Renewable and Sustainable Energy Reviews 175 (2023) 113166

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

An agile heating and cooling energy demand model for residential buildings. Case study in a mediterranean city residential sector

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ARTICLE INFO

Keywords:
3D GIS
Urban energy planning
Heating demand
Cooling demand
Retrofitting
Climate change

ABSTRACT

Climate change will affect people's health, especially in cities. Hence, energy planning will play a key role in the development of sustainable and resilient cities. Urban building energy models facilitate energy planning as heating and cooling demand becomes known, and the consequences of different planning actions can be modelled. This research presents an agile heating and cooling demand model. It combines a European standard's methodology, geometric information of buildings collected from cadastral and altimetric datasets using GIS-based technologies, solar irradiation analysis and the degree-days method. The model is validated with various case studies and then applied to several buildings in different environments.

The model shows the strong influence of the building's age (design and materials), the building surface-to-volume ratio on the energy demand and the importance of the solar irradiation analysis. Furthermore, the model can predict the effects of the temperature rise on energy demand and prioritise the buildings to be retrofitted. Indeed, one of the conclusions obtained from the model is that advanced retrofitting of 17% of the most energy demanding buildings would obtain a 50% decrease in thermal demand; if the percentage was 50%, an 85% reduction could be reached. In conclusion, the energy planning tool hereby presented is a useful tool to viably foresee the energy demand of residential buildings and districts and the effects of climate change on their energy demand, as well as the consequences of countermeasures like retrofitting.

1. Introduction

Despite using only 3% of the earth's useable land area, cities currently account for 72% of global greenhouse gas emissions [1]. The European Union aims to achieve a 90% reduction in emissions from the residential sector by 2050 compared to 1990 [2]. This is a major challenge because cities are expected to be housing 70% of the world's population by 2050 [3]. The increase in the size of cities, the improvement of living standards and the development of third-world countries can lead to a significant increase in energy demand. These factors, coupled with considerable inequality among citizens in terms of social justice [4], create a complex situation to address as a whole.

Focusing on the residential sector, it is responsible for 40% of cities' energy consumption, generating 36% of greenhouse gas emissions [5] and, thus, presenting great potential for improvement. Policies to meet EU targets in this sector are mainly based on building retrofitting, new construction based on the nearly zero energy buildings concept and the implementation of renewable generation technologies to displace fossil fuels [6]. Besides, heating consumption at the European level accounts for 43% of the residential demand, while cooling consumption is only 7% [7]. Even evaluating only the warmest countries in Europe, cooling consumption is still considerably lower compared to heating. This is not because buildings are in good condition (35% of the buildings are older than 50 years and more than 75% are considered inefficient [8]), but because general standards of comfort are not met in most dwellings. This is the case in hidden energy poverty, where households cannot guarantee comfort during the summer season. In addition, Climate change has led to a 1.5-2 °C increase in global temperature compared to a pre-industrial scenario [9], making climates more extreme and endangering the most disadvantaged groups, particularly in cities where the "urban heat island" effect is added. These phenomena, combined with the fact that only 0.4–1.2% of all buildings are renovated per year [8], create a challenging problem that is getting worse every year. For example, according to one study on the city of València [10], 20% of the city's population is estimated to be in a situation of energy vulnerability, in addition to being unable to undertake energy efficiency and retrofitting measures in their houses.

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https://doi.org/10.1016/j.rser.2023.113166
Received 15 February 2022; Received in revised form 30 December 2022; Accepted 4 January 2023

Abbreviations

BuiltE	Building thermal energy assessment model
LiDAR	Laser imaging detection and ranging
UBEM	Urban building energy models
GIS	Geographic information systems
HDD	Heating degree-days
CDD	Cooling degree-days
SFH	Single-family house
MFH	Multi-family house
TH	Terraced house
AB	Apartment block
SSP	Shared socio-economic pathways
S/V	Surface-to-volume ratio of an air conditioned space

Therefore, urban energy planning strategies must analyse in detail the energy consumption because of the heating needs in cities' buildings, but also consider the cooling requirements, characterising it in detail to find the best strategies to reduce it. As cities consist of a large number of districts and buildings groups, simplified methods are necessary in order to analyse the problem from a holistic point of view, so it is possible to calculate the thermal demand of blocks of buildings and entire districts with agile tools. In this regard, GIS based tools become ideal for the analysis of entire districts, making it possible to manipulate big amounts of spatial information with geo-referenced systems. Once the thermal demand of entire districts can be calculated, it is possible to study different strategies to reduce the demand (like retrofitting buildings) and analyse the effect of different urban phenomena, such as the urban heat island.

In section 2, the main challenges of city energy planning and the available tools are introduced for a better understanding of this research contribution. The authors have identified the need for agile but comprehensive energy simulation tools at district/city level. For this, the authors propose a bottom-up urban building energy models (UBEM) tool that evaluates the residential energy demand for heating and cooling with enough accuracy and detail, but in a computationally efficient, rapid manner. The tool should allow, among other energy planning challenges, to evaluate different climate scenarios and their evolution, or to measure the impact of retrofitting a number of buildings or households. To the authors' knowledge, such a comprehensive and efficient tool does not yet exist, although it can be developed by taking advantage of the latest proposals and findings in the literature. This general objective is divided into the following specific objectives.

- To automatically capture GIS-based information, for example from cadastres, LiDAR information, etc., on buildings geometry, age, conservation, etc.
- To combine the information with building archetypes, for example, from TABULA [11] and model their energy profiles.
- To later extrude 3D models of entire districts.
- To capture microclimatic information, including solar radiation on building surfaces, temperatures, and other outdoor conditions, for example, using the degree-days method [12].
- To calculate indoor conditions and, combined with outdoor conditions and the building features, to calculate heating and cooling demands for thermal comfort. For this, the EN 52016:2017 standard [13] can be used.
- To compound all this information both in isolation for each building, or aggregated for neighbourhoods or even the city as a whole.
- To allow sensitivity analysis and to connect the model to optimisation analysis, such as the influences of building characteristics, climate change, building retrofitting, urban redevelopment, etc [14].

To sum up, the hereby presented building thermal energy assessment model (BuiltE) leverages on the previous literature studies and adds the following innovations.

- Use of a detailed radiation model to evaluate thermal demand in an agile bottom-up model.
- Definition of a methodology for detailed energy modelling of large building stocks in an agile way.
- Group demand, retrofitting benefits and global warming assessment in a single methodology for the selected sample of buildings.

2. Literature review

For the re-design of cities, it is necessary to collect a complete picture of the whole city's needs. In this manner, it will be possible to prioritise and analyse which measures are of the most interest. Therefore, it is proposed to shift the ambit from the building level to the district level. Individual actions, such as envelope insulation or equipment efficiency improvement, may not be sufficient to meet the decarbonisation targets. In this fashion, a community approach can achieve greater advantages as opposed to the traditional approach of individual measures in buildings [15]. Hence, district level studies, also called urban building energy models (UBEM), are becoming of great interest, as stated in studies like [16], that compare the implementation of various measures such as retrofitting or renewable energy generation and study their effect on the neighbourhood. Also, in studies like [17], authors focus on the comfort and safety of people and evaluate the resilience to extreme conditions that is obtained through retrofitting.

There are several proposals, literature reviews and handbooks on approaches and tools for UBEM. One of the most comprehensive literature reviews [18] concludes that there is no single tool that offers the best combination of all the relevant factors. Also, that there is no single model that can address all the physical processes involved in UBEM. Such a model remains computationally demanding, to the point of being almost unsolvable [19]. Hence the need for simplified but comprehensive UBEM tools that are both computationally efficient and reasonably accurate [18].

Consequently, the different literature reviews state two main strategies: top-down and bottom-up [20]. Top-down utilises the estimate of total residential sector energy consumption and other pertinent variables to allocate the energy consumption of a particular house or group of houses. Bottom-up methodology calculates the energy consumption of each individual or group of houses, then aggregates these results to calculate that of the district or city. Studies such as [21] state that bottom-up models are a better approach as these parametric models enable better sensitivity analysis and can be integrated into optimisation processes and energy planning.

