Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

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Energy Technologies Area
August 2022

https://doi.org/10.1016/j.seta.2022.102041

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Abstract

Social houses built after the Second World War to accommodate workers and low-income families represent one of the major energy consumers and greenhouse gas emitters in the residential sector. Plans for their renovation are underway in all European countries, and the process is more complicated for Italian cities due to the lack of space and the large number of historical buildings. This study addresses this challenge by proposing a methodology to renovate a low-income district in the city of Venice using CityBES to model and evaluate energy conservation measures. CityBES is a web-based tool that allows users to employ urban building energy modeling for large-scale energy and retrofit analyses of building stocks. In the case study conducted for Venice's Santa Marta district, due to the particular context, four common energy conservation measures covering both the building envelope and heat generation boilers have been applied. The evaluation of energy-saving performances at the district level showed that the four measures together achieved 67% energy savings, an abatement in energy cost equal to 67%, and annual carbon dioxide emissions reduction of 1.1 $MtCO_2$. The case study demonstrates a method and workflow replicable for energy retrofit analysis of building stocks in other historical districts.

Keywords: Urban building energy modeling, Social housing, Venice, Large scale retrofit analysis, CityBES

1. Introduction

Climate change influences the building energy sector in both the operational and design phases, with rising energy use from more cooling demand and systems capacity undersized or oversized for the future needs [1]. Several approaches in literature dealt with the need to increase the sustainability involving also environmental, economic and social perspectives [2] as well as cultural and institutional aspects [3,4]. However, the first step to achieve a sustainable urban development regards the generation and optimization of energy in buildings in order to implement the process of decarbonizing urban cities. In fact, since space heating and cooling in buildings is one of the most energy-consuming end uses, energy conservation measures (ECMs) are the key aspects to achieve the European Union's (EU's) 2050 energy efficiency and greenhouse gas emissions (GHG) goals. Several studies have focused on detailed individual building energy modeling (BEM); optimizing internal loads; envelope insulation and heating, ventilation and air conditioning (HVAC) system operation; or validating results against measurements. For example, a simple approach can be based on decision matrix methodology [5]. Although these methodologies are important, they did not consider the urban environment and its influence on building performance (e.g. relative shading and longwave radiant heat exchange between buildings) [6]. Reducing the energy consumption at urban level is surely one of the current primary challenges since the retrofitting of existing buildings significantly decreases energy use and carbon emissions [7]. However, when dealing with such a large number of buildings, dataset development and computational efforts can be challenging, because databases concerning the energy use and energy savings potential of building stocks in cities are partly complete or missing [8]. One of the possible approaches is the collection of measured data through monitoring campaigns, which is expensive and highly time-consuming, thus unsuitable for most of the studies. In this context, Urban Building Energy Modeling (UBEM, [9]) can support professionals such as urban planners, city energy managers, decision-makers, and researchers to model city's building stock and to evaluate proper retrofit strategies at urban scale simulating several scenarios, considering the building no longer as a single unit but as a part of a complex system with interactions that can significantly influence its performance in terms of surrounding structures, shading, and short-wave solar reflection [10]. This study shows the energy analysis at the urban level of a residential neighborhood in Venice applying a web-based data and computing tool, City Building Energy Saver (CityBES), developed by Lawrence Berkeley National Laboratory. CityBES [11] is a dynamic tool that allows the energy modeling of building datasets, supporting the development of retrofit strategies at the district level, energy benchmarking, and urban planning.

Based on the number of buildings, Veneto is the third largest region in Italy after Lombardy and Sicily with an average proportion of residential buildings equal to 90% compare to other regions (about 80%) [12]. Considered as historical buildings constructed before the World War II, the latest data collected by the EU Building Stock Observatory (BSO) characterizing the European building stocks showed that 19% of the residential buildings in Europe were built before 1945 (Figure 1a). Analyzing data processed by the Italian National Institute of Statistics (ISTAT) [12], the proportion is 26% in Italy (Figure 1b) and 20% in the Veneto region (Figure 2a), whereas in the Venice municipality 29% of the building stock belongs to that period (Figure 2b) due to its well-known history.

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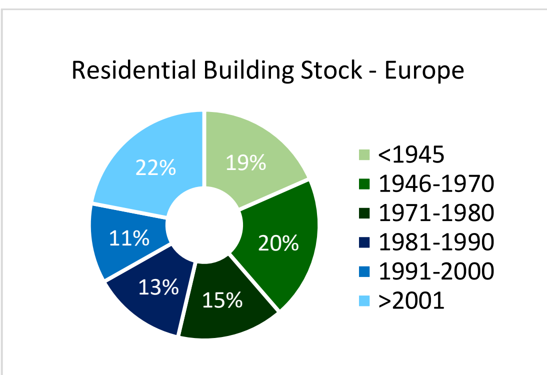

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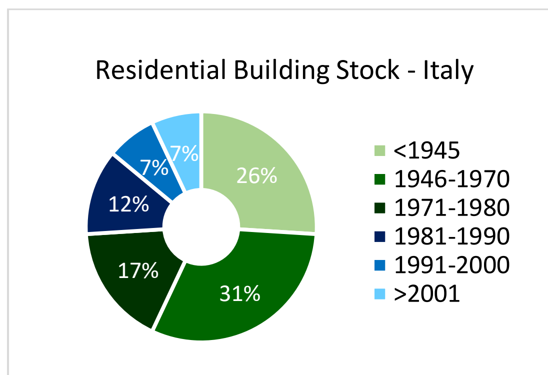
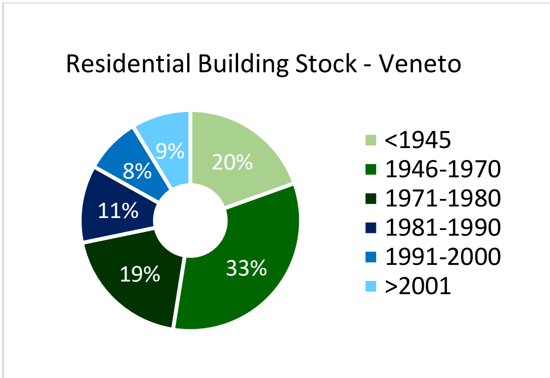


Figure 1. European (a) and Italian (b) building stock represented by vintage. Data from ISTAT [12]



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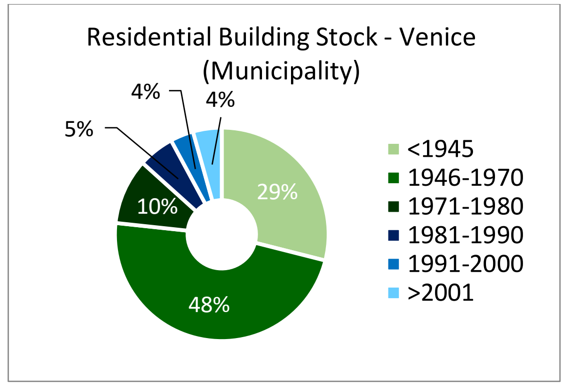


b)

Figure 2. Veneto region (a) and Venice (b) building stock represented by vintage. Data from ISTAT [12]

Even though 1 to 3% of existing buildings in Italy are replaced annually, among which 0.16 to 1.6 are retrofitted [13], they still represent a huge fraction of the Italian building stock, with high energy use, enhancing the need for significant actions to reduce energy use and GHG emissions. Moreover, users' demands for better heating and cooling comfort with lower energy use is increasing, requiring new strategies for deep retrofits, including high-efficiency systems eventually coupled with renewable energy sources.

In addition to the year of built, retrofit actions should consider the eventual protection by law due to their importance as cultural heritage sites. In these cases, which are very common in Italy, improving the energy efficiency requires particular actions that have to take into account the context of the constructions (e.g., materials, configurations, etc.) [14]. Article 4 of the EU's Energy Performance of Building Directive (EPBD) [15] mentions that each Member State should differentiate buildings' minimum energy demand according to their vintage and category, specifying in paragraph 3 that buildings with officially protected status can be excluded from the national requirements. EPBD was integrated into Italian law with Legislative Decree 192/2005 [16] and its recast versions exclude historical buildings related to any type of cultural heritage from mandatory energy retrofits.

The case study presented for the city of Venice is representative of a low-income housing district. This type of construction was popular in urban development for cities before and after World War II when people were moving from the countryside to cities where industrial development was rapidly growing. Venice and other urban centers had to cope with the new housing emergency, developing urban strategies focusing on the neighborhood level as a minimum design unit, which was able to guarantee primary services for the community [17]; for this reason, this model can be scaled up not only for the whole Municipality of Venice but also for multiple low-income neighborhoods in other Italian and European cities. This can be an important action because the refurbishment of existing district can significantly help sustainable and resilient development thus leading to original architecture conservation [18].

Literature presents multiple studies on retrofit interventions for historical buildings in Italy and in Europe. Authors of [19–21] present an overview of current trends and technologies in the application of renovation measures on historical and heritage buildings, discussing the feasibility and convenience of various retrofit measures. In [22–24] historical buildings with public functions, such as museums, schools, and offices, are analyzed and different renovation measures for each category are proposed and discussed. The studies [25,26] analyze historical residential complexes in different part of Italy and propose a series of interventions for their retrofit trying to reconcile energy benefits and intervention costs. What emerges from these studies is that common measures are the one that gives the best results including cost constraints. Finally, in [27,28] authors focus on the application of the cost optimal approach in historic buildings, for different types of energy retrofit, achieving results similar to the one expressed in the previous studies: traditional measures are those with the best ratio of energy saved to price. Even though different dynamic tools have been used to develop the models (e.g., TRNSYS, EnergyPlus, IDA-ICE), most of the studies focused on the optimization of individual building models, developing different methodologies according to local climate and user needs. For example, Anastaselos et al. [29] developed an assessment tool that provides users with the option to select building materials for the thermal insulation of the building envelope, measuring their environmental performance, energy efficiency and construction cost. Other studies focused on the application and analysis of photovoltaic fields to building district belonging to the World War II [30], where limitations related to architectural or urban importance did not apply.

This case study presents the district of Santa Marta in Venice, where an important cotton mill was built in 1883 and currently hosts the Department of Architecture and Arts (IUAV) after several refurbishment actions [31]. Several retrofit scenarios have been implemented to show the possible energy conservation measures that can be applied, distinguishing between actions that can be applied respecting current standards and strategies that must consider the limitation to preserve cultural heritage. As a result, massive interventions on the envelopes and photovoltaic systems are currently not allowed for the case study considered, thus have not been included in the analysis.

1.1 Novelty of the study

The novelty of this study concerns the first UBEM application of a recent study published by Carnieletto et al. [32], that investigated the Italian building stock and developed representative prototype buildings. The case study presented is a particular social-housing residential district in the historic center of Venice (Italy) composed of 57 buildings. The tool CityBES has been applied for the first time to study a district that is located not in the United States, thus modifying the background information. In this particularly difficult context due to the historical significance of the district studied and the limitations imposed by the institution responsible of the protection of buildings related to cultural heritage [33], the case study shows its adaptability even to very different urban environments with respect to the common applications of CityBES. Unfortunately, these strengths of the tool clashes with the lack of a comprehensive database that helps the characterization of the buildings in the district, which has been partially solved by [32]. Contrarily to what happens in the United States, where databases with information on the characteristics of buildings compiled by the U.S Department of Energy (DOE) are used as archetypes for the applications to UBEM, in Italy these resources are absent. This has forced researchers to focus on studies that take into consideration buildings individually or to expand to small districts composed of a limited number of buildings belonging to the same building category that require high-level input information and high computational resources.

