ISO 17772 (6.55 and 6.85 W/m^2, respectively) are comparably the smallest ones. However, the SIA-TARGET, which is considered for high performance new buildings, returns in a seriously lower annual heat load (20.87 kWh/ m^2_{year}) which is the 42% of the UNI/TS one, while the ISO 17772 heat load is closer to the highest level from SIA2024, i.e. the SIA-STANDARD which corresponds to existing buildings, can be reasonably adopted for the existing building stock. It is also interesting noting that the proportion of single internal heat loads contributions. A similar pattern emerges by comparing ASHRAE and ISO 17772 (occupancy 30-42%; equipment 47-40% and lighting 23-18%, respectively), even if the ASHRAE foresees the largest contribution from artificial lighting use. The SIA-TARGET gives the lowest weight to the lighting contribution (5%) while the greatest weight to the occupancy in the minimum level (54%). Briefly, the UNI/TS seems to overestimate the internal loads, possibly due to an increasing load towards night-time that is not reasonable considering the lower metabolic activity and lower electricity consumption; the ASHRAE reports a high consumption too, mainly due to artificial lighting use. Conversely, the ISO 17772 returns in a mean demand among assessed standards.

Regarding the office building case, the total peak heat load density and annual heat load from ISO 18523 are definitively the highest, with values (34.01 W/m^2 and 120.97 kWh/m^2_{year}, respectively) which are more than half greater than the average ones. Then, the SIA-STANDARD, the ASHRAE and the UNI/TS give comparable total peak heat load densities (24.0, 22.72 and 22.0 W/m^2) but the ASHRAE returns in an annual load (86.38 kWh/m^2_{year}) of 6% more than the UNITS one (81.74 kWh/m^2_{year}) while the SIA-STANDARD returns in a quite lower heat load (56.88 kWh/m^2_{year}). This can be explained because the ASHRAE foresees occupancy and use of artificial lighting, even if lower, in more hours on early morning and evening as well as at the weekend days, which is possibly attributable to building maintenance workers. Conversely, the SIA20204:2015 profile considers a gradual fluctuation of occupancy and usage but within working hours and a lower contribution of electric appliances passive consumption in not working hours. Also, the SIA-STANDARD carries out an annual load closer to the ISO17772:2017 (56.89 kWh/m^2_{year}) recalling the previously mentioned analogy. Given that in general in the offices the proportion among single contributions of internal heat loads is dominated by the ones from equipment and a little bit less from lighting (as average 44 and 35%), we can see some slight deviations in the SIA-DEFAULT ISO 17772, where the equipment contribution is greater (58%), and in ISO 18523, where the trend between equipment and lighting is inverted (33 and 46%). Conversely, the SIA-TARGET weekly energy demand is dominated by occupancy (44%) due to the fact that refers to new high energy performance buildings. With slight emphasis compared to the residential heat loads, the ISO 17772 provides mean values among the assessed standards and closed to the SIA level for existing buildings, therefore its adoption for this research scope has been considered as reasonable.

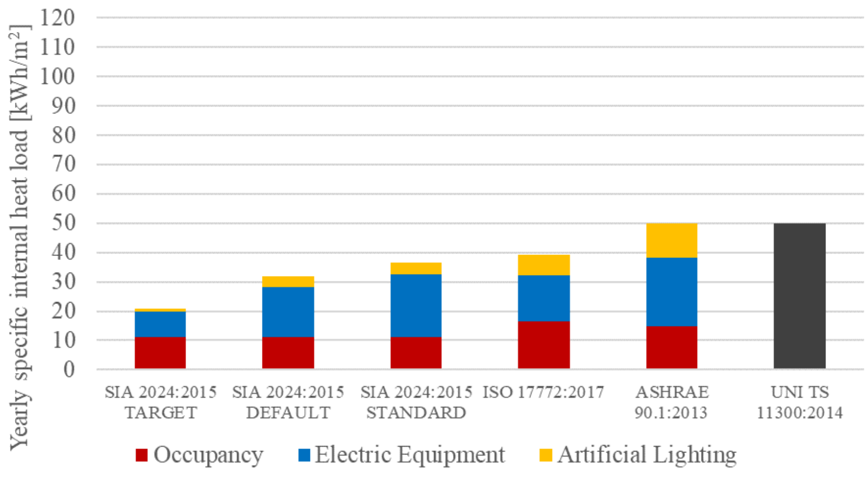


Figure 32. Yearly specific internal heat loads of a residential Building Concept thermal zone.

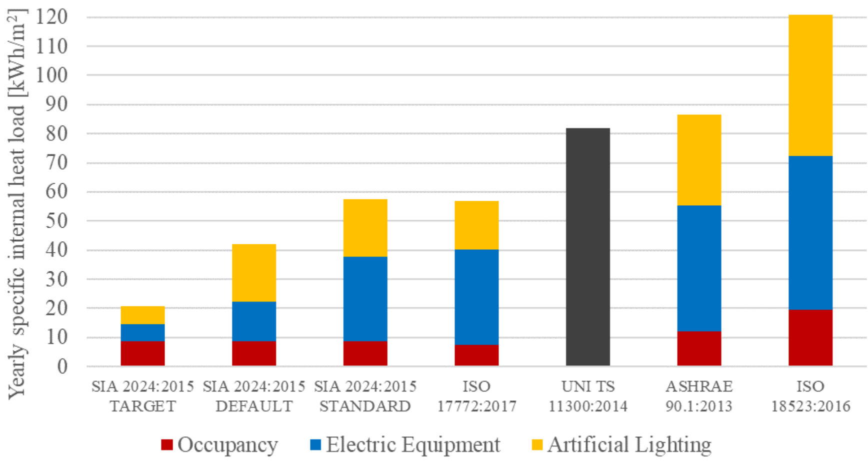


Figure 33. Yearly specific internal heat loads of an office Building Concept thermal zone.

3.5.2.2. Air change rates

To supply fresh air to the room, in order to remove smells and contaminants as well some heat, a minimum air change rate due to ventilation and air infiltration can be determined based on cited standards[9] and compared.

Within the **UNI/TS11300:2014**, in case of tailored rating, if it not possible accomplishing accurate evaluations, the standard refers to previous standards or to the standard rating. Therefore, for the residential buildings, it is possible adopting a total value of air change for ventilation and infiltration equal to 0.5 h^{-1}. While, for the office building, the rate of air change is calculated based on EN 15251 by considering a component depending on the building and one on the population (7.5 $10^{-3} m^3/s{\cdot}p$ and 0.4 $10^{-3} m^3/s{\cdot}m^2$, respectively). In both cases, the ACH has been split in the components due to ventilation and infiltration, considering a typical value of 0.2 h^{-1} for the latter. The rate due to ventilation has been modulated proportionally to the related global internal loads profile, except for null values

[9] The ISO 18523:2016 provides values of air change rate in case of mechanical ventilation so they are hardly comparable with the other standards and have not been compared.

in night-time in residential buildings, while the one due to infiltration has been fixed as constant during the days (Figure 34, Figure 35).

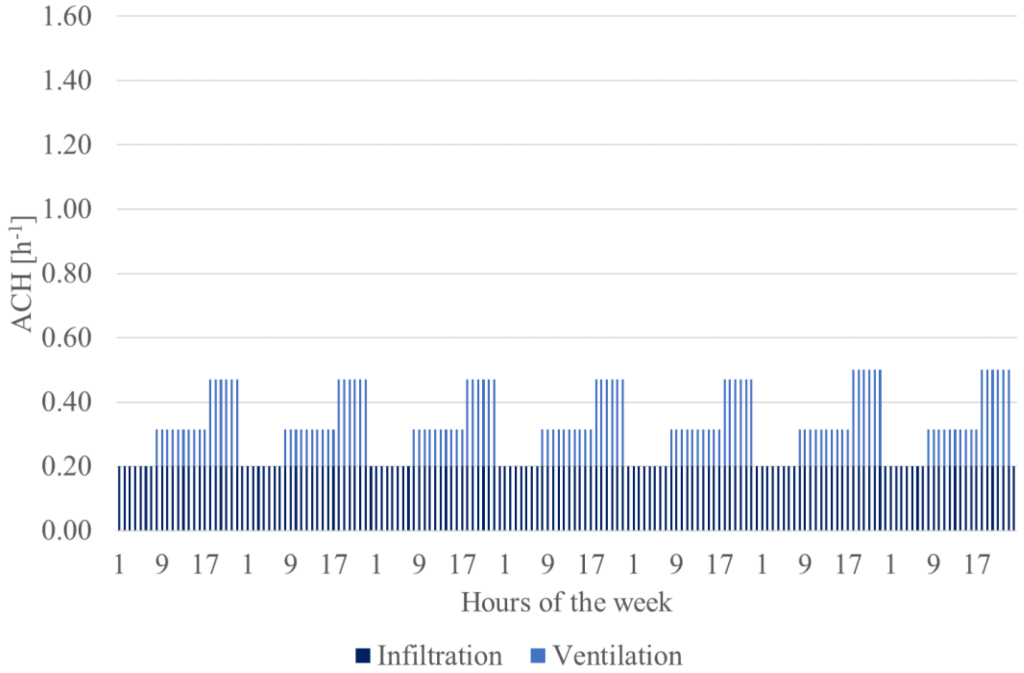


Figure 34. ACH profiles of a residential Building Concept thermal zone during a week according to UNIT/TS 11300:2014.

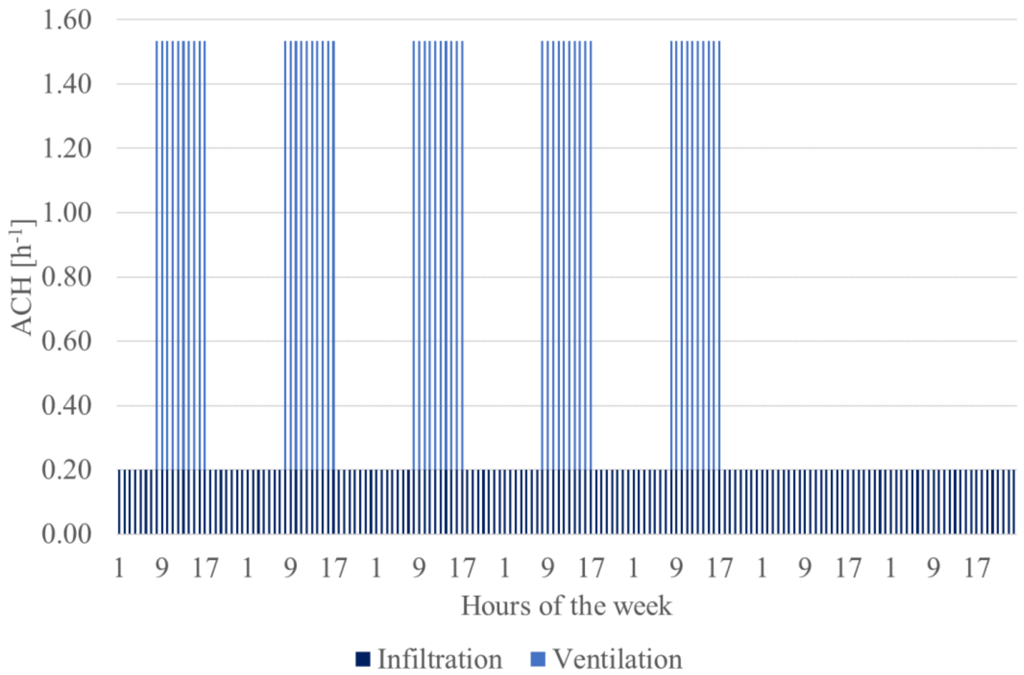


Figure 35. ACH profiles of an office Building Concept thermal zone during a week according to UNIT/TS 11300:2014.

The **SIA 2024:2015** recommends a rate due to ventilation per person (i.e. 30.0 and 36.0 m^3/h for the multi-family house and the office room, respectively) or per net floor area. In case of the residential building, the rate of ventilation per person has been modulated based on the number of people derived from the occupancy profile of residential building but considering null the ventilation in night-time hours in the case of the residential use. The office building profile has been determined since the combination of the ones for the office rooms and the corridor. In particular, the rate of ventilation for the single office room has been determined as in the residential case while for the corridor, the rate of ventilation per floor area (i.e. 2.0 m^3/hm^2) has been used and modulated proportionally to the occupancy profile. Regarding the ACH due to infiltration, two values are provided, namely in case of new (i.e. target and default levels) and existing buildings (i.e. standard level) equal to 0.15 or 0.3 m^3/hm^2, respectively. The infiltration rates have been alternatively assumed as constant during all days. Following, the determined profiles of ACH for a single thermal zone representative of the whole buildings are reported (Figure 36, Figure 37).

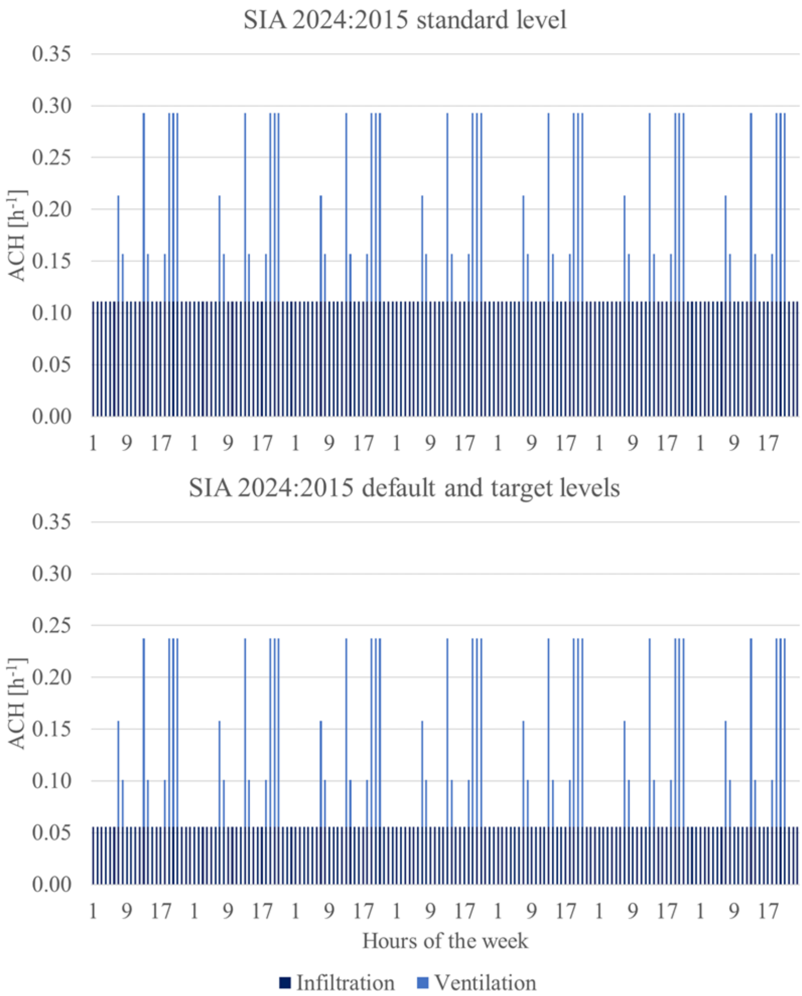


Figure 36. ACH profiles of a residential Building Concept thermal zone during a week according to SIA2024:2015 standard (above), default and target (below) levels.

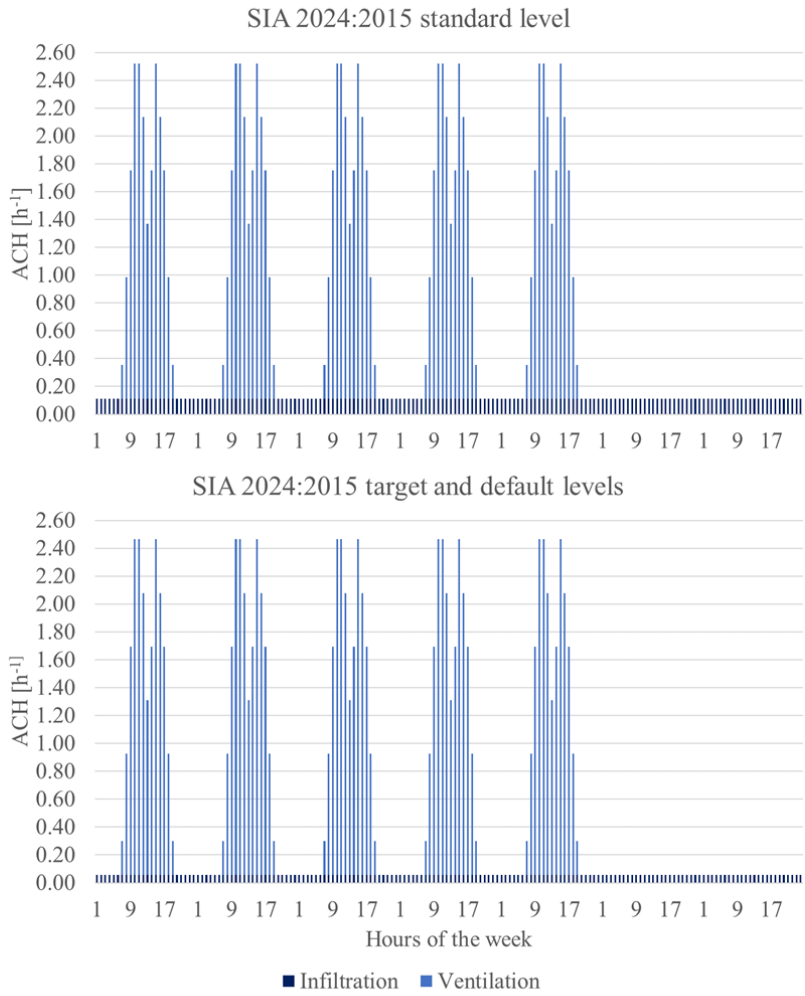


Figure 37. ACH profiles of an office Building Concept thermal zone during a week according to SIA2024:2015 standard (above), default and target (below) levels.

The **ASHRAE 90.1:2013** gives a value of ventilation of 1.097 h^{-1} and 1.65 h^{-1} for the residential and office buildings, while for infiltration a set of equations correcting the value based on the geometry of the building are provided. Based on the equation taking into account the envelope and floor area, a value of 0.32 h^{-1} due to infiltration for both uses was calculated. The nominal values of ACH due to ventilation have been modulated according to the occupancy profiles, except in night-time hours in residential case because we assumed a null rate, consistently with previous assumption. For the infiltration, according to the ASHRAE recommendations, it should be modulated on the basis of the provided profiles, which foresee a constant value in the case of the residential building, while a reduced value in occupancy hours in the case of the office building (Figure 38, Figure 39).

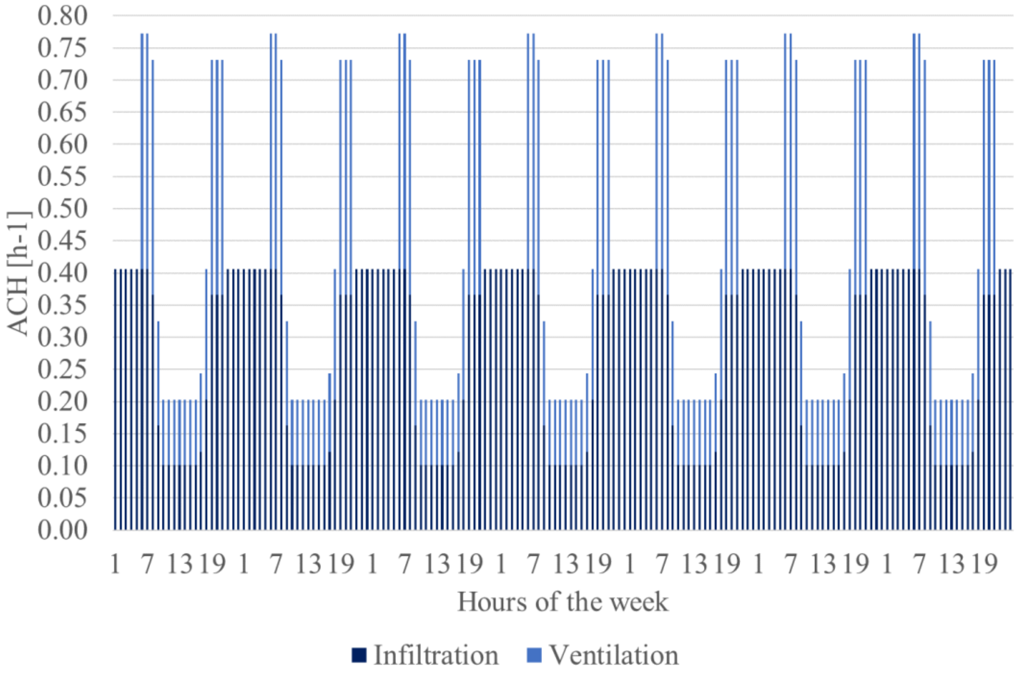


Figure 38. ACH profiles of a residential Building Concept thermal zone during a week according to ASHRAE 90.1:2013.

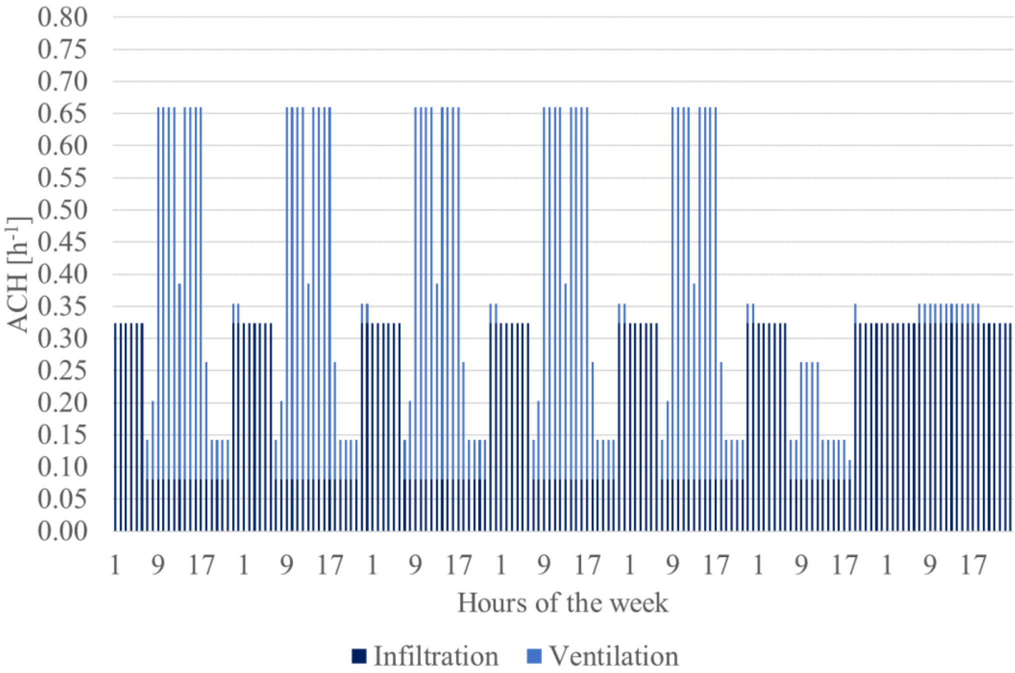


Figure 39. ACH profiles of an office Building Concept thermal zone during a week according to ASHRAE 90.1:2013.

For determining the rate of air change due to ventilation and infiltration, the mentioned **ISO 17772** refers to several alternative methods. The first method allows to determine the design ventilation rate on the basis of perceived air quality by summing two components, one for diluting/removing pollution from occupants and one referring to buildings and systems, which are defined by default for non-adapted people in non-residential and adapted ones in residential buildings. Default values are reported in Annex B of the standard. The second method allows determining the design ventilation rate to dilute an individual substance through a mass balance equation for the substance concentration in the space taking into account the outdoor concentration. Default values for CO_2 are reported in Annex B while the ones for other substances in Annex F. The third method, which has been adopted, allows to determine pre-defined minimum ventilation air flow rate to meet requirements for both perceived air quality and health in the occupied zone, both based on a required rate per person or per floor area. Furthermore, indoor environmental input parameters are given for four categories (from I to IV) referring to the level of occupants' expectations. Values referring to the highest category (i.e. I) should be selected for occupants with special needs (e.g. children, elderly, disabled people, etc.), to the medium category (i.e. II) in normal situations, while to the lower ones (i.e. III or IV) do not provide health risk but could decrease the indoor comfort. Therefore, in selecting the value of air change rate, we referred to the category II.

In case of residential buildings, the pre-defined minimum ventilation air flow rate can be alternatively determined as total air change rate for the dwelling, extract air flows for specific rooms, supply air flows for specific rooms or design opening areas for natural ventilation (Table 16). From Annex I - Basis for the criteria for indoor air quality and ventilation rates, Table I.6 - Criteria based on pre-defined supply ventilation air flow rates: Total ventilation (1), Supply air flow (2) and (3), the following possible ventilation air change rates per hour have been considered. In order to modulate the ventilation flow rate according to number of people, we decided to adopt the values referring to the method (3) for the category II. In particular, the value of 2.5 l/s person has been modulated based on the number of people from the occupancy profile and then summed to a constant value of 0.15 l/sm^2. Consistently with previous assumptions, the ventilation flow rate has been assumed as null in night-time hours.

Table 16. ISO 17772: Default values of air change rate for residential buildings.