For UBEM simplification, many authors recommend the use of building archetypes that reliably represent a building stock, as for example [11], in which the project organised the buildings stock of 20 countries into archetypes. Effectively, an enormous amount of information about built structures (geometry, physical properties of components, etc.) is needed, whereas these are often unknown and difficult to obtain accurately. Computational costs are reduced by physical and model simplifications and computationally efficient urban environmental and climatic approaches [19].

Furthermore, microclimate conditions must be considered, such as solar radiation, shadows, airflows, the already mentioned urban heat island effect, etc. [20]. Incident solar radiation is the major thermal load on the building envelope's exterior [20] which affects heating and cooling demands, particularly in cities with high solar radiation.

2.1. Thermal demand simplified methodologies for urban districts

As explained previously, no validated agile energy simulation tool provides sufficient reliability at a city level, compared to current building simulation software. Simple models are of poor quality on a building scale because they make use of limited information [19]. As more data becomes available, the accuracy of these models will increase considerably [19].

In the context of building thermal demand simulations, there are numerous simplified models for this purpose [20], but all these types of methodologies were left behind with the emergence of dynamic models and specialised software, e.g. Energy+, TRNSYS. These software products have great potential and accuracy with which to analyse the behaviour of one or more buildings. However, they present the problem of being computationally expensive, making the analysis of large areas difficult. The new approach of focusing on the neighbourhood/district rather than the building/dwelling has rekindled interest in simplified, agile methodologies. For example, the authors in Ref. [22] adapt building assessment methodology to be able to assess positive energy districts.

2.2. *GIS-based technologies for urban energy planning*

GIS (geographical information systems) technologies make it possible to work with geo-referenced systems and to obtain and manipulate large amounts of spatial information. In this way, it is possible to obtain information on the building stock and apply it as input to the simulation models, as described in Ref. [23]. In this review, it is described how a number of authors have used this technology for the study of urban energy planning, applying different methods for studying large numbers of buildings. Authors argue that although the individual simulations are not very accurate, the final aggregate value has an acceptable error level of below 20%. Another example can be found in Ref. [24], where the authors give an overview of the GIS-based tools for urban energy systems. They comment that an interesting gap in the literature is the combination of flexibilisation assessment with GIS tools at the urban scale.

As introduced in a previous section, two opposing approaches are present in the literature with regard to the use of GIS for modelling the thermal demand of buildings [25]: the bottom-up approach (preferred by the study) and the top-down approach. Based on the recommendations by Ref. [21] and the needs and expectations of the model, this research presents a bottom-up UBEM. The problem is that this approach needs a lot of information to achieve valuable results, i.e. a high ratio between accuracy and the amount of information obtained. More authors make use of bottom-up models, e.g. Ref. [26], who correlate data from their national building database with TABULA to assess the housing stock.

In [21], the authors use a bottom-up engineering model in Simulink, with archetype classification, which then compares the aggregate with the consumption of each country, achieving a reasonably high level of accuracy. Other research presents interesting results by making use of both methodologies combined, such as [27], where authors combine the use of a top-down model with linear regression of real measures to analyse the most interesting areas of the city to study, and then a bottom-up model based on European regulations to refine the result of the neighbourhoods they wanted to study. Similarly, in Ref. [6], the authors also use both models, and the top-down models help reinforce the bottom-up models and identify their shortcomings. In another interesting publication [28], the authors comment that many papers use the archetype methodology to simplify data collection in bottom-up approaches.

Various works combine the ability to obtain geo-referenced data from GIS technology with simplified calculation methodologies to make a demand assessment of the building stock. As an example, in Ref. [29], the authors make use of a GIS tool and a proprietary model based on real data, to calculate building energy demand. They then aggregate the demands per a 100-m grid to obtain a quick overview of the improvement potential of city areas and their potential to evaluate energy policies.

In [30], the authors extract geometric information from the city census while missing data is estimated. They detail the usefulness for urban planning, but not as a detailed simulation tool for particular cases. Other works use GIS in a similar way to obtain information from the cadastre or the city census, such as [31], where the authors applied the model to a district scale and evaluated the sensitivity of different simulation parameters, or [32], where this information is used to characterise the space heating needs of the district. In Ref. [33], they broaden the scope with GIS to evaluate not only heating but also domestic hot water and photovoltaic generation potential. Finally, in Ref. [34], the authors use the cadastre to obtain the uses of each building by using the GIS tool.

2.3. *Thermal demand assessment on warm climates, the need of cooling*

Regarding the thermal demand assessment on residential buildings, most of the modelling has been mainly focused on the heating demand, being the standard ISO 13790 an example [35], as it is the predominant thermal demand in continental climates, leaving cooling demand aside. Global warming will certainly result in some regions suffering longer and hotter summers, thus endangering people’s health. Therefore, the study of cooling demand is also crucial in many parts of the world in order to obtain the measures required for action.

The authors in Ref. [36] perform a study in several Mediterranean climates where they stipulate that radiation is a crucial term for the accuracy of the results in order to evaluate cooling demand correctly. In Ref. [12], the authors make use of degree-days methodology for heating and cooling. They derive results as a function of the degree-days for different locations. Cooling degree-days (CDD) present a non-linear trend for low values, so the authors have adapted the model to take into account the inertia of heavy walls and irradiation. Another relevant piece of research is [14], where a study of several buildings (social housing) in a Mediterranean climate (Seville) is performed. The authors focus on vulnerable groups and how they will be affected by climate change. Additionally, a review on how climate change affects building performance is also carried out.

2.4. *Retrofitting benefits*

Regarding energy measures in buildings, retrofitting allows for better resilience than changing equipment or installing renewable energy [17]. Addressing demand rather than consumption can not only lead to greater energy savings, but also to better adaptability to climate change [32]. However, it is important to emphasise that the objective should be to ensure dwellers’ comfort, not to reduce demand at all costs. Measures should not only be considered in terms of energy savings, but also in terms of comfort levels [17]. Analysing this idea in more detail, some authors such as [33] state that photovoltaic and solar thermal generation will not be enough to obtain a significant reduction on primary energy consumption. Therefore, retrofitting actions must be implemented to reach energy efficient comfort targets.

Climate change will lead to more extreme weather and worsen the performance of air-conditioning systems. As [37] comments, the efficiency ofheating, ventilation and air-conditioning equipment or the security of the grid may be severely compromised due to these changes in climate. The authors conclude that measures to improve resilience will be key in the years to come [37]. In this context, it is also important not to forget the emissions of every phase of the building’s life. Some authors, such as [38], focusing on the embodied energy of building materials, highlight the potential of using natural materials for retrofitting.

3. Material and methods

This chapter details the different steps of the methodology presented, the process selected to validate the model, and the data used for the chosen case study.