Urban building energy modeling should not be considered as a linear scale-up of a single building analysis, since the main goal is the investigation of the dynamic and complex inter-building effect and between buildings and environment at urban scale. For example, the tool CityBES can automatically identify the surrounding shading surfaces for each building while other tools as EnergyPlus or OpenStudio has to recreate the shading surfaces one by one. Results allow the definition of strategies that consider these mutual influences as well as the load diversity of the buildings, reducing the energy demand and peak load on a wider scale, thus correctly estimating the potential application of renewable energy sources and shared generation systems, possibly optimizing their operation and the related costs.

However, despite in-depth bibliographic research in Italian context, only a few studies conducted at the district level emerge and none of them focuses on poor construction for low-income users. This work is therefore a forerunner towards particularly complicate issues such as the energy renovation of social housing even more than a hundred years old, which was built with simple and inefficient materials and technologies. Moreover, the management of the public administration must deal continuously with a continuous delay of renovation works, thus authors chose conventional interventions using common techniques that still lead to excellent results in terms of energy savings and with accessible investment costs to take into account the real background of the building.

The characteristics of the case study in Venice can be also found in other Italian and European historical cities: non insulated envelopes and inefficient heating and cooling systems, lack of detailed information regarding the building, limitations on the possible actions to protect the historic importance of the urban city centers. This choice was made taking into account the high replicability of the intervention: the workflow described in the following sections can be adopted by policymakers for the application to other districts belonging to the period immediately after World Wars that require massive retrofit actions to contribute to the achievement of the Italian and European objectives in terms of both GHG emissions and primary energy reduction.

2. Methodology

The district-scale approach for energy renovation of buildings in cities is considered one of the most effective methods to tackle energy use and carbon dioxide (CO_2) emissions. The European Commission strongly believes in this approach, supporting several projects focusing on this topic. The goal of this research is to provide a valid methodology to apply retrofit measures on old residential buildings that can be used by cities worldwide. Among the tools developed to support researchers and municipalities to apply efficient renovation strategies, the authors chose to use the web-based platform CityBES, developed by Lawrence Berkeley National Laboratory. Currently, it deals almost exclusively with cities in the United States, but this research will help to increase the flexibility of application of the tool, adapting it to the Italian and possibly European building stocks and context [34].

The methodology aimed to create a virtual model of a residential district in the city of Venice. The first step was to define the geometrical characteristics of the buildings via geographic information system (GIS) mapping and identifying the parameters related to the energy use from accessible building data, such as the year of build and its envelope characteristics, which were used in the following steps as simulation inputs. Once the model is reproduced in the GIS environment and has all the necessary attributes, it can be simulated in CityBES by (1) defining a baseline corresponding to the current situation and (2) applying previously defined energy conservation measures. The simulated results show the energy savings potentially achievable through the building retrofit at a district level.

The approach can be used by lawmakers and municipalities interested in investing in renovation measures, with little to no help. The methodology is explained in more detail in the following sections.

3. Case study

As previously reported, 74% of residential buildings in Italy dates back to the period before 1981 and after more than 40 years of life, the overall performance of these buildings is deeply inefficient. A recent study has shown that more than 20% of these homes are in poor condition or poor state of conservation [35,36]. According to the study, the worst conditions are recorded in southern Italy but also in the suburbs of northern cities the situation is particularly worrying. In particular, in Venice, more than one-third of accommodations (36%) are considered in mediocre or very poor conditions [36,37], which is mainly due to the historic importance of the city that limits the actions to maintain the original layout as far as possible. However, these data refer only to residential construction. On the contrary, the current state of conservation of public buildings is higher. Many studies and researches carried out in recent years deal with improvements to public buildings and their energy upgrading [31,38–41], mostly supported by local and national incentives. In particular, the recent works related to the energy requalification of old buildings located in the historical center of Venice concern buildings that are now used by the universities located in the city. In one of the studies, the generation system of an old monastery now used as university library was replaced by two ground source heat pumps [42,43]. In a second study, an old cotton factory that currently hosts university lecture halls have been replaced with a trigeneration system that supplies energy to other detached university premises by creating a small district system [31]. The particular conditions of the above-mentioned cases, which are less numerous than the residential complexes located in the historical center of Venice and that benefit from public contributions for the realization of uncommon and extended retrofit works, can not be replicated for the case study investigated in this work, because the a low-income residential district includes a great number of buildings with limited space available in the surrounding areas.

From the beginning of the twentieth century, the Italian political class sought to end the precarious condition in which low-income population was living. In 1903, Italian congressman Luigi Luzzatti founded the *Istituto Case Popolari* (Public Housing Institute; ICP) [44], whose goal was to provide workers with low-cost housing that respected the latest sanitary and hygienic regulations. In 1914, a chapter of ICP was opened in Venice, changing the name several times until the mid '90s when the ICP became *Aziende territoriali per l'edilizia residenziale* (Local Agency for Residential Buildings) or ATER [45].

At first, the Venice municipality gave to the newly founded institution 686 complexes already built by other organizations and spread all across the city in the historical center and various other neighborhoods, namely Castello, Cannaregio, and Dorsoduro. Immediately after the First World War, various low-income neighborhoods were built all around Venice: 220 accommodations in the Lido district, 60 in Dorsoduro, 290 in the Giudecca islands, and 135 in Cannaregio. Between 1926 and 1940 more than 1,000 new apartments were built on the islands of Venice: 440 in the Castello neighborhood, 244 in Cannaregio, and 393 in Dorsoduro, specifically in the area known as Santa Marta, which is analyzed in this research. In the same years before the Second World War, more than 1,000 accommodations were built on the mainland to face the high demand for housing started with the industrialization of the area surrounding Venice. After the war, the focus moved mainly to the mainland: between 1950 and 1966, ATER built 1,300 new apartments in various area of Mestre and Marghera (Venice's districts on the firm land where the industries had their locations), but at the same time 280 accommodations were constructed in the historical center of Venice: in San Polo, in the San Marco neighborhood, in Cannaregio, and on Giudecca's islands [46]. Figure 3 shows the location of the major social housing complexes and the division of the city in *Sestieri* (Venice's neighborhoods) in the historical center of Venice.

Figure 3. Map of the historical center of Venice, showing the division in Sestieri (neighborhoods) and, in green, the location of districts with buildings for low-income families

Even though the construction period lasted more than 50 years, the technologies and techniques used for those kinds of works were almost the same: easy construction, healthy, and cheap to build in the fastest possible time. Therefore, even though this research focuses only on one of the above-mentioned examples, the methodology presented can be used to replicate good practices applicable to other publicly owned housing complexes in the city of Venice, and, more generally, to a large share of the Italian housing stock.

The district studied in this manuscript is named "Santa Marta IACP housing" and is located in the western part of Dorsoduro, one of the six areas that compose the historical center of Venice, situated in the southwest end of the city (Figure 4). The shape of the district is not regular, but the dimensions are approximately 400 m x 160 m, for a total surface area of 3.78 hectares (ha) (equal to 0.04 km^2). The project for this neighborhood dated back to 1920, when the municipality started the construction of a first set of 14 buildings for a total of 148 housing units, which were intended for low-income workers from the nearby industries and maritime workshops. These buildings were completed in 1928. In 1930, a second intervention on the area guaranteed the construction of 365 new units divided into more than 21 new buildings [47].

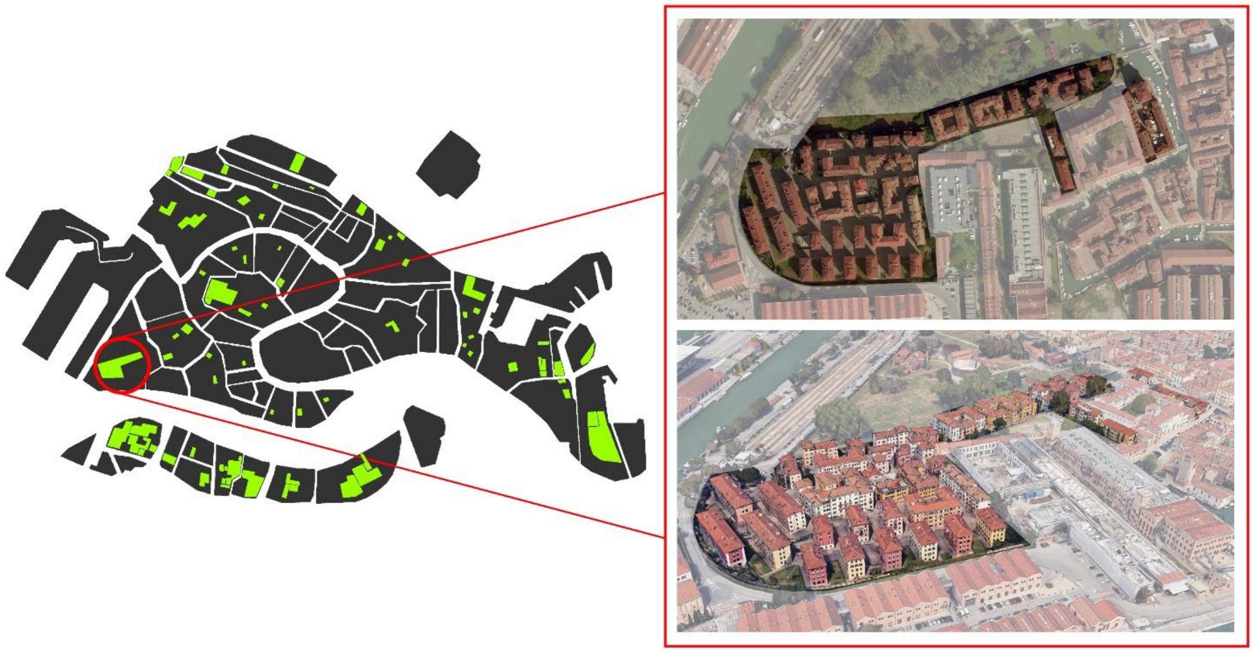


Figure 4. Location in the historical center of Venice of the district (Santa Marta) used as a case study and its satellite and 3D images. In green other social-housing districts in Venice

The case study is composed of multi-family buildings. The constructions can be divided into two groups by age and varies slightly with the geometry of the buildings. The first group of buildings, built between 1920 and 1928, have a regular rectangular shape with dimensions ranging from 18 to 50 m for the long side of the buildings, and the short side a consistent 12.5 m. All have four floors and a number of apartments, between two and six per floor, depending on the building's dimensions. The second group, completed in 1936, shows more complex and varied geometries: the buildings are for the most part built around a central void, or in a "C" shape. The dimensions of these buildings are very different from each other, ranging from footprints of only 170 m^2 to complexes of more than 1,500 m^2. Variation also can be found in the number of floors and apartments; from simple two floor houses with one apartment per floor to considerable five-story buildings with up to fourteen apartments per floor.

