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Assessment of the thermal energy demand of Spain's residential building stock under future climate scenarios

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ABSTRACT

This study uses a bottom-up model of over 200,000 cases to assess Spain`s residential building stock under future climate scenarios for the years 2050 and 2080 (SSP1-2.6 and SSP5-8.5), aiming to inform the critical need for climate adaptation planning in the building sector. The novelty of our approach lies in the simultaneous comparison of real, sensible energy demand (free-running simulation) against the official, restrictive energy certification procedure, an approach not previously performed for the entire Spanish stock.

The analysis yields two major contributions that challenge current policy. First, we observe a significant shift in energy use: cooling demand surges—doubling by 2080 in vulnerable areas—while heating demand declines, resulting in a net change to total final energy demand of less than 4% across all scenarios. Second, Spain's current energy certification procedure underestimates 2022 total demand by approximately 5%, primarily by underestimating cooling needs by 18%, a discrepancy that will worsen with climate change. As a result, it fails to capture real discomfort, especially in summer.

A key policy insight is that retrofitting the entire stock to current building code (CTE) U-values would halve total demand and cap future cooling at today's levels. The Mediterranean region, with half the national stock, is most at risk, facing cooling demand increases of up to 138%. Therefore, a national strategy must prioritize retrofitting the oldest single-family homes in southern Mediterranean areas.

1. Introduction

Buildings play a crucial role in achieving global decarbonization targets. Socioeconomic and environmental factors, notably climate, are critical factors in achieving these goals [1]. In Europe, buildings are responsible for around 40% of the final energy consumption and 36% of CO2 emissions [2]. Given the sector's role in achieving the EU's decarbonisation targets by 2050, the European Commission has expanded the scope of the current Emission Trading System (ETS) to target the building sector. This policy instrument enables ample financial resources obtained from auctions of CO2 allowances to accelerate the sector's transformation within the Social and Climate Fund [3].

On the same basis, the Energy Performance of Buildings Directive (EPBD) (EU/2024/1275) aims to promote a highly energy-efficient and decarbonised building stock by 2050. This ambition must focus on existing buildings. One-third (35%) of the EU building stock is over 50 years old, more than 40% of the building stock was built before 1960, and 90% before 1990. According to current building standards, almost 75% of it is energy inefficient. [4]. As a result, renovating both public and private buildings is a key initiative to drive energy efficiency in the sector and deliver on the objectives outlined in the European Green Deal [5].

A carbon–neutral building stock will only be achieved by combining demand- and supply-side measures. Therefore, buildings, under the principle of energy efficiency, must be designed to minimize their energy needs while incorporating clean and efficient supply systems that run on renewable sources or clean energy fuels. This is particularly relevant for heating and cooling, as well as hot water demands, since they represent 80% of energy consumption in buildings [6], and two-thirds of such consumption still comes from fossil fuels.

However, when it comes to renovation, the lifespan of buildings and renovation measures, especially those involving deep renovation of the building envelope, can extend up to 50 years [7]. This fact, in

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Nomenclature

CDD	Cooling Degree Days
CDH	Cooling Degree Hours
CTE	Código Técnico de la Edificación
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ETS	Emission Trading System
HDD	Heating Degree Days
ktoe	kilotonne of oil equivalent
LMFH	Large multi-family house
MFH	Multi-family house
RCP	Representative Concentration Pathways
SFH	Single-family house
SSP	Shared Socioeconomic Pathways
TMY	Typical Meteorological Year
TWh	Terawatt-hour
U	Thermal transmittance (W/m^2-K)

combination with rapid climate change, could affect the long-term effectiveness of measures and lead to investment lock-in effects. Therefore, climate change could potentially modify the optimal ways to renovate our building stock, and its impact must be carefully assessed.

In this work, a bottom-up model is developed for the Spanish residential building stock. In total, 34,800 dwellings are modelled, including typology, construction year cohort, orientation, location, and historical climate conditions. This bottom-up model is evaluated under both the national energy certification procedure, which limits the periods of use of the heating and cooling system to specific months of the year, and a free simulation approach that allows the systems to supply heating and cooling needs at any time throughout the year. Both methods are assessed under climate scenarios, assuming a complete building stock envelope renovation as prescribed by the current national regulation in Spain, and a building stock as it currently exists.

In total, 208,800 cases are assessed, including building type, year cohort, orientation, climatic scenarios, simulation modes, and climatic zones per province. This comprehensive analysis allows us to evaluate, first, the adequacy of the current energy certification scheme for the entire national residential building stock, and second, the impact of future projections of the heating and cooling demand under different climate scenarios. This analysis lays the groundwork for exploring how the evolution of thermal demand could stress power sector infrastructure, assuming a significant adoption of heat pumps.

1.1. Literature review

The energy needs of building stocks have been at the centre of the research community, even more so in light of the rapid climate change trends observed over the past few years. Some authors have already assessed the impact of climate change on building and the possible impact on energy policy regulation. For instance, D'Agostino et al. [8], assessed specific locations across Europe for different climatic scenarios, concluding that total energy demand will be reduced in colder climates and increased in warmer climates, and that the European regulation is not adequately prepared to face climate change. This critical finding on regulatory inadequacy is a theme supported by other national studies, such as the framework presented in [9] that assesses climate impact using a dynamic building simulation model to evaluate the evolution of energy demand for the Belgian building stock by 2050 and 2100. They estimate that cooling demand will increase significantly in all scenarios assessed.