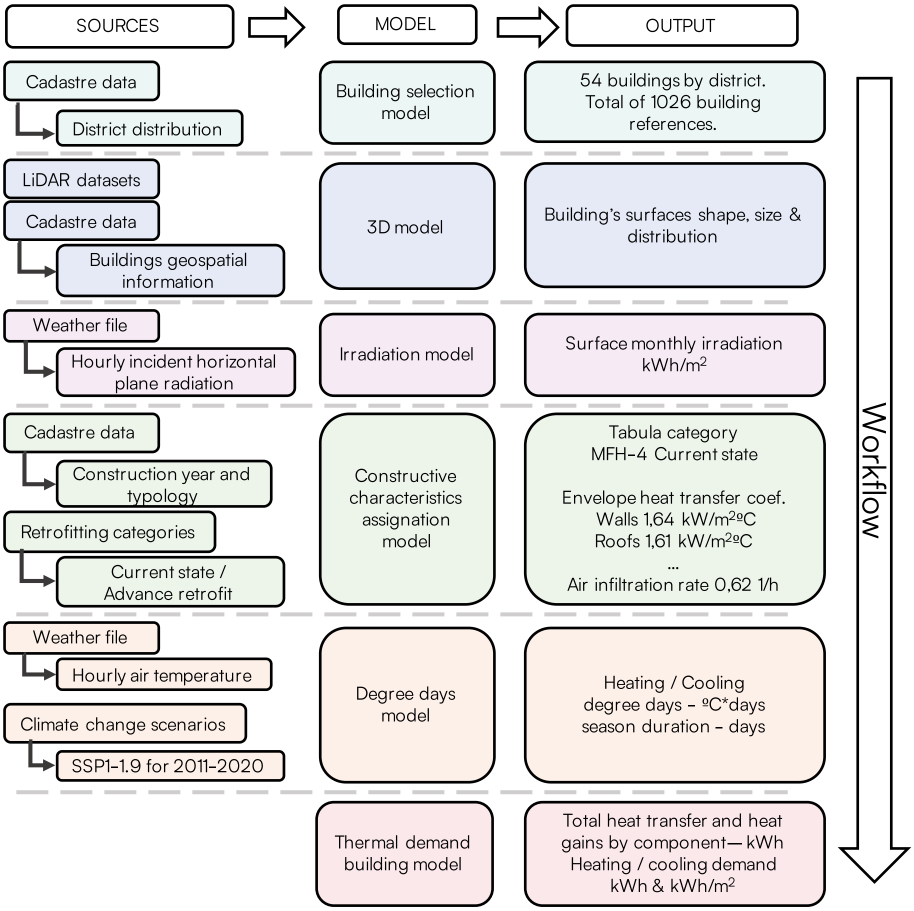

Fig. 1. Model methodology workflow. Including sources used and an example of each model's results.

3.1. *Thermal demand assessment model*

In this section, the different modules that compose BuiltE are explained. Each of them refers to an element of the thermal demand calculation. This model consists of the following steps.

1. Elaboration of a 3D model of the buildings, based on their characteristics and geometry.
2. Evaluation of the incidence of radiation on the surfaces, to determine the solar gains on the buildings.
3. Assignment of a building archetype, which consists of defining the constructive characteristics.
4. Quantification of the heating and cooling degree-days according to the climate file, which will determine the hours to be heated and cooled.
5. Calculation of the thermal demand of the building, based on European regulations, with the input presented in the previous modules.

Fig. 1 represents the workflow of the modules and the connection of the information between them, applied to the case study described in this research. All operations and modules have been carried out with code developed ad-hoc by the authors for the tool, except where otherwise indicated.

3.1.1. *3D model*

The first BuiltE module consists in obtaining a 3D model of the studied area. It is proposed to generate a digital twin to obtain the geometric and spatial information of the buildings under study, as well as the adjacent elements that may cast shadows on them. In this regard, GIS tools are used to obtain the geometry, area and distribution of all the surfaces of each building. Additionally, differentiation between walls in contact with other buildings and external walls has been made.

For this purpose, open data sources provided by the Spanish government have been used [39]. Information from the municipal cadastre has been used for the building footprint, together with LiDAR datasets for the altimetric information to assign the height of each building.

The use of information from the national building register has numerous advantages. First, these databases provide a spatial representation model of every building in the city, which is geolocated and contains the building's measurements and shapes. This make it possible to define the geometries and volumes of the buildings with great accuracy and on an automated basis. Second, the distance between the buildings is determined using the geolocation, which allows the casting of shadows between them. In some cases, it is possible to find buildings that are poorly registered (or not registered at all), which requires correction or new formation in order to be able to evaluate them.

Several authors in the field make use of regional censuses or cadastre information. An example of papers related to the European region are [26]: where the authors use the French census to estimate fuel poverty [29], for heating and domestic hot water demand assessment in Poland [34], in Barcelona Spain, where the authors propose a methodology for the life cycle assessment of the buildings at city scale, or [40], in which the building energy performance of an Italian region is evaluated and ranked by the levelized cost of energy.

The use of LiDAR for the creation of the 3D model facilitates obtaining high values of "level of detail" [41], which indicates how thoroughly the characteristics of the real world have been modelled. Some authors show that even with simplifications in the definition of the 3D model, the results are still quite accurate [34].

The combination of both sources of information allows the creation of a 3D model of the studied area. Thanks to the geolocation of the geometric information, it is possible to calculate the shadows that each element casts on the rest, and to obtain the skyline of the obstacles on each of the surfaces of every building. This information is of great importance for the accuracy of the rest of the models.

3.1.2. Irradiation model

Despite being estimated in a large number of works or obtained by means of simplified models, envelope irradiation is of crucial importance in order to achieve a correct level of accuracy in the energy demand models [19].

This importance is even greater when the study is about cooling demand. In the work [14], the authors discuss the importance of solar irradiation in estimating cooling demand, and how the correct design of glazing and optimal orientation can play a relevant role in future climates.

Thus, the authors of this work have decided to devote special attention to obtaining accurate solar radiation for the evaluation of the thermal demand. Based on the 3D model obtained previously, the orientation, inclination, shadow profile, percentage of the surface in contact with another building and total surface, have been obtained for each building surface (differentiating facades and roofs). With these data, and extrapolating the methodology presented in the work [42], the irradiation for each of these surfaces is obtained on an hourly basis. Then, a precise irradiation representation is obtained using a point grid generated for the 3D building volume. The skyline, and subsequently the hourly irradiation, has been calculated for each of the points. Finally, the irradiation for each point has been aggregated for envelopes and on a monthly basis.

3.1.3. Envelope characteristics

In most of the bottom-up approaches found in the field, this approach is combined with the use of archetypes and constructive typologies to simplify the calculation process [14]. This approach achieves good results, as grouping buildings by construction period provides a robust cluster. Datasets represent the temporal changes in national legislation. Many authors have made use of archetype classification for energy assessment of cities, some examples can be found in Ref. [29], a case study applied to Poland [25], in Portugal, or in several countries such as France, Germany, Spain and the United kingdom as authors of [21] showed.

Some authors have directly considered the distribution of uses already recorded in their countries' censuses [34]. In this context, the TABULA project is a widespread source used in several works in the research field, such as [43]. The TABULA project defines archetypes for each of the typologies studied, these being a combination of the type of dwelling (apartment block - AB, single family house - SFH, multi-family house - MFH, terraced house - TH), and the period of construction (period 1 for years before 1900, period 2 for 1901 to 1936, period 3 for 1937 to 1959, period 4 for 1960 to 1979, period 5 for 1980 to 2006 and period 6 from 2007) [26]. The project has a database for different countries in Europe and several climates per country. For each typology, three different scenarios are presented: the base case, a simple retrofit and an advanced retrofit. An example of the application of TABULA information is found in Ref. [40], where the authors focus on the scope of retrofitting using TABULA and the PasivHaus standard.

Each building under study has been given a TABULA typology based on data from the 3D model. And in this manner, the constructive properties required for the simulation (such as the heat transfer coefficient of the envelope elements or the infiltration and ventilation rates) are assigned. The base case and the advanced retrofit case, both obtained from TABULA, have been assessed in this study (see section 3.2.1.).

3.1.4. Degree-days calculation

The degree-days models estimate the thermal demand requirements in a given climate. These models have been widely used in the literature due to their ease of calculation and extrapolation of results. Other authors, such as [33], employ the heating degree-days (HDD) with the TABULA database in two different urban cells of an Italian city. Despite the fact that the vast majority of studies on degree-days focus on heating, some authors, such as [12], also apply it for cooling. They identify that cooling degree-days (CDD) are much more sensitive in the low values range (see our results in Fig. 6).

As explained later, the European standard demand model used in this research applies the difference between the indoor and outdoor temperatures of the building on a monthly basis, using the average temperatures of each month. To improve this part of the process, the use of degree-days is proposed to quantify the heating and cooling needs throughout the year. To do this, setpoint temperatures are assigned for the heating and cooling season, and the HDD and CDD are obtained, respectively, as well as the days on which the heating and cooling demand must be satisfied. This calculation is applied for each day of the year and then aggregated by month. For this study, the València airport climate file from the Energy + database has been used (typical meteorological year, TMY file). The base temperature for heating had been set to 18 °C and the cooling temperature to 26 °C. These temperatures were chosen in relation to the results of the validation.