The techniques used for the building envelope were the same in the two phases. The exterior walls are made of solid brick masonry, without any kind of insulation, and plaster on both the internal and external sides. The ground floor consists of a non-insulated concrete slab laid down on a rock foundation with tiles on the internal surface. An inclined wooden roof with no insulation and clay tiles covers the building. Some differences can be found in the transparent envelope: double glazed wooden frame windows have replaced some single glazed systems with a wooden frame, depending on the owners' willingness to retrofit the apartment. Heating is provided to the apartments by a centralized gas boiler installed in every building, whereas cooling systems were not planned and are usually not present. In some cases, a simple one-apartment air conditioner has been installed over the years. Domestic hot water (DHW) is provided by an electric or gas-fired water heater installed in every apartment.

The overall efficiency used to define boiler characteristics considers generation, distribution, emission, and regulation efficiencies, provided that pipes are commonly not insulated due to the age of construction, and heat is mainly supplied by cast iron radiators.

Characteristics of the building envelope construction and space heating system are summarized in Table 1 and Table 2.

Table 1. Characteristics of the building envelope construction

ELEMENT	COMPONENTS From exterior to interior	THERMAL TRANSMITTANCE [W/(m^2 K)]
External wall	External plaster (1.5 cm)	1.8
	Solid bricks (25 cm)	
	Internal plaster (1.5 cm)	
Floor slab	Scree (30 cm)	1.9
	Concrete casting (10 cm)	
	Traditional screed (3 cm)	
	Stoneware floor (1.5 cm)	
Roof	Terracotta tiles (1.2 cm)	2.5
	Wood panels (3 cm)	
Single glazed windows	Wood frame	4.5
	Single glazing	
Double glazed windows	Wood frame	3.5
	Double glazing	

Table 2. Description of space heating and DHW systems of the buildings

ELEMENT	ENERGY SOURCE	SYSTEM TYPE	OVERALL EFFICIENCY
Space heating	Natural gas	Centralized boiler	80%
DHW	Natural gas	Individual boilers	80%

First, the current energy need was investigated through simulations, to characterize the buildings according to the construction period. This analysis was needed to determine a realistic baseline from which to compare retrofit results and develop a possible cost analysis. Two buildings, representing the two categories discussed, were simulated in a building energy modeling software, EnergyPlus [48], using DesignBuilder [49] as the graphic interface. The simulation for the buildings completed in 1928 calculated an energy use intensity (EUI) of about 255 kWh/(m^2 y), while for the buildings belonging to 1936 the EUI is about 250 kWh/(m^2 y), which is acceptable considering both the period of construction and the common materials used.

The layering of the walls and the properties of the opaque and glazed materials were the same defined for the UBEM application, as well as the definition of internal loads and related schedules that were based on a typical residential use as described by UNI TS 11300 and EN 16798 [50,51]. The zoning strategy divides the floor in a major heated space and a smaller unheated space corresponding to the stairwell. Although the influence of other buildings on solar radiation is excluded, the building is modelled considering the real orientation and respecting the footprint dimensions and shape.

Considering Italian Legislative Decree 192 and its following modifications, which are the transposition into Italian legislation of the European Performance Building Directives [52–54] describing the overall discipline regulating the energy performance of buildings, it is possible to determine the energy label of the buildings. According to the results obtained, the case study belongs to class E (energy consumption for space heating between 200 and 260 kWh/m^2 y) [16].

4 CityBES and Workflow

CityBES is an open-source web-based tool developed by Lawrence Berkeley National Laboratory (available at CityBES.lbl.gov). The workflow is based on three layers: the data layer, the simulation engine and tools layer, and the application (use-cases) layer.

As shown in Figure 5, within the data layer, is foreseen the operation of defining the building footprint within the district or city analyzed, using GIS software and integrating geometry information with other available data regarding the building's vintage, type, and height, and the number of stories. All the information can be compiled in CityGML or GeoJSON format to be imported into CityBES.

The software or engine layer includes the Commercial Building Energy Saver (CBES) that is used as backend simulation engine. CBES provides a prototype building database for all U.S. climate zones, and a database of cost and performance data for almost 100 energy conservation measures (ECMs) to perform energy retrofit analyses of individual buildings in U.S. cities. CBES is based on OpenStudio, which is an open-source tool to facilitate simulation development with EnergyPlus 9.3 [55].

The simulations carried out with CityBES in this work consider uniform weather data (air velocity, air temperature, etc.) in the whole district, which is reasonable considering that the main objective is the analysis of the energy used and the possible retrofit strategies at a wider scale than the single building detailed analysis. For the same reason, the simulations also include the mutual shading between the buildings object of the study, and also the buildings adjacent to the district. Thanks to its modeling feature, CityBES is able to represent the surrounding buildings as shading objects, which reduce the solar heat gains received by the neighborhood, thus slightly reducing the cooling energy demand and increasing the space heating demand. A more detailed description can be found in [56].

CityBES enables energy modelling through CBES, thus Openstudio and Energy Plus simulation engine, to generate a baseline for the district that describes the current energy use and CO_2 emissions for every building and the whole neighborhood, eventually applying ECMs to investigate different retrofit scenarios. Results are stored in the CityBES database and it is possible to visualize them in a 3D georeferenced map that shows color-coded simulated performance as explained in the workflow represented in Figure 5. Moreover, both baseline and retrofit results are available for download in a comma-separated values (CSV) file to be further analyzed. The generated EnergyPlus model files (in IDF format) also can be downloaded for other uses.

Finally, the Use Cases layer provides the results that can be further analyzed for potential applications, including energy benchmarking, energy retrofit and renewable energy analysis, providing strategies for energy systems and improving the building operation of the city stock.

A more detailed explanation of the workflow is available at [57].

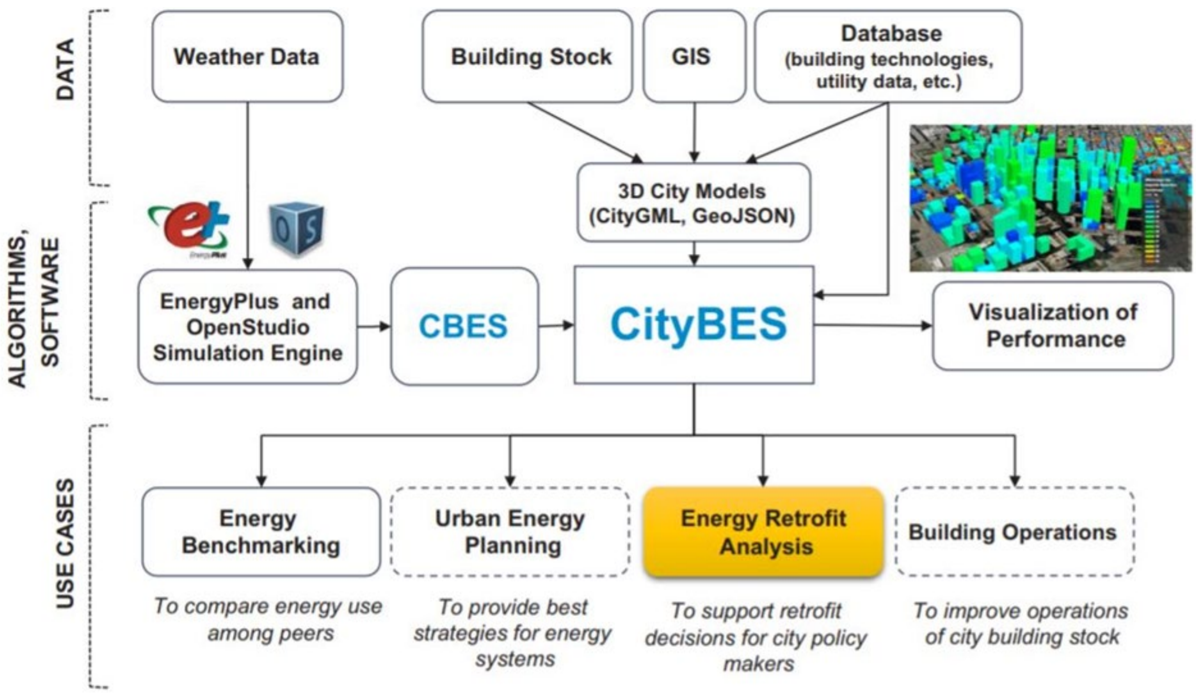


Figure 5. Scheme of the workflow with preliminary data, CityBES components, and use cases. From [57]

4.1 Data Preparation for the Case Study

According to the procedure presented by Chen et al. [34,58], the first step was the creation of the dataset for the pilot case study. A wide range of data sources was used to collect the necessary information for developing the building dataset for the case study, starting with the definition of the buildings' footprint using digital technical cartography available for each region [59]. The workflow (Figure 6) starts with the generation of the 2D virtual model of the area using a free and open-source GIS application, in this case, QGIS release 3.10.0 [60], which allows the user to view, edit, and analyze geospatial data. In this particular environment, it is possible to import from online map services like Open Street Maps (OSM) [61] a geo-referenced 2D spatial representation of the entire historical city center of Venice. Usually, Open Street Maps has many available information about buildings stored in the attribute table, such as area, perimeter, height, use, vintage, and other information. Unfortunately, this did not apply to the case study presented, due to the limited digitalization of Italian cadastral data. The only information stored in Venice's polygons is area, perimeter, and, for some few public buildings, use type. Therefore, the following strategy was applied.