To address this challenge, researchers have increasingly relied on detailed bottom-up modelling approaches to accurately capture the impact of climate change at the building level. Studies like that of Kinay et al. [10] on Finland found that heating demand will be significantly reduced by half in 2050. Similarly, Nik and Sasic [11] focused on assessing the performance of the building stock in Stockholm, based on a sample of buildings, and discussing cooling strategies to mitigate climate change. Extending this scope, other works such as Wang et al. [12] follow a broader scope, incorporating not only the effect of climate but also population evolution and power system decarbonization trends to understand energy use in buildings. The same approach is followed by Sandberg et al. in [13] whose focus was on predicting the evolution of building stocks for eleven countries, with an emphasis on socioeconomic indicators and the probability of building renovation and demolition.

Building on the need for detailed analysis, other works confirm that high-resolution bottom-up models are essential for robust energy planning and decision-making. Regarding modelling approaches, Nägeli et al. [14] developed a bottom-up building stock model based on an agent-based modelling approach, which was calibrated using historical data. Furthermore, the strategic utility of this methodology is evident in studies like Penaka et al. [15] who have used the same bottom-up approach to improve retrofit decision-making.

From a policy perspective, research has focused on the adequacy of policy initiatives to achieve climate targets. For instance, Vivier et al. [16] assessed policy combinations for heating supply-side complemented with supply-side decarbonization efforts. Their work concluded that current policy initiatives fall short of achieving targets, demanding stronger interventions.

In our work, we start by questioning whether policymakers have an accurate overview of thermal energy demand in buildings, Specifically, we aim to examine whether inputs based on the current energy certification scheme are providing reliable information on real energy demand in buildings to policymakers, especially in a climatic context where energy demand is rapidly changing.

The general trend of shifting energy needs towards cooling is particularly acute in the Mediterranean basin, which has been consistently identified as a highly vulnerable region. This regional evidence is crucial for informing climate adaptation policy in Spain. For instance, Salata et al. in [17] reported a notable and almost exponential increase in the demand for cooling residential buildings in Italy, a nearby country with a similar climatic profile. Their analysis using Cooling Degree Hours (CDHs) shows that the median CDH in the most recent five-year period (2016–2022) was four times that of the early 2000 s. They further highlight that a combination of CDHs and demographic data can effectively prioritize interventions for upgrading the existing building stock, a methodology that strongly supports our policy recommendation for targeted retrofitting in the most densely populated, vulnerable Spanish regions.

Furthermore, studies utilizing climate models to assess not only mean changes but also extremesdemonstrate the severity of future impacts. Larsen et al. in [18], conducted a comprehensive European analysis and confirmed the general trend of decreased heating and increased cooling demands. Crucially, they found that while the average increase in cooling demand across Europe is moderate (change ratios of 1.25–1.5), the average ratio for extreme maximum cooling demands reaches 2.76 (a 176% increase). This finding aligns directly with our key assumption that the greatest risk lies in the surge of peak cooling demand, supporting our projection of a doubling of demand in vulnerable Spanish areas.

Beyond energy figures, the literature also corroborates issues concerning thermal comfort under climate change context. Chetouni et al. [19], analyse modular single-family homes in Morocco (a climate-adjacent context), and project a significant increase in cooling demand (up to 54.5% by 2050 under RCP 8.5) and an increase in overheat hours. They explicitly warn that extreme heatwave events will cause non-liveable indoor temperatures that could persist for several days. This reinforces the need to assess the adequacy of Spain's current energy certification procedure to capture real discomfort. The analysis of monitored Danish apartments by Tognon et al. [20] also highlights the current challenge, showing that conditions of thermal discomfort already arose in modern, cold-climate apartments where occupants kept windows closed during the 2023 summer, further underlining the global emergence of cooling-related comfort issues.

Within the Spanish context, López-Ochoa et al. [21] studied the impact of climate on a specific building segment in a particular geographical location. For the region assessed, authors concluded that total energy demand will be reduced as cooling energy demand increases less than heating energy demand decreases. Rincón et al. [22] focused on specific solutions for the office building stock in Spain. Tackling the effect of climate change, Díaz-López et al. [23] explored the evolution of climatic zones for buildings under the RCP 4.5 and RCP 8.5 scenarios, which would imply variations in 90% of climatic zones and, thus, the reassessment of building envelope requirements. The same authors have explored optimal U-values for the external wall of the provincial capital in Spain. They based the analysis on heating degree days (HDD) and cooling degree days (CDD). They compared the optimal U-values with the maximum U-values required by the Spanish building thermal regulation [24]. The authors of this present work already assessed the energy demand past-trends based on the bottom-up approach proposed in this work but for some specific locations representative of climatic zones in Spain [25].

Despite these foundational contributions, a critical gap remains in the Spanish context that hinders effective national climate adaptation policy. The existing literature either focuses on specific, localized building segments, technical solutions, or changes in climatic zones. Crucially, no previous national-scale effort has simultaneously employed a high-resolution, bottom-up model to: 1) Quantify the severe regulatory flaw by comparing real, sensible energy demand (including discomfort) against the official Spanish energy certification procedure for the entire residential building stock, and 2) Provide a clear, actionable policy roadmap that identifies the most vulnerable segment (by typology and geography) for prioritized national retrofitting investment.