3.1.5. Thermal demand model

For the calculation of the thermal demand of buildings, the methodology of the 52,016–1:2017 standard [13] has been selected on a monthly basis. This standard replaces standard 13,790, which was widely used in the literature [43]. One of the fundamental differences is the inclusion of the cooling demand assessment in buildings.

In several works, such as [36], the monthly methodology of the 52,016 standard is used. In this research, it is pointed out that its accuracy in assessing cooling demand for buildings with large, glazed surfaces is low, proposing several correlations to correct this, also highlighting that the radiation term is crucial for the cooling calculation. Regarding the model presented in the current study, the required input data are those generated in the previous sections: building geometry, dimensions and characteristics of the building envelope, the radiation received by each surface and temperature evolution. As the percentage of the walls that are in contact with other buildings has been obtained, a very precise definition of the window area is achieved, as well as a concrete identification of which walls are in contact with the exterior or not, and therefore, the corresponding transmittances that are assigned to them.

The calculation process is followed as described in the standard, except for the modification of the general thermal demand equation, where the term that represents the monthly temperature difference has been replaced by the HDD/CDD. In this way, the estimation of the heating and cooling needs throughout the year is more accurate because it takes every day's needs into account. The total heat transfer by transmission is then calculated as expressed in equations (1) and (2), as presented in the standard and BuiltE models, respectively. The same approach has been made in the rest of the thermal demand components.

$$Q_{tr;H\!/_{C};m} = \left(\left(H_{tr;H\!/_{C};m} + H_{gr;H\!/_{C};m} \right) * \left(\theta_{int;calc;m} - \theta_{e;m} \right) \right) * \Delta t_m \qquad 1$$

$$Q_{tr;H\!/_{C};m} = \left(H_{tr;H\!/_{C};m} + H_{gr;H\!/_{C};m} \right) * DD_{H\!/_{C};m} \qquad 2$$

Where $Q_{tr;H\!/_{C};m}$ represents the total heat transfer by transmission for heating and cooling, respectively, for each month (m), in kWh; $H_{tr;H\!/_{C};m}$, represents the overall heat transfer coefficient for all building elements except ground, in kW/°C; $H_{gr;H\!/_{C};m}$ represents the heat transfer coefficient for elements in contact with the ground, in kW/°C; $\theta_{int;calc;m}$ represents the calculation of the thermal comfort temperature for the zone, in °C;

Table 1

Constructive characteristics from the buildings selected for the validation.

id	Cadastre Reference	Conditioned area (m^2)	TABULA archetype	Construction year	U wall W/(m2°C)	U roof W/(m2°C)	U floor W/(m2°C)	U windows W/(m2°C)	Air renovation 1/h	Air Infiltration 1/h
1	8826801YJ2782F	2849	MFH-3	1960	2.94	1.67	1.26	5.7	0.4	0.4
2	8723806YJ2782D	1282	AB-4	1970	1.33	1.92	1.72	5.7	0.4	0.4
3	8823114YJ2782D	5137	AB-5	2001	0.6	0.61	2.16	3.37	0.4	0.1
4	8823107YJ2782D	1173	MFH-4	1972	1.64	1.61	0.91	5.7	0.4	0.4
5	8823101YJ2782D	6224	AB-4	1973	1.33	1.92	1.72	5.7	0.4	0.4
6	8723102YJ2782D	2721	AB-5	2001	0.6	0.61	2.16	3.37	0.4	0.1

$\theta_{e;m}$ represents the average external temperature for each month, in °C; Δt_m is the duration of the month, in hours; and $DD_{H/C;m}$ accounts for the heating/cooling degree-days, and it is the number of days per month with needs for heating and cooling, which must be converted to °C*hour.

$H_{tr;H/C;m}$ refers to the envelope elements and is divided into walls in contact with air, walls in contact with other buildings, windows and thermal bridges. Each of these elements has different constructive properties and accordingly, has a different heat transfer coefficient assigned.

Walls in contact with other buildings and the floor have a temperature adjustment correction. Resistances have been added at the end of the heat transfer to take this effect into account. The resulting formula is:

$$U_{eff;i} = \frac{b_i}{\frac{1}{U_{w;i}} + R_{add;i}} \tag{3}$$

Where $U_{eff;i}$ is the final heat transfer coefficient considered for the element i, b_i is the adjustment factor due to soil, $U_{w;i}$ is the thermal heat transfer of the constructive element i and $R_{add;i}$ is an additional thermal resistance included due to unheated space bordering the construction element. For walls in contact with other buildings, b_i has been considered as 1 and $R_{add;i}$ as 0.3. For the elements in contact with the ground, the values were 0.5 and 0, respectively [44].

The dynamic effects are taken into account by correction factors, which are different for heating and cooling. The heating and cooling thermal demand for each month, m, is calculated as follows:

$$Q_{H;m} = Q_{ht;H;m} - \eta_{gn;H;m} * Q_{gn;H;m} \tag{4}$$

$$Q_{C;m} = Q_{gn;C;m} - \eta_{ht;C;m} * Q_{ht;C;m} \tag{5}$$

Where $Q_{ht;H/C;m}$ is the total heat transfer for heating/cooling in the month m. Which is the sum of the transmission and ventilation components. $Q_{gn;H/C;m}$ is the total heat gains for heating/cooling. This term is composed of the internal and solar gains. $\eta_{gn;H;m}$ and $\eta_{ht;C;m}$ are the dimensionless factors applied to the gains in heating and to the heat transfer component in cooling mode. The dimensionless factors η include in the results of the thermal demand the effect of the buildings inertia. The calculation for the heating and cooling factor can be consulted in the standard [13].

3.2. *Model validation*

In the absence of real data, a comprehensive modelling of the energy performance of six buildings was carried out as a reference to validate BuiltE. For the reference models, the Design Builder (DB) software has been used, which makes use of the Energy + calculation engine (Fig. 2). The six buildings were then simulated with BuiltE, using the same information for all the matching inputs (constructive characteristics, air changes, projected shadows, envelope irradiation …). The information of the buildings and constructive typology is shown in Table 1. The selected buildings belong to different construction periods between 1960 and 2000 from the Algirós district (cadastre reference is provided in the table) and are representative of the district building stock. The aim of the validation is to compare the results of both simulations and to see if the one performed with BuiltE, which is much faster to prepare and compute, obtains the same results as the one performed with DB, with hourly or sub-hourly timestep dynamic simulations and a powerful calculation engine, but slower computation.

Therefore, the annual thermal demand for heating and cooling calculated with BuiltE was compared to the results obtained with DB, as the aim of BuiltE is to estimate the annual thermal demand of a great number of buildings in a faster way.

3.3. *Case study application*

BuiltE represents a tool to assess the thermal behaviour of different buildings or districts under different scenarios. Therefore, it is possible to propose optimal solutions in order to reduce the thermal demand and, therefore, the energy consumption. In this research, an example of an application of the model is presented. In addition to this, several future scenarios have been proposed to estimate the possible evolution of this thermal demand and, subsequently, to propose different solutions to mitigate the increase of the thermal demand.

3.3.1. *Climate change scenarios*

Using degree-days to quantify the demand needs of the climate file has the advantage of facilitating the evaluation of future scenarios. In this regard, the model is intended to enable assessing how changes in climate will affect the demand of buildings. In this respect, several authors have studied the way to propose global warming scenarios [45].

In the field of climate change scenarios, the World Climate Research Programme created the Coupled Model Intercomparison Project (CMIP), which is currently in its 6th phase [46]. In this project, a set of different climate scenarios were developed according to the sixth Intergovernmental Panel on Climate Change report (IPCC AR6). These scenarios are called “shared socioeconomic pathways (SSPs)" [47] and represent different possible climate change scenarios, supposing various socioeconomic developments in the world states, with consequently different atmospheric greenhouse gas concentration pathways. The SSPs are numbered from SSP1 to SSP5, where SSP1 represents a sustainable “green” pathway to a sustainable world and SSP5 represents a fossil-fuelled development. The consequences of the different pathways are estimated with different increases in the radiative forcing (because of the anthropogenic greenhouse gas effect) and therefore, a different temperature evolution.