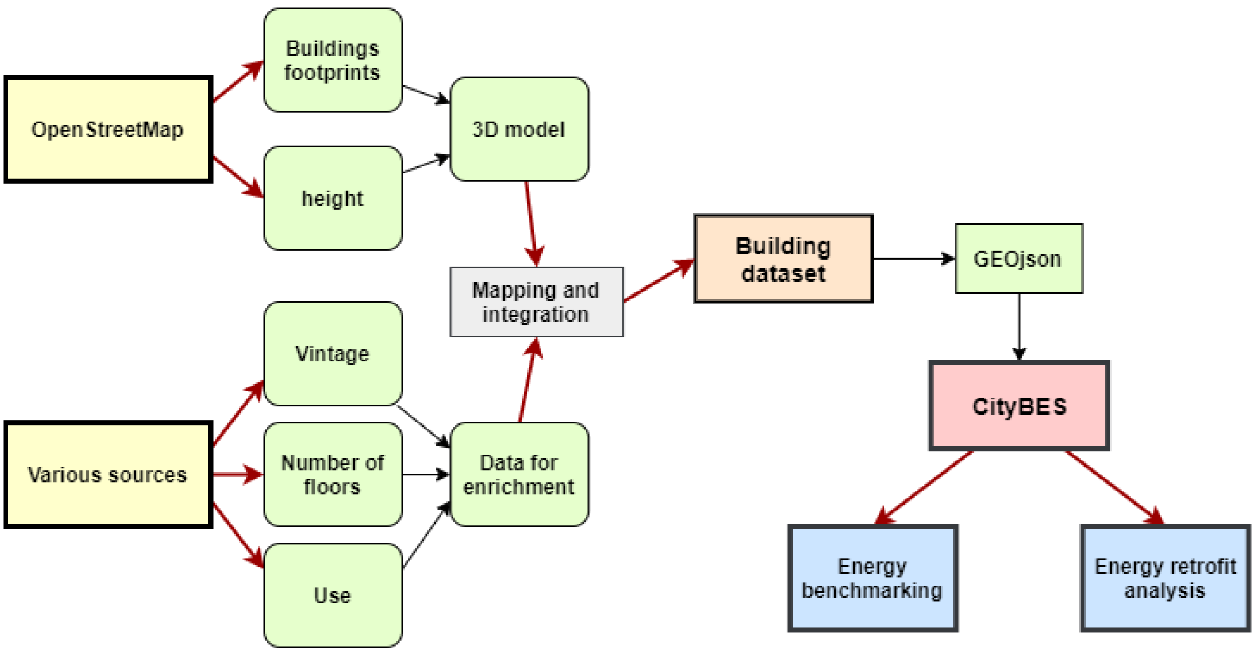


Figure 6. Workflow for the creation of the buildings dataset, adapted from [26], [43]

4.2 Building dataset development

The analysis of building performance at the urban scale can be performed for a new dataset in CityBES, which can be created in CityGML or GeoJSON formats. As described by developers [58], the datasets provided should include minimum required data regarding the basic inputs for the tool, but additional information can be added to better define the characteristics of the district considered.

As previously described, building footprint is the first input required and can be prepared using GIS tools; other minimum information concerning the building dataset is:

- ID, uniquely related to the building footprint
- Building use, i.e., function or occupancy type of the building (Office, Multi-Family, Hotel, etc.)
- Year of build
- Number of stories (above ground level)
- Building height

These information can be collected using a CSV file, which can be merged later with the QGIS footprint polygon data.

4.2.1 Santa Marta Dataset

Since most of the available Italian maps do not have specific data related to building height, number of floors, use type, or vintage, it was necessary to use several other resources to collect the information needed for the model enrichment. Several other studies, in particular the ones focused on typical Italian urban city centers, explained the difficulty of researching information to enrich the dataset by studying different sources, varying from official cadastral data to amateurish historical reports [62–65]. This difficult and long phase of the research enhanced the need of a complete dataset of information describing the national building stock.

The final dataset for the case study consisted of 57 buildings which is around 0.4% of the residential buildings in the city, but represents around 79% of the Venetian residential building stock. Their height, use type, and vintage were collected by manual research. Some of them has been grouped to fasten the simulation time, since they have the same building properties and they are adjacent to each other, resulting in a total number of buildings of 57. Vector cadaster maps issued by the Municipality of Venice were used, integrating an existing map from ArcGIS 10.5, a geographic information system that integrates 3D geographic data to obtain information regarding the buildings' heights and number of floors. Among all other information available in these maps, it was possible to identify, validate, or eventually correct the buildings' footprint, to assign a unique identification number (ID), and to verify a first rough classification of the building type different from the investigated residential use (religious, industrial, educational, other) and their height.

To validate the presence and the information concerning commercial activities, a thorough analysis was conducted using cartography web portals and cadaster web tools containing a map of Venice [66,67]. Eventually, the retrieved information can be validated simply by using an online map provider such as Google Maps or Bing Maps to check the number of floors and the presence of commercial activities in the case study [68,69]. Even though buildings may have various use types, only the residential units were selected for this analysis.

The last step was to define the vintage of the buildings. By consulting various historical maps of the city of Venice, it was possible to define roughly the year in which the majority of the buildings that compose the case study were built. Since this work focused on the residential part of a low-income residential district, research targeted that category. A detailed account of the construction history was available, thus it was possible to determine the building vintages in detail [47,70]. In some cases, the ground floor of a residential building may be a retail establishment or have some other nonresidential use; in that case, the building was categorized as mixed-use.

Finally, it was possible to collect the fundamental characteristics of each building, namely vintage, use type, height, number of floors, and floor area, as described in [58,71] and prepared in GeoJSON format: the database of buildings created through the procedure above was exported from QGIS in a GeoJSON file that contained all the fundamental details of every building and was then ready to be uploaded into CityBES [34].

The second step was the definition of the residential use. Due to the lack of precise data, occupancy density has been defined according to standard EN 16798 [51], which suggests 28.3 m^2/person for multi-family residential buildings; this can be considered an average value corresponding to three to four people per apartment. Infiltration rate was set to 0.5 ACH (air changes per hour)[72,73], which is a significant airflow rate considering the envelopes of old buildings without refurbishment actions and with major air leaks through joints and gaps.

Considering that houses for people with low incomes have few light spots, and CityBES considers both lighting and plug-loads distributed evenly over a building's surface, the average specific load for lights was estimated to be 1 W/m^2 according to Italian standard UNI/TS 11300-1 [73]. The same value was used to approximate the energy use of domestic electric appliances. The reference schedule applied for lighting and electric appliances for residential use was defined according to standard EN 16798 [51].

4.3 Weather data

CityBES automatically assigns corresponding weather data to the simulation based on the geographic information of the buildings. It covers all the ZIP codes in the United States and a few cities from other countries. However, as CityBES has not been applied in the Italian context, local weather data should be obtained and implemented in CityBES. As stated previously, weather data were extracted from the database available on the EnergyPlus website [74]. The climate data present in this file are collected by the meteorological station installed at the Venice international airport, guaranteeing that the data are representative of the particular microclimate of the Venetian lagoon, which presents hot and humid summers and cold winters that are mitigated periodically by warm winds coming from North Africa [75]. Section 4.3.1 presents a more detailed description of the climate used for the case study.

4.3.1 Venice weather data

According to the Köppen-Geiger [76] classification, Venice has a subtropical climate (Cfa) with cold winters and hot and humid summers. Situated by the Adriatic Sea, which helps to mitigate the hot summer temperature, it is seasonally subjected to cold and warm winds; in particular, instances of warm winds during the winter lessen the low temperatures during different time frames. Temperatures vary widely during the year, spanning between -0.1°C in January and 27.7°C in July. On average there are 78.3 rainy days per year, and the annual precipitation averages 748.4 mm.

Simulations were run using hourly weather data of the Test Reference Year (TRY) of Venice available for EnergyPlus [74]. The scheduling related to the switch on of the heating system has been set according to Italian Standards that regulate the heating season depending on degree days [77], and Venice is associated with the climatic zone E, with 2,345 degree days; therefore, the conventional heating is from October 15 to April 15, for a maximum of 14 hours a day [78].

4.4 Energy conservation measures

A wide range of ECMs are available to be applied to the case study, however the common actions were considered due to the particularity of buildings investigated. Therefore, these include common retrofit actions for the building envelope (wall and roof insulation and installation of better performing windows), HVAC system improvement and use of natural or mechanical ventilation to increase indoor air quality, rising refurbishment levels permissible by local limitations concerning, for example, lighting, photovoltaic or solar systems [79,80].

Each measure should be applied according to the user's goal and the district analyzed. For example, Italian historical urban centers have multiple limitations on envelope actions from the outside, due to the architecture's cultural importance, so this study does not consider ECMs such as adding exterior shadings to the windows. Therefore, the ECM considered in the case study can be easily extended to other districts in Venice, showing the potential impact on energy savings and CO_2 emissions avoided.

4.4.1 Configuration of the Energy Conservation Measures

The case study focused on the definition of a set of retrofit measures able to determine a drastic reduction in energy consumption and GHG emissions in extremely challenging situations like low-income residential buildings built almost one hundred years ago. In particular, the primary objective of the study was to show the feasibility of a multi-district approach, easy to replicate even in different contexts. The selected ECMs allows the achievement of thermal transmittance limits given by the Italian legislator through the Ministerial Decrees 26/06/2015, which are necessary to obtain national incentives[81].

As reported in the previous sections, the energy renovation actions in a particular city like Venice focus mainly on public buildings. However, some cases belonging not to the historic center but within the municipality, have been concerned the refurbishment of residential buildings intended to accommodate families with low income [82]. In these cases, the interventions carried out are more traditional and have lower investment costs than interventions carried out on public buildings. Examples of other interventions carried out show that the ECMs concern the insulation of the roof and walls, the replacement of fixtures, and the upgrade of the heating system. The main reasons behind these choices are the reduction of intervention costs with the use of techniques and technologies that have been consolidated for a long time and the guaranteed results that can be achieved given the numerous applications in other cases. Moreover, some restrictions in the city building regulations prevent the application of certain interventions, such as the installation of photovoltaic panels or thermal collectors to ensure that the historical and artistic context remains unchanged [83]. Thus, the strategies to reduce the energy use and exploit renewable energy sources are rather limited. However, four ECMs were selected for the basic retrofit analysis, covering the most commonly retrofit building systems: namely, envelope and HVAC. In this set of measures, one was related to the HVAC: substituting the installed boiler, which was worn out and obsolete, with a more modern condensing boiler. The EnergyPlus model of the heating system does not take into account the position of the HVAC system distribution pipes inside the wall, nor their insulation or other properties; since pipes simply serve as connectors [84]; thus, this refurbishment measure did not consider the substitution of the pipes with more insulated pipes, so this inefficiency was taken into account by reducing the potential efficiency of the boiler to 0.9. The other three ECMs were about the envelope. They included the following: (1) Windows replacement, (2) Roof insulation, (3) External wall improvement. The windows currently installed have a U-value between 3.5 and 4.5 W/(m^2 K), which are supposed to be replaced with better-performing elements having a U-value of 2.2 W/(m^2 K). The roof insulation would be an easy-to-implement measure thanks to the presence of an accessible unheated attic that allows a low-impact installation of the insulation, reaching a U-value of 0.23 W/(m^2 K). About the external wall improvement, there are restrictions on possible interventions since the district is located in the historical center of the city of Venice. Specifically, since the buildings are classified as historical buildings as a result of the Legislative Decree 62, dated March 26, 2008, it is not possible to act on the building envelope from the exterior. Therefore, this leaves two other possibilities. The first is to not intervene on the buildings' walls; as a consequence, retrofit actions will not result in a huge reduction of the buildings' energy need [85–87]. The second is the use of advanced technologies (e.g., aerogel or vacuum-sealed insulation panels) in the retrofit works. Although aerogel insulation panels and similar could guarantee the needed energy reductions, several drawbacks must be taken into account. First of all, acting from the inside means a reduction of the indoor available space, and the people living inside should be temporarily relocated. Afterwords, the technology installed should optimize the costs and the benefits obtained, planning the retrofit actions to achieve the national incentives [88–91].