Category	Method Total ventilation including infiltration (1)		Supply air flow per person (2)	Supply air flow based on perceived IAQ for adapted persons (3)	
	[l/sm^2]	[ACH]	[l/s person]	[l/s person]	[l/sm^2]
I	0.49	0.7	10.0	3.5	0.25
II	0.42	0.6	7.0	**2.5**	**0.15**
III	0.35	0.5	4.0	1.5	0.10
IV	0.23	0.4	-	-	-

In case of non-residential buildings, from ISO 17772-2:2018, Table C.2 - Non-adapted persons - Examples of recommended ventilation rates for non-residential buildings with default occupancy density for three categories of pollution from the buildings itself, values for several use categories (e.g. single office, landscaped office, conference room, department store, etc.) are provided and the ones proper for landscaped office buildings are reported in Table 17. Additionally, the input parameters are provided for buildings with different level of pollution: the very low-polluted ones are predominantly featured by very low-emitting materials and furniture, holds activities with prohibited emission of pollutants and without previous emitting sources (e.g. tobacco smoke, cleaning, etc.); the low-polluting ones are predominantly featured by low-emitting materials and holds activities with limited emission of pollutants, instead non-low polluting ones are the ones where no effort have been done. Considering this, the values referring to the average condition, as the low-polluted buildings, have been adopted. Consistently with previous assumptions, only during occupancy hours, we modulated the value of 7 l/s person according to the number of people, based on the previously determined occupancy profiles, and summed to a fixed value of 0.7 l/sm^2.

Table 17. ISO 17772: Default values of air change rate for landscaped office buildings.

Category	Floor area per person [m^2/person]	Minimum ventilation rate for occupants (q_P) [l/sm^2]	[l/s person]	Minimum ventilation rate for buildings (q_B) very low-polluted [l/sm^2]	low-polluted [l/sm^2]	non-low polluted [l/sm^2]
I	15	0.7	10	0.50	1.0	2.0
II	15	0.5	**7**	0.35	**0.7**	1.4
III	15	0.3	4	0.20	0.4	0.8
IV	15	0.2	2.5	0.15	0.3	0.6

Additionally, a fixed infiltration rate of 0.2 h^{-1} is adopted. Averagely, a daily ACH of 0.7 h^{-1} in the office building and of 0.37 h^{-1} in the residential one is obtained. Elaborated ACH profiles are reported in Figure 40 and Figure 41.

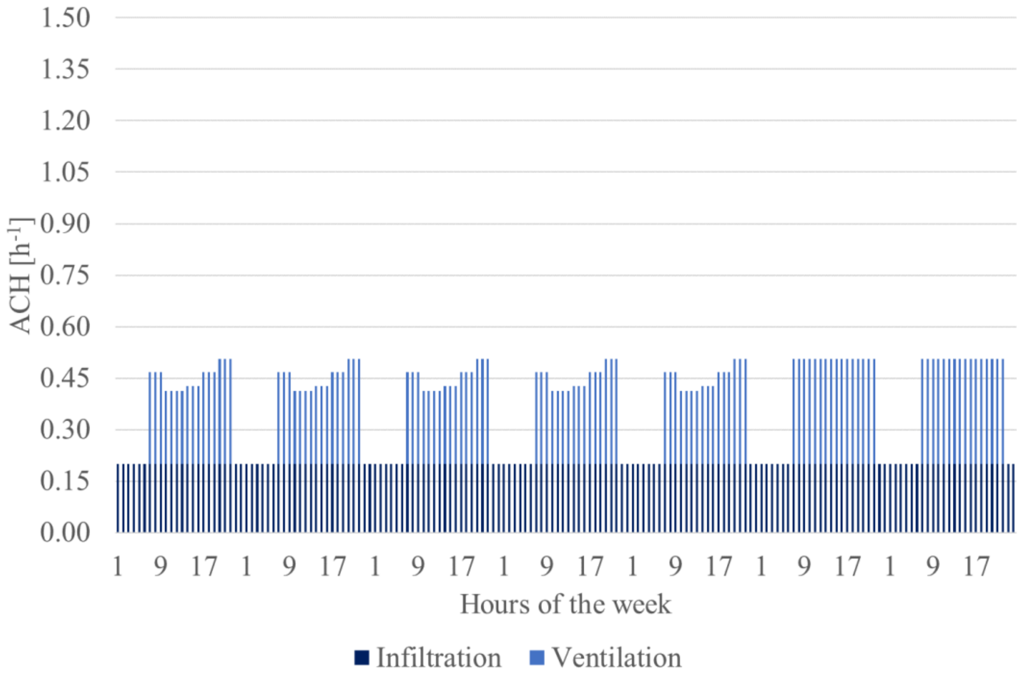


Figure 40. ACH profiles of a residential Building Concept thermal zone during a week according to ISO 17772:2017.

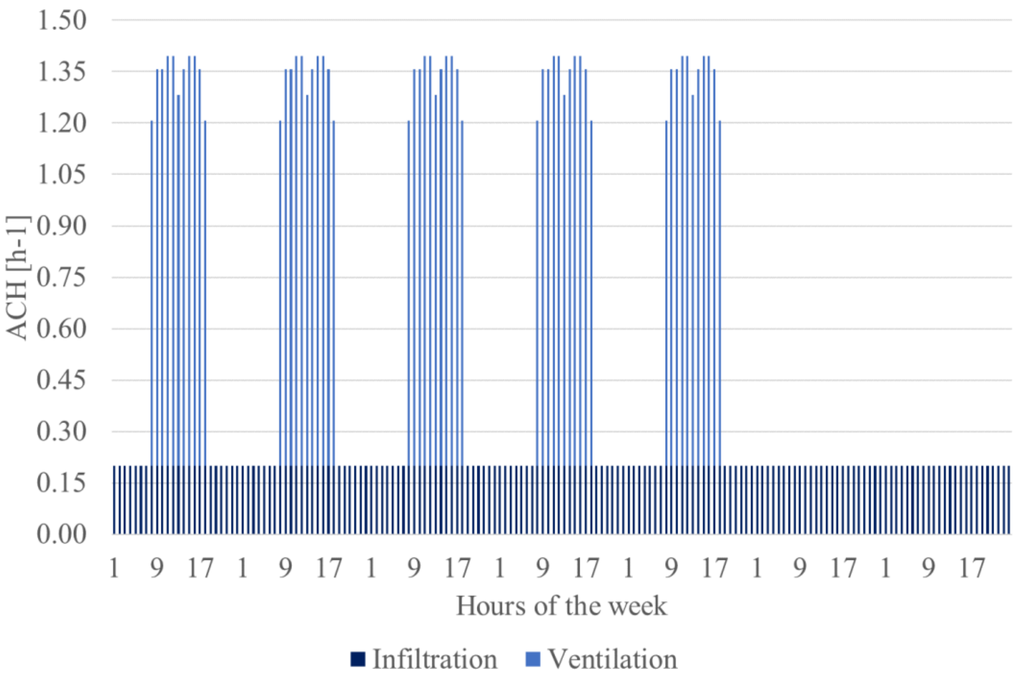


Figure 41. ACH profiles of an office Building Concept thermal zone during a week according to ISO 17772:2017.

In Figure 42, the hourly profiles of overall air change rate determined according to the SIA 2024:2015 levels (SIA-STANDARD, SIA-DEFAULT, SIA-TARGET), ASHRAE 90.1:2013 (ASHRAE) and ISO 17772:2017 (ISO 17772), during a working day are compared. Since in most cases, they have been determined based on the occupancy profiles, they are consistent with the related assumptions. In fact, this has led, in residential building case, to obtain three increased air changes in morning, lunchtime and dinner-time according to SIA 2024 levels, two peaks according to ASHRAE, which considers full-time working people, gradual increases towards night-time according to UNI/TS11300 and ISO17772, thus considering different type of families and in the latter case with even a more realistic profile. Regarding the office building, a strongly stepped chart based on UNI/TS 11300 has been determined, neglecting lunchtime, as conversely considered in ASHRAE and SIA levels, or a more gradual behaviour, as in ISO 17772.

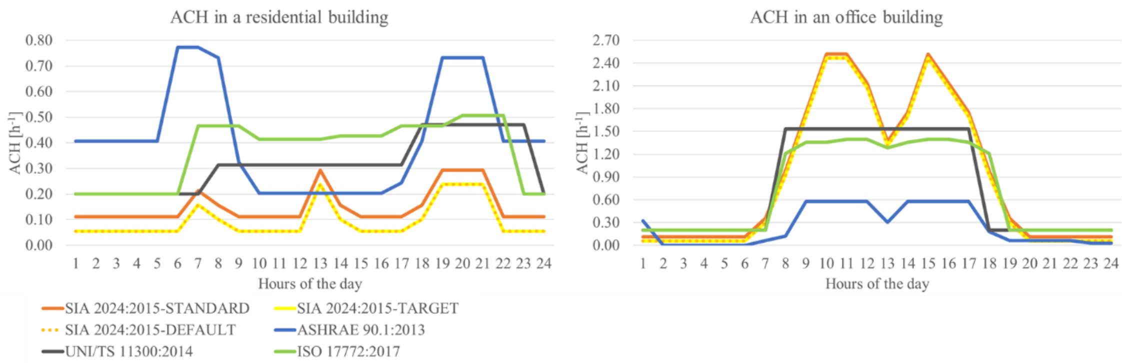


Figure 42. Profiles of ACH due to both natural ventilation and infiltration of a residential (a) and an office (b) Building Concept thermal zone in a working day.

In Figure 43, by assuming an air capacity of 1200 J/m^{3}K, the resulting total volume of air changed during a year, is reported for both Building Concepts thermal zones according to the assessed standards. Consistently with the previous section, it can be noted that the standard ISO 17772 leads to mean values so, considering that it is a recent standard valid for all contexts, it has been adopted for this research.

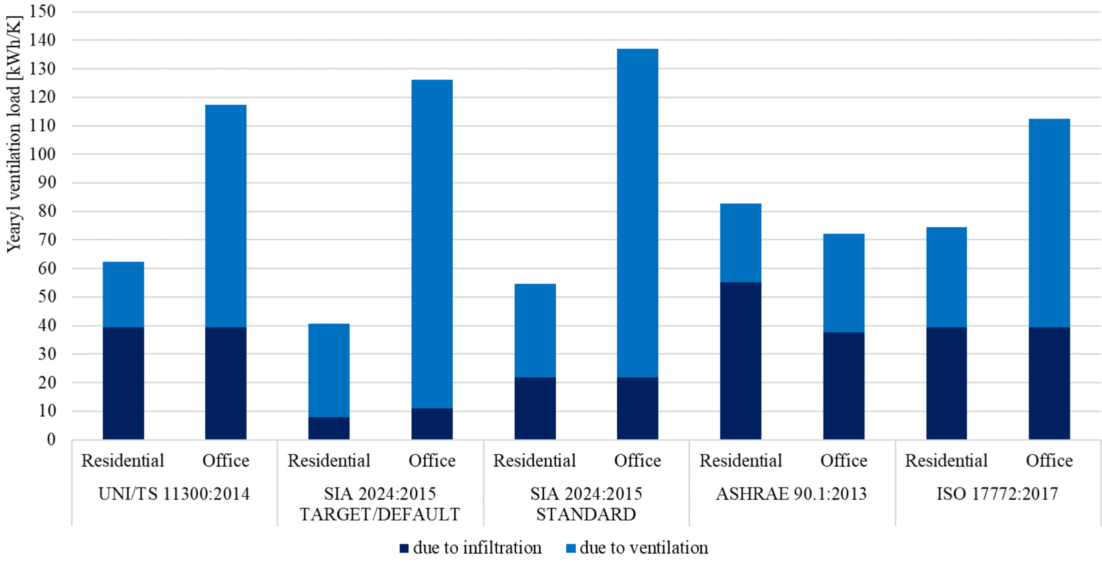


Figure 43. Yearly ventilation load of a residential and office Building Concept thermal zone.

3.5.2.3. Space heating and cooling settings

For defining the thermal systems activation settings, we referred to national regulation and solid previous research.

In Italy, the heating season length, and the limited number of hours per day in which the use of heating systems is allowed, is defined based on the heating degree days (HDDs) according to [41] (Table 18) while any national rule doesn't concern the cooling systems use. In the climatic zone E, where the case study of the city of Milan (2404 HDDs) is placed, the space heating activation is foreseen from October the 15th to April the 15th for no more than 14 hours per day.

Table 18. Climatic zones and related space heating settings in Italy.

Climate zone	HDDs	Heating season	Maximum number of space heating per day
A	<=600	December 1st – March 15th	6
B	601-900	December 1st – March 31st	8
C	901-1400	November 15th – March 31st	10
D	1401-2100	November 1st – April 15th	12
E	2101-3000	October 15th - April 15th	14
F	>3000	not limited	not limited

Consistently, the daily space heating activation period is adopted for the residential buildings in two ranges, chosen according to common practice, while for the office one, as slightly extended respect to the occupancy one. Regarding the daily space cooling period of activation, no limitations have been set for the residential building, while it has been referred to the occupancy hours too for the office one. Related profiles are in Figure 44.

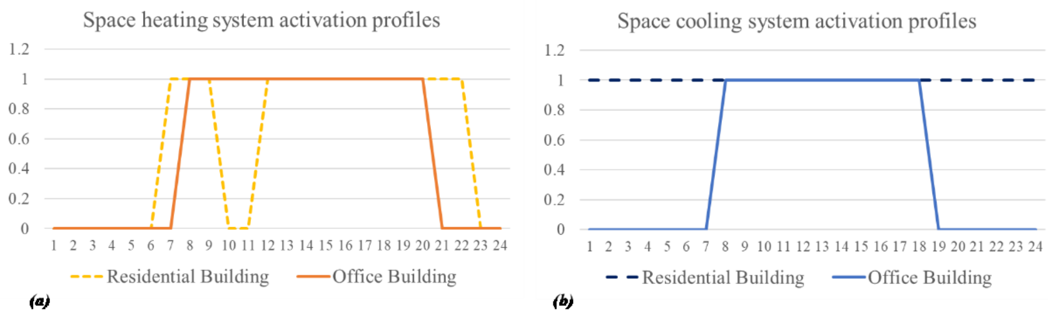


Figure 44. Profiles of space heating (a) and space cooling (b) activation for a residential and an office Building Concept thermal zone during a working day.

Regarding the set-point temperatures (referred to 20°C for heating and 26°C for cooling, as usually), the following considerations are assumed.

For the design of the thermal environment criteria, the recent standard on the hourly calculation method [42] recommends adopting the operative temperature. Indeed, in common practice, active systems are regulated according to air temperature sensors and the building simulation praxis refers to the same approach. However, the set-point regulation adopted for the Building Energy Models of this study is performed according to operative temperature: thanks to this assumption, it is possible to properly take into account the performances of the different building envelopes in contributing to overall thermal comfort sensation, i.e. in providing suitable surface radiant temperatures. These last ones, in case of unfavourable resulting values, are often responsible for an overusing the active climatization systems for correcting the indoor condition, air side, implying additional energy consumptions.

Additionally, the adaptive method, which is also foreseen in the recent standards [34],[42], for not mechanically cooled buildings for office buildings and other similar ones (e.g. residential), whose occupants are mainly engaged in sedentary activities, are able to freely adapt their clothing to the indoor and/or outdoor thermal conditions and have easy access to operable windows, has been considered. In particular, for the residential Building Energy Models, variable operative temperature values are considered for assessing the thermal energy needs in summer according to the adaptive comfort approach, which has a dynamic form depending on a transient parameter such as the external temperature of the considered period. Adaptive comfort equations were developed within a previous research, for different building uses and climatic contexts, on the assumption that the occupants are an active part of the enclosed environment: they can interact with the construction and can affect the building boundary conditions regardless of the presence of an active climatization system, as usual in Italian residential sector. In these conditions, the real thermal needs strongly depend on the comfort mitigation strategies adopted by users, and the thermal expectations are strictly related to the outside mean climatic conditions (thermal experience). In particular, the equations adopted in [43]-[44] were assumed for this study as well as the calculated adaptive comfort temperatures for Milan (Figure 45).

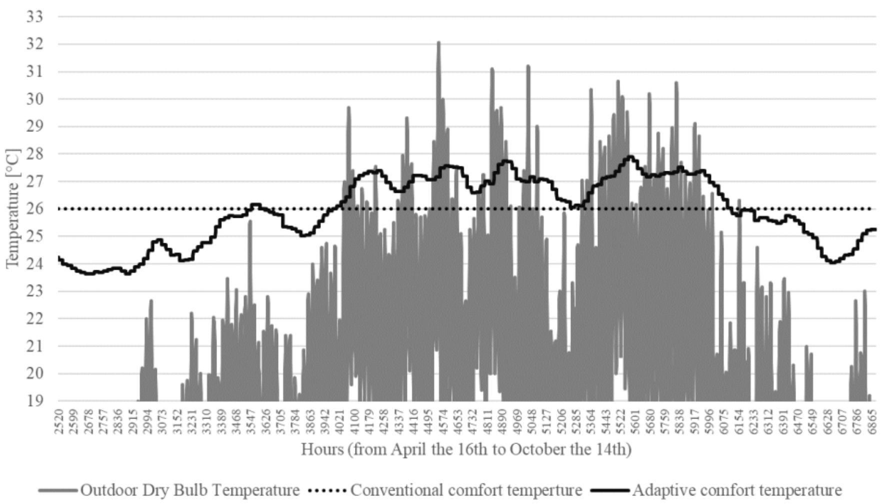


Figure 45. Adopted adaptive comfort temperatures in non-heating season for the city of Milan.

As an addition, considering that in residential buildings, especially in Mediterranean climate, the use of natural ventilation through opening of the windows, is a common practice for contrasting the indoor overheating and contributes in reducing the energy consumption for space cooling, a free cooling strategy in summer has been modelled. For taking into account a more realistic behaviour, the space cooling activation in residential buildings is constrained to the activation of an additional air change rate, simulating the windows opening, fixed equal to $5h^{-1}$ according to a previous study [45]. In detail, when the inside environment is overheated (i.e. the operative temperature is greater than the adaptive comfort one), if it is revealed a cooler outside temperature (i.e. the adaptive comfort temperature is greater than the dry bulb one), the natural ventilation is activated otherwise (i.e. the adaptive comfort temperature is lower than the dry bulb one) the space cooling need is calculated. From an operative perspective, considering the equations of operative temperature and adaptive temperature in [43]-[44]:

$T_{co}=a*T_{ext}+b$

$T_{op}=(T_{air}+TMR)/2$

$T_{co}=(0.11*T_{mr}+22)*2.5$

they had been set in the TRNSYS Simulation Studio calculator as:

- $Tsp\_heat_{ij}=(2*20°C-TMR_{ij})*Schedule_{heat}$
for the hourly set-point temperatures in case of space heating demand for both the residential and office buildings

- $Tsp\_cool_{ij}=(2*26°C-TMR)+50*Schedule_{cool}$
for the hourly set-point temperatures in case of space cooling demand for the office building

- $Vent_{ij}=and(gt(T_{op},T_{adaptive}),gt(T_{adaptive},T_{out}))*and(gt(time,start),lt(times,stop))$
for the hourly ventilation satus for the residential building in cooling season

- `Tsp_cool`$_{ij}$`=(2*T`$_{adaptive}$`-TMR)*and(gt(time,start),lt(times,stop))+60* Vent`$_{ij}$
for the set-point temperatures in case of space cooling demand for the residential building

where:

T_{ext} = mean running temperature
T_{mr} = average daily temperature of previous days
TMR(ij) = mean radiant temperature (of thermal zone ij)
Tsp-heat$_{ij}$ / Tsp-cool$_{ij}$ = space heating/cooling set-point temperature of thermal zone ij
Schedule$_{heat\ /\ cool}$= schedule of space heating/cooling activation
Tadaptive = comfort temperature according to adaptive approach
Vent$_{ij}$ = summer ventilation activation for thermal zone ij
T_{out} = dry bulb temperature
and (a,b) = Trnsys function for verifying if two conditions are both satisfied
gt (a,b) = Trnsys function for verifying if a is greater than b
lt (a,b) = Trnsys function for verifying if a is lower than b

3.5.3.Buildings Energy Models energy density profiles

Once modelled the Building Energy Models according to the two uses and five envelope solutions, we determined hourly profiles for one year of thermal energy need as well as electricity demand.
Dynamic energy simulations of sensible energy need for space heating and cooling were performed on hourly time-step for one year by means of TRNSYS 2017 [10]. The simulations have been carried out for each Building Energy Model and, in order to appreciate the effects of solar radiation, Building Concepts have been rotated through the four main exposures (i.e. north, south, east and west). For each one of the mentioned nine typical thermal zones, related hourly energy needs [kJ/h] for a whole year have been determined. For considering with good approximation the buildings random orientations in urban context, final energy needs profiles refer to the average of the four main exposures [46]. As an example, we present the charts of space heating and cooling energy need density profile for one typical thermal zone, in particular placed on the corner on the top floor (TC) which is the one more affected by solar radiation, for a residential (Figure 46) and a tertiary (Figure 47) Building Energy Model.

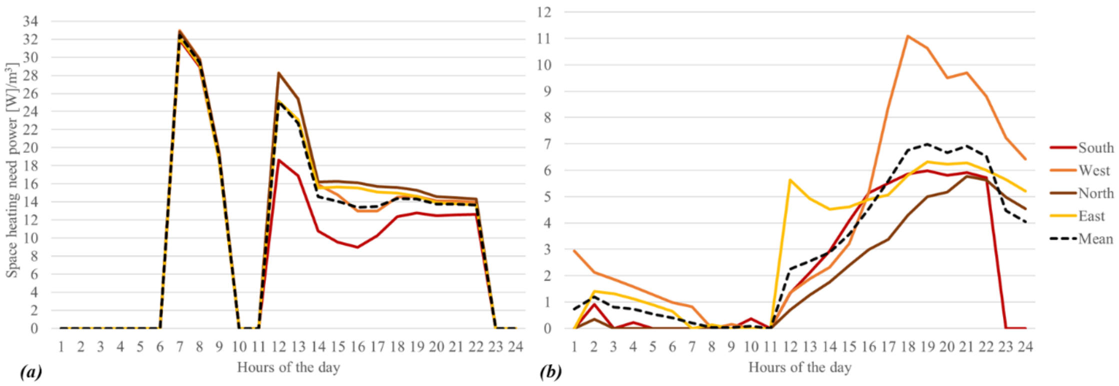


Figure 46. Energy density profiles of space heating (a) and cooling (b) need of a 60s-80s residential Building Energy Model TC typical thermal zone for four opposite orientations and as average.

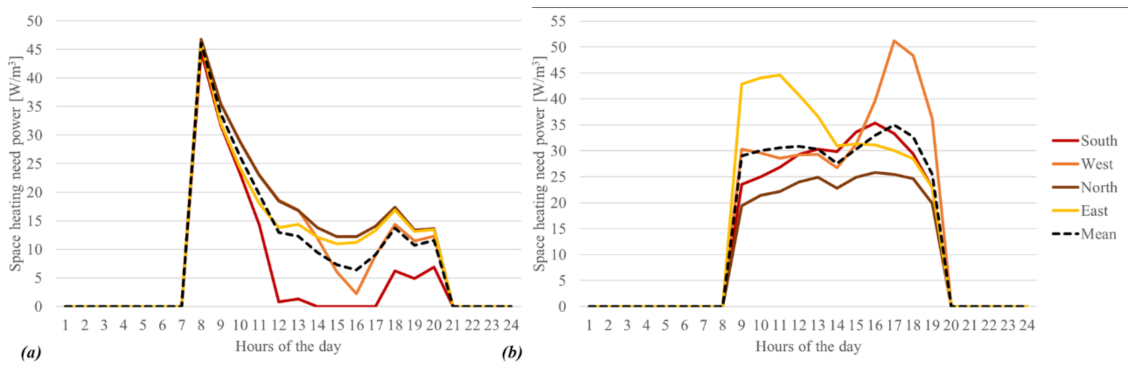


Figure 47. Eenergy density profiles of space heating (a) and cooling (b) need of a 60s-80s sandwich largely glazed office Building Energy Model TC typical thermal zone for four opposite orientations and as average.

Consistently with the previously described GIS-based procedure, where it has been possible modelling only six typical thermal zones, we averaged per each floor the energy values referring to typical thermal zones placed on the corners and on the edges, thus obtaining profiles for six typical thermal zones. In order to associate the energy profiles to the built volume, they have been first expressed as energy density per unit of net conditioned volume [W/m^3] and then converted into energy need density per unit of gross volume, by assuming a net-to-gross ratio of 0.6 for old buildings and 0.7 for the 60s-80s and recent ones.

Besides, the hourly-based profiles of electricity demand for equipment and artificial lighting for one year have been derived through calculation of the installed power and its modulation according to profiles defined in section 3.5.2.1. Then, the profiles determined per unit of net conditioned volume [W/m^3] have been converted into ones per unit of gross volume, assuming the ratios as previously specified.

In Figure 48, the matrix of assessed cases is reported.