1.2. Novelty and motivation

The evolution of energy demand in building stocks under climate change is a well-researched area. However, a critical gap persists between the overview that policymakers rely on for decision-making and the actual, climate-resilient performance of the stock. While most studies focus on projecting future demand, few explicitly assess whether the official frameworks used to measure and regulate that demand remain valid under changing climatic conditions.

This work directly addresses that gap by evaluating Spain's building energy certification scheme, which establishes operational conditions, such as predefined winter and summer periods, that may be outdated due to climate change. We uniquely combine three critical elements:

- An official policymaker's perspective: our analysis is grounded in the most comprehensive and official national residential building stock dataset dynamically simulated using CERMA, an official software tool mandated for energy certification. This replicates the exact methodology that underpins current policy.
- A reality check through free simulation: we contrast the restrictive assumptions of the official "certification mode" (fixed seasonal periods and thermostat schedules) with a "free simulation mode" that allows quantifying heating or cooling demand at any time of the year. This exposes the methodological limitations in capturing real energy needs and occupant discomfort.
- A long-term climate resilience test: we evaluate both the current stock and a fully renovated stock (meeting current code standards) to future climate scenarios (SSP1-2.6 and SSP5-8.5 for 2050 and 2080). This test not only examines the adequacy of the certification procedure but also the long-term effectiveness of the mandated building envelope standards (CTE U-values) over a renovation's typical 50-year lifespan.

Therefore, our primary motivation is to critically assess the assumptions underlying the national decarbonisation strategy based on an officially recognised simulation tool. We ask: does the current certification accurately reflect present and future energy demands? Are the retrofit standards we are promoting today robust against the climate of tomorrow? By answering these questions, we aim to provide evidence-based insights for policymakers to future-proof Spain's building energy policies, avoid lock-in effects from inadequate standards, and prioritise retrofit efforts where they are most urgently needed.

1.3. Paper structure

The paper is organised as follows: Section 2 outlines the methods, which detail the description of the climates used, the residential building stock characteristics, and the description of simulated cases. Section 3 presents the results and their discussion, and Section 4 summarises the conclusions drawn from this study, including policy recommendations.

2. Methods

Our study does not simply rely on a research-grade dynamic model (free-running simulation) to project future demand. Instead, the core of our methodological novelty lies in the simultaneous comparison of these projections against the results derived from the official Spanish Energy Certification procedure. This provides a unique and direct measure of policy inadequacy. By directly contrasting the results, we obtain quantitative evidence of the specific flaws present in the current policy tool—such as the underestimation of cooling demand—which are actively informing real-world decisions and investment planning. To do so, the proposed methods include characterising the residential building stock, defining climate scenarios, and building thermal modelling and simulation environments. In the following subsections, these three aspects are described in more detail.

2.1. National building stock set-up

To describe the national residential building stock, we have utilised the most recent and official dataset provided by the Spanish authority [26], combined with national statistics [27].

In [26], the Spanish residential building stock is broken down into three archetypes: single-family house (SFH), multi-family house (MFH) with three or fewer storeys, and large multi-family house (LMFH) with more than four storeys and the year cohort of construction; before 1940 (<40), between 1941 and 1960 (41–60), 1961 to 1980 (61–80), 1981 to 2007 (81–07), and 2008 to 2011 (08–11). Based on this classification and considering four possible main orientations (SN, NS, EW, WE), the stock is built based on 60 building units (i.e., LMFH 41–60, SN). Available information for each type includes all the parameters presented in Table 1.

To develop a bottom-up comprehensive national residential building stock it is necessary to quantify the number of each type of dwelling at municipality level. The province level is not sufficient since these entities may be exposed to different climate conditions. To provide readers with an example, the province of Granada in southern Spain encompasses six distinct climatic zones, ranging from a subtropical microclimate along the coast to subarctic locations in the high mountains that are part of the province.

To perform such breakdown, we rely on available official national statistics and made additional estimations. We start by computing the number of a certain type of dwelling and municipality size cohort retrieved from the National Statistics Office (Table 2).

Then, we assign the number of dwellings to the climatic zone by using information available for municipalities with more than 2000

Table 1
Example of a typology information for SFH built in 2008–2011 [26].

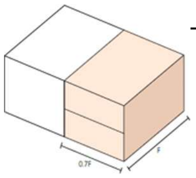
SFH 08–11				
	Average surface (m^2)	137.42	Envelope surfaces	Per dwelling
	Number of floors	2	Façade (m^2)	195.38
	Number of dwellings per building	1	Opaque façade (m^2)	119.36
	Ratio width/depth	0.7	Glazing surface (m^2)	18.55
	Width (m)	6.94	Dividing wall (adiabatic)	57,46
	Ratio dividing wall in contact with another dwelling	50%	Roof (m^2)	68.71
			Floor (m^2)	68.71

Table 2
Number of dwellings per municipality size cohort at province level for SFH built before 1940 (SFH < 40) (extract) [26].