However, since these considerations are case-specific, the authors decided to proceed in two parallel ways. The first, assuming that the restrictions were not in place, in order to create a case study that would be vastly replicable. For this reason, an insulation layer composed by Expanded Polystyrene (EPS) panels was considered to be added to the wall from the exterior, improving the wall performance with a U-value of 0.3 W/(m^2 K). The second way, taking into consideration the restriction imposed, foresee a scenario in which the EPS panels are installed from the inside of the dwellings in order to reach the same wall performances of 0.3 W/(m^2 K). The difference between these two scenarios can be observed when discussion the economic aspects of these hypothesis since the main difference concerns the investment costs.

5 Results and Discussion

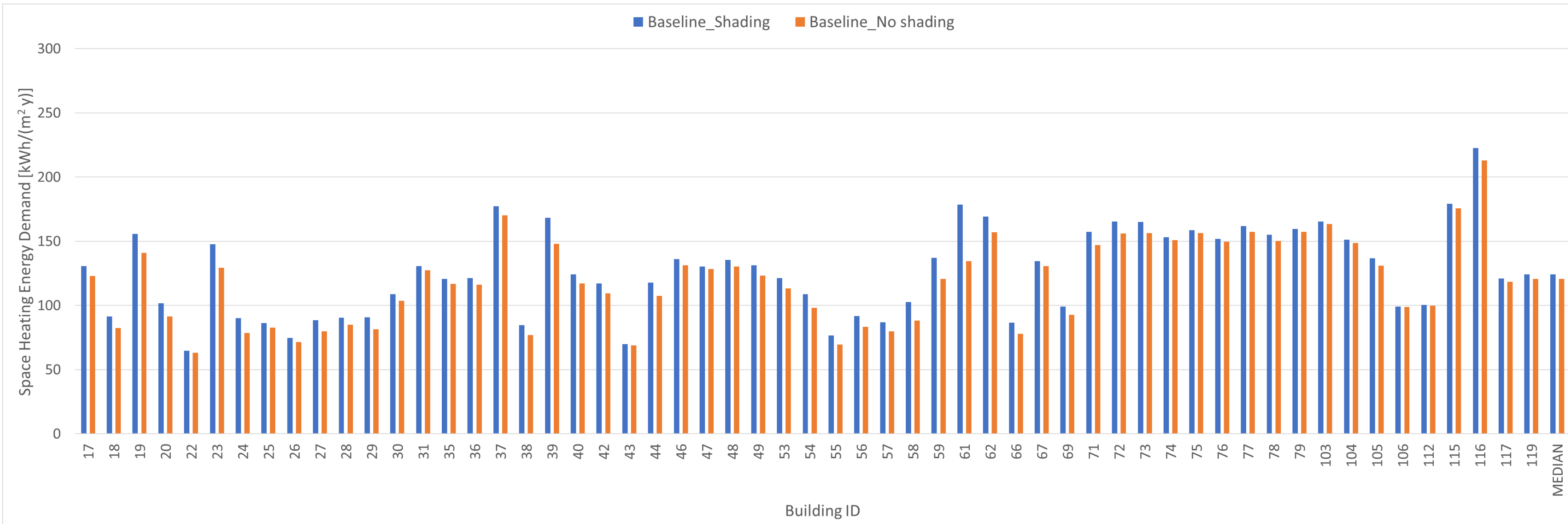
The achievement of realistic results is bound to the choice of representative inputs of the building classes studied. Due to the lack of precise data, many information has been assumed based on national standards that describe the residential occupancy and the related uses.

Figure 7 represents the color coded gas energy use of the Santa Marta district in Venice simulated with CityBES, displayed in a 3D visualization.

Figure 7. CityBES: color coded performance concerning gas use

The same results are shown in Figure 8 from the single building perspective (ignoring shading from surrounding buildings). Around 65% of the housing units (the color coded buildings showed in Figure 7) have an EUI of more than 100 kWh/(m^2 year), which is reasonable if compared to the Tabula database for the same period of construction and climatic zone in Italy [92] and to Legislative Decree 192/2005 [16] according to their vintage and envelope characteristics. Only 20% were lower than 85 kWh/(m^2 year), probably due to the window to wall ratio (about 20%) used in the tool, which slightly underestimates the window area.

However, if the buildings were modeled in a wider perspective of urban context considering mutual shading of the buildings that influences the building energy demand, these results would significantly change. As a consequence, 72% of the studied buildings had an EUI higher than 100 kWh/(m^2 year), while only 19% were lower than 85 kWh/(m^2 year). The differences range between 3 to 15% on average, depending on the building orientation and on the direction of the main shading, and can be attributed to the fact that the buildings, when shaded, have a lower contribution of solar heat gains, thus the space heating energy demand slightly increases. This results show the importance of urban modelling for the correct estimation of building energy demand when planning large scale retrofit interventions or large scale energy policies. A wrong estimation of the energy demand would definitely lead to a wrong estimation of the actions required and related investment costs as well.


Baseline_Shading
Baseline_No shading
Space Heating Energy Demand [kWh/(m² y)]
0
50
100
150
200
250
300
17 18 19 20 22 23 24 25 26 27 28 29 30 31 35 36 37 38 39 40 42 43 44 46 47 48 49 53 54 55 56 57 58 59 61 62 66 67 69 71 72 73 74 75 76 77 78 79 103 104 105 106 112 115 116 117 119 MEDIAN
Building ID

For the retrofit analysis, first, simulations were carried out applying ECMs as a single action to understand their impact on the energy use reduction; the second hypothesis combined the intervention, to see the real potential of these actions on the energy reduction.

Considering that currently the buildings have no insulation, the measures were first applied to the external envelope. The insulation of the roof led to a 5% energy savings on average, while the insulation of the external wall was more efficient, with up to 55% energy savings due to the wider application. Even though a significant improvement of thermal properties was implemented as an ECM, changing the U-value from 4.5 and 3.5 $W/(m^2 K)$ to 2.2 $W/(m^2 K)$, window replacement only led to a 5% energy savings, due to the small window area and reduction of solar heat gains, leading to more heating demand. The combination of the three actions to evaluate a complete refurbishment of the building envelope resulted in energy savings of 65%.

Figure 9 shows the space heating energy demand in the building's current state compared to the reduced energy demand achievable with the ECMs described.

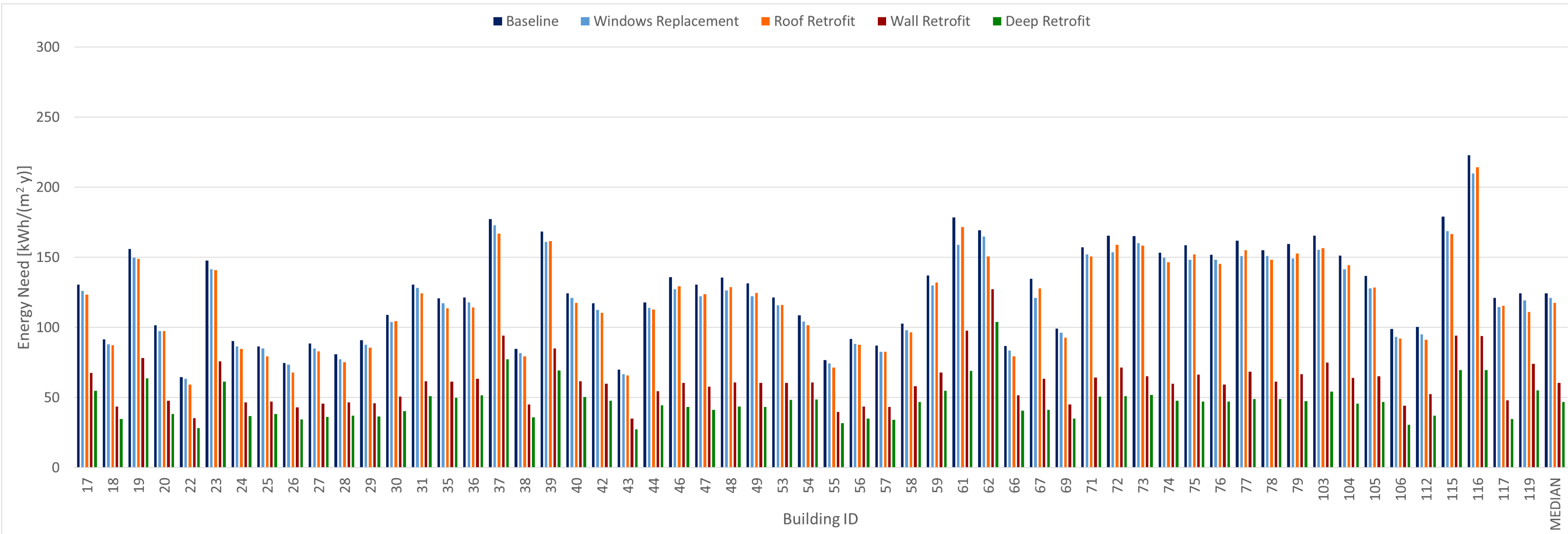


Figure 9. Space heating energy demand with application of envelope related ECMs

Moving from energy needs to energy use, the performance of the system installed was analyzed. Usually, determining the overall efficiency of heating systems includes evaluation of generation, distribution, and control efficiencies, which were considered to be an average value of 0.8 [93]. The typical heat generation system in Venice for multi-family buildings today is an independent gas boiler for each housing unit, which supplies both space heating and domestic hot water. However, this can be considered as an early refurbishment because originally in the 1920s and 1930s the systems used for space heating were wood stoves [12].

Figure 10 shows the energy use for space heating, comparing the performance of the traditional gas boiler to the installation of a condensing gas boiler. Even though the generation performance of the new generation system is higher, the overall efficiency for the system was considered to be equal to 0.9, to include the thermal losses of the whole distribution plant, which cannot be improved in most buildings due to their historical nature [93].

The impact of the improvement of a better generation system was 12%, which brought the median value of heating energy use down to 136 kWh/(m^2 year). If including the complete refurbishment of both the system and the envelope, the average energy use was reduced to 52 kWh/(m^2 year), which was confirmed also by the Tabula dataset for refurbished buildings belonging to the same period of construction.

The results obtained by applying simple ECMs at the urban level show that a significant energy use reduction can be obtained by improving the building envelope and the heating system. The ECMs considered for this case study took into account the urban context of Venice. Therefore, even though the analyzed district does not present important legal limitations on the action that can be taken to protect the historical memory of the city, simple interventions were chosen to extend the analysis to other districts on the island.