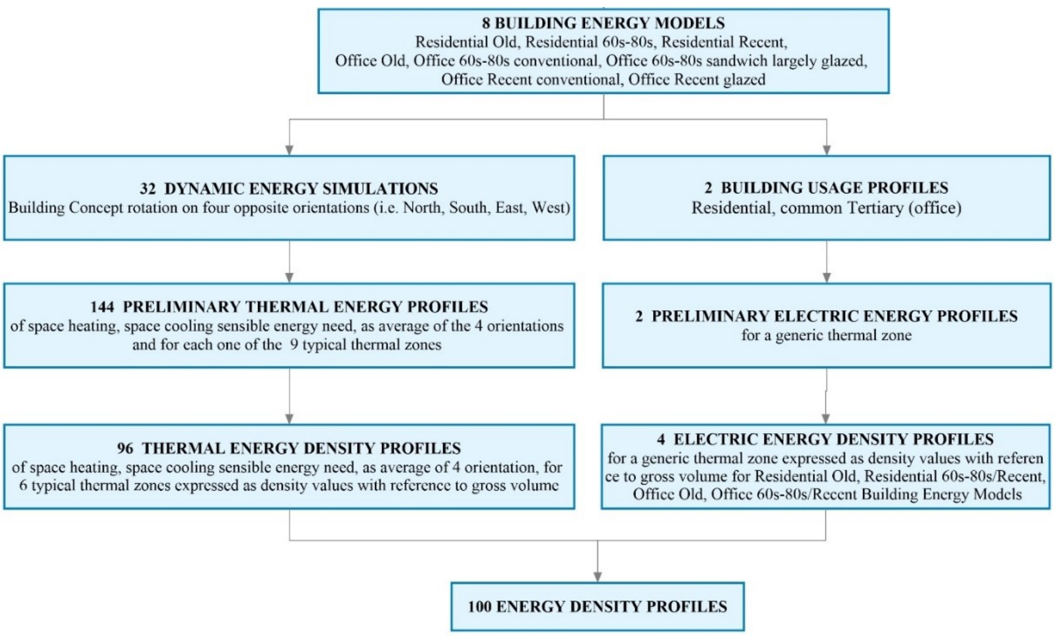


Figure 48. Matrix of assessed Building Energy Models and determined energy density profiles.

3.5.3.1.Exemplary energy density profiles

Below, as an example, density profiles in W/m³ of gross volume for all Building Energy Models placed in Milan, are reported by typical thermal zone and for two representative days (working and weekend ones) of the season, with reference to: space heating energy need (from Figure 49 to Figure 56), space cooling energy need (from Figure 57 to Figure 64) and electric energy demand (from Figure 65 to Figure 68).

3.5.3.1.1.Space heating energy need density profiles

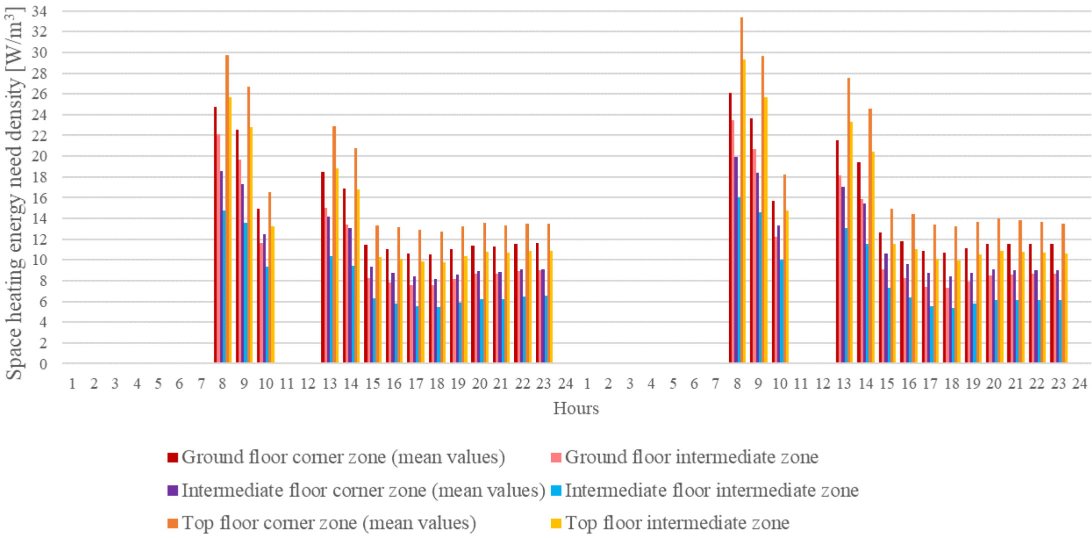


Figure 49. Space heating energy density profiles [W/m³gross] of typical thermal zones of the Residential Old Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

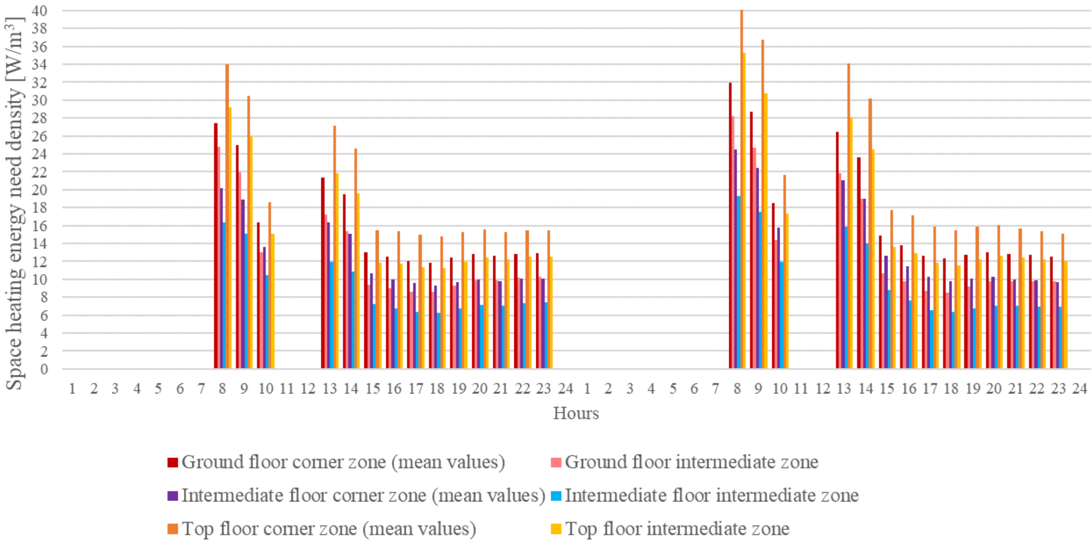


Figure 50. Space heating energy density profiles [W/m³gross] of typical thermal zones of the Residential 60s-80s Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

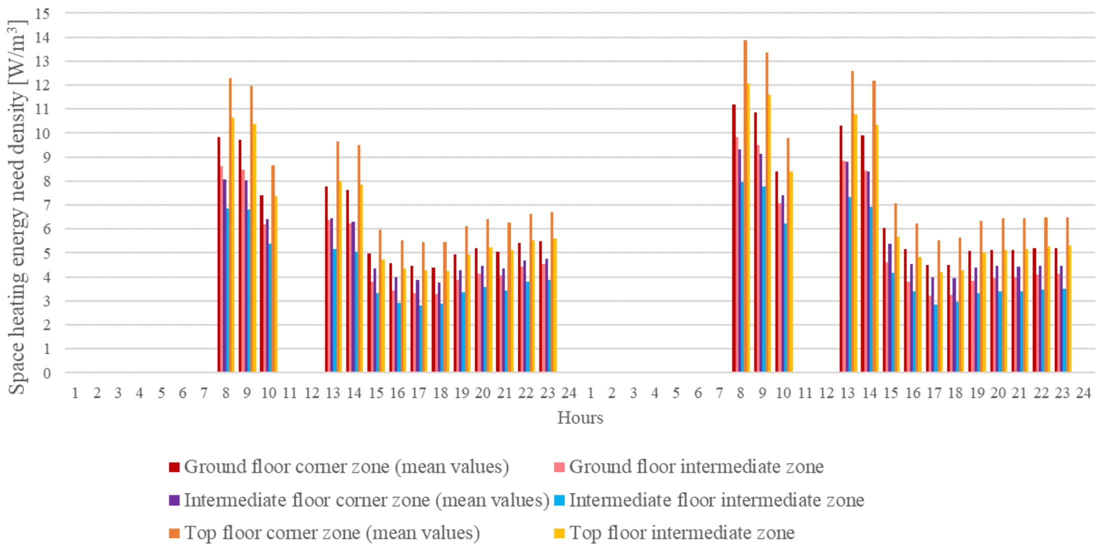


Figure 51. Space heating energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Residential Recent Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

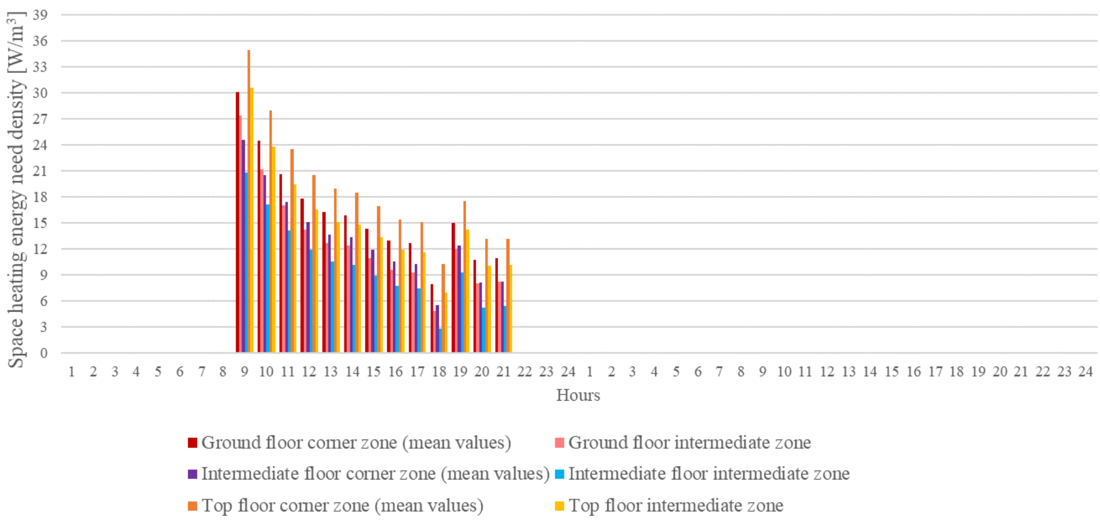


Figure 52. Space heating energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office Old Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

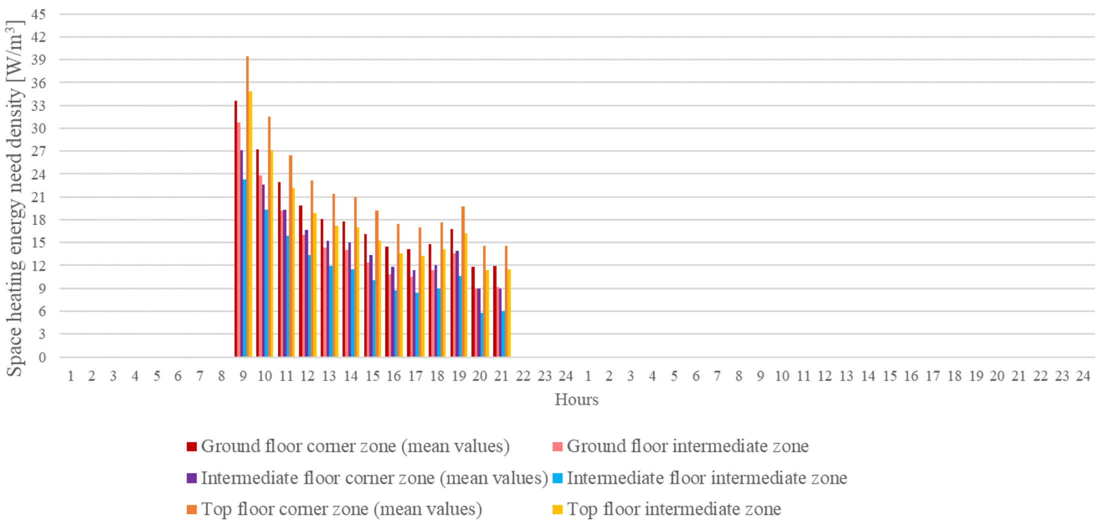


Figure 53. Space heating energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office 60s-80s Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

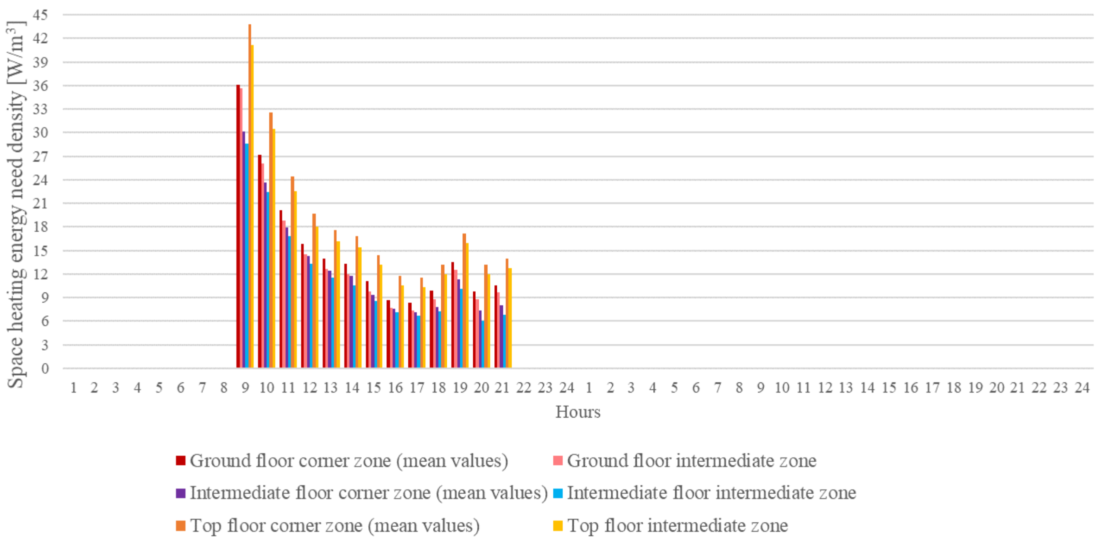


Figure 54. Space heating energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office 60s-80s Sandwich Largely Glazed Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

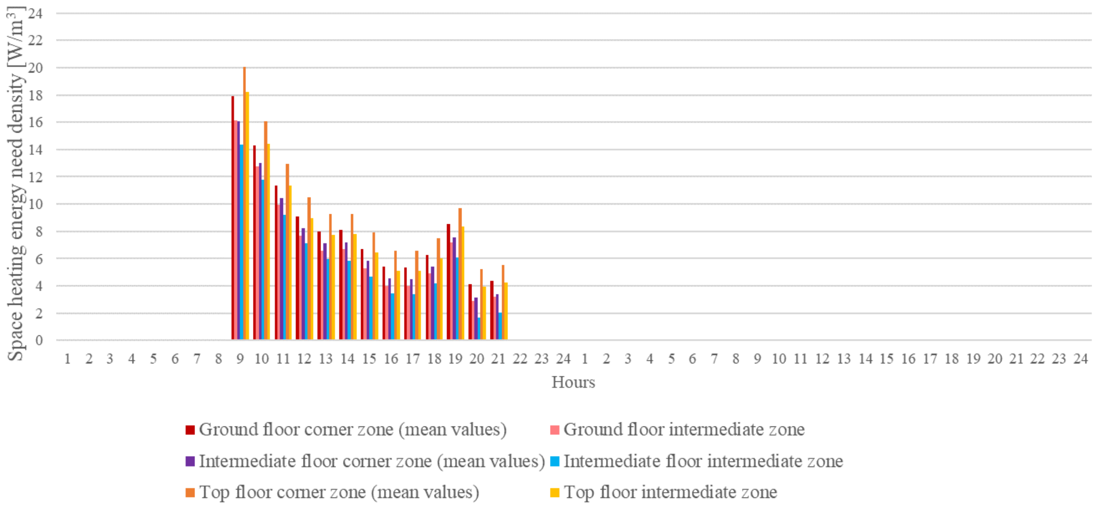


Figure 55. Space heating energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office Recent Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

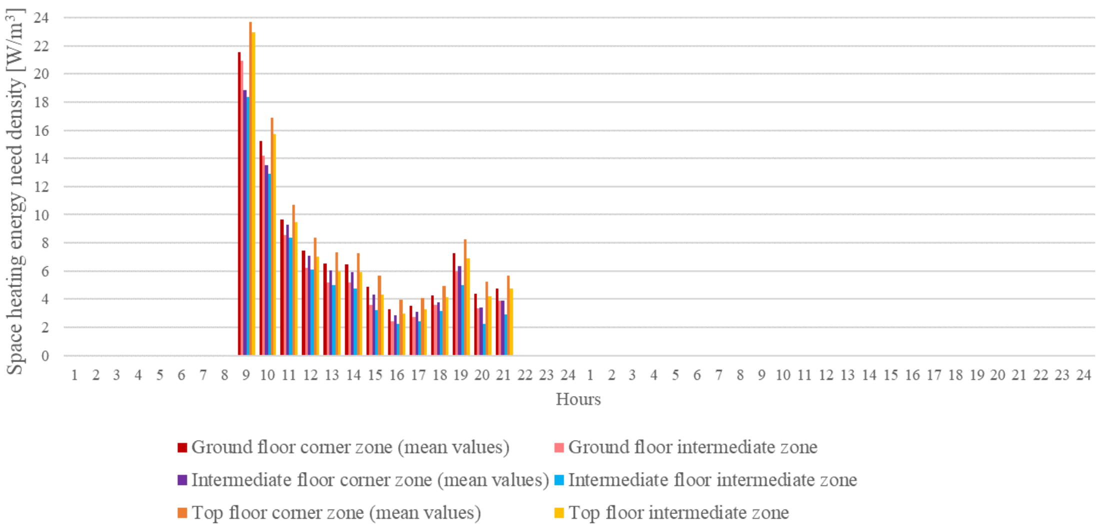


Figure 56. Space heating energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office Recent Glazed Building Energy Model during a working day (on the left) and a weekend (on the right) day within January middle week.

3.5.3.1.2. Space cooling energy need density profiles

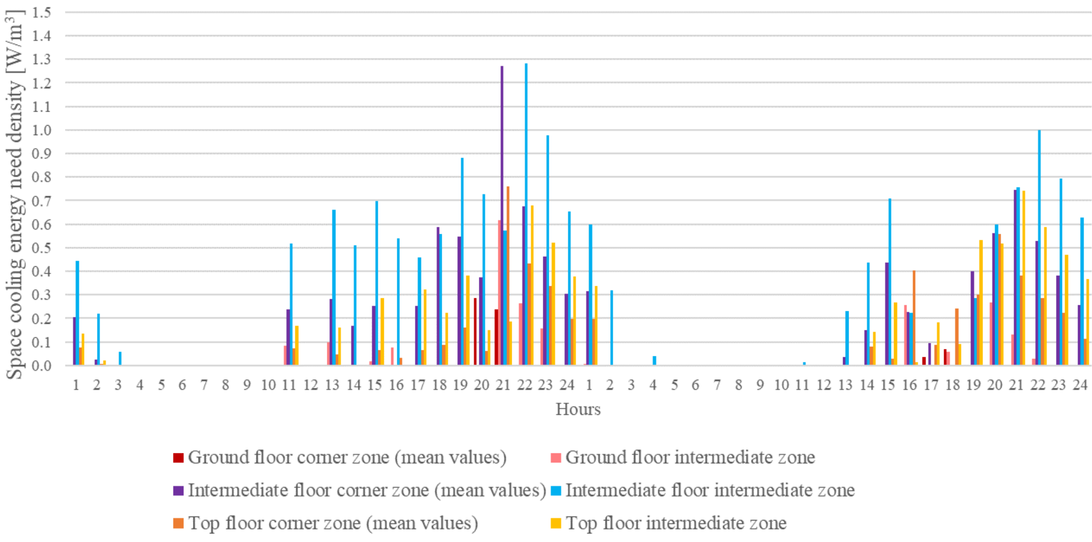


Figure 57. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Residential Old Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

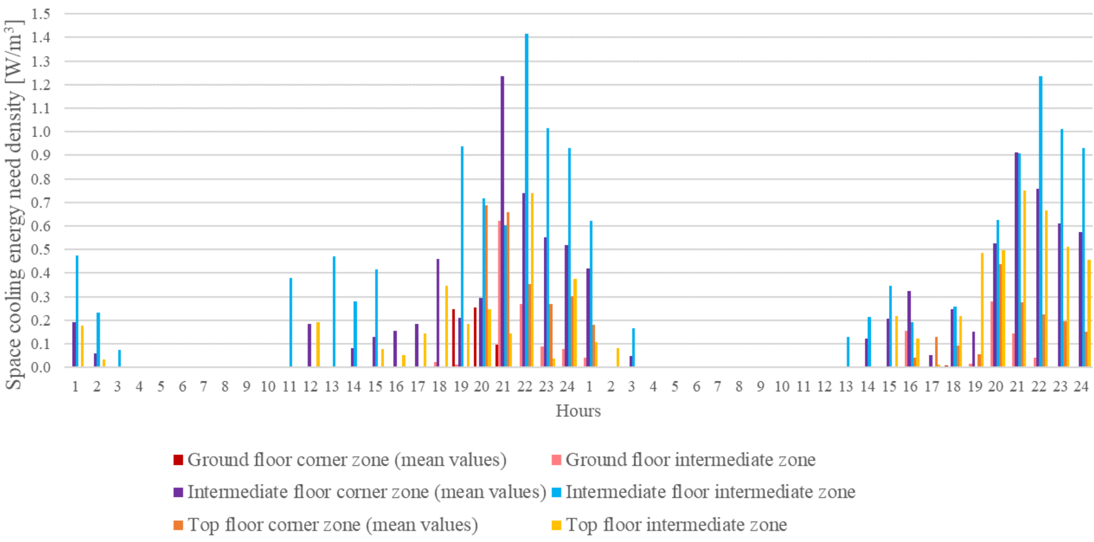


Figure 58. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Residential 60s-80s Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

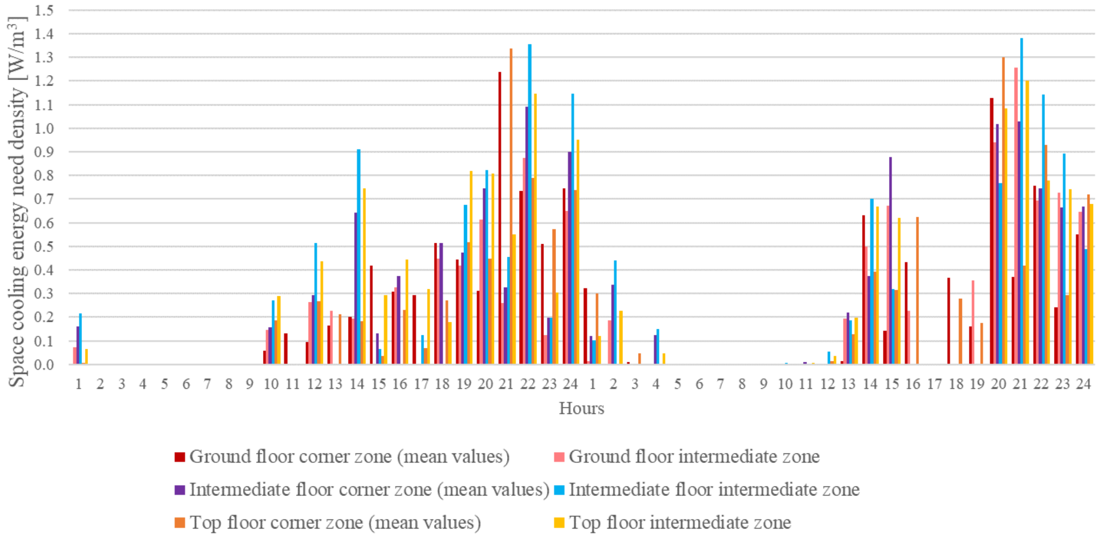


Figure 59. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Residential Recent Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

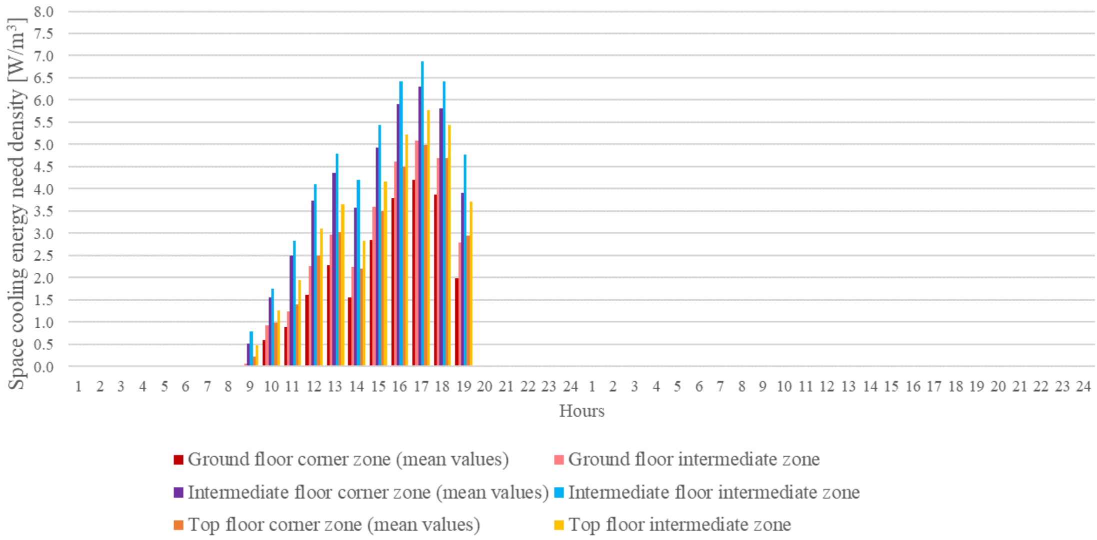


Figure 60. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office Old Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