SFH < 40	**Municipality population cohort**				
Province	<5,000	5,001–20,000	20,001–50,000	50,000<	**Total**
Araba/Álava	6,857	334		403	**7,594**
Albacete	13,002	2,097	3,512	811	**19,422**

inhabitants (Table 3).

For municipalities with fewer than 2000 inhabitants, we estimate the number of dwellings based on the average number of inhabitants per dwelling in municipalities with available information (more than 2000 inhabitants) in the province. The ratio of the number of inhabitants per dwelling of the province is assumed and then added to the cohort < 5000. By doing so, we estimate the number of dwellings per climatic zone and per municipality size cohort in the province. Last, these shares are applied to each typology (Table 2) obtaining the number of dwellings per typology and climatic zone.

The Spanish residential building stock consists of 22.89 million of dwellings classified into three types of buildings: single-family houses (SFH), multifamily houses up to 3 storeys (MFH) and large multifamily dwellings with more than 3 storeys (LMFH) and five-year cohorts (before 1940, between 1941 and 1960, 1961 to 1980, 1981 to 2007, and 2008 to 2011) [28]. In addition, the stock is distributed over 12 climatic zones (Fig. 1).

The total surface area reaches 2.35 billion m^2, which leads to an average surface area of 102.84 m^2. The LMFH is the most common type of construction and accounts for more than half of the national residential building stock (52.5%), followed by MFH (31.4%) and SFH (16.1%). In terms of climatic zones, C3 holds the largest share of the stock (22%) followed by C2 and B3 with a 11% share each. This is linked to the location of big cities in the country; Madrid (the largest city) and Zaragoza (the 5th largest city) fall under the climatic zone C3 while Barcelona (the 2nd largest city) falls under the C2. Looking across years, constructions periods 1960–80 and 1981–2007 attained almost three-quarter of the residential building stock — 35.1% and 38.7% respectively — which coincides with periods of relevant national economic growth.

Table 3
Number of dwellings per municipality above 2,000 inhabitants [27].

Municipality	Climatic Zone	Province	Postal Code	Number of dwellings
Alegría-Dulantzi	E1	01	01001	1251
Vitoria-Gasteiz	D1	01	01059	111,325

2.2. *Climatic zones*

The proposed approach considers the current definition of climatic zones regardless the potential impact of climate in the redefinition of new climate zones that could capture new energy needs as presented in [23]. As our main goal is to question the current understanding of policymakers regarding the energy needs of the residential building stock, we decided to keep current climatic zones which implies specific heat transfer coefficients requirements for the building envelope elements. The Spanish Technical Building Code (CTE) [29] sets out climatic zones across the territory to determine minimum building energy requirements and evaluate buildingś energy performance. These are defined based on climatic severity indices that are determined by the Cooling Degree Days (CDD) and Heating Degree Days (HDD) for each location [30]. Each climatic zone is defined by a letter for winter (A-E, A less severe; E most severe) and a number for summer (1–4; 1 less severe and 4 most severe). Weather data utilised to model the residential building stock has been selected based on these climatic zones, assuming that this data accurately represents the average weather conditions for each individual municipality.

Climate has been selected for a specific geographical location in each municipality. However, for large municipalities the single climate data point may introduce potential deviations due to large distances within the municipality that could even present different altitude, exposure to predominant wind currents or any other specific weather conditions.

2.3. *Thermal characteristics of the Spanish residential building stock*

The first national building code in Spain came into force in the late 70s. Subsequent versions have set conditions for improved thermal performance of buildings, with a focus on heating needs. As a result, the U-values for building envelope elements have improved over time. Information on U-values has been retrieved from [28].

In Fig. 2, we present the U-values for floors, ceilings/roofs, and walls, for the three building typologies across year cohorts in the different climatic zones defined for the Spanish territory. As observed, U-values have declined over the years in all climatic zones, showing an improvement in the reduction of thermal losses. From this analysis, one can expect that older buildings should be prioritised when it comes to renovation.

In addition to current U-values, we consider relevant to assess the adequacy of requested U-values for new buildings or those undergoing a large renovation according to the CTE (the CTE-cases). In Table 4 the maximum U-values for new or retrofitted buildings are presented. Assuming these values is equivalent to consider that the buildings stock has been fully renovated. If we compare values in Table 4 and in Fig. 2, it is observed how new buildings built after 2008 show values close to those requested by the CTE. As an example, the wall U-value in the climatic zone E1, the coolest zone, has evolved from 2.12 W/m^2-K for SFH built before 1940 to 0.74 for SFH built after 2008 while the CTE calls for a value of 0.37 W/m^2-K.

In the result section we discuss the energy demand of a fully renovated residential building stock to assess the adequacy of the CTE values in view of future climate evolution.