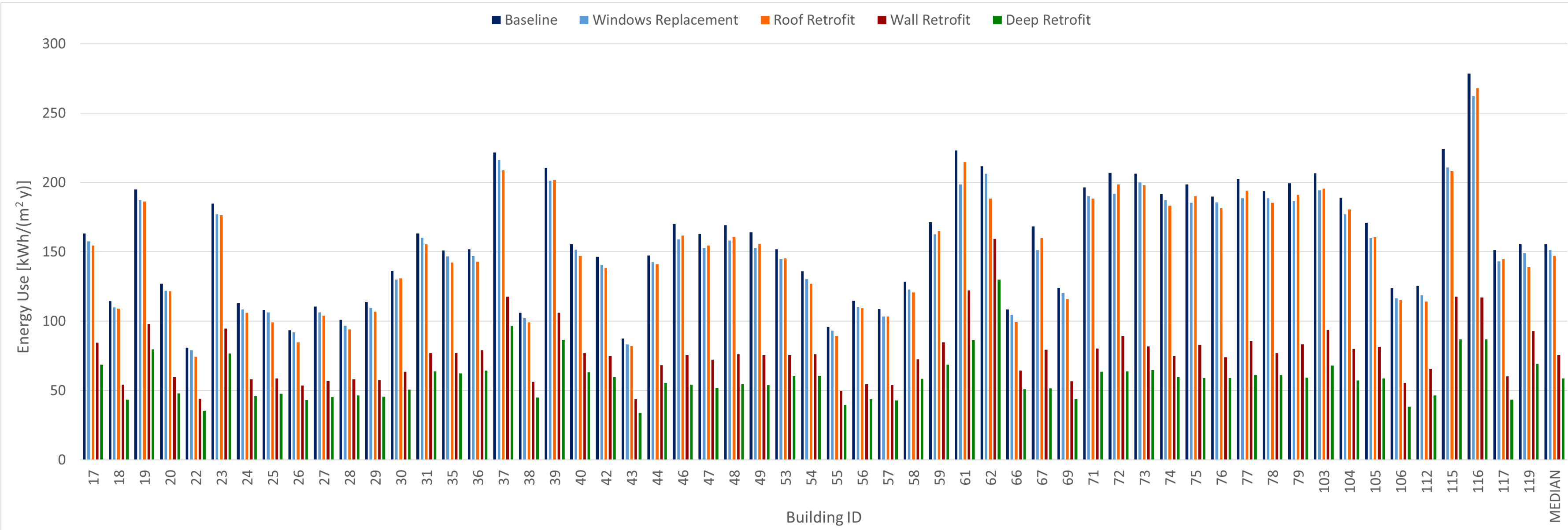


Figure 10. Energy use for space heating with application of different ECMs

Figure 11 summarizes the potential of ECMs applied at the district level, showing both energy need and energy use. The application of both envelope refurbishment and the improvement of the boiler efficiency reduces the energy use by 67% on average within the district. As shown at a single building level, the highest fraction of energy reduction is related to the retrofit of external walls, which accounts for almost 50% of the total due to the wider application.

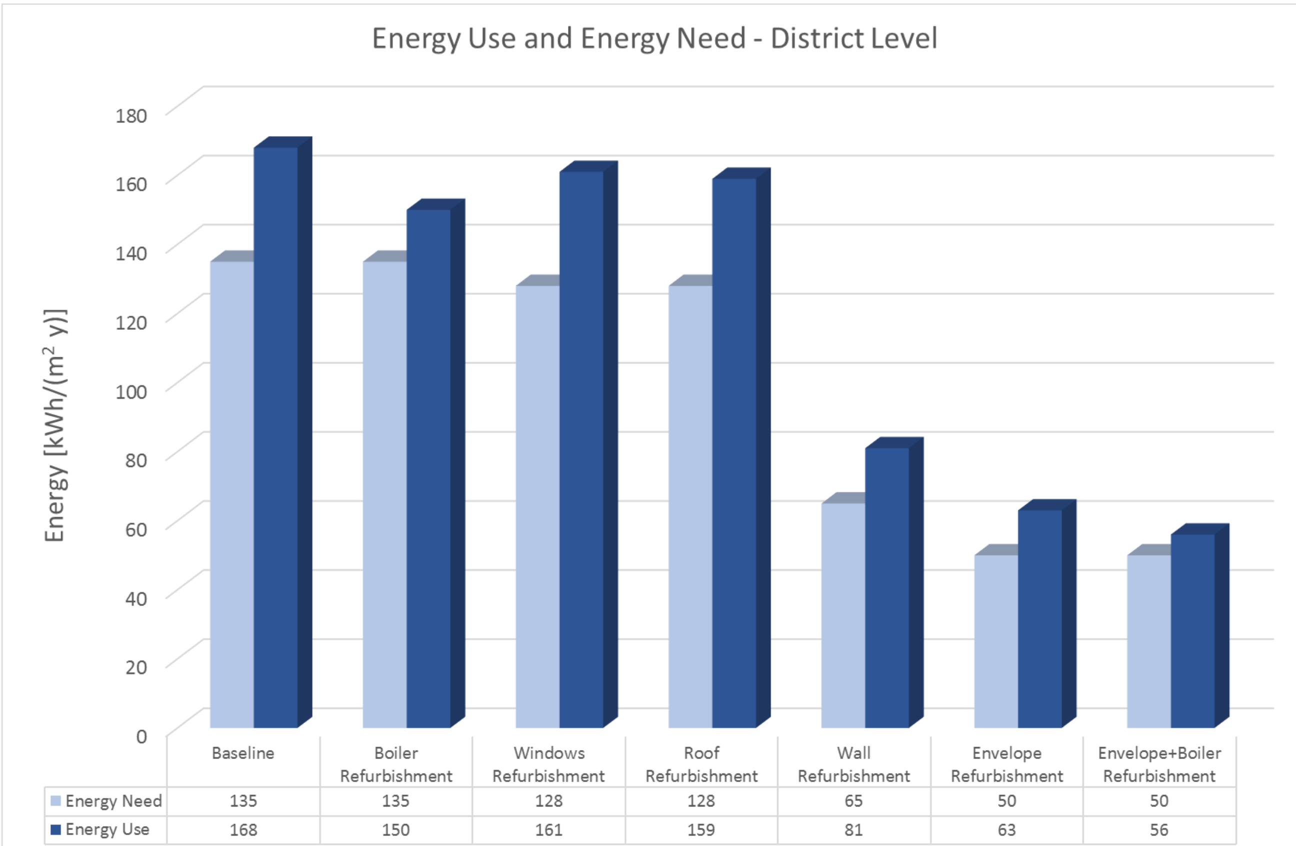


Figure 11. Energy need and energy use at the district level

Moreover, CO_2 emissions have been calculated using the conversion factor by the Italian Higher Institute for Environmental Protection and Research (ISPRA) to define the National inventory for CO_2 emissions for the United Nations Framework Convention for Climate Change (UNFCCC), updated in 2017 [94]. The potential emissions avoided, applying both a complete refurbishment of the envelope and generation system, corresponding to 1.1 $MtCO_2$ per year, which averages 20 $ktCO_2$ per building per year.

These results are even more significant when analyzed in the context of limitations related to their historical belonging, showing that simple interventions applied respecting the existing constraints can lead to a significant energy reduction, thus of CO_2 emissions and the energy costs for a typical family.

5.1 Economic analysis

Over the past two decades, the EU paid increasing attention to the role of historic buildings in the context of energy efficiency in cities. In particular, in Italy, the transposition of European regulations has been applied to different areas, mostly related to the efficiency of historic buildings owned by the state and used for public activities. Various projects deal with this topic (3ENCULT, GOVERNEE, ATTESS), focusing on the integration of renewable energy sources in energy efficiency strategies applied to public buildings of historical value [95–97]. What can be deduced from these projects and from the good practices they want to disseminate is certainly of considerable importance, especially in the case of Italian historical centers, but it is only partially applicable to the case study analyzed in the previous paragraphs. Literature studies deal with state-owned buildings of value, thus several incentive policies can be used. On the contrary, the district presented in this manuscript does not have a significant historic value, since the aim of the buildings is to give better living conditions to the less wealthy. Therefore, it is often impossible to carry out important and effective interventions due to economic difficulties.

Since it is not possible to trace the costs that might be necessary for the retrofit of the district it is necessary to refer to regional documents that estimate the prices for the categories of works supposed in the case study. The values belonging to this regional analysis are a realistic approximation but they can change due to the market variations. For this reason, the following analysis is intended as a first economic draft in the case of energy efficiency of an entire residential district for low-income families.

Analyzing the price list of the Veneto region [98] for costs related to energy efficiency in residential buildings the following values can be obtained. These values, together with the data concerning the district already obtained in the first phases of the development of the work, allow to obtain the calculation of the total cost to invest in the retrofit works of the whole district. The data used are presented in the following Table 3.

Table 3. Unitary cost and total cost of the retrofit measures applied to the district's buildings

ELEMENT	**UNITARY COST**	**SURFACE/NUMBER**	**TOTAL COST**
Roof	76.52 €/m^2	15,100 m^2	1,115.452 k€
External walls (retrofit from outside)	53.93 €/m^2	41,160 m^2	2,219.759 k€
External walls (retrofit from inside)	38.93 €/m^2	34,986 m^2	1,362.005 k€
Windows	333.85 €/m^2	19,900 m^2	6,643.615 k€
Boilers	100 €/kW	57 (from 25 kW to 700 kW)	1,427.500 k€
Entire envelope (wall retrofit from outside)	/	/	10,018.826 k€
Entire envelope (wall retrofit from inside)	/	/	9,161.072 k€
Entire envelope+Boilers (wall retrofit from outside)	/	/	11,446.326 k€
Entire envelope+Boilers (wall retrofit from inside)	/	/	10,588.572 k€

The retrofit actions applied and investigated can impact also the energy costs; in this case, the reduction of the space heating energy demand will reduce the gas use, thus the yearly operation costs (€/(m^2 y)). Considering the cost of natural gas in Italy, equal to 0.094 €/kWh as reported by

Eurostat [99], the cost for energy use in the *Business As Usual* (BAU) scenario results in 15.79 €/(m^2 y)[99]. The solutions that had the least impact on energy savings were the replacement of traditional gas boilers, roof insulation, and windows replacment with better-performing units. This impact on energy savings is also reflected in the decrease in the cost of energy. Replacing the boilers results in an 11% savings (14.10 €/(m^2 y)), roof insulation drops the cost of energy by only 5 percentage points (14.95 €/(m^2 y)), and window replacement is accompanied by a 4% savings (15.13 €/(m^2 y)). The single intervention that results in the greatest savings is the insulation of the external walls: the cost for energy use drops to 7.61 €/(m^2 y), representing a 52% reduction compared to the BAU scenario, because of the greatest area involved with respect to the roof or the glazed area. At the same time, the combined strategy (i.e. walls, windows, and roof improvement) leads to even greater savings of 63%, with an energy cost of 5.92 €/(m^2 y) because of the wider area improved. Besides, combining these interventions on the envelope with the replacement of heat generators further lowers the cost to 5.26 €/(m^2 y), equal to a decrease of 67%, making this the intervention that leads to the best results, as already pointed out in the analysis of ECMs.

As highlighted by the energy results, the economic analysis carried out in the previous paragraphs states the importance of renovation intervention in the residential sector. The achievement obtained with traditional and proven interventions are of particular interest in an urban context like the Venetian city center, in which the restrictions imposed for historical reasons force the use of non-invasive interventions.

6. Conclusions

This study focused on the energy renovation of a city district in a particularly challenging historical city center. The case study presented is located on the main island of Venice, a very particular district of historical and low-income housing units. For this reason, data collection has been complicated due to the lack of available information related to buildings, even at the municipal level. Hence, the study shows the importance of this information, as well as the replicability of the proposed analyses at a district scale, in helping decision-makers select the most adequate retrofit scenario among several alternatives. In fact, results were presented both with and without the mutual shading among buildings, showing the impact on the energy demand of buildings due to the lower solar heat gains; this result is important when planning large-scale retrofit intervention to properly estimate the action need and the related investment costs.