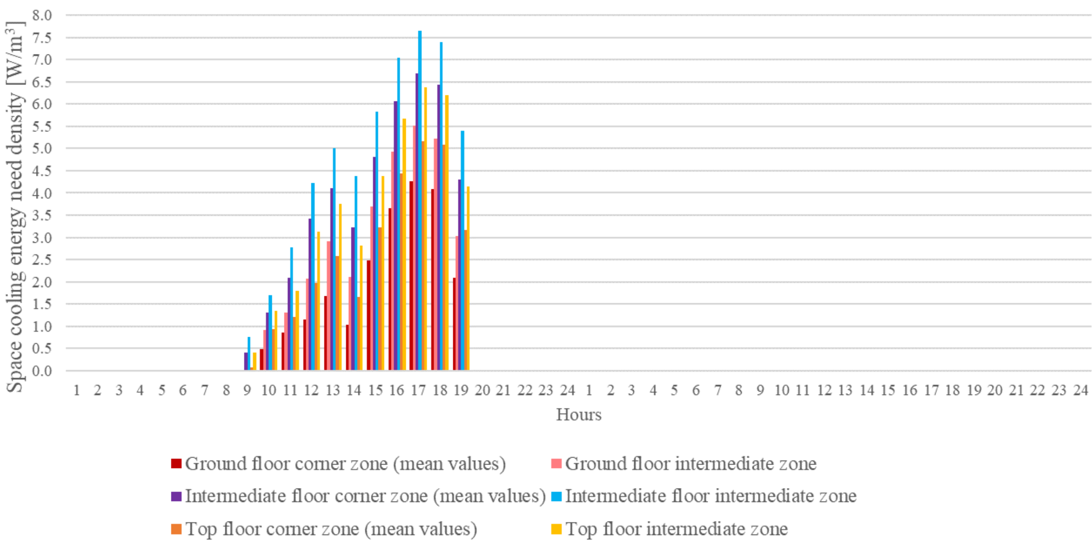


Figure 61. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office 60s-80s Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

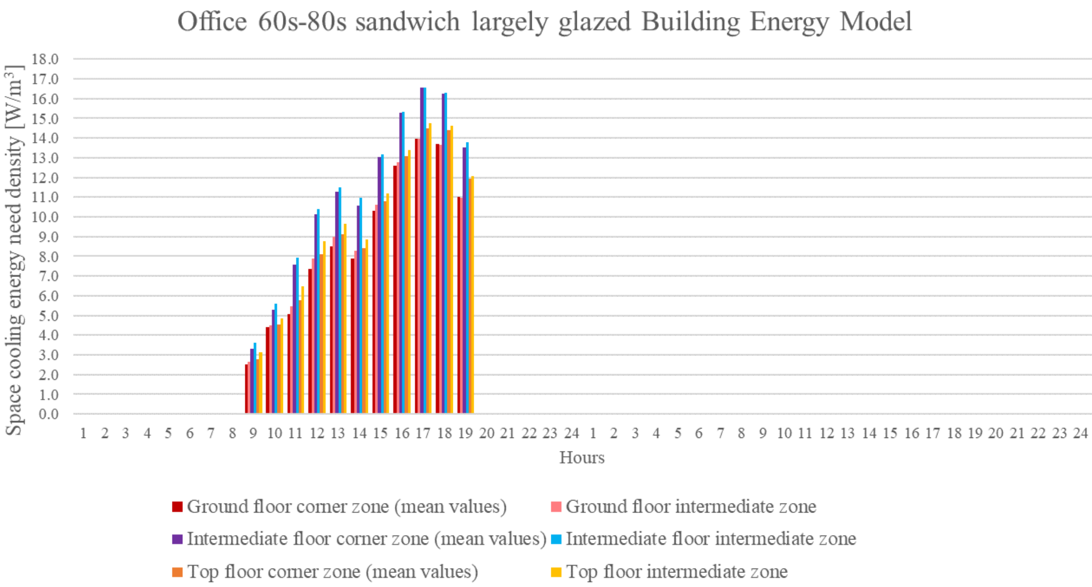


Figure 62. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office 60s-80s Sandwich Largely Glazed Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

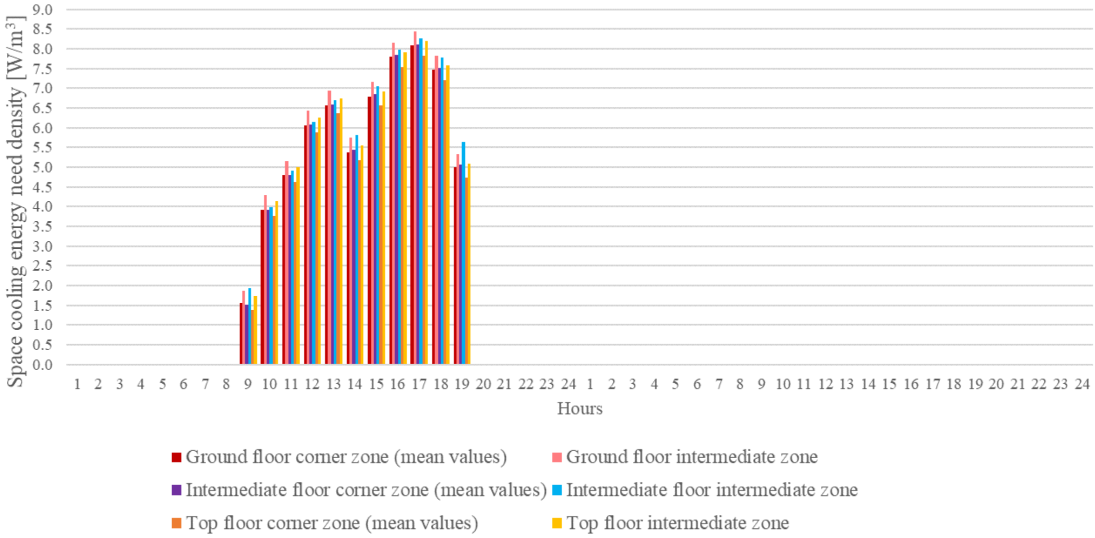


Figure 63. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office Recent Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

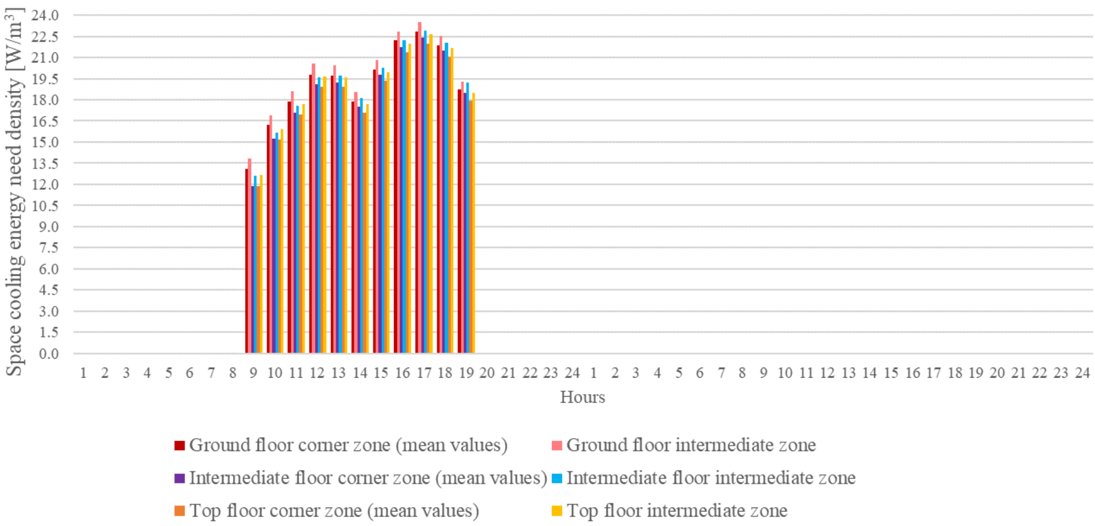


Figure 64. Space cooling energy density profiles [W/m$^3_{gross}$] of typical thermal zones of the Office Recent Glazed Building Energy Model during a working day (on the left) and a weekend (on the right) day within July middle week.

3.5.3.1.3. Electric energy demand density profiles

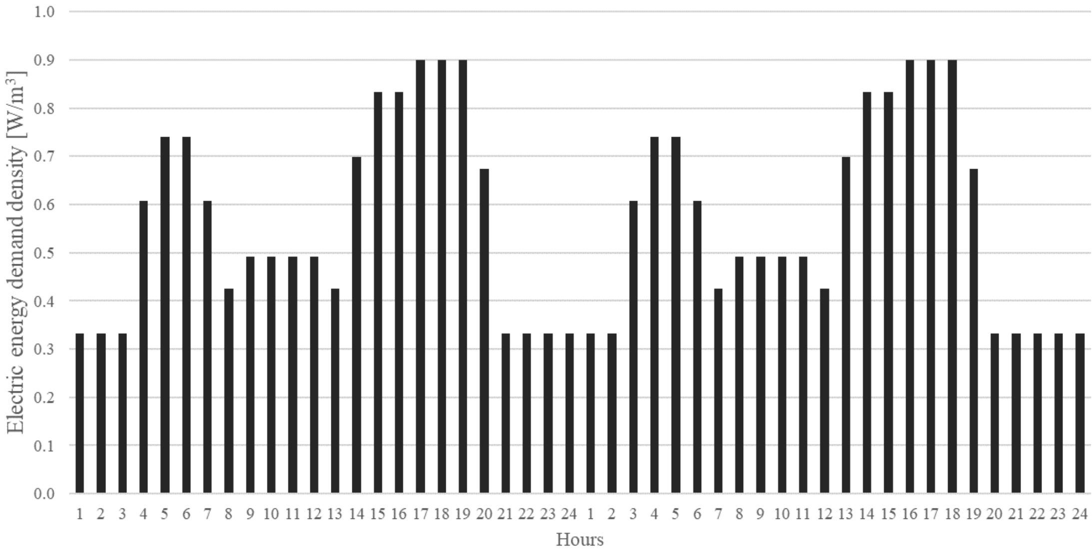


Figure 65. Electric energy demand density profiles [W/m$^3_{gross}$] of a thermal zone of the Residential Old Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within a generic week.

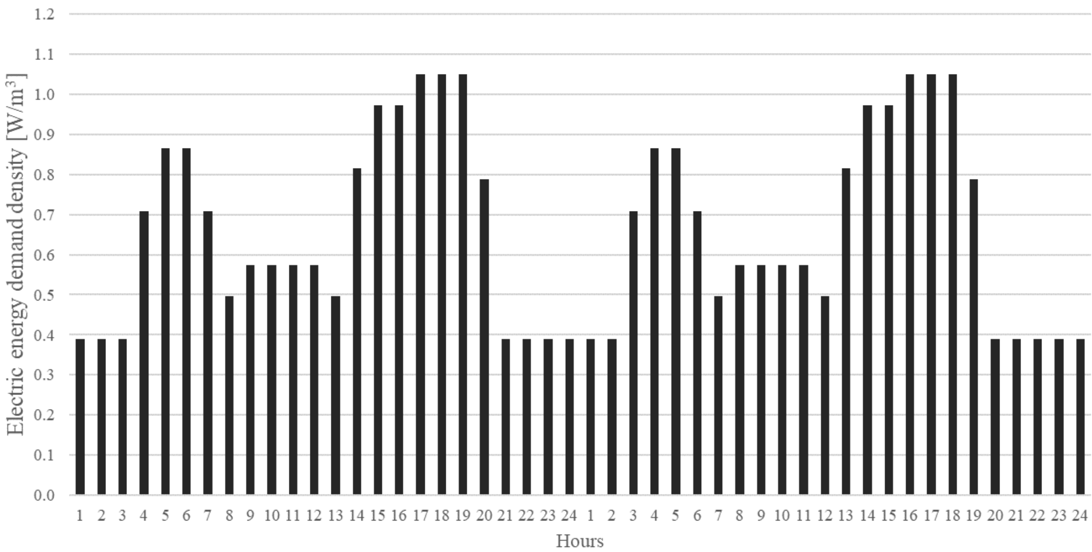


Figure 66. Electric energy demand density profiles [W/m$^3_{gross}$] of a thermal zone of the Residential 60s-80s and Recent Building Energy Models during a working day (on the left) and a weekend (on the right) day within a generic week.

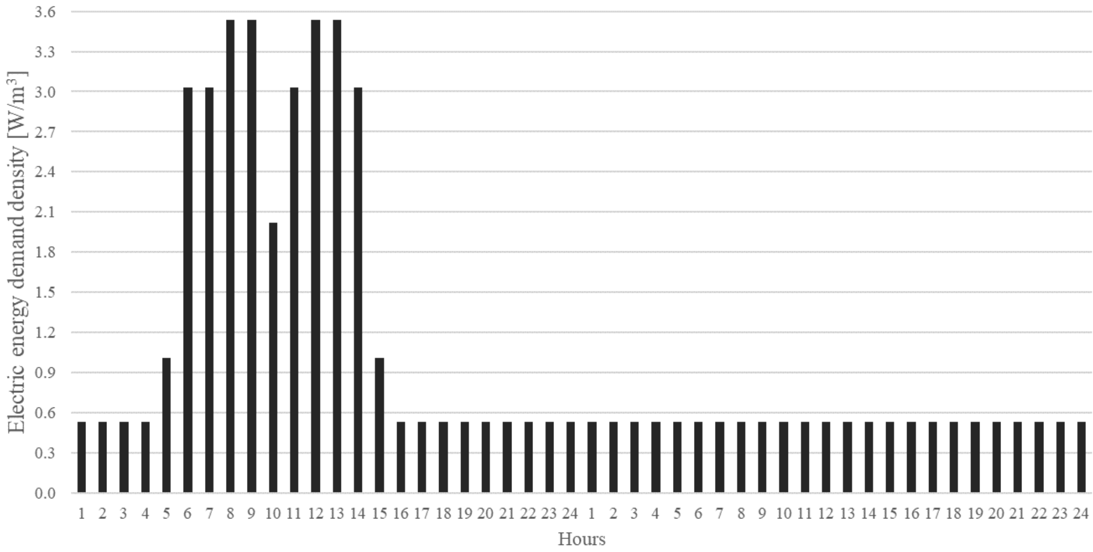


Figure 67. Electric energy demand density profiles [W/m$^3_{gross}$] of a thermal zone of the Office Old Conventional Building Energy Model during a working day (on the left) and a weekend (on the right) day within a generic week.

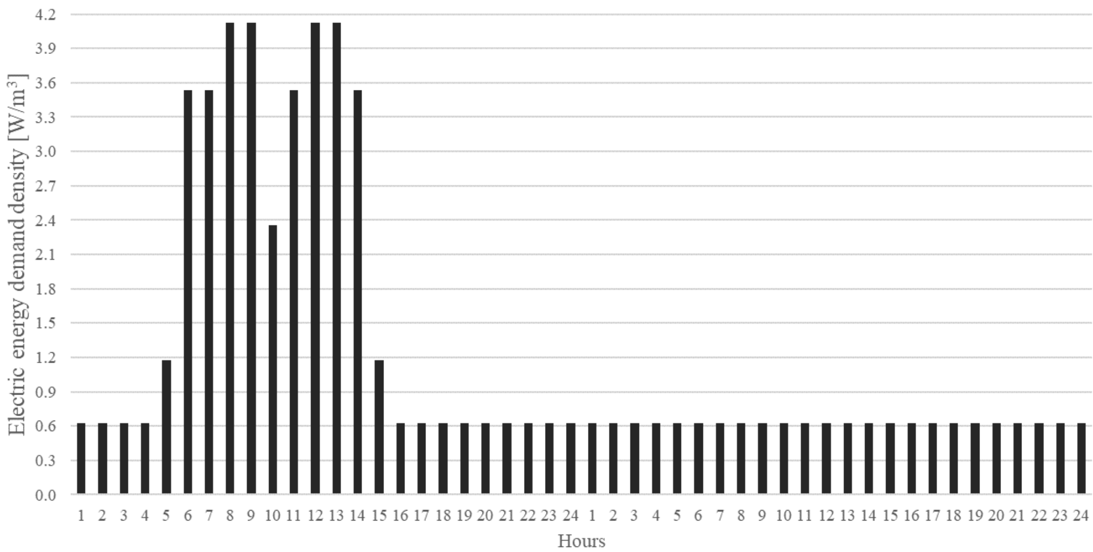


Figure 68. Electric energy demand density profiles [W/m$^3_{gros}$s] of a thermal zone of the Office 60s-80s and Recent Building Energy Models during a working day (on the left) and a weekend (on the right) day within a generic week.

3.5.3.2. Yearly energy density demand

For the sake of completeness and for comparison purposes, with reference to the façade scheme below (Figure 69) the total energy densities in kWh/m^3 of gross volume for a year required for space heating need (Figure 70), space cooling need (Figure 71) and electricity demand (Figure 72) are reported per each Building Energy Model and typical thermal zone.

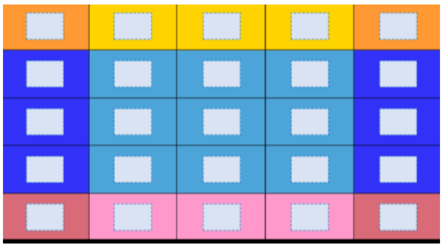


Figure 69. Scheme of the Building Concept façade with typical thermal zones.

Residential Old Conventional

27.65	22.00	22.00	22.00	27.65
17.74	12.39	12.39	12.39	17.74
17.74	12.39	12.39	12.39	17.74
17.74	12.39	12.39	12.39	17.74
23.61	18.21	18.21	18.21	23.61

Residential 60s-80s Conventional

32.11	25.32	25.32	25.32	32.11
19.83	14.11	14.11	14.11	19.83
19.83	14.11	14.11	14.11	19.83
19.83	14.11	14.11	14.11	19.83
26.46	20.68	20.68	20.68	26.46

Residential Recent Conventional

11.24	9.05	9.05	9.05	11.24
7.49	5.89	5.89	5.89	7.49
7.49	5.89	5.89	5.89	7.49
7.49	5.89	5.89	5.89	7.49
9.15	7.26	7.26	7.26	9.15

Office Old Conventional

22.79	17.98	17.98	17.98	22.79
16.16	12.36	12.36	12.36	16.16
16.16	12.36	12.36	12.36	16.16
16.16	12.36	12.36	12.36	16.16
19.55	12.36	12.36	12.36	19.55

Office 60s-80s Conventional

26.07	21.10	21.10	21.10	26.07
18.53	14.61	14.61	14.61	18.53
18.53	14.61	14.61	14.61	18.53
18.53	14.61	14.61	14.61	18.53
22.29	17.93	17.93	17.93	22.29

Office Recent Conventional

10.62	8.76	8.76	8.76	10.62
7.99	6.63	6.63	6.63	7.99
7.99	6.63	6.63	6.63	7.99
7.99	6.63	6.63	6.63	7.99
9.04	6.63	6.63	6.63	6.63

Office 60s-80s Sandwich Largely Glazed

21.67	20.16	20.16	20.16	21.67
15.49	14.61	14.61	14.61	15.49
15.49	14.61	14.61	14.61	15.49
15.49	14.61	14.61	14.61	15.49
17.54	16.45	16.45	16.45	17.54

Office Recent Glazed

9.67	8.19	8.19	8.19	9.67
7.83	6.76	6.76	6.76	7.83
7.83	6.76	6.76	6.76	7.83
7.83	6.76	6.76	6.76	7.83
8.40	7.11	7.11	7.11	8.40

Figure 70. Yearly specific energy needs of space heating per each Building Energy Model typical thermal zone [kWh/m$^3_{gross}$y].

Residential Old Conventional

0.96	1.17	1.17	1.17	0.96
1.09	1.46	1.46	1.46	1.09
1.09	1.46	1.46	1.46	1.09
1.09	1.46	1.46	1.46	1.09
0.25	0.48	0.48	0.48	0.25

Residential 60s-80s Conventional

1.08	1.46	1.46	1.46	1.08
1.47	1.81	1.81	1.81	1.47
1.47	1.81	1.81	1.81	1.47
1.47	1.81	1.81	1.81	1.47
0.40	0.62	0.62	0.62	0.40

Residential Recent Conventional

1.27	1.44	1.44	1.44	1.27
1.43	1.58	1.58	1.58	1.43
1.43	1.58	1.58	1.58	1.43
1.43	1.58	1.58	1.58	1.43
1.13	1.28	1.28	1.28	1.13

Office Old Conventional

2.71	3.17	3.17	3.17	2.71
3.38	3.77	3.77	3.77	3.38
3.38	3.77	3.77	3.77	3.38
3.38	3.77	3.77	3.77	3.38
1.90	2.32	2.32	2.32	1.90

Office 60s-80s Conventional

3.18	3.75	3.75	3.75	3.18
3.98	4.49	4.49	4.49	3.98
3.98	4.49	4.49	4.49	3.98
3.98	4.49	4.49	4.49	3.98
2.26	2.78	2.78	2.78	2.26

Office Recent Conventional

5.78	6.31	6.31	6.31	5.78
6.32	6.64	6.64	6.64	6.32
6.32	6.64	6.64	6.64	6.32
6.32	6.64	6.64	6.64	6.32
5.90	6.39	6.39	6.39	5.90

Office 60s-80s Sandwich Largely Glazed

9.74	10.22	10.22	10.22	9.74
12.18	12.46	12.46	12.46	12.18
12.18	12.46	12.46	12.46	12.18
12.18	12.46	12.46	12.46	12.18
9.03	9.33	9.33	9.33	9.03

Office Recent Glazed

24.53	24.53	24.53	24.53	24.53
26.31	27.19	27.19	27.19	26.31
26.31	27.19	27.19	27.19	26.31
26.31	27.19	27.19	27.19	26.31
25.39	26.70	26.70	26.70	25.39

Figure 71. Yearly specific energy needs of space cooling per each Building Energy Model typical thermal zone [kWh/m^3_{gross} y].

Residential Old Conventional

5.08	5.08	5.08	5.08	5.08
5.08	5.08	5.08	5.08	5.08
5.08	5.08	5.08	5.08	5.08
5.08	5.08	5.08	5.08	5.08
5.08	5.08	5.08	5.08	5.08

Residential 60s-80s and Recent Conventional

5.93	5.93	5.93	5.93	5.93
5.93	5.93	5.93	5.93	5.93
5.93	5.93	5.93	5.93	5.93
5.93	5.93	5.93	5.93	5.93
5.93	5.93	5.93	5.93	5.93

Office Old Conventional

12.12	12.12	12.12	12.12	12.12
12.12	12.12	12.12	12.12	12.12
12.12	12.12	12.12	12.12	12.12
12.12	12.12	12.12	12.12	12.12
12.12	12.12	12.12	12.12	12.12

Office 60s-80s and Recent (Conventional, Sandwich Largely Glazed and Glazed)

14.15	14.15	14.15	14.15	14.15
14.15	14.15	14.15	14.15	14.15
14.15	14.15	14.15	14.15	14.15
14.15	14.15	14.15	14.15	14.15
14.15	14.15	14.15	14.15	14.15

Figure 72. Yearly specific energy demand of electricity per each Building Energy Model typical thermal zone [kWh/m_{gross}^3y].

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4. CASE STUDY APPLICATION

For testing the practical application of the defined method, a first-analysis is driven for a selected case study: the city of Milan, having a mixed consistence of buildings in terms of use category, period of constructions and geometry. Based on information provided by the local Topographic Database and the last ISTAT census, the geodatabase of the building stock, containing the mentioned information has been developed and the hourly energy demand estimated. Then resulting data on volume and energy use have been compared with official statistical data.

4.1. IMPLEMENTATION OF THE GEODATABASE FOR THE CITY OF MILAN

It is worth mentioning that some changes have occurred compared with the previously described procedure, but only and partially regarding the datasets gathering and the base-map preparation. Hence, in order to not provide misunderstanding and overlapping information, only the differences respect to the procedure are below described.

4.1.1. Base-map preparation

The Lombardy Region has started to implement own Regional Topographic Database (DbTR) in 2005 [1],[2], which is now maintained by the Infrastruttura per l'Informazione Territoriale della Lombardia (IIT)[10]. Datasets are provided per each Province and in particular, the dataset for the territory of Milan has been used.

As mentioned in Chapter 3, the DbTR of Lombardy Region is not perfectly in comply with the INSPIRE specifications; in particular, the main differences with reference to the Built Environment Theme are:

- the Building Class is split into two ones, Building Ground Floor and Building Largest Extension Footprint Classes;
- the Minor Building Class does not exist and the related information is included as an attribute in the Building Ground Floor Class;
- the attributes describing the typology and use of buildings are still under definition.

To accomplish the defined procedure, the Building Ground Floor Class is used in place of the Building one, because it is the reference Class to which all the other ones are associated.

Besides, the publicly provided data in the GCPH are available overall national territory. However, for maintaining the official request process within sustainable time, the local statistical institute (Unità Statistica di Milano) [3] was consulted for obtaining, for the only city of Milan, these more accurate original data:

- Number of building units by period of construction per each Census Unit;
- Number of buildings broken down by each not residential use per each Census Unit.