In this case study, three of these scenarios were considered.

- SSP1-1.9: a scenario in which an additional radiative forcing of 1.9 W/m2 by the year 2100 is supposed, then leading to an increase in the average temperature of 0.75 °C in Spain.
- SSP3-7.0: an additional radiative forcing of 7.0 W/m2 by the year 2100 and an increase in the average temperature of 3.8 °C in Spain.
- SSP5-8.5: an additional radiative forcing of 8.5 W/m2 by the year 2100 and an increase in the average temperature of 4.97 °C in Spain.

In addition, different decades were also considered for the thermal

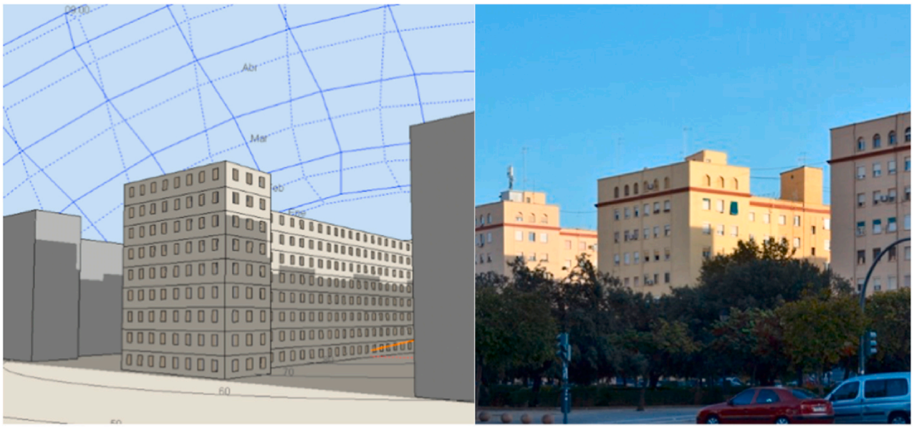

Fig. 2. Visual comparison between Design Builder model and the real building.

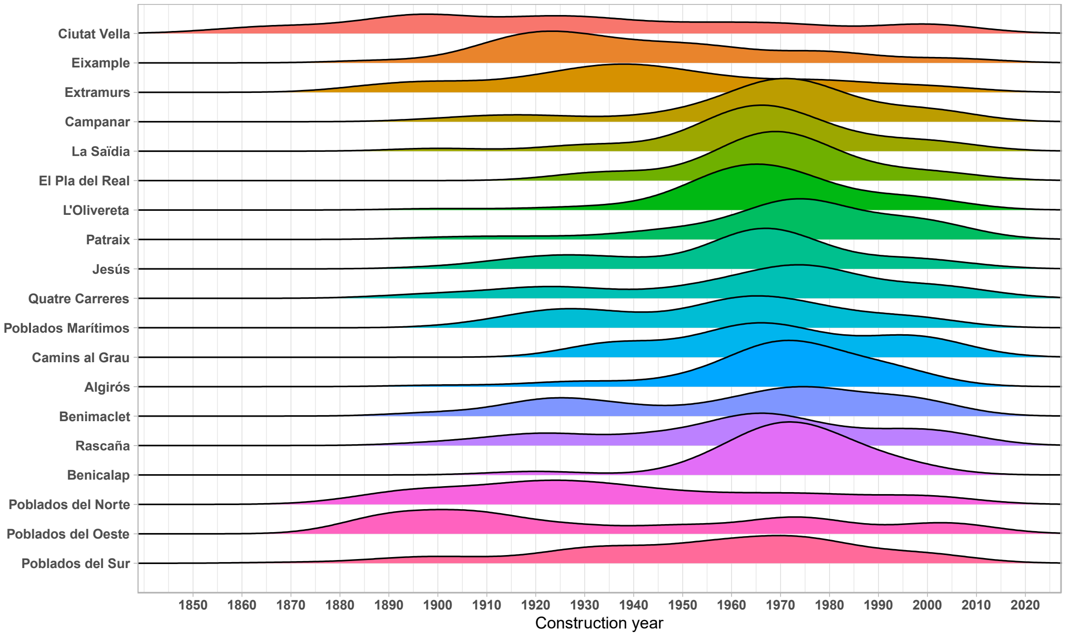

Fig. 3. Distribution of buildings by the period of construction for the 19 districts of València.

demand assessment: 2011–2020, 2051–2060 and 2091–2100. These scenarios represent, respectively, a base case, the decade chosen by the European decarbonisation objectives, and the final projection of the Coupled Model Intercomparison Project. For the simulations, data of the estimated average temperature increase on each month for the different scenarios and decades was used, extracted from the Climate Change Knowledge Portal of the World Bank Group [48]. This temperature evolution is considered by modifying the weather file according to the temperature increase estimation.

3.3.2. Building selection

The city of València has approximately 36,000 buildings [39] spread over 19 districts [49]. 54 buildings have been selected in each district to study a sample that represent the behaviour of the city, for a total of 1026 buildings. The choice of the buildings to be studied was based on the period of construction. Fig. 3 shows the distribution for each of the districts of the city of València. The sample for each district was selected according to the distribution of buildings for each period of construction in each district [39].

As can be seen in Fig. 3, there are districts like Benicalap that were mainly built in the period 1950–1990, while other districts like Poblados del Sur have been built over a much wider period. Considering this distribution of construction periods for the 19 districts in València, the selected building cases can be consulted in Fig. 4. This graph shows the number of buildings selected per year of construction, aggregated in groups of 5 years. The figure shows to which district these buildings belong, adding the number of buildings per construction period in each district. Most buildings were constructed in the period between 1960 and 1980, followed by the period between 1990 and 2010. This information indicates that the vast majority of buildings in the city are over 50 years old. As it is a representative sample, the results obtained could be extrapolated to the whole city.

A visual representation of the 1026 buildings studied can be found in Fig. 5. The cases are geolocated on the map of the city of València and show to which district they belong.

4. Results and discussion

This chapter first presents the results of the validation process, comparing the results of the BuiltE model with those of the Design Builder on the sample of six buildings. Subsequently, the results of the case study and different analyses related to the constructive

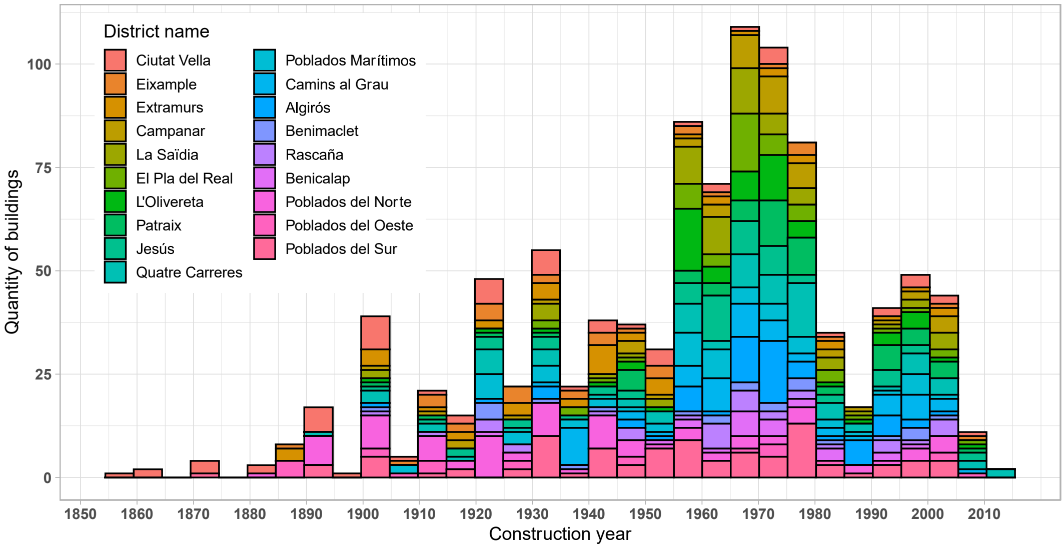

Fig. 4. Buildings studied in the present research, grouped by construction year and district.