According to the period of construction of the buildings considered, no envelope thermally insulation was present. Therefore, the first action applied was the replacement of existing single pane windows with double pane windows achieving an average energy saving of about 5% throughout the district. A comparable energy savings reduction (5%) was possible by applying an insulating layer on the interior side of the roof. This measure would be more disruptive for the tenants because the retrofit implementation may interfere with residents' everyday life. The last intervention on the envelope was the insulation of the external wall. The wider application and the possibility of reaching higher performance make this intervention the most effective; it reached a 55% reduction of the district's energy demand. Nonetheless, the impact of this measure in terms of disruption and length of work is the highest. The last retrofit action was to upgrade the heating generation system: replacing old and obsolete boilers with more recent and advanced ones can lead to an energy saving of 12%. Although the retrofit measures applied are quite common, their combination allowed the achievement of 67% overall energy saving at the district level, corresponding to 1.1 $MtCO_2$ emissions avoided per year and, consequently, decreasing the air pollution respecting the cultural and architectural heritage limitations. Further important results concern the possibility of the containment of costs related to energy consumption. Compared to the current situation, it is possible to go from a saving of 4%, with a minimally invasive solution (i.e. windows substitution), up to 67% with a scenario in which the entire building envelope and generators are more efficient. For this last scenario, the investment cost to be faced is 5.8 million €, a value that decreases in the scenarios in which the measures are applied on individual elements of the envelope or on generators.

The Italian building stock is mostly composed of ancient buildings requiring significant renovation, particularly in traditional and historical urban city centers. This choice of neglecting limitations imposed by the Venetian cultural heritage (Superintendency) was made deliberately, to use this district as an example to create a methodology for district-scale retrofit strategies of the old social housing buildings in a city center that became common after World War II. For the same reason, the heat generation system was upgraded, considering more-efficient condensing gas boilers instead of applying photovoltaic panels or other renewable energy sources.

This research aimed to investigate retrofit measures at a district scale in a historical district, providing citizens with a more comfortable and energy-efficient built environment, and optimizing resources in territorial governance. The fundamental requirements for the development of plans for district renovation are quality, accessibility, and availability of data. The work done in this study represents an element of novelty in the Italian context because it represents one of the few examples in which GIS software was used to set up a building dataset for the application of energy efficiency measures at the district level, utilizing a UBEM tool. Moreover, the particular context in which the study is conducted shows how it is possible to plan and apply retrofit strategies for energy improvement even in a less investigated urban context such as are the districts of social housing buildings, which present unique characteristics and constraints and became extremely diffuse in Italy and Europe after the World Wars. This "district" approach to renovation strategies needs to be supported as well as the culture of up-to-date, accurate, and reliable data shared to predefined platforms to help policymakers and municipalities to promote energy savings in public and private buildings.

Future developments of this research include economical assessments of refurbishment actions to give a complete example based on a real case study to other municipalities that aim to replicate strategies applied at the historical center of Venice. Data collection will be fundamental to validate the input and output processed by the tool. Even though significant energy savings, as high as 67% reduction in energy use, are demonstrated employing conventional interventions, further research can include the replacement of single building boilers with a district heating network, comparing the efficiency of a shared generation with existing individual systems. In addition, suitable materials and technologies have to be investigated to support the implementation of these common retrofit actions in contexts similar to the analyzed case study to respect all the limits of the historical buildings. In conclusion, the dataset defined for Santa Marta in Venice should be expanded to a national level dataset, representing more categories of buildings (e.g., offices, mixed-use construction, retail, and others) and climatic conditions, to create a wider dataset of validated data representing the Italian building stock.

This work shows the opportunities for computer simulations at the urban level. Other modeling features, such as considering longwave radiation between exterior surfaces of surrounding buildings as well as using local weather data (for a more accurate representation of local temperature, and wind velocity, etc.), have to be surely implemented to better represent the real heat transfer processes in future studies

7 Acknowledgments

The authors would like to thank their universities, namely Free University of Bozen-Bolzano, University IUAV of Venezia, and University of Padova for the opportunity granted by making this collaboration possible. This study belongs to a joined collaboration between these institutions and LBNL and shows the far-reaching results coming from teamwork. LBNL's work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies of the United States Department of Energy, under Contract No. DE-AC02-05CH11231.

References

[1] J.L. Perera, L.T.D., Nick, V.m., Scartezzini, Impacts of extreme climate conditionsdue to climate change on the energy system design and operation, in: Energy Procedia 159, 2019: pp. 358–363.

[2] F. Hernandez-Roman, C. Sheinbaum-Pardo, A. Calderon-Irazoque, "Socially neglected effect" in the implementation of energy technologies to mitigate climate change: Sustainable building program in social housing, Energy Sustain. Dev. 41 (2017) 149–156. https://doi.org/10.1016/j.esd.2017.09.005.

[3] J. Morrissey, R.E. Horne, Life cycle cost implications of energy efficiency measures in new residential buildings, Energy Build. 43 (2011) 915–924. https://doi.org/10.1016/j.enbuild.2010.12.013.

[4] R.B. Hiremath, P. Balachandra, B. Kumar, S.S. Bansode, J. Murali, Indicator-based urban sustainability-A review, Energy Sustain. Dev. 17 (2013) 555–563. https://doi.org/10.1016/j.esd.2013.08.004.

[5] S. Soutullo Castro, M.J. Suarez Lopez, D.G. Menendez, E.B. Marigorta, Decision matrix methodology for retrofitting techniques of existing buildings, J. Clean. Prod. 240 (2019) 118–153.

[6] C.F. Reinhart, C. Cerezo Davila, Urban building energy modeling - A review of a nascent field, Build. Environ. 97 (2016) 196–202. https://doi.org/10.1016/j.buildenv.2015.12.001.

[7] O. Pombo, B. Rivela, J. Neila, The challenge of sustainable building renovation: assessment of current criteria and future outlook, J. Clean. Prod. 123 (2016) 88–100.

[8] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: Approaches, challenges and opportunities, Renew. Sustain. Energy Rev. 16 (2012) 3847–3866. https://doi.org/https://doi.org/10.1016/j.rser.2012.02.047.

[9] F. Johari, G. Peronato, P. Sadeghian, X. Zhao, J. Widén, Urban building energy modeling: State of the art and future prospects, Renew. Sustain. Energy Rev. 128 (2020) 109902. https://doi.org/https://doi.org/10.1016/j.rser.2020.109902.

[10] T. Hong, L. Xuan, Modeling building energy performance in urban context, in: Build.

Perform. Anal. Conf. Chicago, IBPSA-USA, n.d.: pp. 100–106.

[11] CityBES, (n.d.).

[12] ISTAT, http://dati-censimentopopolazione.istat.it/, (2014). http://dati-censimentopopolazione.istat.it/.

[13] Ministero dello Sviluppo Economico, Ministero dell'Ambiente e della Tutela del Territorio e del Mare, Ministero delle Infrastrutture e dei Trasporti, Strategia per la riqualificazione energetica del parco immobiliare Nazionale, 2020.

[14] A. Annibaldi, F. Cucchiella, P. De Bernardinis, M. Gastaldi, M. Rotilio, An integrated sustainable and profitable approach of energy efficiency in heritage buildings, J. Clean. Prod. 251 (2020).

[15] D. 2002/91/EC, Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings, (2003) 65–71.

[16] Decreto Legislativo 19 agosto 2005, n. 192 - Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia, 2005.

[17] La Storia di Venezia, (n.d.).

[18] R. Taherkhania, N. Hashempoura, M. Lotfib, Sustainable-resilient urban revitalization framework: Residential buildings renovation in a historic district, J. Clean. Prod. (2020) In press.

[19] L.F. Cabeza, A. de Gracia, A.L. Pisello, Integration of renewable technologies in historical and heritage buildings: A review, Energy Build. 177 (2018) 96–111. https://doi.org/10.1016/j.enbuild.2018.07.058.

[20] A. Galatioto, G. Ciulla, R. Ricciu, An overview of energy retrofit actions feasibility on Italian historical buildings, Energy. 137 (2017) 991–1000. https://doi.org/10.1016/j.energy.2016.12.103.

[21] A. Galatioto, R. Ricciu, T. Salem, E. Kinab, Energy and economic analysis on retrofit actions for Italian public historic buildings, Energy. 176 (2019) 58–66. https://doi.org/10.1016/j.energy.2019.03.167.

[22] L. de Santoli, F. Mancini, S. Rossetti, B. Nastasi, Energy and system renovation plan for Galleria Borghese, Rome, Energy Build. 129 (2016) 549–562. https://doi.org/10.1016/j.enbuild.2016.08.030.

[23] G. Luddeni, M. Krarti, G. Pernigotto, A. Gasparella, An analysis methodology for large-scale deep energy retrofits of existing building stocks: Case study of the Italian office building, Sustain. Cities Soc. 41 (2018) 296–311. https://doi.org/10.1016/j.scs.2018.05.038.

[24] T. Dalla Mora, M. Pinamonti, L. Teso, G. Boscato, F. Peron, P. Romagnoni, Renovation of a school building: Energy retrofit and seismic upgrade in a school building in Motta Di Livenza, Sustain. 10 (2018). https://doi.org/10.3390/su10040969.

[25] G. Ciulla, A. Galatioto, R. Ricciu, Energy and economic analysis and feasibility of retrofit actions in Italian residential historical buildings, Energy Build. 128 (2016) 649–659. https://doi.org/10.1016/j.enbuild.2016.07.044.

[26] G. Salvalai, M.M. Sesana, G. Iannaccone, Deep renovation of multi-storey multi-owner existing residential buildings: A pilot case study in Italy, Energy Build. 148 (2017) 23–36. https://doi.org/10.1016/j.enbuild.2017.05.011.

[27] M. Tiberi, E. Carbonara, Comparing Energy Improvements and Financial Costs of Retrofitting Interventions in a Historical Building, Energy Procedia. 101 (2016) 995–1001. https://doi.org/10.1016/j.egypro.2016.11.126.

[28] E. Lucchi, M. Tabak, A. Troi, The “cost Optimality” Approach for the Internal Insulation of Historic Buildings, Energy Procedia. 133 (2017) 412–423. https://doi.org/10.1016/j.egypro.2017.09.372.

[29] D. Anastaselos, E. Giama, A. Papadopoulos, An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions, Energy Build. 41 (2009) 1165–1171.

[30] J.K. Kazak, M. S´wia˛der, SOLIS—A Novel Decision Support Tool for the Assessment of Solar Radiation in ArcGIS, Energies. 11 (2018) 2105.

[31] P.R. D. Balboni, T. Dalla Mora, A. Righi, F. Peron, Optimal measures for energy retrofit on the university building “Ex Cotonificio Olcese” in Venice, in: Seism. Energy Renov.

Sustain. Cities, 2018: pp. 600–609.