[10] Since 2011, Lombardia Region is uniformizing the municipal maps into the DbTR according to D.G.R. n. 8/6650 of 2008/20/02 and "Regole tecniche per la definizione delle specifiche di contenuto dei database geotopografici", supplemento n. 37 alla G.U.R.I. n. 48 del 27-2-2012).

As mentioned before, the GCPH datasets are provided by Istat for the entire Region, so the selection of data for the city of Milan has been accomplished thanks to the proper municipality municipality code (i.e. 15146). The DbTR shapefiles are provided for the whole province so, consistently with the previously described methodology, the buildings geometries overlapping the selected Census Units Boundary have been extracted.

Compared to the procedure described above, the Building Ground Floor Class underwent further filtering processes than the Building Class. Indeed, besides removing buildings in ruins and under construction, it was also necessary removing minor buildings. Moreover, on the basis of the attribute regarding the typology of buildings and in order to remove monumental buildings and industrial warehouses, which do not reveal a conventional energy behaviour, only those classified as "generic" have been selected. Finally, through the attribute concerning the use of buildings, those that clearly refer to unconventional uses (e.g. factories, hospitals, department stores, etc.) were removed, keeping only the following categories (and subcategories): residential (generic and housing), public service (generic, educational, legal and postal), administrative (municipal, provincial, regional) and also generic industrial since it has been experimented that contains tertiary buildings.

4.1.2. Building stock characterization

From the described procedure accomplishment, it is possible determining the consistency of the built environment in a considered urban context and visualizing the outcomes trough maps. As an example, the maps of Milan with Census Units featured by prevailing period of construction (Figure 73), typical thermal zone (Figure 74) and use (Figure 75) are hereinafter attached. It can be noted the reasonable greater presence of buildings featured by old age, large size and office use in the city centre and vice versa of buildings featured by middle and recent ages, small size and residential or other uses (e.g. hospital, industrial, etc.) in the outskirts.

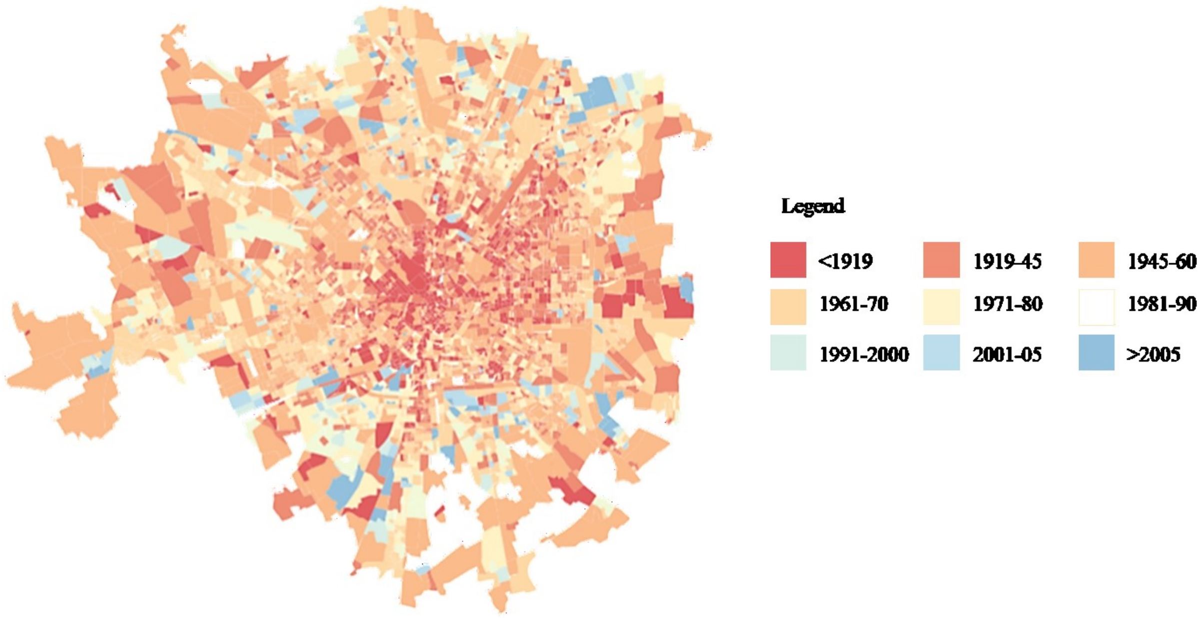

Figure 73. Map of Census Units' characterization by prevailing period of construction in the city of Milan.

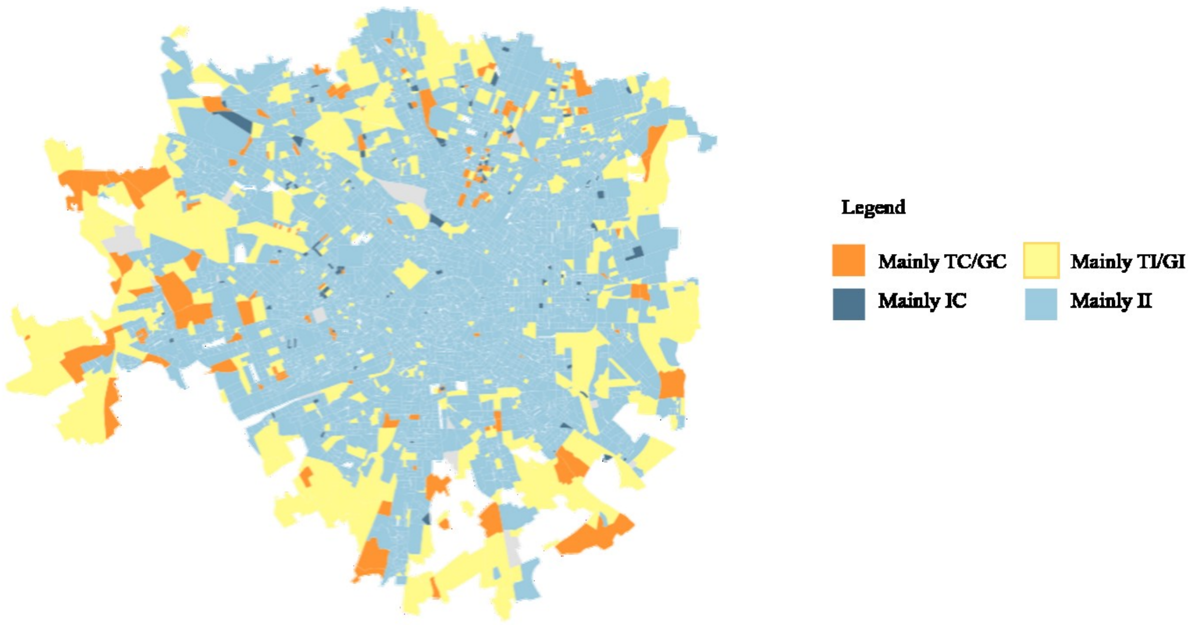

Figure 74. Map of Census Units' characterization by prevailing typical thermal zone in the city of Milan.

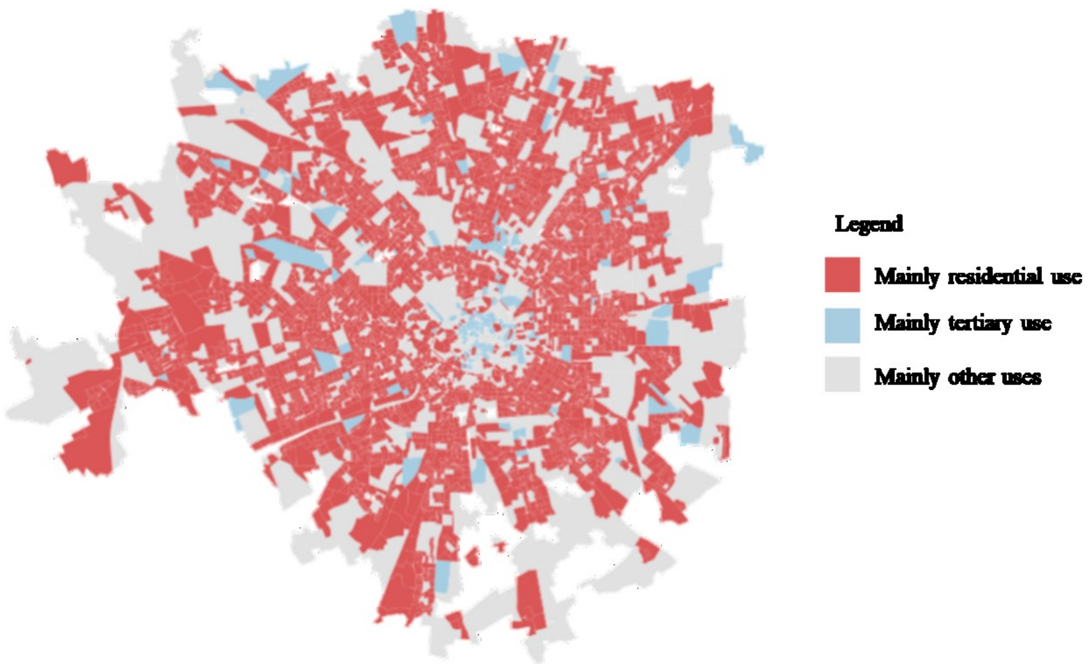

Figure 75. Map of Census Units' characterization by prevailing use in the city of Milan.

As a result, the trend in calculated residential built volume per each prevailing period of construction from the developed geodatabase is approximately in line with the number of buildings per each age given by Istat [4] (Figure 76). Clearly, since in the geodatabase the period of construction for tertiary buildings has been assigned based on the residential ones, the resulting pattern catches the former ones, except for a larger share of old office buildings, which could be attributable to the city centre, mainly featured by old and tertiary buildings.

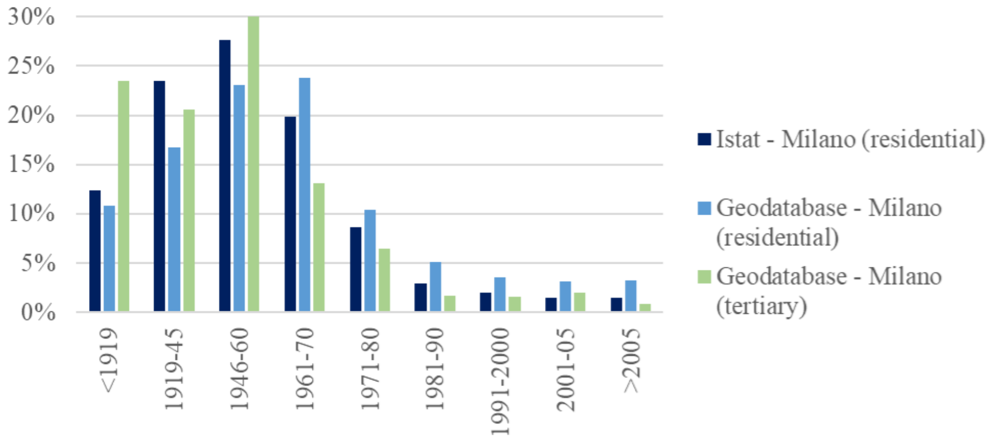

Figure 76. Comparison of building stock consistency per period of construction in Milan between Istat and the developed geodatabase.

For checking the consistency of the building stock regarding the use category, following comparisons were accomplished. The Agenzia delle Entrate annually publishes the statistics on buildings, based on data from the Building Cadastre [6] and useful for real estate issues. Residential real estate units include a set of different categories (for instance, luxury, social housing, rural, villas, castles, private offices/studios, vernacular, etc.) therefore, for comparing consistent data, we ignored the categories A/9 "castles, palaces of eminent artistic or historical merits", A/10 "private offices and studios," and A/11 "vernacular houses". Data on 2012, after the national census, report an estimated[11] gross surface for considered residential categories of 69.35 Mm^2 which returns – assuming a typical inter-floor height of 3.00 m, to 208.04 Mm^3. Additionally, Istat reports a net surface area of apartments, inhabited by residing people, equal to 50.82 Mm^2 returning, by assuming an average corrective factor net-to-gross of 0.65 (from already used UNI 10379:1994) and a gross height of 3.00 m, a gross volume of 211.12 Mm^3, which is significantly closed to the estimated value from Agenzia delle Entrate. From the implemented geodatabase, it is derived a residential volume of 226.58 Mm^3, whose reasonable gaps with Agenzia delle Entrate and Istat values are equal to +8.9% and +7.3%, respectively.

Concerning the office use, from Agenzia delle Entrate we considered the gross floor area for building units used as private offices and studios plus the gross volume of office buildings. The combined volume, assuming a height of 3.00 m, is 26.06 Mm^3. CRESME [7] estimated, based on data from the Agenzia delle Entrate and a survey on the real estate market, the consistence of the office building stock in Milan in 2015. CRESME included

[11] The surface area is estimated based on the recorded number of rooms and the calculated average surface per room.

offices and studios building units, office buildings and also buildings hosting banks and insurance companies, deriving a gross surface value of 9.20 Mm^2, which returns into 27.60 Mm^3. Also, the tertiary gross volume determined through the geodatabase is 26.29 Mm^3, which is strictly closed to mentioned statistical values of Agenzia delle Entrate and Cresme (gaps are -0.9% and +4.8%, respectively). Additionally, from the local urban plan [8], it was estimated based on Istat general census data, that in Milan the 60.2% of buildings are residential and the 4.4% tertiary (directional), which are slightly different from the shares of built volume elaborated by means of the developed geodatabase (66% and 8%, respectively).

4.1.3. Determination of the building stock energy profiles

The association between the assessed real built volumes with the energy density profiles from the determined matrix of Building Energy Models has been done accordingly to these considerations.

Concerning the association based on the typical thermal zone, the energy profiles by each zone have been associated to the built conditioned volume of the homonymous typical thermal zones. As mentioned, average profiles of angular zones per floor have been derived and associated to mirrored zones.

Concerning the association based on the buildings age, the profiles of the Old Building Energy Models have been associated to the real volume data back in the three oldest Istat construction periods (i.e. before Sixties), since related buildings are generally featured by traditional structure; the profiles of the 60s-80s Building Energy Models have been associated to the real volume data back in the following three periods (i.e. before Nineties), since related buildings are generally featured by light and low energy performing structure; finally, the profiles of the recently built Building Energy Models have been associated to the real volume data back in the last three periods (i.e. until today), since related buildings have been built according to energy saving recommendations. Additionally, only in the case of tertiary buildings, the average of conventional and lighter/more glazed profiles in 60s-80s and recent periods has been used since it was not possible determining the related shares of the building stock.

As an example, profiles for two exemplary weeks for two selected urban areas in Milan (Figure 77) have been reported (from Figure 78 to Figure 81): in particular, an area within city centre, mainly featured by old office buildings and reporting high energy demand during business days both in winter and summer, and an area in suburbs, mainly featured by more recent residential buildings and having lower energy demand during all days.

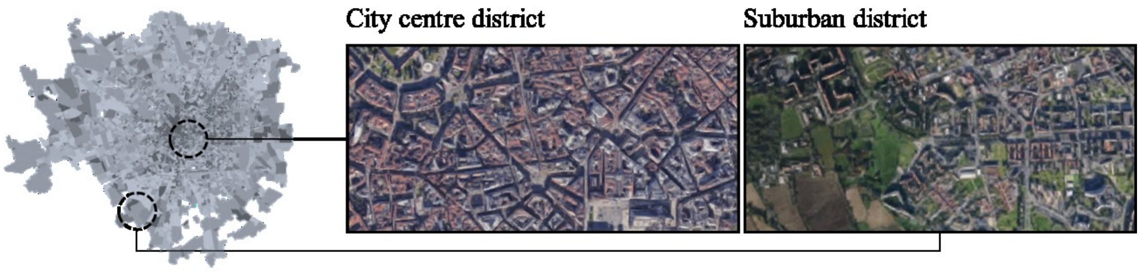

Figure 77. Selected urban areas in Milan.

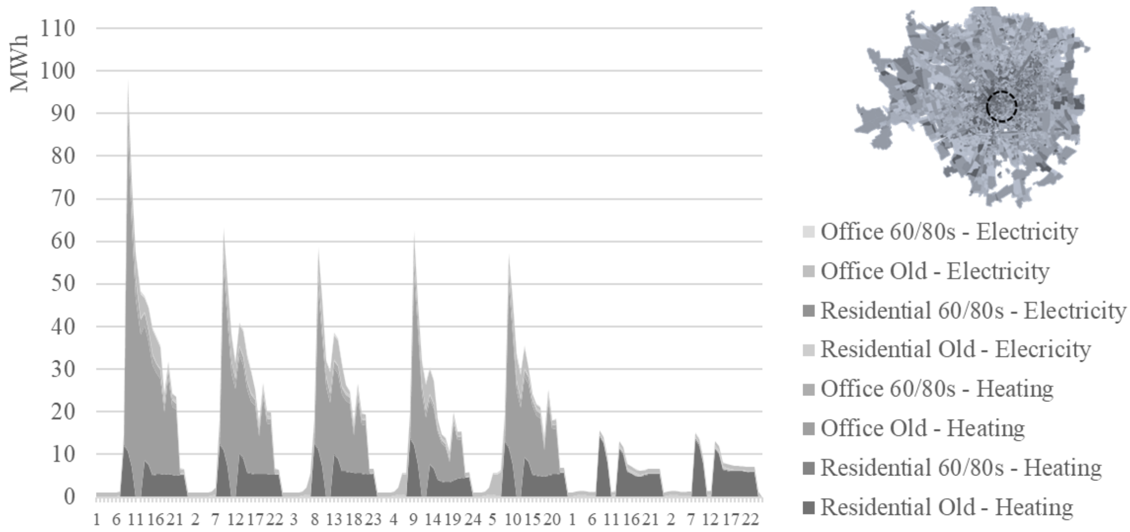

Figure 78. Space heating energy need and electricity demand profiles in a winter week for a city centre district in Milan.

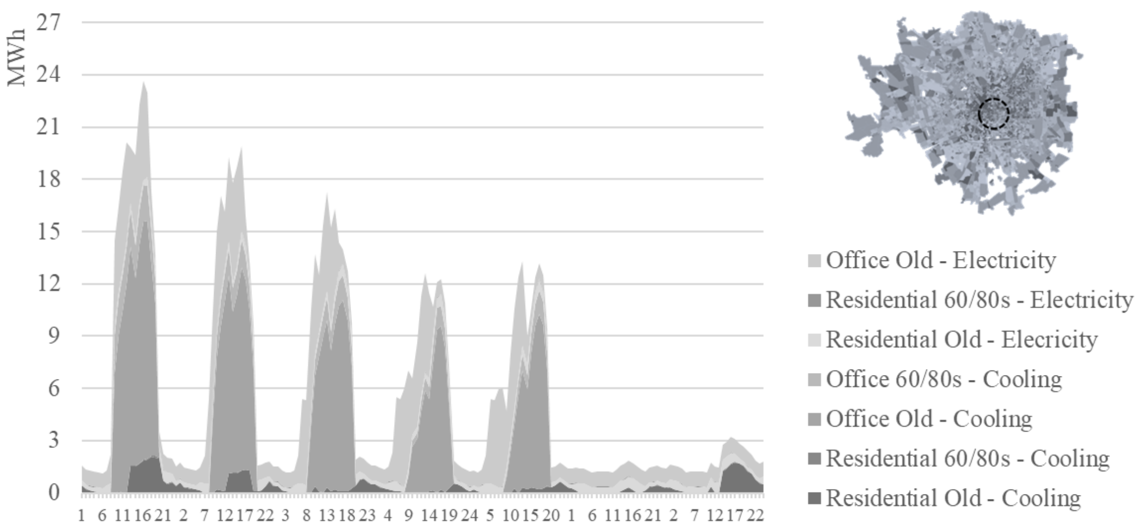

Figure 79. Space cooling energy need and electricity demand profiles in a summer week for a city centre district in Milan.

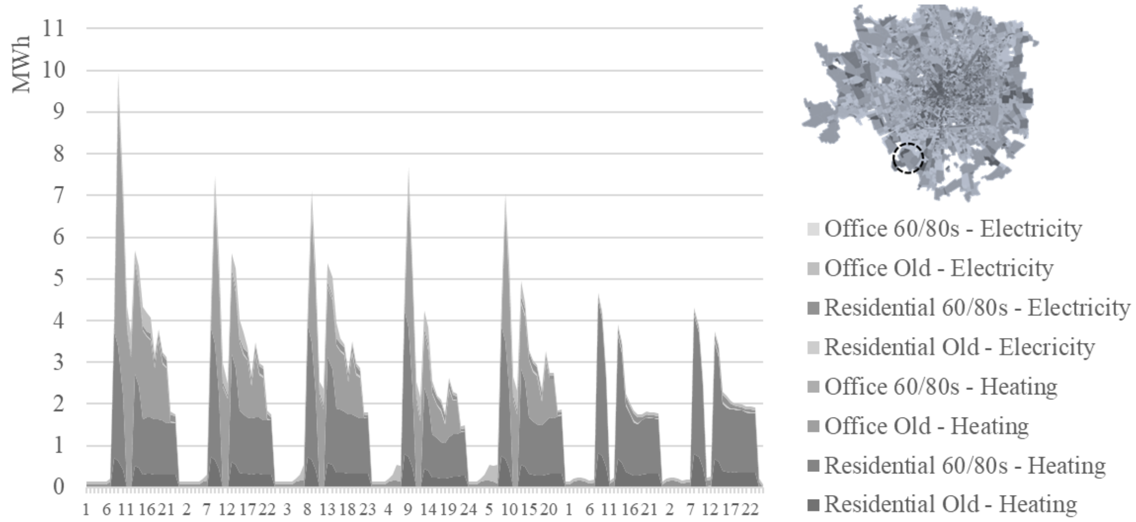

Figure 80. Space heating energy need and electricity demand profiles in a winter week for a suburban district in Milan.

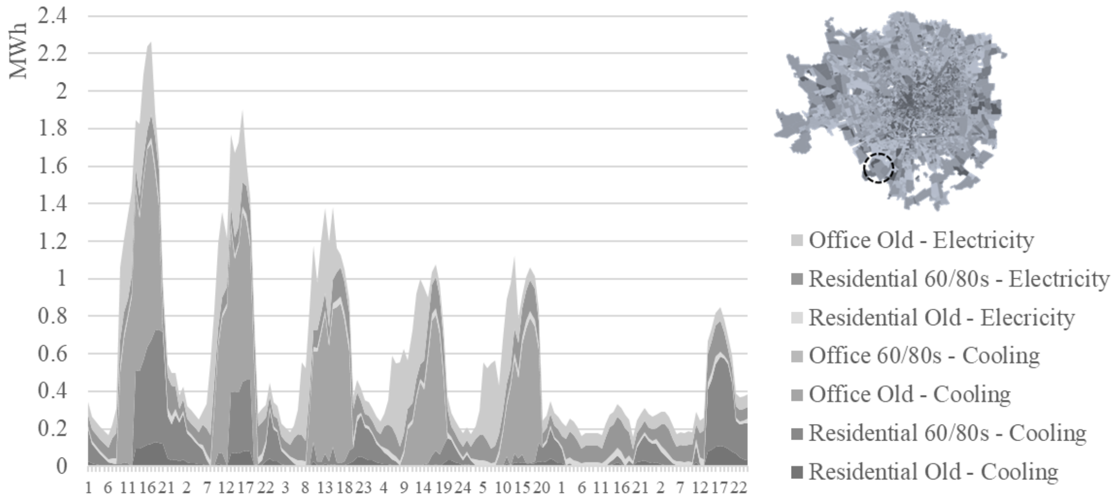

Figure 81. Space cooling energy need and electricity demand profiles in a summer week for a suburban district in Milan.

4.2. COMPARISON OF OUTCOMES WITH ACTUAL CONSUMPTIONS

Finally, the annual energy consumption from energy balances of an urban context can be compared with the one resulting from the urban energy mapping procedure. The energy balance is a tool for synthetizing the energy sector of a given area, by providing for a certain period the type and quantity of consumed energy and how it was produced.

The Energy Department of Infrastrutture Lombarde S.p.A. within Lombardy Region manages a platform for local energy data monitoring, which was implemented in 2007, and whose current name is SIRENA20 (Sistema Informativo Regionale ENergia Ambiente). The SIRENA database [9]-[10] has been developed since the Factor20 Project, whose aim was to formulate a set of tools to support the regional energy planning and define common methodologies and databases for the regular collection and organization of relevant energy data in three Italian Regions, included Lombardy. The SIRENA methodology is based on a top-down approach through which measured energy consumptions per each fuel are broken down in sectors by considering statistical data (e.g. built area by use, number of residing and employed people). Currently, the SIRENA database provides the regional energy balances from 2005 to 2012 with data on energy consumptions, emissions, production, RES production and some developed scenarios' effects given at different levels of disaggregation, from regional down to municipal scale.

With regard to the energy consumptions, annual data for each single sector and/or fuel for one municipality could be used so fossil fuels, district heating and electricity consumptions for residential and tertiary sector have been preliminary extracted.