The longitudinal assessment proposed in this work includes both historical and future climate data. This provides us a better understanding of the trends the residential building stock can experience in terms of energy requirements in the years to come. Historical climate data has been retrieved using the methods offered in [31]. Regarding future climate evolution, we have considered the Coupled Model Intercomparison Project (CMIP 6) [32] and have considered two

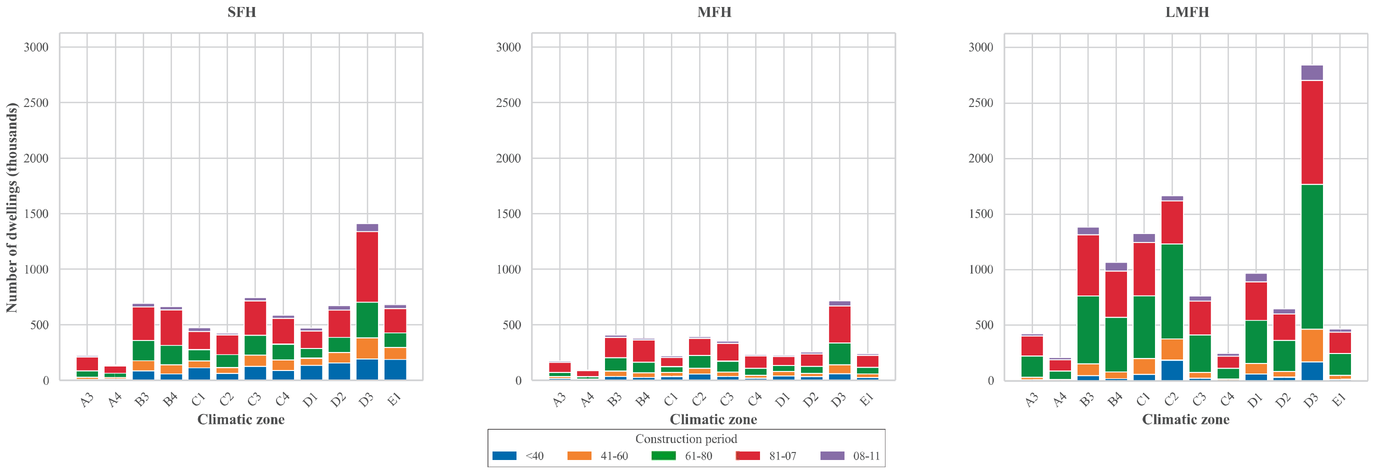


Fig. 1. Distribution of dwellings per type, year cohort and climatic zone (in thousands).

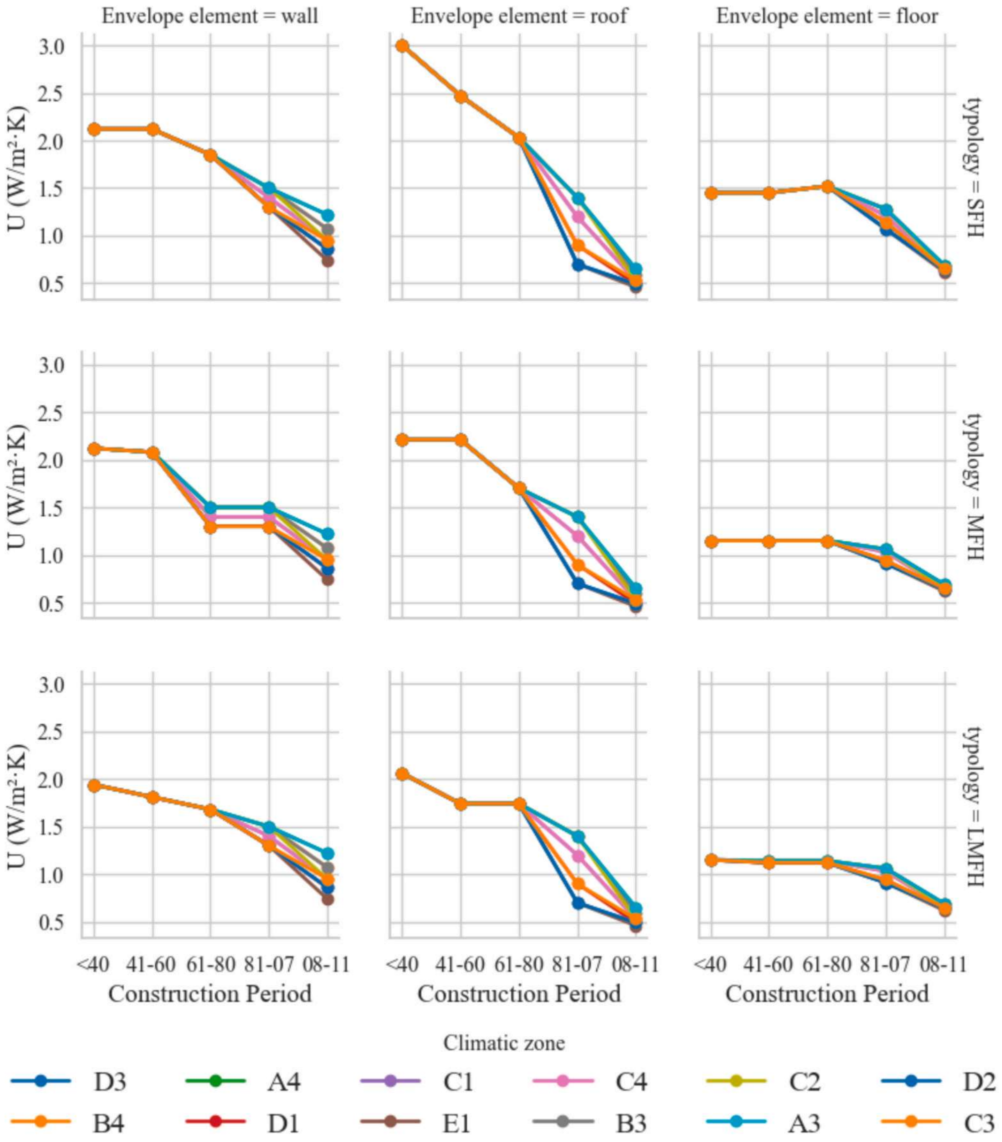


Fig. 2. Building envelop U-values [W/m2-K] by climatic zone, surface type and year cohort.