[32] Carnieletto L., Ferrando, M., Teso L., Sun K., Zhang W., Causone F., Romagnoni P., Zarrella A., Hong T., Italian prototype building models for urban scale building performance simulation, Build. Environ. 192 (2021).

[33] Soprintendenza Archeologia, Belle Arti e Paesaggio per il Comune di Venezia e Laguna, (n.d.).

[34] Y. Chen, T. Hong, M.A. Piette, Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis, Appl. Energy. 205 (2017) 323–335. https://doi.org/10.1016/j.apenergy.2017.07.128.

[35] Confartigianato » COSTRUZIONI – 2 milioni di case italiane a rischio. Allarme Confartigianato, (n.d.).

[36] Ance, Osservatorio congiunturale sull ' industria delle costruzioni, (2019) 1–146.

[37] Città di Venezia, Osservatorio Casa, (2009).

[38] I. Magrini, Abaco delle strutture costituenti l ' involucro opaco degli edifici . Parametri termofisici . Testo revisionato a seguito dell ' inchiesta pubblica UNI, (2014) 1–44.

[39] S. Paiho, J. Ketomäki, L. Kannari, T. Häkkinen, J. Shemeikka, A new procedure for assessing the energy-efficient refurbishment of buildings on district scale, Sustain. Cities Soc. 46 (2019) 101454. https://doi.org/10.1016/j.scs.2019.101454.

[40] S. Torabi Moghadam, J. Toniolo, G. Mutani, P. Lombardi, A GIS-statistical approach for assessing built environment energy use at urban scale, Sustain. Cities Soc. 37 (2018) 70–84. https://doi.org/10.1016/j.scs.2017.10.002.

[41] A. Kamari, R. Corrao, S. Petersen, 1 st to 3 rd Febru a ry 2018 Un iversity of Catania Department of Civil Engineering and Architecture, 2018.

[42] L. Schibuola, M. Scarpa, Ground source heat pumps in high humidity soils: An experimental analysis, Appl. Therm. Eng. 99 (2016) 80–91. https://doi.org/10.1016/j.applthermaleng.2016.01.040.

[43] L. Schibuola, C. Tambani, A. Zarrella, M. Scarpa, Ground source heat pump performance

in case of high humidity soil and yearly balanced heat transfer, Energy Convers. Manag. 76 (2013) 956–970. https://doi.org/10.1016/j.enconman.2013.09.002.

[44] Legge 31 maggio 1903, n. 254, "Sulle case popolari," Gazz. Uff. (1903).

[45] L'ATER di Venezia e la sua storia | ATER Venezia, (n.d.).

[46] Azienda Territoriale per l'Edilizia Residenziale L'ATER di Venezia e la sua storia |, (n.d.).

[47] Case dello IACP a Santa Marta, già Quartieri "Benito Mussolini" e "SADE" | Conoscere Venezia, (n.d.).

[48] EnergyPlus | EnergyPlus, (n.d.).

[49] DesignBuilder Software Ltd - Home, (n.d.).

[50] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300, Milano, Italy, 2008.

[51] European Committee for Standardization-CEN, BS EN 16798 - Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acousti, Brussels, Belgium, 2019.

[52] The European Parliament and the Council of the European Union, Directive 2002/91/EC of 16 December 2002 on the energy performance of buildings, Brussels, Belgium, 2003.

[53] The European Parliament and the Council of the European Union, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings - EPBD, Brussels, Belgium, 2010.

[54] The European Parliament and the Council of the European Union, Directive 2018/844/EU of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, Brussels, Belgium, 2018. https://doi.org/10.1007/3-540-47891-4_10.

[55] T. Hong, M.A. Piette, Y. Chen, S.H. Lee, S.C. Taylor-Lange, R. Zhang, K. Sun, P. Price, Commercial Building Energy Saver: An energy retrofit analysis toolkit, Appl. Energy. 159 (2015) 298–309. https://doi.org/10.1016/j.apenergy.2015.09.002.

[56] F. Peron, M.M. De Maria, F. Spinazzè, U. Mazzali, An analysis of the urban heat island of Venice mainland, Sustain. Cities Soc. 19 (2015) 300–309. https://doi.org/10.1016/j.scs.2015.05.008.

[57] T. Hong, Y. Chen, S.H. Lee, M.A. Piette, CityBES: A web-based platform to support city-scale building energy efficiency, 5th Int. Urban Comput. Work. San Fr. (2016) 10. https://doi.org/10.1016/j.jclepro.2015.05.105.

[58] Y. Chen, T. Hong, M.A. Piette, City-Scale Building Retrofit Analysis: A Case Study using CityBES, Proc. BS2017. (2017). https://doi.org/10.26868/25222708.2017.071.

[59] Carta Tecnica Regione Veneto, (n.d.).

[60] QGIS - A Free and Open Source Geographic Information System, (n.d.).

[61] OpenStreetMap, (n.d.).

[62] G. Mutani, G. Vicentini, Analisi del fabbisogno di energia termica degli edifici con software geografico libero. Il caso studio di Torino., La Termotec. 6 (2013) 63–67.

[63] G. Agugiaro, Energy planning tools and CityGML-based 3D virtual city models: experiences from Trento (Italy), Appl. Geomatics. 8 (2016) 41–56. https://doi.org/10.1007/s12518-015-0163-2.

[64] G. Mutani, V. Todeschi, Space heating models at urban scale for buildings in the city of Turin (Italy), Energy Procedia. 122 (2017) 841–846. https://doi.org/10.1016/j.egypro.2017.07.445.

[65] G. Agugiaro, J. Benner, P. Cipriano, R. Nouvel, The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations, Open Geospatial Data, Softw. Stand. 3 (2018) 2. https://doi.org/10.1186/s40965-018-0042-y.

[66] UrbisMap | Geoportale e Catasto del Comune di Venezia, (n.d.).

[67] Cartografia completa, (n.d.).

[68] Google Maps, (n.d.).

[69] Bing Maps - Directions, trip planning, traffic cameras & more, (n.d.).

[70] E. Barbiani, Edilizia popolare a Venezia, Electa, 1983.

[71] Y. Chen, T. Hong, X. Luo, B. Hooper, Development of city buildings dataset for urban building energy modeling, Energy Build. 183 (2019) 252–265. https://doi.org/10.1016/j.enbuild.2018.11.008.

[72] Comitato Termotecnico Italiano (CTI), EN 12831 - Prestazione energetica degli edifici - Metodo per il carico termico di progetto, 2018.

[73] Ente Nazionale Italiano di Unificazione, UNI/TS 11300 - Part 1: Evaluation of energy need for space heating and cooling, Milan, Italy, 2014.

[74] Venice EPW weather data, (n.d.).

[75] D. Camuffo, M. Colacino, S. Enzi, C. Cocheo, E. Pagan, G. Sturaro, Extreme events in Italy from documentary sources: Venice as a case study, Nuovo Cim. Della Soc. Ital. Di Fis. C. 29 (2006) 33–39. https://doi.org/10.1393/ncc/i2005-10218-x.

[76] T.A.M. M.C. Peel, B. Finalayson, Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 11 (2007) 1633–1644. https://doi.org/https://doi.org/10.5194/hess-11-1633-2007.

[77] Il Presidente della Repubblica, Italian legislative decree n.412/1993, Gazz. Uff. 26 Agosto 1993. (1993).

[78] Il Presidente della Repubblica, Italian law n.74/ 2013, Gazz. Uff. 27 Giugno 2013, n. 149. (2013) 1–11.

[79] G.N. Gugul, M. Aydinalp Koksal, V.I. Ugursal, Techno-economical analysis of building envelope and renewable energy technology retrofits to single family homes, Energy Sustain. Dev. 45 (2018) 159–170. https://doi.org/10.1016/j.esd.2018.06.006.

[80] R. Khalid, M. Sunikka-Blank, Housing and household practices: Practice-based sustainability interventions for low-energy houses in Lahore, Pakistan, Energy Sustain. Dev. 54 (2020) 148–163. https://doi.org/10.1016/j.esd.2019.11.005.

[81] Ministro della Salute, Ministro dell'Ambiente, Ministro delle Infrastrutture, Decreto Ministeriale 26/06/2015, 2015.

[82] Azienda Territoriale per l'Edilizia Residenziale Prossima la riqualificazione dei tre edifici di via Monte Prabello |, (n.d.).

[83] Comune di Venezia, Regolamento Edilizio, (2020) 84.

[84] U.S. Department of Energy, EnergyPlus Engineering Reference, (2018).

[85] R. Walker, S. Pavía, Thermal performance of a selection of insulation materials suitable for historic buildings, Build. Environ. 94 (2015) 155–165. https://doi.org/10.1016/j.buildenv.2015.07.033.

[86] E. Mazzola, T.D. Mora, F. Peron, P. Romagnoni, An integrated energy and environmental audit process for historic buildings, Energies. 12 (2019). https://doi.org/10.3390/en12203940.

[87] Il Presidente della Repubblica, Decreto Legislativo 26 Marzo 2008, n. 62, 2008.

[88] M. Pedroso, I. Flores-Colen, J.D. Silvestre, M.G. Gomes, L. Silva, P. Sequeira, J. de Brito, Characterisation of a multilayer external wall thermal insulation system. Application in a Mediterranean climate, J. Build. Eng. 30 (2020). https://doi.org/10.1016/j.jobe.2020.101265.

[89] E. Cuce, P.M. Cuce, C.J. Wood, S.B. Riffat, Toward aerogel based thermal superinsulation in buildings: A comprehensive review, Renew. Sustain. Energy Rev. 34 (2014) 273–299. https://doi.org/10.1016/j.rser.2014.03.017.

[90] L. Zhang, Z. Liu, C. Hou, J. Hou, D. Wei, Y. Hou, Optimization analysis of thermal insulation layer attributes of building envelope exterior wall based on DeST and life cycle economic evaluation, Case Stud. Therm. Eng. 14 (2019) 100410. https://doi.org/10.1016/j.csite.2019.100410.

[91] J. Lucero-álvarez, N.A. Rodríguez-Muñoz, I.R. Martín-Domínguez, The effects of roof and wall insulation on the energy costs of low income housing in Mexico, Sustain. 8 (2016) 1–19. https://doi.org/10.3390/su8070590.

[92] Tabula WebTool, (n.d.). http://webtool.building-typology.eu/#bm (accessed April 29, 2020).

[93] UNI Ente Nazionale Italiano di Unificazione, UNI/TS 11300 - Part 2: Evaluation of primary energy need and of system efficiencies for space heating and domestic hot water production, (2008).

[94] Istituto Superiore per la Prevenzione e la Ricerca Ambientale, Tabella parametri standard nazionali per il onitoraggio e la comunicazione dei gas ad effetto serra, (2019) 2–3.

[95] Project - Good Governance in Energy Efficiency, (n.d.).

[96] 3encult - Project - Welcome - Home, (n.d.).

[97] Progetto A.T.T.E.S.S. | Segretariato regionale del Ministero della Cultura per il Veneto, (n.d.).

[98] Prezzario on-line 2019 - Regione del Veneto, (2021).

[99] Natural gas price statistics - Statistics Explained, (n.d.).