Tertiary buildings are usually equipped with quite complex HVAC systems, including mechanical ventilation, chillers, etc., whose assessments is out of the boundary of this research, thus a reliable estimation of the tertiary sector energy consumptions and their calibration with measured data is quite delicate. In addition, it should be considered that the tertiary sector data from SIRENA are separately provided for the market and the non-market services, which are two categories taken from the Italian Transmission System Operator Terna with reference only to electricity [11]. In particular, from publicly provided data at not lower level that the regional one, the so-called market services comprise facilities used for transports or communications, buildings holding activities related to trade, tourism, bank and insurance companies, private offices, and so on, while the so-called non-market services include the consumptions of public administration buildings and street lighting. Hence, considering also that it is not possible breaking down the subcategories that have been taken into account in this study, we decided to compare only the energy consumptions referring to the residential sector.

For comparing the data, from SIRENA we considered the final energy consumptions in 2012 of residential sector, by fossil fuels, district heating and electricity. Fossil fuels and district heating consumptions have been corrected on the basis of the HDDs from the TRY used in the TRNSYS simulations (2689 HDDs), while real HDDs (2393 HDDs) have been calculated based on the measured temperatures in 2012 at the Lambrate station of ARPA-Lombardia [12], which is the closest one to the station which the TRY refers. An energy consumption of 7023.85 GWh for fossil fuels and DH has been derived.

For determining the thermal energy consumptions from the developed geodatabase, we assumed, in first analysis, some thermal systems configurations and, based on UNI/TS 11300-2:2014 [15], the related seasonal efficiencies. In particular, for the old and 60s-80s residential building stock, we assumed a centralized thermal system based on vertical distribution averagely insulated, regulation based both on external and internal probes, radiators on external walls and old gas-based boiler with blown air burner (thermal system seasonal efficiency η_{global} equals 0.72), while for the recently built ones we assumed that the vertical distribution is well insulated, the radiators are installed on external insulated walls and the boiler is a condensing one (η_{global}=0.87). Moreover, based on a study on energy efficiency measures for a typical multi-family building developed within a collaboration with the International Energy Agency within Annex 56 and whose contents have been published in an article presented at the 6th International Building Physics Conference - IBPC 2015 in Turin [16], the DHW consumption has been added to the space heating one assuming a DHW need of 17.1 kWh/m^2 y and a gas-based water heater with a seasonal efficiency of 0.88. The resulting energy consumptions for thermal uses is 6586.49 GWh, which is the 6.2% lower than the SIRENA one. This slight difference could be attributed to not accounted energy consumptions. Hence, we estimated the energy consumption for cooking based on the average one reported per one flat in [17] and we corrected the total fossil fuel consumption proportionally to the share of not empty flats, which are the ones possibly truly responsible for measured consumptions, returning in a value of 7252.06 GWh, which is even closer to the SIRENA one (+3.2%).

Regarding the residential electricity consumption, the data from SIRENA is equal to 1636.13 GWh in 2012. Additionally, the residential annual electricity consumptions in the period 2011-2016 directly provided by Terna [11] at the Province level were used to derive the consumptions at the municipal level proportionally to the residing population in those years from Istat [14], returning in an average consumption of 1632.8 GWh (values range from a minimum of 1564.1 GWh in 2014 to a maximum of 1708.0 GWh in 2011).

Concerning the electricity consumption from the developed geodatabase, along by the one for electric equipment and artificial lighting, the one for space cooling, by adopting an energy efficiency ratio of 2.5 of an electric compression heat pump [18], has been considered. Thus, the resulting electricity consumption for electric appliances, artificial lighting and space cooling, is 1302.21 GWh (around -20% respect to both SIRENA and Terna), while if calculated proportionally to the not empty flats is 1226.28 GWh (around -25% respect to both SIRENA and Terna).

Briefly, by comparing the elaborated urban annual thermal energy consumptions, there is a slight difference. The gap is larger when comparing the electricity consumptions, which could be due to the negligence of shared use and spaces (e.g. artificial lighting in staircases, elevators, circulation pumps, etc.). Not least, the level of aggregation of provided data from SIRENA and of uncertainties in the adopted process of data breaking down, could hardly lead to a consistent comparison.

4.3. References

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5. DISCUSSION AND CONCLUSIONS

In the framework of smart energy transition, which will involve the cities and the districts as crucial areas where developing strategies for large RES integration and energy efficiency, the need of accurate estimates of energy demands is raising since it is fundamental for ensuring a proper energy balance at hourly resolution (see chapter 1. Introduction). Moreover, the sharp increasing diffusion of energy planning tools witnesses the need of reliable buildings hourly energy demand profiles as input data, whose availability for different contexts is still controversy (see chapter 2. State of the art).

For dealing with these issues, during this Ph.D. research, a method for the accurate estimation of the energy demand profiles of a building stock has been drawn up in order to support the widespread planning of smart energy districts in urban areas.

In paragraph 3.4, the defined procedure for implementing a geodatabase of the building stock, characterized by age, use and geometry, is outlined. In particular, the procedure allows the accurate assessment of the building stock through the identification of the six typical thermal zones, representative of the main boundary conditions, which compose it. In paragraph 3.5, since the definition of a Building Concept, a set of Buildings Energy Models has been modelled, according to diffuse use categories and technological solutions in urban contexts, based on technical literature, and detailed usage settings, accurately defined based on recent standards recommendations. Such Building Energy Model have been dynamically simulated with TRNSYS, thus resulting in a matrix of a hundred energy profiles (of space heating and cooling need and electricity demand for appliances and artificial lighting for each one, considering an average orientation and six typical thermal zones). As a result, the energy density profiles per unit volume of each Buildings Energy Models typical thermal zone can be multiplied to the analogous built volume in order to determine the energy profiles of an entire building stock.

The whole method, which is synthetized in Figure 82, has been applied to the case study of the city of Milan in order to test its reliability (see chapter 4). In particular, the calculated built volume by age and use has been compared with statistical data according to Istat, Agenzia delle Entrate and Cresme (obtaining gaps lower than 10%). Then, considering the difficulties in associating thermal systems efficiencies to tertiary buildings due to their complexity, the estimated annual energy consumptions of only residential buildings have been compared with the consumptions in 2012 reported in the urban energy balance of the SIRENA database (obtaining gaps not greater than 25%).

As defined in paragraph 3.2, the aim of this research was to define an easy updatable method for supporting public and private bodies involved in energy planning and policies and energy planners, mainly within public administration, in defining smart energy strategies in urban contexts. Hourly energy density profiles of typical buildings in northern Italy have been derived and could be also updated in order to define Buildings Energy Models. Hence, once calibrated the existing buildings energy profiles with measured consumptions, the same Buildings Energy Models can be modified, updating the envelope physical properties and systems efficiencies in order to simulate the implementation of energy performance improved strategies. Then, the whole procedure can be rerun in order to assess the effects on urban scale of improved energy scenarios. Additionally, the determined urban energy profiles can be imported in one of the surveyed tools for comparing baseline and updated energy scenarios.

The procedure foresees the implementation of a database in GIS in order to characterize an urban building stock, which is also useful to accomplish any related spatial energy assessments (e.g. identifying areas with higher potentiality of retrofitting, etc.). Furthermore, the procedure single steps and related scripts have been thoroughly described in the Appendices A-C, respectively, so can be directly implemented as well as customized in the open-source QGIS software with Python platform embedded. Finally, since the procedure adopts data that are almost uniformly retrievable on the whole national territory as well as under standardization according to the European Directive INSPIRE, it can be noted that it has also the merit of not being case-specific and can be adopted for different locations.

This study lays in the path of previous Ph.D. researches, carried out by the same academic group, that have investigated the topic of distributed energy or buildings energy planning at urban level. Considering the previous researches' outcomes, in this case a double effort has been devoted in order to achieve greater accuracy (i.e. detailed hourly profiles complying with last standards have been defined; the building stock is characterized through typical thermal zones with different boundary conditions) and to boost for its adoption in other contexts (i.e. the GIS-based procedure considers the minimum level of available data in Italy; all its single steps are described with accuracy).

Given this, we are aware that further developments could be exploited by next contiguous researches in the future. For instance, the matrix of Building Energy Models and related energy profiles could be enlarged for considering more building features, effects of pitched roofs, installed shadings, more periods of construction and so more envelope solutions, more energivorous buildings (e.g. hospitals or department stores, which are quite interesting in smart energy networks). Profiles have been provided for buildings located in Milan but, for considering the national wide climatic variability, more locations should be included modifying the climatic data and if needed the envelopes properties. For the accurate estimation of the energy consumption profiles, it could be useful also modelling the installed thermal systems and estimating the electricity consumptions, including auxiliary services. Also, with more detailed spatial data, and in particular the ones provided by the Spatial Cadastres of Thermal Systems, a more precise estimation of the urban energy consumption, including the performances of systems, plants and the types of fuels, could be possible. Finally, from a merely computing perspective, the codes in Python programming language could be refined to provide a more efficient calculation procedure.

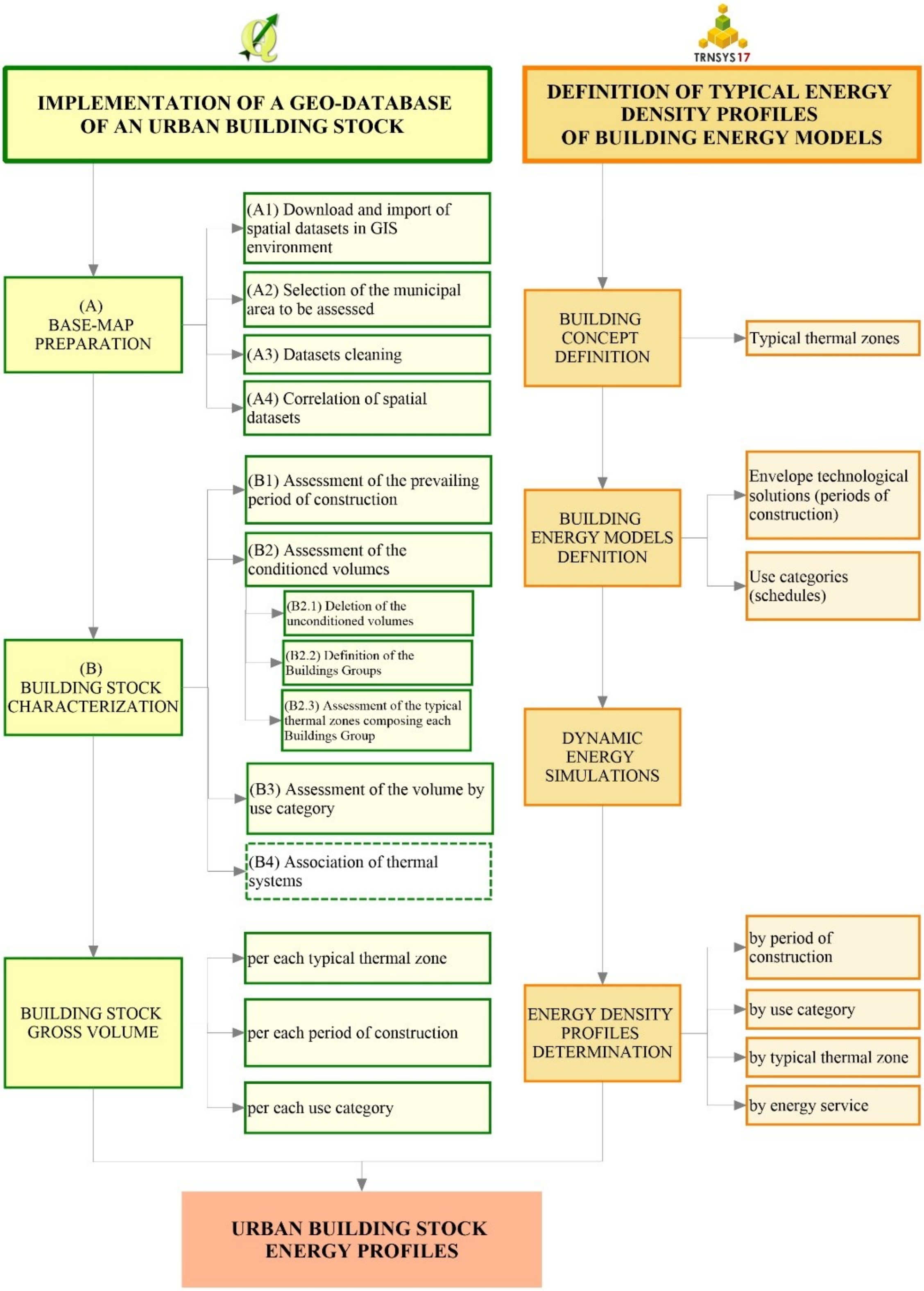

Figure 82. Diagram of the defined method for estimating the buildings hourly energy demand for Smart Energy District planning.

6. APPENDICES

A. USED DATA IN THE GIS-BASED PROCEDURE

In following tables, the data adopted in the procedure, defined for implementing the geodatabase of a building stock, are associated to the names used in the following appendices, with reference to the single procedure steps and routines to be used in QGIS 2.18.14 with the Python 2.7 console embedded. The data used only in the application case study are red coloured.

Table 19. TDb dataset: Volumetric Units attributes.

Attribute Name	Attribute description
UUID	ID code
UN_VOL_AV	Height
UN_VOL_POR	Portion type
CRE_EDF-UUI	Enclosing Building ID code
Shape_Area	Floor Area
SEZ	Enclosing Census Unit ID code
RefHeight	Height of the largest Volumetric Unit within the same Building
UVstatus	If it is a staircase or not
Group_ID	Enclosing Building Group ID code
Surface	Volumetric Unit floor surface
Volume	Volumetric Unit volume
Tot_Surf	Sum of floor surfaces of enclosed Volumetric Units per each Building Group
Tot_Vol	Sum of volumes of enclosed Volumetric Units per each Building Group

Table 20. TDb dataset: Buildings attributes.

Attribute Name	Attribute description
CRE_EDF-UUI	ID code
CR_EDF_ST	Maintenance status
CR_EDF_CT	Type (minor or not)
edifc_ty	Typology
edifc_uso	Use category
SEZ	Enclosing Census Unit ID code
maxun_vo_1	Area of the enclosed Volumetric Unit with the largest floor surface
ReferenceH	Height of the enclosed Volumetric Unit with the largest floor surface

Table 21. TDb dataset: Building Group attributes.

Attribute Name	Attribute description
Group_ID	ID code
SEZ	Enclosing Census Unit ID code
SezMainAge	Prevailing period of construction of the enclosing Census Units
SURF_TOT	Sum of floor surfaces of enclosed Volumetric Units
VOL_TOT	Sum of volumes of enclosed Volumetric Units
WeightedH	Weighted mean height
FloorsNum	Number of floors
FloorHeigh	Height of floors
COEFF_VOL	Net-to-gross volume conversion ratio
ThZoneSurf	Surface of a typical thermal zone
TZperFloor	Number of thermal zones per floor
TopCorner	Volume of the corner thermal zones placed on top level
TopCentral	Volume of the central thermal zones on top level
Edge	Volume of the corner thermal zones placed on intermediate levels
Internal	Volume of the central thermal zones on intermediate levels
Tot_TC	Sum of top corner thermal zones volumes per each enclosing Census Unit
Tot_TI	Sum of top central thermal zones volumes per each enclosing Census Unit
Tot_E	Sum of intermediate levels corner thermal zones volumes per each enclosing Census Unit
Tot_Mid	Sum of intermediate levels central thermal zones volumes per each enclosing Census Unit

Table 22. GCPH dataset: Census Units attributes.

Attribute Name	**Attribute description**
PRO-COM	municipality ID code
SEZ	Census Unit ID code
ACE	Census Area ID code
TotI<1919	Number of building units built before 1919
TotI<1946	Number of building units built in the period 1919-45
TotI<1961	Number of building units built in the period 1946-60
TotI<1971	Number of building units built in the period 1961-70
TotI<1981	Number of building units built in the period 1971-80
TotI<1991	Number of building units built in the period 1981-90
TotI<2001	Number of building units built in the period 1991-2000
TotI<=2005	Number of building units built in the period 2001-05
TotI>2005	Number of building units built after 2005
Abit>1res	Number of flats inhabited by at least 1 residing person
Sup_ab1res	Net surface of flat inhabited by at least 1 residing person
Abit_altre	Number of flats empty or inhabited by not residing people
EdNoRes	Number of not residential buildings
ComplNoRes	Number of not residential groups of buildings
EdifDirez	Number of tertiary buildings
CompDirez	Number of tertiary groups of buildings
ResSez_Age	Prevailing period of construction of Census Units with only residential buildings
ACE_Age	Prevailing period of construction of Census Area
SezMainAge	Prevailing period of construction of Census Units
COEFF_VOL	Net-to-gross volume conversion ratio
Tot_TC	Sum of top corner thermal zones volumes
Tot_TI	Sum of top central thermal zones volumes
Tot_E	Sum of intermediate levels corner thermal zones volumes
Tot_Mid	Sum of intermediate levels central thermal zones volumes
BuiltVol	Sum of all thermal zones volume
ResidVol	Volume with residential use
Off%NotRes	Percentage of office use buildings on not residential ones
RES%	Percentage of residential volume on the built one
OFF%	Percentage of office volume on the built one
ResidTCVol	Residential top-level corner thermal zones volume
ResidTIVol	Residential top level central thermal zones volume
ResidMCVol	Residential intermediate levels corner thermal zones volume
ResidMIVol	Residential intermediate levels central thermal zones volume
OffTCVol	Office toplevel corner thermal zones volume
OffTIVol	Office top level central thermal zones volume
OffMCVol	Office intermediate levels corner thermal zones volume
OffMIVol	Office intermediate levels central thermal zones volume

Table 23. GCPH dataset: Census Areas attributes.

Attribute Name	**Attribute description**
ACE	Census Area ID code
ACE_mAge	Prevailing period of construction of Census Area

B. Steps of the GIS-based procedure

In following tables, the single steps for implementing the procedure in the open-source software QGIS 2.18.14 for implementing a geodatabase of an urban building stock are listed. The actions differently accomplished in the application case study are red coloured.

Table 24. Procedure for the base-map preparation.

ACTIONS	INPUT SPATIAL DATASETS	SPECIFICATIONS	OUTPUT SPATIAL DATASET
(A1) Download of spatial datasets	Istat - Spatial Bases	https://www.istat.it/it/archivio/104317#accordions	
	Istat - Statistical Variables	https://www.istat.it/it/archivio/104317#accordions	
	DbT – Built Environment	http://www.geoportale.regione.lombardia.it/en/download-ricerca	
(A1) Import of spatial datasets in GIS canvas	Istat - Spatial Bases	shapefile	
	Istat - Statistical Variables	csv file	
	TDb – Buildings	shapefile	
	TDb – Volumetric Units	shapefile	
	TDb – typology	CSV file	
	TDb - use	CSV file	
(A2) Selection of the municipality area to be assessed	Istat - Spatial Bases Census Units Boundary	Use of the “Select by value” algorithm to select the census units in Milano through the municipality id code field “PRO-COM” (for Milano PRO_COM= 15146)	Spatial Bases - Milano
	Spatial Bases – Milano Istat - Statistical Variables	Use of the “Join attributes” algorithm to add the useful statistical variables to the Spatial Bases – Milano dataset through the census unit id code field “SEZ”	Census Units - Milano
	Istat - Spatial Bases	Use of the “Dissolve” algorithm through the municipality id code field “PRO-COM” (for Milano PRO_COM= 15146)	Census Units Boundary
	Spatial Bases - Milano	Use of the “Dissolve” algorithm through the census area code field “ACE”	Census Areas - Milano
	TDb – Buildings Census Units Boundary	Use of the “Select by position” algorithm to select the buildings overlapping the census unit boundary	Buildings - Milano
	Buildings - Milano TDb - typology DbT - use	Use of the “Join attributes” algorithm to add the “edifc_ty” and “edifc_uso” fields to the Buildings dataset through the building id code field “CRE_EDF-UUI”	Buildings – Milano
	TDb – Unit Volumes Census Units Boundary	Use of the “Select by position” algorithm to select the Unit Volumes overlapping the census unit boundary	Volumetric Units - Milano
(A3) Datasets cleaning	Census Units - Milano	Deletion of Census Units without Statistical Variables	Census Units - filtered
		Deletion of Census Units for which Statistical Variables on buildings are null	
		Deletion of Census Units on the homeless, i.e. with an id code field “SEZ” >8888880	
	Buildings – Milano	Use of the “Select by value” algorithm to select the liveable buildings through the field “CR_EDF_CT” = “edifici”	Buildings – filtered1
		Use of the “Select by value” algorithm to select the already built buildings through the field “CR_EDF_ST” = “edifici costruiti”	Buildings – filtered2
		Use of the “Select by value” algorithm to select the buildings with a diffuse typology through the field “edifc_ty” = “generica”	Buildings – filtered3
		Use of the “Select by value” algorithm for selecting the buildings with a diffuse use category through the field “edifc_uso” = “residenziale”, “residenziale – abitativa”, “amministrativo – municipio”, “amministrativo - sede provincia”, “amministrativo - sede regione”, “servizio pubblico”, “servizio pubblico - sede di tribunale”, “servizio pubblico - sede di poste-telegrafi”, “servizio pubblico - istruzione - sede di scuola”, “industriale”	Buildings – filtered4
	Volumetric Units - Milano	Use of the “Select by value” algorithm to select the Volumetric Units with a height measured from the ground through the field “UN_VOL_POR” = “al suolo”	Volumetric Units – filtered1

		Use of the "Select by value" algorithm to select Volumetric Units with a liveable height through the height field "UN_VOL_AV" >=3	Volumetric Units – filtered2
	Volumetric Units - filtered Buildings filtered	Use of the "Spatial Join" algorithm to select the Volumetric Units which are equal to or contained in the Buildings' area.	Volumetric Units - joined
(A4) Correlation of spatial datasets	Buildings - filtered	Use of the "Polygon centroid" algorithm	Buildings - centroids
	Buildings - centroids Census Units - filtered	Use of the "Spatial Join" algorithm for associating to the centroids within census units the related census unit id code	Buildings - centroids - joined
	Buildings - filtered Buildings - centroids - joined	Use of the "Join attributes" algorithm for adding the "SEZ" field to the Buildings dataset through the building id code field "CRE_EDF_UUI"	Buildings - census associated
	Volumetric Units – joined Buildings - census associated	Creation of the field "SEZ" and association of the Census Unit id code through the field "CRE_EDF_UUI"	Volumetric Units - joined

Table 25. Procedure to determine the prevailing period of construction per each Census Unit.

ACTIONS	INPUT SPATIAL DATASETS	SPECIFICATIONS	OUTPUT SPATIAL DATASET
(B1) Assessment of the prevailing period of construction per each Census Unit	Census Units - filtered	Creation of the field "ResSez_Age and calculation of the prevailing period of construction per each Census Unit	Census Units - filtered
	Census Units - filtered	Creation of the field "ACE_Age" and calculation of the most occurrent prevailing period of construction per each Census Area	Census Units - filtered
	Census Areas - Milano	Creation of the field "ACE_mAge" and association of the prevailing period of construction per each Census Area	Census Areas - Milano
	Census Units - filtered	Creation of the field "SezMainAge" and association of the corrected prevailing period of construction per each Census Unit	Census Units - filtered
	Census Units - filtered	Creation of the field "COEFF_VOL" and association of the net-to-gross ratio value per each Census Unit	Census Units - filtered

Table 26. Procedure to determine the equivalent conditioned volume per each Buildings Group.

ACTIONS	INPUT SPATIAL DATASETS	SPECIFICATIONS	OUTPUT SPATIAL DATASET
(B2.1 and B2.2) Assessment of the conditioned volumes (calculation of the equivalent conditioned volume per each Buildings Group)	Volumetric Units - joined	Use of the "Dissolve" algorithm through the field "SEZ" to merge per each Census Unit all enclosed Volumetric Units	Volumetric Units - dissolved
	Volumetric Units - dissolved	Use of the "Multi to single parts" algorithm to separate Volumetric Units not having adjacent sides	Volumetric Units – single parts
	Volumetric Units – single parts	Creation of the field "Group_ID" for identifying each Building Group	Buildings Groups
	Volumetric Units – joined Buildings Groups	Use of the "Spatial Join attributes" algorithm	Volumetric Units - union
	Volumetric Units – joined Volumetric Units - union	Creation of the field "Group_ID " and association of the Buildings Groups id code based on the field "UUID"	Volumetric Units – joined
	Buildings - census associated Volumetric Units - joined	Use of the "Spatial Join attributes" algorithm for calculating per each Building the maximum floor surface of the enclosed Volumetric Units	Buildings - census associated
	Buildings - census associated Volumetric Units – joined	Creation of the field "ReferenceH " and association of the Volumetric Unit height corresponding to the Volumetric Unit with the maximum floor surface	Buildings - census associated
	Volumetric Units – joined Buildings - census associated	Creation of the field "RefHeight" and association of the reference height to each Volumetric Unit	Volumetric Units - joined

	Volumetric Units – joined	Creation of the field “Surface" and association of the corrected floor area	Volumetric Units – joined
	Volumetric Units – joined	Creation of the field “Volume" and calculation of the corrected volume	Volumetric Units – joined
	Volumetric Units – joined	Creation of the field “Tot_Surf " and calculation of the sum of Volumetric Units’ floor areas per each Buildings Group	Volumetric Units – joined
	Volumetric Units – joined	Creation of the field “Tot_Vol" and calculation of the sum of Volumetric Units’ volumes per each Buildings Group	Volumetric Units – joined
	Buildings Groups Volumetric Units – joined	Creation of the field “SURF_TOT" and association of the total floor area of enclosed Volumetric Units	Buildings Groups
	Buildings Groups Volumetric Units – joined	Creation of the field “VOL_TOT" and association of the total volume of enclosed Volumetric Units	Buildings Groups
	Buildings Groups	Creation of the field “WeightedH" and calculation of the weighted mean height per each Buildings Group	Buildings Groups
	Buildings Groups	Creation of the field “FloorsNum" and calculation of the number of floors per each Buildings Group	Buildings Groups
	Buildings Groups	Creation of the field “FloorHeigh" and calculation of the floor gross height per each Buildings Group	Buildings Groups

Table 27. Procedure to determine the volume by typical thermal zones.