extreme scenarios: the SSP1-2.6 [33] assuming significant mitigation efforts and the SSP5-8.5 [34] that assumes an important presence of fossil fuels in our economies. For each scenario, 2050- and 2080-time horizons has been selected. To produce the time series to be used in

Table 4
Thermal transmittance of building envelope element advocated by the CTE (W/m^2-K).

U-values	Climatic zones				
	A	B	C	D	E
Walls	0.7	0.56	0.49	0.41	0.37
Roofs	0.5	0.44	0.4	0.35	0.33
Floors	0.8	0.75	0.7	0.65	0.59
Windows	2.7	2.3	2.1	1.8	1.8

our simulations we have taken profit from the works done by [35]. The computation of time series is based on morphing techniques, which provide a computationally efficient and widely adopted method for generating future weather files from typical meteorological years (TMYs). However, this approach, has recognised limitations, particularly concerning extreme events and peak loads. Specifically, it cannot simulate unprecedented extreme temperatures that fall outside the historical range [36]. Furthermore, morphing does not alter the underlying synoptic sequences of the base year, which precludes the simulation of critical changes the persistence of weather changes (e.g., prolonged consecutive days of extreme heat) or the altered frequency of specific atmospheric patterns [36]. Last, this method relies on a single historical year, thereby assuming the temporal structure of the selected baseline year. This can lead to an underestimation of inter-annual variability and fails to capture increased climate volatility [37]. These limitations suggest that findings on extremes may be conservative.

In total, we consider four future climatic scenarios, i.e. SSP1-2.6–2050, and four historical climate scenarios over the past 30 years including 1992, 2002, 2012 and 2012 and 2022 (Fig. 3).

2.4. Description of cases and simulation tool

To evaluate the impact of climate on building energy requirements, we use the software CERMA [38]. CERMA is an hourly dynamic simulation tool based on single thermal zone building models. This tool, developed by the authors and freely available, enables users to obtain official building energy certificates for both new and existing buildings, in all Spanish territory.