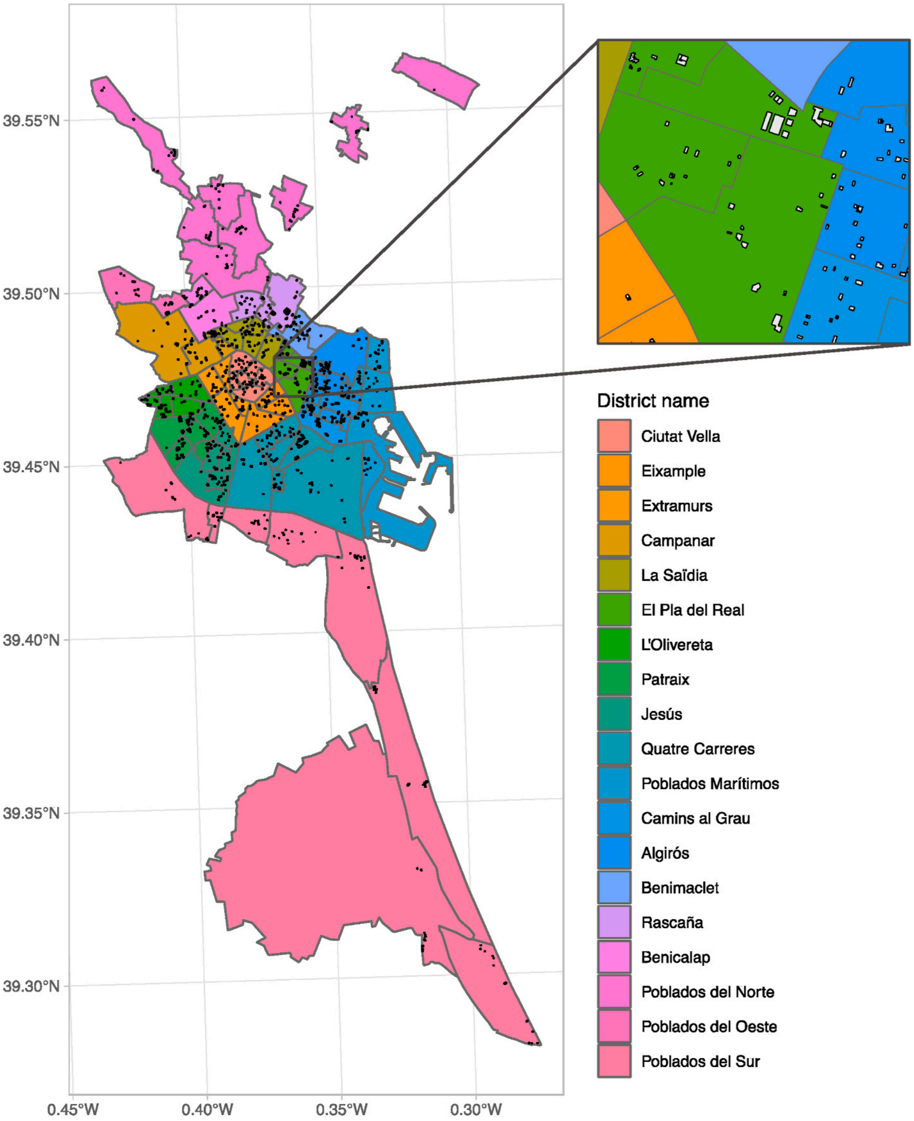

Fig. 5. Spatial representation of the studied buildings in the research, located in the city of València. The X and Y axes show the geographical coordinates.

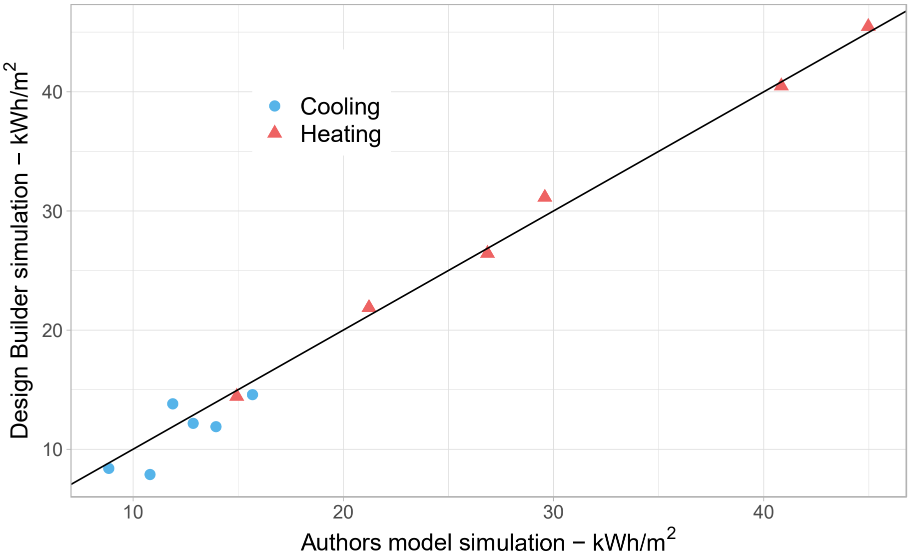

Fig. 6. Normalised heating and cooling demand for the BuiltE and Design Builder models.

Table 2
Validation results for author's and Design Builder models.

Building id	Heating demand (kWh/m^2)		Cooling demand (kWh/m^2)	
	BuiltE	Design Builder model	BuiltE	Design Builder model
1	29.58	31.14	12.86	12.18
2	40.83	40.48	15.68	14.58
3	14.93	14.43	10.81	7.88
4	44.97	45.46	11.89	13.82
5	26.86	26.43	8.85	8.40
6	21.22	21.88	13.95	11.90

characteristics of the buildings are presented to illustrate the utility of the proposed methodology.

4.1. Model validation

The information concerning each simulated building can be found in Table 2, with the simulated thermal demand for heating and cooling for each building and each model (Design Builder and BuiltE). Fig. 6 shows the results of the demand for each of the buildings for both heating and cooling. It has been normalised according to the conditioned area to facilitate the comparison of the results.

As can be seen in the table and the figure, the results for the heating are almost the same for both models for all the range of values. The deviation for the cooling cases is larger than for the heating cases. Hence, for small values of cooling demand, the results have to be considered carefully, as commented by various authors when using the degree-day approach [36]. In this context, the analysis of the model

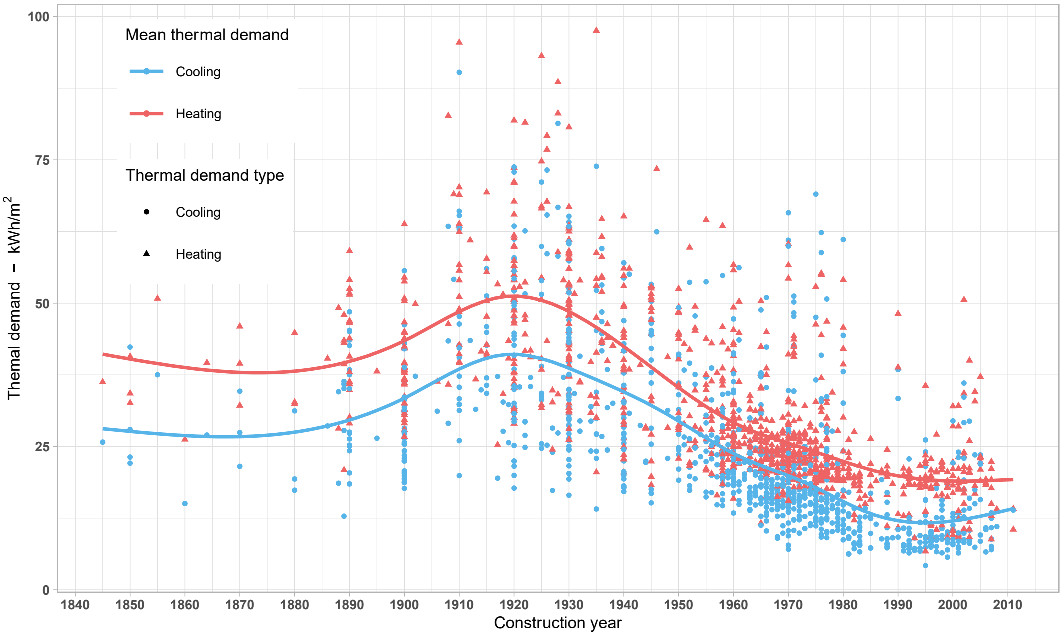

Fig. 7. Normalised heating and cooling demand related to the construction year.