ACTIONS	INPUT SPATIAL DATASETS	SPECIFICATIONS	OUTPUT SPATIAL DATASET
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones - preliminary actions)	Buildings Groups Census Units - filtered	Creation of the field “SezMainAge" and association of the Census Units prevailing period of construction to all enclosed Buildings Groups	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones - preliminary actions)	Buildings Groups Census Units - filtered	Creation of the field “COEFF_VOL" and association of the net-to-gross ratio to each Buildings Group	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones - preliminary actions)	Buildings Groups	Creation of the field “ThZoneSurf" and calculation of the floor gross area of a typical thermal zone per each Buildings Group	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones - preliminary actions)	Buildings Groups	Creation of the field “TZperFloor" and calculation of the number of thermal zones per each floor and each Buildings Group	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones per each Buildings Group)	Buildings Groups	Creation of the field “TopCorner" and calculation per each Buildings Group of the volume of thermal zones placed in the corner on the upper floor	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones per each Buildings Group)	Buildings Groups	Creation of the field “TopCentral" and calculation per each Buildings Group of the volume of thermal zones placed in the central position on the upper floor	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones per each Buildings Group)	Buildings Groups	Creation of the field “Edge" and calculation per each Buildings Group of the volume of thermal zones placed in the corner on the intermediate floor/s	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal zones per each Buildings Group)	Buildings Groups	Creation of the field “Internal" and calculation per each Buildings Group of the volume of thermal zones placed in the central position on the intermediate floor/s	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal	Buildings Groups	Creation of the field “Tot_TC" and calculation per each Census Unit of the total volume of thermal zones placed in the corner on the upper floor	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal	Buildings Groups	Creation of the field “Tot_TI" and calculation per each Census Unit of the total volume of thermal zones placed in the central position on the upper floor	Buildings Groups
(B2.3) Assessment of the conditioned volumes (calculation of the volume by typical thermal	Buildings Groups	Creation of the field “Tot_E" and calculation per each Census Unit of the total volume of thermal zones placed in the corner on the intermediate floor/s	Buildings Groups

zones per each Census Unit)		Creation of the field "Tot_Mid" and calculation per each Census Unit of the total volume of thermal zones placed in the central position on the intermediate floor/s	
	Census Units - filtered Buildings Groups	Creation of the field "Tot_TC" and association per each Census Unit of the total volume of thermal zones placed in the corner on the upper floor	Census Units - filtered
		Creation of the field "Tot_TI" and association per each Census Unit of the total volume of thermal zones placed in the central position on the upper floor	
		Creation of the field "Tot_E" and association per each Census Unit of the total volume of thermal zones placed in the corner on the intermediate floor/s	
		Creation of the field "Tot_Mid" and association per each Census Unit of the total volume of thermal zones placed in the central position on the intermediate floor/s	
	Census Units - filtered	Creation of the field "BuiltVol" and sum per each Census Unit of the total volume of thermal zones	

Table 28. Procedure to determine the volume by use category and typical thermal zone per each Census Unit.

ACTIONS	INPUT SPATIAL DATASETS	SPECIFICATIONS	OUTPUT SPATIAL DATASET
(B3) Determination of the volume by use category (and thermal zones) per each Census Unit	Census Units - filtered	Creation of the field "ResidVol" and calculation per each Census Unit of the total volume of building units in residential buildings	Census Units - filtered
		Creation of the field "Off%NotRes" and calculation per each Census Unit of the percentage of tertiary buildings to the not residential ones	
		Creation of the field "RES%" and calculation per each Census Unit of the percentage of residential use volume to the built one	
		Creation of the field "OFF%" and calculation per each Census Unit of the percentage of tertiary use volume to the built one	
		Creation of the field "ResidTCVol" and calculation per each Census Unit of the total volume of residential use corner upper zones	
		Creation of the field "ResidTIVol" and calculation per each Census Unit of the total volume of residential use central upper thermal zones	
		Creation of the field "ResidMCVol" and calculation per each Census Unit of the total volume of residential use corner intermediate thermal zones	
		Creation of the field "ResidMIVol" and calculation per each Census Unit of the total volume of residential use central intermediate thermal zones	
		Creation of the field "OffTCVol" and calculation per each Census Unit of the total volume of tertiary use corner upper thermal zones	
		Creation of the field "OffTIVol" and calculation per each Census Unit of the total volume of tertiary use central upper thermal zones	
		Creation of the field "OffMCVol" and calculation per each Census Unit of the total volume of tertiary use corner intermediate thermal zones	
		Creation of the field "OffMIVol" and calculation per each Census Unit of the total volume of tertiary use central intermediate thermal zones	

C. Python scripts of the GIS-based procedure

For facilitating the diffuse implementation and possible customization of the defined georeferenced procedure in the open-source software QGIS 2.18.14, most of calculations have been coded in Python 2.7 and related scripts are hereinafter attached per each step.

(A) Base-map preparation

```
from PyQt4.QtCore import *
from PyQt4.QtGui import *
import processing, NumPy as np

# Definition and upload of layers
layer_UV=QgsVectorLayer (r'C:/Users/…/VolumetricUnit.shp',"VolumetricUnit","ogr")
layer_IS=QgsVectorLayer (r'C:/Users/…/Buildings.shp',"Buildings","ogr")
layer_sezcens=QgsVectorLayer (r'C:/Users/…/CensusUnits.shp',"CensusUnits","ogr")
layer_districts= QgsVectorLayer (r'C:/Users/…/ACE.shp',"ACE","ogr")
```

(B1) Assessment of the prevailing period of construction

```
# (a) Determination of the prevailing period of construction of each
(residential)Census Unit
layer_sezcens.startEditing()
field_AGE=layer_sezcens.dataProvider().addAttributes([QgsField("ResSez_AGE",QVarian
t.Int)])
layer_sezcens.commitChanges()

layer_sezcens.startEditing()
field_AGE=layer_sezcens.dataProvider().fieldNameIndex(ResSez_AGE')
print field_AGE
features=layer_sezcens.getFeatures
for feat in features ():
        age_list=[feat['TotI<1919'],feat['TotI<1946'],feat['TotI<1961'],feat['TotI<19
        71'],feat['TotI<1981'],feat['TotI<1991'],feat['TotI<2001'],feat['TotI<=2005']
        ,feat['TotI>2005']]
             Maxflatsnumber=max(age_list)
             if age_list is NULL:
                  age_result=0
             elif
        feat['TotI<1919']+feat['TotI<1946']+feat['TotI<1961']+feat['TotI<1971']+feat[
        'TotI<1981']+feat['TotI<1991']+feat['TotI<2001']+feat['TotI<=2005']+feat['Tot
        I>2005']==0:
                  age_result=0
             elif feat['TotI>2005']==Maxflatsnumber:
                  age_result=9
             elif feat['TotI<=2005']==Maxflatsnumber:
                  age_result=8
             elif feat['TotI<2001']==Maxflatsnumber:
                  age_result=7
             elif feat['TotI<1991']==Maxflatsnumber:
                  age_result=6
             elif feat['TotI<1981']==Maxflatsnumber:
                  age_result=5
             elif feat['TotI<1971']==Maxflatsnumber:
                  age_result=4
             elif feat['TotI<1961']==Maxflatsnumber:
                  age_result=3
             elif feat['TotI<1946']==Maxflatsnumber:
                  age_result=2
             elif feat['TotI<1919']==Maxflatsnumber:
                  age_result=1
             print Maxflatsnumber, age_result
     layer_sezcens.changeAttributeValue(feat.id(), field_AGE, age_result)
layer_sezcens.updateFields()
layer_sezcens.commitChanges()
```

```
# (b) Determination of the prevailing period of construction of each Census Area
layer_sezcens.startEditing()
layer_sezcens.dataProvider().addAttributes([QgsField("ACE_AGE",QVariant.Int)])
layer_sezcens.commitChanges()

layer_sezcens.startEditing()
field_censusarea=layer_sezcens.dataProvider().fieldNameIndex('ACE')
field_age=layer_sezcens.dataProvider().fieldNameIndex('SezRes_AGE')
ace_age_field=layer_sezcens.dataProvider().fieldNameIndex('ACE_AGE')
print field_censusarea, field_age,ace_age_field
uniquevalues=layer_sezcens.uniqueValues(field_censusarea,limit=10000)
for uv in uniquevalues:
    values = []
    exp = QgsExpression('ACE = ' + str(uv))
    request = QgsFeatureRequest(exp)
    featuresforthisuniquevalue=layer_sezcens.getFeatures(request)
    for feat in featuresforthisuniquevalue:
          attrs = feat.attributes()
          values.append(attrs[field_age])
           expr=(values)
           age1=expr.count(1)
           age2=expr.count(2)
           age3=expr.count(3)
           age4=expr.count(4)
           age5=expr.count(5)
           age6=expr.count(6)
           age7=expr.count(7)
           age8=expr.count(8)
           age9=expr.count(9)
           age_list=[age1,age2,age3,age4,age5,age6,age7,age8,age9]
           maxagefrequency=max(age_list)
           if age9==maxagefrequency:
               ACEage=9
           elif age8==maxagefrequency:
               ACEage=8
           elif age7==maxagefrequency:
               ACEage=7
           elif age6==maxagefrequency:
               ACEage=6
           elif age5==maxagefrequency:
               ACEage=5
           elif age4==maxagefrequency:
               ACEage=4
           elif age3==maxagefrequency:
               ACEage=3
           elif age2==maxagefrequency:
               ACEage=2
           elif age1==maxagefrequency:
               ACEage=1
           print uv,ACEage
    layer_sezcens.changeAttributeValue(feat.id(),ace_age_field,ACEage)
layer_sezcens.updateFields()
layer_sezcens.commitChanges()


layer_districts.startEditing()
field=layer_districts.dataProvider().addAttributes( [QgsField("ACE_mAGE",
QVariant.Int)])
layer_districts.commitChanges()

layer_districts.startEditing()
field_sezcens_age=layer_sezcens.dataProvider().fieldNameIndex('ACE_AGE')
field_ace_age=layer_districts.dataProvider().fieldNameIndex('ACE_mAGE')
field_sezcens_ace=layer_sezcens.dataProvider().fieldNameIndex('ACE')
field_ace_ace=layer_districts.dataProvider().fieldNameIndex('ACE')
print field_sezcens_age,field_ace_age,field_sezcens_ace,field_ace_ace
```

```
for feat in layer_districts.getFeatures():
    for f in layer_sezcens.getFeatures():
        if f['ACE_AGE']==NULL:
            pass
        elif f['ACE_AGE']!=NULL:
            if feat['ACE']==f['ACE']:
                builtarea_result=f['ACE_AGE']
    print feat['ACE'], builtarea_result
    layer_districts.changeAttributeValue(feat.id(),field_ace_age,builtarea_result)
layer_districts.updateFields()
layer_districts.commitChanges()

# (c) Determination of the prevailing construction period definition for each
Census Unit
layer_sezcens.startEditing()
field=layer_sezcens.dataProvider().addAttributes( [QgsField("SezMainAge",
QVariant.Int)])
layer_sezcens.commitChanges()

layer_sezcens.startEditing()
field_sezcens_age=layer_sezcens.dataProvider().fieldNameIndex('SezMainAge')
field_ace_age=layer_districts.dataProvider().fieldNameIndex('ACE_mAGE')
field_sezcens_ace=layer_sezcens.dataProvider().fieldNameIndex('ACE')
field_ace_ace=layer_districts.dataProvider().fieldNameIndex('ACE')
field_sezcens_age_res=layer_sezcens.dataProvider().fieldNameIndex('SezRes_AGE')
print
field_sezcens_age,field_ace_age,field_sezcens_ace,field_ace_ace,field_sezcens_age_r
es
for feat in layer_sezcens.getFeatures():
    for f in layer_districts.getFeatures():
        if feat['SezRes_AGE']>0:
            constructionperiod_result=feat['SezRes_AGE']
        else:
            if feat['ACE']==f['ACE']:
                constructionperiod_result=f['ACE_mAGE']
    print constructionperiod_result

layer_sezcens.changeAttributeValue(feat.id(),field_sezcens_age,constructionperiod_r
esult)
layer_sezcens.updateFields()
layer_sezcens.commitChanges()

# (d) Association of the net-to-gross correction factor based on the prevailing
period of construction
layer_sezcens.startEditing()
layer_sezcens.dataProvider().addAttributes([QgsField("COEFF_VOL",
QVariant.Double)])
layer_sezcens.commitChanges()

layer_sezcens.startEditing()
field_Vol=layer_sezcens.dataProvider().fieldNameIndex('COEFF_VOL')
print field_Vol
for feat in layer_sezcens.getFeatures():
    if feat['SezMainAge']== NULL:
        pass
    elif feat ['SezMainAge']<=3:
        coeff=0.6
    elif feat ['SezMainAge']>3:
        coeff=0.7
    print coeff
    layer_sezcens.changeAttributeValue(feat.id(), field_Vol, coeff)
layer_sezcens.updateFields()
layer_sezcens.commitChanges()
```

(B2) Assessment of the conditioned volumes

(B2.1) Deletion of the unconditioned volume

```
# (a) Determination of the reference height per each Building
layer_IS.startEditing()
layer_IS.dataProvider().addAttributes([QgsField("ReferenceH",QVariant.Double)])
layer_IS.commitChanges()

layer_IS.startEditing()
refheight_field=layer_IS.dataProvider().fieldNameIndex('ReferenceH')
area_field=layer_IS.dataProvider().fieldNameIndex('maxun_vo_1')
BLfield=layer_IS.dataProvider().fieldNameIndex('CR_EDF_UUI')
hfield=layer_UV.dataProvider().fieldNameIndex('UN_VOL_AV')
afield=layer_UV.dataProvider().fieldNameIndex('Shape_Area')
bfield=layer_UV.dataProvider().fieldNameIndex('CR_EDF_UUI')
print refheight_field,area_field,BLfield,hfield,afield,bfield
height=0
for feat in layer_IS.getFeatures():
    for f in layer_UV.getFeatures():
        if feat['CR_EDF_UUI']==f['CR_EDF_UUI'] and abs(feat['maxun_vo_1']/
      -f['Shape_Area'] )< 0.0001:
            height=f['UN_VOL_AV']
        else:
            pass
    print height
    layer_IS.changeAttributeValue(feat.id(),refheight_field,height)
layer_IS.updateFields()
layer_IS.commitChanges()

# (b)Pasting of reference height in Volumetric Units
layer_UV.startEditing()
layer_UV.dataProvider().addAttributes([QgsField("RefHeight",QVariant.Double)])
layer_UV.commitChanges()

layer_UV.startEditing()
BLfield=layer_IS.dataProvider().fieldNameIndex('CR_EDF_UUI')
bfield=layer_UV.dataProvider().fieldNameIndex('CR_EDF_UUI')
MHfield=layer_IS.dataProvider().fieldNameIndex('ReferenceH')
rhfield=layer_UV.dataProvider().fieldNameIndex('RefHeight')
print BLfield,bfield,MHfield,rhfield
refh_result=0
for f in layer_UV.getFeatures():
    for feat in layer_IS.getFeatures():
        if f['CR_EDF_UUI']==feat['CR_EDF_UUI']:
            refh_result=feat['ReferenceH']
    print f['CR_EDF_UUI'], refh_result
    layer_UV.changeAttributeValue(f.id(),rhfield,refh_result)
layer_UV.updateFields()
layer_UV.commitChanges()

#(c)Determination of the staircase volumes
layer_UV.startEditing()
layer_UV.dataProvider().addAttributes([QgsField("UVstatus",QVariant.Int)])
layer_UV.commitChanges()

layer_UV.startEditing()
status_field=layer_UV.dataProvider().fieldNameIndex('UVstatus')
print status_field
for feat in layer_UV.getFeatures():
    gap=feat['UN_VOL_AV']-feat['RefHeight']
    if gap<=6 and gap>0 and feat['Shape_Area']<=50:
        status_result=0
    else:
        status_result=1
    print status_result
    layer_UV.changeAttributeValue(feat.id(), status_field, status_result)
```

```
layer_UV.updateFields()
layer_UV.commitChanges()

# (d)Calculation of the  Volumetric Units' floor surface, except for staircases
layer_UV.startEditing()
layer_UV.dataProvider().addAttributes([QgsField("Surface",QVariant.Double)])
layer_UV.commitChanges()
layer_UV.startEditing()
area_field=layer_UV.dataProvider().fieldNameIndex('Surface')
print area_field
for feat in layer_UV.getFeatures():
    gap=feat['UN_VOL_AV']-feat['RefHeight']
    if gap<=6 and gap>0 and feat['Shape_Area']<=50:
        area_result=0.0
    else:
        area_result=feat ['Shape_Area']
    print area_result
    layer_UV.changeAttributeValue(feat.id(), area_field, area_result)
layer_UV.updateFields()
layer_UV.commitChanges()

# (e)Calculation of the Volumetric Units' volume, except for staircases
layer_UV.startEditing()
layer_UV.dataProvider().addAttributes([QgsField("Volume",QVariant.Double)])
layer_UV.commitChanges()

layer_UV.startEditing()
h_field=layer_UV.dataProvider().fieldNameIndex('UN_VOL_AV')
area_field=layer_UV.dataProvider().fieldNameIndex('Shape_Area')
vol_field=layer_UV.dataProvider().fieldNameIndex('Volume')
print h_field,area_field,vol_field
for feat in layer_UV.getFeatures():
    gap=feat['UN_VOL_AV']-feat['RefHeight']
    if gap<=6 and gap>0 and feat['Shape_Area']<=50:
        vol_result=0.0
    else:
        vol_result=feat ['Surface']*feat ['UN_VOL_AV']
    print vol_result
    layer_UV.changeAttributeValue(feat.id(), vol_field, vol_result)
layer_UV.updateFields()
layer_UV.commitChanges()
```

(B2.2) Definition of the Buildings Groups

```
# (a)Calculation of the total floor surface, excluding staircases one, per each
Buildings Group
layer_UV.startEditing()
layer_UV.dataProvider().addAttributes([QgsField("Tot_Surf",QVariant.Double)])
layer_UV.commitChanges()

layer_UV.startEditing()
bld_field=layer_UV.dataProvider().fieldNameIndex('Group_ID')
areabld_field=layer_UV.dataProvider().fieldNameIndex('Surface')
area_field=layer_UV.dataProvider().fieldNameIndex('Tot_Surf')
print bld_field,areabld_field,area_field
uniquevalues=layer_UV.uniqueValues(bld_field,limit=10000)
for uv in uniquevalues:
    tot = 0.0
    exp = QgsExpression('Group_ID = ' + str(uv))
    request = QgsFeatureRequest(exp)
    features=layer_UV.getFeatures(request)
    for feat in features:
        tot+=feat.attributes()[areabld_field]
    print uv,tot
    layer_UV.changeAttributeValue(feat.id(),area_field,tot)
layer_UV.updateFields()
layer_UV.commitChanges()
```

```
# (b)Calculation of the total volume, excluding staircases one, per each Buildings Group
layer_UV.startEditing()
layer_UV.dataProvider().addAttributes([QgsField("Tot_Vol",QVariant.Double)])
layer_UV.commitChanges()

layer_UV.startEditing()
bld_field=layer_UV.dataProvider().fieldNameIndex('Group_ID')
volbld_field=layer_UV.dataProvider().fieldNameIndex('Volume')
volume_field=layer_UV.dataProvider().fieldNameIndex('Tot_Vol')
print bld_field,volbld_field,volume_field
uniquevalues=layer_UV.uniqueValues(bld_field,limit=10000)
for uv in uniquevalues:
    tot = 0.0
    exp = QgsExpression('Group_ID = ' + str(uv))
    request = QgsFeatureRequest(exp)
    features=layer_UV.getFeatures(request)
    for feat in features:
        tot+=feat.attributes()[volbld_field]
    print uv,tot
    layer_UV.changeAttributeValue(feat.id(),volume_field,tot)
layer_UV.updateFields()
layer_UV.commitChanges()

# (c)Pasting of the total floor surface, excluding staircases one, per each Buildings Group
layer_groups.startEditing()
layer_groups.dataProvider().addAttributes([QgsField("SURF_TOT",QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
BLDsurffield=layer_groups.dataProvider().fieldNameIndex('SURF_TOT')
UVsurffield=layer_UV.dataProvider().fieldNameIndex('Tot_Surf')
BLDfield=layer_groups.dataProvider().fieldNameIndex('Group_ID')
UVfield=layer_UV.dataProvider().fieldNameIndex('Group_ID')
print BLDsurffield,UVsurffield,BLDfield,UVfield
for feat in layer_groups.getFeatures():
    for f in layer_UV.getFeatures():
        if f['Tot_Surf']==NULL:
            pass
        elif f['Tot_Surf']!=NULL:
            if feat['Group_ID']==f['Group_ID']:
                surf_result=f['Tot_Surf']
    print feat['Group_ID'], surf_result
    layer_groups.changeAttributeValue(feat.id(),BLDsurffield,surf_result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (d)Pasting of the total volume, excluding staircases one, per each Buildings Group
layer_groups.startEditing()
layer_groups.dataProvider().addAttributes([QgsField("VOL_TOT",QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
BLDvolfield=layer_groups.dataProvider().fieldNameIndex('VOL_TOT')
UVvolfield=layer_UV.dataProvider().fieldNameIndex('Tot_Vol')
BLDfield=layer_groups.dataProvider().fieldNameIndex('Group_ID')
UVfield=layer_UV.dataProvider().fieldNameIndex('Group_ID')
print BLDvolfield,UVvolfield,BLDfield,UVfield
for feat in layer_groups.getFeatures():
    for f in layer_UV.getFeatures():
        if f['Tot_Vol']==NULL:
            pass
        elif f['Tot_Vol']!=NULL and feat['Group_ID']==f['Group_ID']:
            vol_result=f['Tot_Vol']
    print feat['Group_ID'], vol_result
```

```
    layer_groups.changeAttributeValue(feat.id(),BLDvolfield,vol_result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (e)Calculation of the average weighted height per each Buildings Group
layer_groups.startEditing()
layer_groups.dataProvider().addAttributes([QgsField("WeightedH",QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
height_field=layer_groups.dataProvider().fieldNameIndex('WeightedH')
print height_field
for feat in layer_groups.getFeatures():
    if feat['SURF_TOT']==0:
        height_result=0.0
    else:
        height_result=feat['VOL_TOT']/feat['SURF_TOT']
    print feat['Group_ID'],height_result
    layer_groups.changeAttributeValue(feat.id(),height_field,height_result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (f)Calculation of the number of floors per each Buildings’ Group
layer_groups.startEditing()
layer_groups.dataProvider().addAttributes([QgsField("FloorsNum",QVariant.Int)])
layer_groups.commitChanges()

layer_groups.startEditing()
nfloors_field=layer_groups.dataProvider().fieldNameIndex('FloorsNum')
height_field=layer_groups.dataProvider().fieldNameIndex('WeightedH')
print nfloors_field,height_field
for feat in layer_groups.getFeatures():
    if feat['WeightedH']==0:
        nfloors_result=0.0
    else:
        nfloors_real=feat['WeightedH']/3.0
        round_nfloors=round(nfloors_real)
        int_nfloors=int(nfloors_real)
        h_interpiano=feat['Weighted_H']/round_nfloors
        if h_interpiano>=3.0:
            nfloors_result=int(round_nfloors)
        else:
            nfloors_result=int_nfloors
    print feat['Group_ID'],nfloors_result
    layer_groups.changeAttributeValue(feat.id(),nfloors_field,nfloors_result)
layer_groups.updateFields()
layer_groups.commitChanges()

#(g)Calculation of the floor gross height per each Buildings Group
layer_groups.startEditing()
field=layer_groups.dataProvider().addAttributes([QgsField("FloorHeigh",QVariant.Dou
ble)])
layer_groups.commitChanges()

layer_groups.startEditing()
Hfloors_field=layer_groups.dataProvider().fieldNameIndex('FloorHeigh')
print Hfloors_field
for feat in layer_groups.getFeatures():
    if feat['N_FLOORS']==0:
        Hfloors_result=0.0
    else:
        Hfloors_result=feat['WeightedH']/feat['FloorsNum']
    print feat['Group_ID'],Hfloors_result
    layer_groups.changeAttributeValue(feat.id(),Hfloors_field,Hfloors_result)
layer_groups.updateFields()
layer_groups.commitChanges()
```

```
# (h)Pasting of the Census Unit prevailing period of construction in Buildings
Group dataset
layer_groups.startEditing()
layer_groups.dataProvider().addAttributes([QgsField("SezMainAge",QVariant.Int)])
layer_groups.commitChanges()

layer_groups.startEditing()
BLfield=layer_groups.dataProvider().fieldNameIndex('SEZ')
SEZfield=layer_sezcens.dataProvider().fieldNameIndex('SEZ')
BLD_agefield=layer_groups.dataProvider().fieldNameIndex('SezMainAge')
SEZ_agefield=layer_sezcens .dataProvider().fieldNameIndex('SezMainAge')
print BLfield,SEZfield,BLD_agefield,SEZ_agefield
result=0
for f in layer_groups.getFeatures():
    for feat in layer_sezcens .getFeatures():
        if f['SEZ']==feat['SEZ']:
            result=feat['SezMainAge']
    print f['SEZ'], result
    layer_groups.changeAttributeValue(f.id(),BLD_agefield,result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (i)Pasting of the Census Unit net-to-gross volume factor in Buildings Group
dataset
layer_groups.startEditing()
layer_groups.dataProvider().addAttributes([QgsField("COEFF_VOL",QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
BLfield=layer_groups.dataProvider().fieldNameIndex('SEZ')
SEZfield=layer_sezcens .dataProvider().fieldNameIndex('SEZ')
BLD_agefield=layer_groups.dataProvider().fieldNameIndex('COEFF_VOL')
SEZ_agefield=layer_sezcens .dataProvider().fieldNameIndex('COEFF_VOL')
print BLfield,SEZfield,BLD_agefield,SEZ_agefield
result=0
for f in layer_groups.getFeatures():
    for feat in layer_sezcens .getFeatures():
        if f['SEZ']==feat['SEZ']:
            result=feat['COEFF_VOL']
    print f['SEZ'], result
    layer_groups.changeAttributeValue(f.id(),BLD_agefield,result)
layer_groups.updateFields()
layer_groups.commitChanges()
```