Spanish energy authorities have approved the use of six software

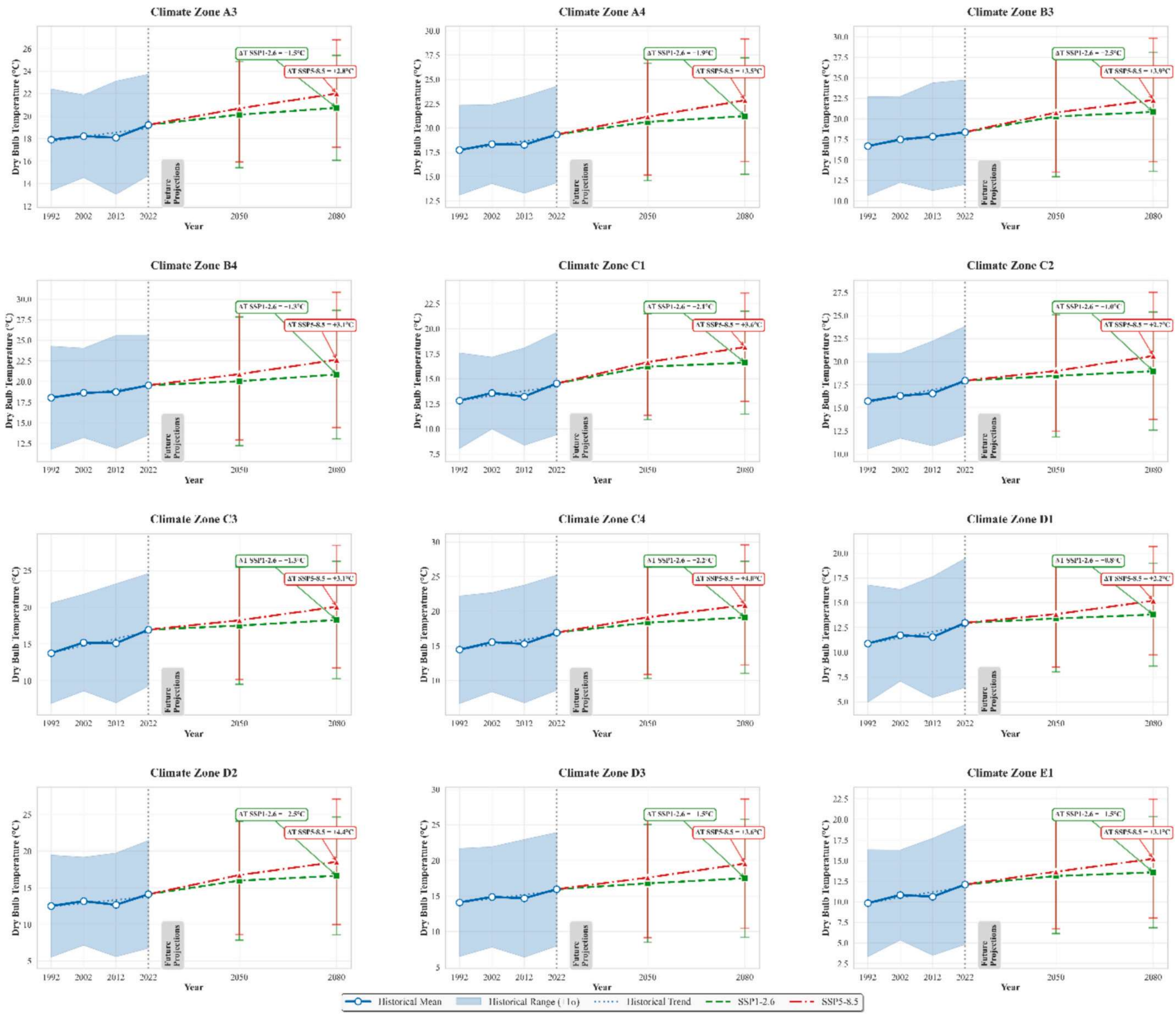


Fig. 3. Average temperature evolution across climatic zones in Spain. Historical trend (1992–2022) and future projections for 2050 and 2080 under the SSP1-2.6 and SSP5-8.5 scenarios.

tools valid to perform energy certifications being CERMA one of those [38]. CERMA's more important features are the following: (i) it considers the building as a single thermal zone, which complies with the standard requirements that impose a single control setpoint for all habitable rooms; (ii) the energy modelling of a thermal zone is based on calculating the air energy balance and a humidity balance; (iii) the conversion of heat gain into cooling/heating load within the thermal zone is performed using the Radiant Time Series (RTS) method. The methodological approach implemented in CERMA was developed using broadly recognised thermal simulation tools such as EnergyPlus [39] as a reference, particularly to assess the adequacy of simplified dynamic methods in residential buildings.

In addition to the above, the Spanish Ministry for the Ecological Transition and the Demographic Challenge has published an official validation document of CERMA for energy certification, in which the annual heating and cooling demands, CO_2 emissions, and energy performance indicators estimated by CERMA are compared with results obtained using the official unified tool HULC [40]. This validation demonstrates that CERMA's outputs are consistent with those of a broadly recognised reference tool for energy certification in Spain, thereby supporting its use for EPBD-oriented residential building assessments. The adequacy of CERMA for residential energy certification has also been assessed in comparative international studies. In particular, CERMA was analysed as the Spanish national methodology within a broader investigation of Mediterranean EPC calculation methods, where its results were compared with those obtained using the dynamic simulation software and monitored data for real dwellings. The study concluded that CERMA provides consistent estimates of heating and cooling demand and that discrepancies between certification methodologies are largely driven by assumptions on building operation rather than by the calculation approach itself [41].

CERMA serves the purpose of this study. First, it provides a predefined set of inputs related to internal gains, fixed winter and summer periods and hourly thermostat availability that fully complies with the requirements set under the national building certification schemes. This allows us to replicate and aggregate at national level the information on the energy performance of buildings that responsible entities in the country has available ("certification mode"). Second, it offers the flexibility of customising input data and parameters including flexible winter and summer periods or flexible daily thermostats ("simulation mode"). These particular features are essential to quantify and, thus, discuss on the adequacy of the current certification schemes.

2.5. *Official operational conditions*

On the operational conditions, winter and summer are defined as fixed periods. This assumption is evaluated in our analysis given that the climate is getting warmer. On an hourly basis, thermostats are set as: winter from 00:00 to 07:00 at 17 °C and 20 °C for the rest; summer from 00:00 to 07:00 at 27 °C, off from 07:00 to 14:00, from 15:00–24:00 at 25 °C. Based on this, we consider two simulation modes: the certification modes that takes into account the thermostat program and the simulation mode that assumes that both heating and cooling systems are available at any time across the year instead of setting specific summer — June-September —and winter period — October-May as considered in the official certification scheme.

Concerning internal loads, these have been set based on those predefined by the certification procedure for residential buildings [25]. Table 5 shows the value of the internal loads from occupants, lighting, and equipment for weekdays and weekends.

Restriction on the availability of the thermostat to compute the heating and cooling needs is a critical aspect of the certification mode. According to the official procedure, the cooling demand is calculated only between June and September (inclusive), while the heating demand is calculated for the remaining months. In Table 6, the thermostat schedule for heating and cooling are presented.

For the energy simulation analysis, the same thermostat values from the certification were used. However, in this case, there is no restriction on the months applied in the certification, so the energy demand for cooling and heating is also computed for any month of the year.

Regarding ventilation, a value of 0.6 renovations per hour has been used in accordance with CTE requirements for residential buildings. Infiltrations are calculated using the CERMA methodology, which is based on the wind speed affecting the building façade as determined by available meteorological data, and on an envelope permeability set by the CTE, ranging from 27 to 50 $m^3/h\text{-}m^2$ depending on the climatic zone.

2.6. *Summary of scenarios*

Based on the alternatives presented above, we create scenarios considering simulation modes, scenarios, simulation years, building typologies, orientations or level of insulation (Table 7).