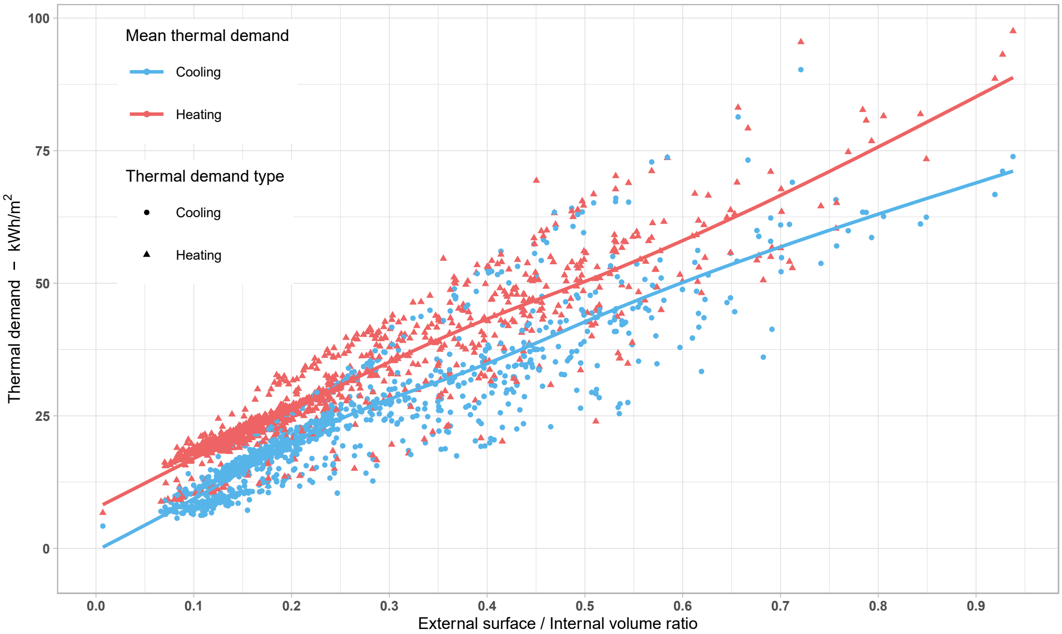

Fig. 8. Normalised heating and cooling demand related to the S/V ratio.

behaviour for cooling will be extended in detail in further steps of the research. Finally, aggregating the results of the simulations, the total demand obtained with the model presented by BuiltE and the Design Builder model is 952 and 933 MWh, respectively, which gives a difference in the aggregate of less than 2% [36].According to the results obtained, it can be concluded that the model predicts heating and cooling demand within an acceptable error range.

4.2. Case study application

The case study computes 1026 buildings spread throughout the city of València. All the buildings have been simulated with the information of the base case and, afterwards, with advanced retrofitting, as proposed by TABULA [26]. When analysing the year of construction of the buildings studied, it is observed that 75% of the buildings were built before 1975, meaning that the housing stock is quite old. Starting with the results of the current status, (without retrofitting), the total yearly demand of the studied sample reaches 102.75 GWh, 61.79 GWh for heating and 40.96 GWh for cooling.

4.2.1. Results analysis related to characteristic parameters

In this section, the results will be presented in terms of several characteristic parameters of the buildings. Firstly, the yearly thermal demand for heating and cooling as a function of the year of construction is presented in Fig. 7. The demand has been normalised by the conditioned area of each building. Thanks to this graph, it is possible to understand which buildings and typologies have the worst thermal performance. Trend lines representing the average values per year are

Fig. 9. Buildings thermal demand reduction due to retrofitting by TABULA construction archetypes.

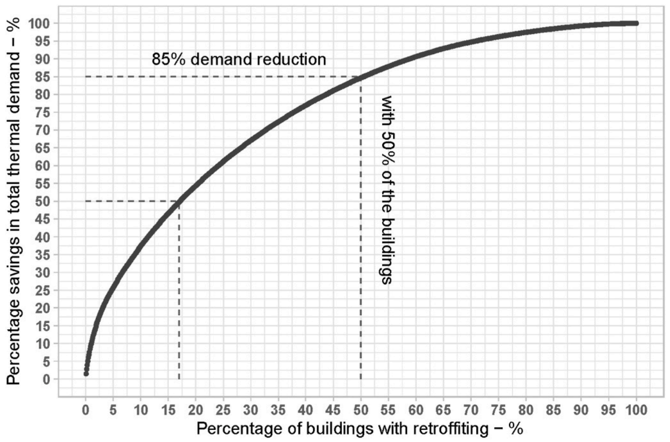

Fig. 10. Estimation of the aggregated thermal demand reduction based on a prioritisation of the buildings to be retrofitted.

presented in the results. These lines represent the average value for each building year. As the figure shows, buildings from the period 1900–1940 seem to show the poorest performance, while new buildings from the period 1990 onwards have the best performance. However, there is a wide dispersion of buildings profiles, in which the amount of buildings is greater in periods when building quality standards were very lax or non-existent: up to 1980. This dispersion of performances for each period is explained by several factors: constructive factors such as the surface-to-volume ratio, the type of construction: AB, MFH, SFH … The solar radiation reaching the building, etc. Therefore, the year of construction does not seem to be a good proxy to estimate the energy performance of the building.

A more promising parameter for estimating the energy performance of a building is the ratio between the external surface of the building that is not in contact with another construction and the internal volume to be air-conditioned (the S/V ratio). Authors such as [26] have used building data combined with TABULA typologies demand assessment, and a strong linear relationship between demand and S/V ratio was found. In Fig. 8, it can be concluded that this parameter presents a good correlation for predicting and can be used for the elaboration of simple correlations to evaluate the housing stock with easily obtainable data. As in the previous graph, the trend lines representing the average for each S/V value have been plotted. Moreover, the plot shows a better energy performance the lower the S/V ratio (because the heat exchange decreases), and also a lower dispersion (less influenced by factors such as building typology, radiation received, year of construction, etc.). Hence, the S/V ratio is more accurate as a proxy of the energy demand as the S/V ratio is lower. It is interesting to note that no significantly different behaviour was found in the curved plots for heat demand and cooling demand.

For the 1026 buildings, the base case and an advanced retrofit case have been simulated. Constructive information for both scenarios has been collected from TABULA, as explained in the method section. Fig. 9 represents, for each year of construction, the percentage of yearly energy demand savings (heating and cooling) when the building is retrofitted.

Each building has a colour code indicating the type of construction (AB - Apartment block, SFH - Single family house, MFH - Multi-family house, TH - Terraced house) and the period (1 for years 0–1900, 2 for 1901–1936, 3 for 1937–1959, 4 for 1960–1979, 5 for 1980–2006, 6 from 2007), according to TABULA.