(B2.3) Assessment of volume by typical thermal zones

```
# (a) Calculation of the gross floor area of a typical thermal zone
layer_groups.startEditing()
field=layer_groups.dataProvider().addAttributes([QgsField("ThZoneSurf",QVariant.Dou
ble)])
layer_groups.commitChanges()

layer_groups.startEditing()
area_field=layer_groups.dataProvider().fieldNameIndex(ThZoneSurf )
print area_field
for feat in layer_groups.getFeatures():
    if feat['FloorHeigh']==0:
        area_result=0
    else:
        area_result=(25*2.7)/ (feat['COEFF_VOL']*feat['FloorHeigh'])
    print feat['Group_ID'],area_result
    layer_groups.changeAttributeValue(feat.id(),area_field,area_result)
layer_groups.updateFields()
layer_groups.commitChanges()

#(b) Calculation of the number of thermal zones per floor
layer_groups.startEditing()
```

```
field_ground=layer_groups.dataProvider().addAttributes( [QgsField("TZperFloor",
QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
field_zones=layer_groups.dataProvider().fieldNameIndex('TZperFloor')
print field_zones
for feat in layer_groups.getFeatures():
    if feat['ThZoneSurf']==0:
        zones_result=0.0
    else:
        zones_result=round(feat['SURF_TOT']/feat['ThZoneSurf'])
    print feat['Group_ID'],zones_result
    layer_groups.changeAttributeValue(feat.id(), field_zones, zones_result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (c) Calculation of the gross volume of corner typical thermal zones on ground or
top floor
layer_groups.startEditing()
field_TopCorner=layer_groups.dataProvider().addAttributes( [QgsField("TopCorner",
QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
field_volume=layer_groups.dataProvider().fieldNameIndex('TopCorner')
print field_volume
for feat in layer_groups.getFeatures():
    if feat['FloorsNum']==0:
       volumme_result=0.0
    elif feat['TZperFloor']<4:
        volume_result=0.0
    elif feat['FloorsNum']<=2:
        if feat['TZperFloor']==4:
            volume_result=0.5*feat['VOL_TOT']
        elif feat['TZperFloor']>4:
            volume_result=(0.5*feat['WeightedH'])*(4*feat['ThZoneSurf'])
    elif feat['FloorsNum']>2:
        if feat['TZperFloor']==4:
            volume_result=feat['VOL_TOT']/feat['FloorsNum']
        elif feat['TZperFloor']>4:
            volume_result=feat['FloorHeigh']*4*feat['ThZoneSurf']
    print feat['Group_ID'],volume_result
    layer_groups.changeAttributeValue(feat.id(), field_volume, volume_result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (d) Calculation of the gross volume of central typical thermal zones on ground or
top floor
layer_groups.startEditing()
field_TopIntermediate=layer_groups.dataProvider().addAttributes( [QgsField("TopCent
ral", QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
field_volume=layer_groups.dataProvider().fieldNameIndex('TopCentral')
field_gtc=layer_groups.dataProvider().fieldNameIndex('TopCorner')
print field_volume,field_gtc
for feat in layer_groups.getFeatures():
    if feat['FloorsNum']==0:
       volume_result=0.0
    elif feat['TZperFloor']<=4:
        volume_result=0.0
    elif feat['FloorsNum']<=2 and feat['TZperFloor']>4:
        volume_result=0.5*feat['VOL_TOT']-feat['TopCorner']
    elif feat['FloorsNum']>2and feat['TZperFloor']>4:
        volume_result=feat['FloorHeigh']*feat['SURF_TOT']-feat['TopCorner']
    print feat['Group_ID'],volume_result
```

```
    layer_groups.changeAttributeValue(feat.id(), field_volume, volume_result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (e) Calculation of the gross volume of corner typical thermal zones on
intermediate floors
layer_groups.startEditing()
field_IntermediateCorner=layer_groups.dataProvider(.addAttributes([QgsField("Edge",
QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
field_volume=layer_groups.dataProvider().fieldNameIndex('Edge')
print field_volume
for feat in layer_groups.getFeatures():
    if feat['FloorsNum']<=2:
        volume_result=0.0
    elif feat['TZperFloor']<4:
        volume_result=0.0
    elif feat['FloorsNum']>2 and  feat['TZperFloor']==4:
        volume_result=feat['VOL_TOT']-2*feat['TopCorner']
    elif feat['FloorsNum']>2and  feat['TZperFloor']>4:
        volume_result=4*feat ['ThZoneSurf']*feat['WeightedH']-2*feat['TopCorner']
    print feat['Group_ID'],volume_result
    layer_groups.changeAttributeValue(feat.id(), field_volume, volume_result)
layer_groups.updateFields()
layer_groups.commitChanges()

#(f)Calculation of the gross volume of internal typical thermal zones
layer_groups.startEditing()
field_Internal=layer_groups.dataProvider().addAttributes( [QgsField("Internal",
QVariant.Double)])
layer_groups.commitChanges()

layer_groups.startEditing()
field_volume=layer_groups.dataProvider().fieldNameIndex('Internal')
print field_volume
for feat in layer_groups.getFeatures():
    if feat['FloorsNum']>2 and feat['TZperFloor']>4:
        volume_result=feat['VOL_TOT']-
(2*feat['TopCorner']+2*feat['TopCentral']+feat['Edge'])
    else:
        volume_result=0.0
    print feat['Group_ID'],volume_result
    layer_groups.changeAttributeValue(feat.id(), field_volume, volume_result)
layer_groups.updateFields()
layer_groups.commitChanges()

# (g)Sum of the volume by each thermal zone of all enclosed Buildings Groups per
each Census Unit (only the script for one thermal zone is reported as an example)
layer_groups.startEditing()
layer_groups.dataProvider().addAttributes([QgsField("Tot_TC",QVariant.Double)]))
#redo and alternatively replace "Tot_TC" with "Tot_TI","Tot_E","Tot_Mid"
layer_groups.commitChanges()

layer_groups.startEditing()
census_field=layer_groups.dataProvider().fieldNameIndex('SEZ')
volume_field=layer_groups.dataProvider().fieldNameIndex('TopCorner') #redo and
alternatively replace 'TopCorner' with ' TopCentral', ' Edge ', ' Internal'
result_field=layer_groups.dataProvider().fieldNameIndex('Tot_VTC') #redo and
alternatively replace 'Tot_TC' with 'Tot_TI', 'Tot_E', ' Tot_Mid'
print census_field,volume_field,result_field
uniquevalues=layer_groups.uniqueValues(census_field,limit=10000)
for uv in uniquevalues:
    tot = 0.0
    exp = QgsExpression('SEZ = ' + str(uv))
    request = QgsFeatureRequest(exp)
    features=layer_groups.getFeatures(request)
```

```
    for feat in features:
        tot+=feat.attributes()[volume_field]
    print uv,tot
    layer_groups.changeAttributeValue(feat.id(),result_field,tot)
layer_groups.updateFields()
layer_groups.commitChanges()

# (h) Pasting of volume by thermal zone per Census Unit in Census Unit dataset
(only the script for one thermal zone is reported as an example)
layer_sezcens .startEditing()
layer_sezcens .dataProvider().addAttributes([QgsField("Tot_TC",QVariant.Double)])
#redo and alternatively replace "Tot_TC" with 'Tot_TI', 'Tot_E', ' Tot_Mid'
layer_sezcens .commitChanges()

layer_sezcens .startEditing()
bld_field=layer_groups.dataProvider().fieldNameIndex('SEZ')
sez_field=layer_sezcens .dataProvider().fieldNameIndex('SEZ')
vol_bldfield=layer_groups.dataProvider().fieldNameIndex('Tot_VTC') #redo and
alternatively replace "Tot_TC" with 'Tot_TI', 'Tot_E', ' Tot_Mid'
vol_sezfield=layer_sezcens .dataProvider().fieldNameIndex('Tot_VTC') #redo and
alternatively replace "Tot_TC" with 'Tot_TI', 'Tot_E', ' Tot_Mid'
print bld_field,sez_field,vol_bldfield,vol_sezfield
result=0.0
for f in layer_sezcens .getFeatures():
    for feat in layer_groups.getFeatures():
        if f['SEZ']==feat['SEZ']:
            result=feat['Tot_TC']
    print f['SEZ'], result
    layer_sezcens .changeAttributeValue(f.id(),vol_sezfield,result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()

# (i) Calculation of built gross volume per Census Unit
layer_sezcens .startEditing()
layer_sezcens .dataProvider().addAttributes([QgsField("BuiltVol",QVariant.Double)])
layer_sezcens .commitChanges()

layer_sezcens .startEditing()
sez_field=layer_sezcens .dataProvider().fieldNameIndex('SEZ')
vol_field=layer_sezcens .dataProvider().fieldNameIndex('BuiltVol')
print sez_field,vol_field
result=0.0
for feat in layer_sezcens .getFeatures():
    result=2*feat['Tot_TC']+2*feat['Tot_TI']+feat['Tot_E']+feat['Tot_Mid']
    print feat['SEZ'], result
    layer_sezcens .changeAttributeValue(feat.id(),vol_field,result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()
```

(B3) Assessment of volume by use category

```
# (a) Calculation of residential gross volume per each Census Unit
layer_sezcens.startEditing()
layer_sezcens.dataProvider().addAttributes([QgsField("ResidVol",QVariant.Double)])
layer_sezcens.commitChanges()

layer_sezcens .startEditing()
field_volume=layer_sezcens .dataProvider().fieldNameIndex('ResidVol')
print field_volume
for feat in layer_sezcens .getFeatures():
    if feat['Abit>1res']== 0 or feat['Abit>1res']== NULL:
        vol_result=0.0
    else:
        area=((feat['Sup_ab1res']/feat['Abit>1res'])*feat['Abit_altre'])+feat
['Sup_ab1res']
        if feat ['SezMainAge']==0:
            vol_result=0.0
        elif feat ['SezMainAge']<=3:
```

```
            vol_result=(area*2.7)/feat ['COEFF_VOL']
        else:
            vol_result=(area*2.7)/feat ['COEFF_VOL']
        print feat['SEZ'],vol_result
        layer_sezcens .changeAttributeValue(feat.id(), field_volume, vol_result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()

# (b) Calculation of the tertiary buildings weighted share compared to not
residential buildings
layer_sezcens .startEditing()
layer_sezcens .dataProvider().addAttributes([QgsField("Off%NotRes",QVariant.Double)
])
layer_sezcens .commitChanges()

layer_sezcens .startEditing()
field_OffPercentage=layer_sezcens .dataProvider().fieldNameIndex('Off%NotRes')
print field_OffPercentage
for feat in layer_sezcens .getFeatures():
    if feat['EdNoRes']==0.0:
        share_edifici=0.0
    else:
        share_edifici=feat['EdifDirez']/feat['EdNoRes']
    if feat['ComplNoRes']==0:
        share_complessi=0.0
    else:
        share_complessi=feat['ComplDirez']/feat['ComplNoRes']
    numerator=feat['EdifDirez']*share_edifici+feat['ComplDirez']*share_complessi
    denominatore=feat['EdifDirez']+feat['ComplDirez']
    if denominator==0.0:
        share_result=0.0
    else:
        share_result=numerator/denominator
    print share_result
    layer_sezcens .changeAttributeValue(feat.id(), field_OffPercentage,
share_result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()

# (c) Calculation of the residential buildings share compared to the total built
volume
layer_sezcens .startEditing()
layer_sezcens .dataProvider().addAttributes([QgsField("RES%",QVariant.Double)])
layer_sezcens .commitChanges()

layer_sezcens .startEditing()
field_percentage=layer_sezcens .dataProvider().fieldNameIndex('RES%')
print field_percentage
for feat in layer_sezcens .getFeatures():
    if feat['BuiltVol']==0 or feat['BuiltVol']==NULL or feat['ResidVol']==0 or
feat['ResidVol']==NULL:
        percentage_result =0.0
    elif  feat['ResidVol']<feat['BuiltVol']:
        percentage_result = feat['ResidVol']/feat['BuiltVol']
    elif  feat['ResidVol']>feat['BuiltVol']:
        percentage_result =1.0
    print percentage_result
    layer_sezcens .changeAttributeValue(feat.id(), field_percentage,
percentage_result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()

# (d) Calculation of the tertiary buildings share compared to the total built
volume
layer_sezcens .startEditing()
layer_sezcens .dataProvider().addAttributes([QgsField("OFF%",QVariant.Double)])
layer_sezcens .commitChanges()
```

```
layer_sezcens .startEditing()
field_percentage=layer_sezcens .dataProvider().fieldNameIndex('OFF%')
print field_percentage
for feat in layer_sezcens .getFeatures():
    if feat['BuiltVol']==NULL or feat['Off%NotRes']==NULL or feat['BuiltVol']==0 or
feat['Off%NotRes']==0:
        percentage_result =0.0
    else:
        percentage_result=(1.0-feat['RES%'])*feat['Off%NotRes']
    print percentage_result
    layer_sezcens .changeAttributeValue(feat.id(), field_percentage,
percentage_result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()

#(e) Calculation of the residential volume by typical thermal zone (only the script
for one thermal zone is reported as an example)
layer_sezcens .startEditing()
layer_sezcens .dataProvider().addAttributes([QgsField("ResidTCVol",QVariant.Double)
]) #redo and alternatively replace " ResidTCVol" with "ResidTIVol", "ResidMCVol",
"ResidMIVol"
layer_sezcens .commitChanges()

layer_sezcens .startEditing()
field_volume=layer_sezcens .dataProvider().fieldNameIndex(ResidTCVol ) #redo and
alternatively replace ResidTCVol with ResidTIVol ,'ResidMCVol', 'ResidMIVol'
print field_volume
for feat in layer_sezcens .getFeatures():
    volume_result=feat['RES%']*feat['Tot_TC'] #redo and alternatively replace
'Tot_TC' with 'Tot_TI','Tot_E','Tot_Mis'
    print volume_result
    layer_sezcens .changeAttributeValue(feat.id(), field_volume, volume_result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()

#¨(f) Calculation of tertiary volume by typical thermal zone (only the script for
one thermal zone is reported as an example)
layer_sezcens .startEditing()
layer_sezcens .dataProvider().addAttributes([QgsField("OffTCVol",QVariant.Double)])
#redo and alternatively replace "OffTCVol"with "OffTIVol","OffMCVol", "OffMIVol"
layer_sezcens .commitChanges()

layer_sezcens .startEditing()
field_volume=layer_sezcens .dataProvider().fieldNameIndex('OffTCVol') #redo and
alternatively replace 'OffTCVol' with 'OffTIVol', 'OffMCVol', "OffMIVol"
print field_volume
for feat in layer_sezcens .getFeatures():
    volume_result=feat['DIRbuilt%']*feat['Tot_VTC'] #redo and alternatively replace
'Tot_TC' with 'Tot_TI', 'Tot_E', 'Tot_Mid'
    print volume_result
    layer_sezcens .changeAttributeValue(feat.id(), field_volume, volume_result)
layer_sezcens .updateFields()
layer_sezcens .commitChanges()
```

D. Publications

For the dissemination of this Ph.D. research, the following articles have been published:

Ferrari S., Zagarella F. *Costs assessment for building renovation cost-optimal analysis*. Energy Procedia 2015; 78: 2378-2384. https://doi.org/10.1016/j.egypro.2015.11.193

In the frame of the IEA-EBC project "Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation", the Politecnico di Milano research group elaborated the information required to perform the renovation measures cost-optimal analysis of two case study buildings, representative of the most common ones of the Italian residential stock. Renovation costs have been composed accurately and, additionally, an analysis of several references has been accomplished for collecting national energy consumptions and GHG emissions values, current and projected, and energy career indexes. Adopted approach can provide insights for analogous researches and outcomes can be considered for similar retrofit cases in Italy.

Ferrari S., Zagarella F. *Assessing Buildings Hourly Energy Needs for Urban Energy Planning in Southern European Context*. Procedia Engineering 2016; 161: 783-791. https://doi.org/10.1016/j.proeng.2016.08.707

For decreasing the fossil fuels consumption and reducing air pollution at urban level, current policies encourage a transition to distributed energy generation (DG) and support initiatives towards district heating and cooling networks (DES - district energy systems), promoting the integration of renewable energy sources (RES). Based on these approaches, the assessment of the energy demand fluctuations of the building stock is preliminary for energy planning at district scale, since systems' operation requires a complex balancing for maximizing the efficiency or minimizing the cost, combining the intermittent nature of RES (except biomasses) with non-RES and/or storage technology. Surveyed literature concerning recent studies aimed at optimizing district energy scenarios revealed that most of the assessment are limited to the seasonal and/or annual based buildings energy needs, while the ones that deal with a proper time scale (i.e. hourly based) refer to specific case studies, which are hardly replicable in other urban contexts. The purpose of the study presented in this paper was to provide reliable reference profiles of buildings thermal energy needs (for both space heating and cooling) with reference to the Italian context. Therefore, a set of building models, representative of typical solutions of different historical periods, was defined for both residential and diffuse tertiary (offices) use. Once elaborated accurate hourly internal loads curves, it was possible to provide, performing detailed simulations with TRNSYS model, profiles of energy need density, referred to cubic meter of building volume, for typical buildings placed in different climatic locations, covering the wide range of Italian context. Based on both the building typologies and the climatic variability considered, assumptions adopted for the study could be extended to other comparable contexts in southern Europe.

Zagarella F., Ferrari S., Caputo P. *Accurate and user-friendly tools for local energy planning*, 13th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), Faculty of Mechanical Engineering and Naval Architecture; 2018: 1-13, Palermo, Italy. http://hdl.handle.net/11311/1070193

For low carbon district/urban energy planning, several computational tools have been developed although guidelines for a more diffuse use in common planning out of the academic ambit are needed. We first assessed 17 selected easy-access and well documented tools based on: analysis type, operation spatial scale, outputs time scale, use and licence. Hence, we identified 6 tools that enable both energy calculations and outputs visualization on hourly base and can be considered as viable of widespread use. General information, functionalities, structure, graphic user interface, required input data and outputs were described. A plenty of information is provided on the data quality and level of details and the related constraints to implement an energy system analysis. The possible final user is guided in choosing the tool based on the related outputs and potentialities, but also on available data for a given context and the required skills.

Zagarella F., Ferrari S., Caputo P. *Methods for estimating buildings energy demand at district level as input for defining distributed energy scenarios*, 13th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), Faculty of Mechanical Engineering and Naval Architecture; 2018: 1-16, Palermo, Italy. http://hdl.handle.net/11311/1070192

In the framework of distributed energy planning, evaluating reliable energy profiles of different sectors has a prominent role. At the same time, it is a quite challenging task, since the availability of actual energy profiles is not widespread. For guiding stakeholders involved in local smart energy planning to choose the proper method for assessing the buildings energy demand, we surveyed 70 studies, adopting different methods including some case-studies applications and highlighting the ones adopting hourly energy profiles. From the methodological perspective, a set of criteria for classifying the selected contributions was defined and, as final results, tables summarizing the main methods characteristics and a selection of studies providing directly usable energy profiles are reported. The research, broadly, demonstrates that the potential replicability of analysed methods is constrained to the datasets availability and, particularly, highlights the need of reliable hourly energy profiles definition for developing accurate energy scenarios.

On completion of this Ph.D. research, I am also preparing following articles, whose extended abstracts have been accepted at the 14th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES), 1-6 October 2019, Dubrovnik, Croatia:

Ferrari S., Caputo P., Zagarella F. *A Method to Estimate Urban Building Stocks Energy Demand Profiles for Smart Energy Districts Planning*.

The assessment of hourly energy demand of the existing building stock, as well as the prediction of its variation due to energy efficiency measures, are fundamental activities for planning strategies of distributed generation, district heating and/or cooling networks, renewables integration, energy storages, etc., toward smart energy districts. However, the technical literature underlines the need of accurate methods adoptable in several urban contexts for detailed energy demand assessment. Based on this framework, a method for estimating the energy demand profiles of building stocks has been developed with particular regard to the Italian urban contexts. The method includes a geo-referenced procedure, based on data largely available on the national territory, to define the volumetric consistency of the considered building stock, characterized by different ages and most widespread uses. Besides, the method foresees the dynamic simulation of a set of building energy models, covering the main use categories and technological solutions referred to different periods of construction. The simulation models are based on a simple Building Concept in which selected thermal zones, representative of the different boundary conditions options composing any actual building geometry, are accounted. Hence, by associating the simulated hourly energy density profiles of the selected thermal zones to the geo-referenced building stock, the whole hourly energy demand profile can be assessed at district or at urban scale. Furthermore, the method could support also the definition of improved scenarios. In fact, the effects of the energy demand variation due to energy efficiency measures can be easily evaluated by rerunning the entire procedure with updated technological features and/or loads profiles. The method has been tested on the entire building stock of the city of Milan, selected as a case study, and validated based on the residential annual energy consumption deduced from the available regional database. The method could be useful for Italian bodies involved in the energy planning and policies, since it allows analysing urban/district energy demand profiles to be used for developing smart energy scenarios, investigating the matching with the energy supply and supporting also the evaluation of the economic impacts of energy effective or de-carbonizing measures.

Ferrari S., Caputo P., Zagarella F. *A GIS-based Procedure for Urban Building Stock Characterization Towards Energy Planning.*

Several methods for the buildings energy demand estimation based on the use of Geographic Information Systems exist in scientific literature, although often lack accuracy in the detailed buildings characterization or implementation procedure description for being adoptable in other urban contexts. Therefore, a procedure to implement a geo-database characterizing an existing building stock, valid at least for all the Italian urban contexts, has been defined and reported in detail in this article. The procedure adopts the geo-referenced data on building ages/uses, collected by the National Institution of Statistics (Istat) for all the cities, and on building geometries, coming from the Topographic Databases under provision at national level according to the Infrastructure for Spatial Information in the European Community (INSPIRE) rules, established by the European Directive 2007/2/EC. The developed GIS-based procedure enables to calculate and characterize the considered built volume based on the mostly diffuse building use categories on urban context (i.e. residential and offices) and on the periods of construction, featuring different technological solutions. The characterized built volume can be therefore used for spatially assessing the urban energy demand and for planning energy scenarios. The procedure has been tested to the urban context of Milan, one of the Italian cities having already implemented the Topographic Database, by characterizing the geo-referenced building stock and carrying out related maps. The comparison between the percentage by ages of buildings based on Istat and of mapped built volume revealed a similar pattern and the comparison of the calculated built volume by use category with available statistical data, aggregated for the entire city, returned in acceptable gaps in both residential (i.e. from 6.8% to 8.2%) and office cases (from 0.87% to 4.98%). Hence, the procedure could be useful to support energy planners in defining urban strategies in all Italian cities, once the INSPIRE-based data will be provided everywhere, as well as in other EU cities having both Topographic Databases and similar statistical data on building ages/uses.

Ferrari S., Caputo P., Zagarella F. *Building Usage Profiles for Dynamic Energy Simulation.*

The usage profiles inputs to be adopted in the building heat balance assessment through dynamic energy simulation have very high importance in influencing the final thermal and electric energy consumptions. Existing local and international standards concerning the buildings energy demand evaluation provide different nominal values and schedules of usage patterns, leading to different outcomes. In the frame of a wider research on building energy performance assessment in Italian context, standards provided by the Italian National Unification body (UNI), the Swiss Society of Engineers and Architects (SIA), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the International Organization for Standardization (ISO) have been analysed. For this purpose, a building energy model has been defined and alternatively characterized based on the two common residential and office uses. According to the recommendations provided in the selected standards, a set of weekly profiles, considering typical working and weekend days, of internal heat loads densities due to occupancy, equipment and artificial lighting as well as of air change rate due to ventilation and infiltration have been determined and compared. As additional outcome, the different contribution of each internal heat load in composing the resulting overall annual energy density values has been evaluated. Hence, the different levels of detail of the approaches foreseen by the standards have been deeply discussed. The study findings could support researchers in choosing the more suitable standard for the determination of usage profiles towards building energy simulations based on the studied context. Moreover, the reported data on equipment and artificial lighting shares can provide insights to unbundle aggregated measured electric consumptions in existing buildings.