Older buildings have a construction date in the cadastre that is not real, as it corresponds to when they were included. Therefore, they tend to be grouped in the same year (the vertical coincidence of points in the graph), but this does not alter the discussion of the results. As can be seen, there is a clear difference in the savings between the periods before and after 1980, i.e. the older the building the more energy can be saved by retrofitting. However, the wide dispersion of performances reappears. In addition, in general, single family houses (SFH) from the period 1901 to 1936 are the buildings with the worst energy quality, i.e. the ones that improve the most with retrofitting, 66.7% on average. Furthermore, apartment blocks (AB) and terraced houses (TH) improve less with retrofitting, on average. Finally, although buildings from period 6 (1981 onwards) have less room for improvement because they were already quite energy efficient, savings of between 5% and 15% of the annual energy demand can be achieved. Therefore, this presentation of the results can facilitate the selection of buildings and areas for retrofitting. Once known each building's potential for renovation, the next issue might be deciding which buildings to begin retrofitting and whether it is appropriate to prioritise these initiatives.

All the cases have been sorted from the top to the lowest based on the demand (kWh) that may be decreased by retrofitting that building in order to provide answers to these concerns. Subsequently, the improvement has been accumulated according to this order. The results of this analysis can be consulted in Fig. 10. By retrofitting 17% of the buildings with the highest energy saving potential, 50% of the maximum reduction in the buildings' thermal demand is achieved. In addition, savings potential of 85% can be achieved by retrofitting 50% of the buildings.

This analysis, when applied to the whole city, would enable us to know how many buildings should be retrofitted in the municipality to achieve the 2030 and 2050 targets for the residential sector. It is clear at this point that a correct prioritisation of the actions in the residential sector can make a difference in achieving the city's objectives of sustainable development.

4.2.2. *Climate change scenarios assessment*

As a final result of the study, the sample of buildings has been simulated for several scenarios from the coupled model intercomparison project 6th phase, as described in section 3.3.1 of the methodology. Table 3 shows the results for each of the scenarios, as well as the differentiation between heating and cooling thermal demand and total thermal demand. It also shows the average temperature increase (ΔT_{avg}) for each scenario. The base case used for the study is the one belonging to SSP1-1.9. In this way, the information in the climate file has been adjusted to the current temperature increase.

From the results obtained, it can be concluded that.

- In the scenarios with higher temperature increase, the heat demand decreases while the cooling demand acquires greater weight, even surpassing the heat demand.

Table 3

Thermal demand results based on the climate change scenarios selected.

	SSP1-1.9			ssp 3-7.0		ssp 5-8.5		
	2011–2020	2051–2060	2091–2100	2051–2060	2091–2100	2051–2060	2091–2100	
ΔT_{avg}	0.32	1.01	0.75	1.76	3.80	2.31	4.97	°C
Heating	61.79	54.22	56.49	42.86	23.57	37.70	14.19	GWh
Cooling	40.96	51.20	45.83	61.85	91.04	69.53	111.28	GWh
Total	102.75	105.42	102.33	104.71	114.60	107.23	125.47	GWh

- Total demand remains practically constant for all scenarios, except for the most restrictive ones where total demand increases. It reaches a 25% increase for the SSP5-8.5 projection for the decade 2090–2100.

It is well known that much of the cooling demand is not met in Mediterranean climates [14]. But a considerable increase in the earth's temperature can mean that the demand for cooling will grow to dangerous levels, with increases of up to almost 300%. Extra cooling demand may lead to an increase in the percentage of demand, from 1.02% in scenario SSP1-1.9 (2051–2060) to almost 25% in scenario SSP5-8.5 (2091–2100). This effect, together with others such as the heat Island effect, or heat waves, could lead to an increase in final consumption that is much larger than the demand forecast. This is why the study of adaptation and mitigation to climate change in warm climates such as the Mediterranean will be crucial in the coming years.

5. Conclusions

The development of a methodology for estimating the thermal demand of large areas, such as cities or districts, has been the main aim of this research. The authors have taken advantage of the benefits of GIS technology, energy databases, cadastre information and local weather conditions while at the same time allowing an agile and complete simulation. For the definition of the buildings, different building archetypes were used, extracted from the TABULA database, while a degree-days-based model was used to evaluate the thermal demand. This model follows the European standard 52,016. And, as pointed out by many authors, special attention was paid to a correct evaluation of the irradiation on the building, considering separately the different construction surfaces. Another aim of BuiltE was to connect it with energy demand forecasting, such as assessing the effect of retrofitting on buildings as well as the effects of climate change.

Subsequently, a validation of 6 buildings was carried out by comparing BuiltE with models created using Design Builder software. The results show that the model achieves reasonably accurate results, both individually and aggregated, while it is more agile than the developed model.

Finally, although this methodology could be applied to any city, provided that the information is available or can be adapted, a particular case study in a European Mediterranean city is carried out to illustrate its application. For this purpose, a sample of buildings was taken, selected from the different districts of the city of València and the proposed model was applied. A total of 1026 buildings distributed across the 19 districts that make up the city were simulated. How the thermal demand behaves in relation to various parameters such as: the year of construction, air-conditioned area, compactness ratio and the construction typology (based on the TABULA project) has been studied. Also, the potential for refurbishment has been analysed by year of construction and typology. It shows that buildings constructed before 1970 can save, on average, more than 40% of their thermal demand with an advanced refurbishment. Thus, a prioritisation of the buildings to be refurbished has been presented, indicating that refurbishing 17% of the building stock would achieve a saving of 50% of the total thermal demand of the sample.

The aim of this proposal of a planning tool is to enable urban planners to know which are the most interesting areas, typologies and/or buildings to reduce thermal demand in order to implement actions to reduce the carbon footprint of the city and improve the comfort level of its citizens. It should be borne in mind that climate change will radically change the current climate and, therefore, current thermal needs. In fact, based on the simulations presented in the assessment of future scenarios, average rises of 3–5 °C in cities will lead to increases in cooling demand of 200–300%. These increases mean that previously unmet demand will need to be met. A radical change in the strategies to combat thermal demand would be needed.

Although the research objectives were achieved, some concerns about the sources of information and the limitations of the study need to be understood in order to replicate or further develop the methodology. Firstly, the cadastral information presents several mismatches among its data and the real situations, which had to be cleared. The same cautionary task had to be carried out for LiDAR and TABULA data.

Moreover, the study had to assume some limitations, which will be tackled in the coming research. For example, the same microclimate was assigned to all building locations. A new line of research is currently addressing how to adapt the weather files to the location of each building. The aim is to distinguish the most interesting buildings for retrofitting not only based on their characteristics but also on their surroundings. Another limitation of the study is the lack of information for several buildings due to imperfect databases. In this study, those few buildings were substituted, but another line of research is currently focused on predicting the thermal behaviour of those buildings with easily obtainable building parameters. In fact, the whole methodology could be optimised, i.e. made more agile, based on the results of this line.

- Finally, the work carried out has allowed to identify other research questions that are raised as future lines of research that will complete the methodology. Among the most important of these, a research line will focus on the difference between cooling demand and cooling consumption due to the widespread lack of equipment in the case study, Valencia, representative of a number of southern cities in scenarios of climate change. In addition, the prioritisation of buildings to apply energy improvement actions should be improved by defining a retrofitting cost for each of the typologies used in the research, among other parameters.

Author contribution

Prades-Gil, C., Conceptualization; Data curation; Methodology; Investigation; Software; Validation; Visualization; Roles/Writing - original draft; Viana-Fons, J.D, Conceptualization; Investigation; Methodology; Software; Masip, X, Conceptualization; Writing – review & editing.Cazorla-Marín, A., Supervision; Methodology; Writing – review & editing.Goméz-Navarro, T.1, Supervision; Writing – review & editing.

For transparency, we encourage authors to submit an author statement file outlining their individual contributions to the paper using the relevant CRediT roles: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.

Authorship statements should be formatted with the names of authors first and CRediT role(s) following. More details and an example.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work has been possible thanks to the support of the Cátedra de Transición Energética Urbana, UPV - Las Naves & València Clima i Energia, and Grupo ImpactE planificación Urbana S.L.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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