In total, 208,800 cases are modelled and simulated. The orientation has been averaged, and cases are reduced to 52,200. For the CTE cases, which are those assuming that the buildings stock has been retrofitted to the U-values advocated by the CTE, only future scenarios (SSP1-2.6 and SSP5-8.5) have been assessed (17,400 cases) while for the non-CTE, which are those considering the current U-values, have been assessed for historical and future scenarios (34,800 cases).

3. Results

This work aims to assess the future needs of the Spanish residential building stock and discuss the adequacy of the current energy certification scheme in the context of rapid climate change. Taking advantage of the bottom-up model, we also examined which building segment could be affected the most by the new climate. The results centres on three variables: the sensible heating and cooling demands, and the number of hours of discomfort.

Before introducing the results, it is important to stress that the bottom-up approach outlined in this work establishes an upper boundary for estimating the energy demand of the national building stock. There are two primary reasons for this. First, our analysis is based on dwellings rather than households, which entails accounting for second homes and those owned by summer visitors, a common occurrence along the Mediterranean coast. Second, we assume that dwellings are conditioned according to a daily thermostat setting for every day of the year. However, empirical evidence indicates that heating and cooling systems are not utilised even when temperatures exceed or fall below comfort thresholds, due to variations in comfort perception and

Table 5
Schedule for internal loads of occupants, lights, and equipment.

Internal loads [W/m^2]	Days	0:00 – 6:59	7:00 – 14:59	15:00—17:59	18:00—18:59	19:00—22:59	23:00—23:59
People (sensible)	Weekdays	2,15	0,54	1,08	1,08	1,08	2,15
	Weekend	2,15	2,15	2,15	2,15	2,15	2,15
People (latent)	Weekdays	1,36	0,34	0,68	0,68	0,68	1,36
	Weekend	1,36	1,36	1,36	1,36	1,36	1,36
Lights	All days	0,44	1,32	1,32	2,2	4,4	2,2
Equipment	All days	0,44	1,32	1,32	2,2	4,4	2,2

Table 6
Cooling and heating thermostat schedule in certification mode.

Thermostat	Period	0:00–6:59	7:00–14:59	15:00–22:59	23:00–23:59
Cooling [°C]	January – May	––	––	––	––
	June – September	27	––	25	27
	October – December	––	––	––	––
Heating [°C]	January – May	17	20	20	17
	June – September	––	––	––	––
	October – December	17	20	20	17

Table 7
List of scenarios and dwelling models.

Simulation mode	Scenarios	Levels of insulation	Typology	Construction period	Orientation	Years
Certification	Historical	CTE	SFH	<1940	SN	1992
Simulation	SSP1-2.6	non-CTE	MFH	1941 < 1960	NS	2002
	SSP5-8.5		LMFH	1961 < 1980	EW	2012
				1981 < 2007	WE	2022
				2008 < 2011		2050
						2080

consumption patterns. Consequently, the value of our analysis resides in the relative comparisons across different scenarios.

We start presenting the results of the heating and cooling needs across the historical and future scenarios for the certification and simulation modes. Fig. 4 shows the aggregated heating and cooling demand across scenarios. Focusing on the certification mode (Fig. 4-left), which provides the overview of the sector in the hands of policymakers, the total thermal demand varies between −4% in the SSP1-2.6 scenario and + 1% in the SSP5-8.5 scenario when comparing the future scenarios to the 2022 values. The large differences are observed in the heating and cooling needs. The SSP5-8.5 scenario shows an increase in the cooling demand of almost 130% (from 59 to 135 TWh) and a decrease in the heating demand of 41% (from 179 to 105 TWh) compared to 2022 values. This result has significant implications from the point of view of the selection of technologies to supply the thermal needs as well as on the grid infrastructure. A larger share of cooling, which today is mostly supply by heat pumps implies a larger electricity consumption which at the same time require more resilient grid infrastructures. On the other hand, the predominance of cooling needs which may be synchronised with the sunlight hours could benefit the absorption of solar energy contributing to reduce the need for flexibility assets.

Another important aspect addressed in this work is the adequacy of the current thermostat scheduled assumed in the official certification scheme. By comparing the certification and simulation modes in Fig. 4, the total energy demand for the year 2022 is underestimated by 5.4% (13 TWh) being the cooling underestimated by 19% (11 TWh) and the heating by 1% (2 TWh). Over the years and based on the scenarios considered, these differences become larger. Thus, in the case of the SSP1-2.6 for 2080 heating declines by 4% but cooling increases by 23% (21 TWh). In the case of SSP5-8.5 for 2080 cooling difference goes up to 28% (38 TWh).

Having a thermostat schedule does not only have an implication in the estimation of heating and cooling needs but also in the comfort achieved in dwellings. In Fig. 5, the number of discomfort hours, defined as those where indoor temperatures go above 26C, are presented. As expected, the certification mode does not capture comfort requirements in buildings. In 2022, the number of hours in the certification mode is around 827 h and the simulation mode reduces it to 403 h (51% reduction). This effect exacerbates when looking into future scenarios. For the time horizon 2080, the certification mode underestimate discomfort hours by roughly 100% both in the SSP1-2.6 and in the SSP5-8.5 scenarios. Therefore, in addition to the inaccuracy related to energy requirements, comfort is not guaranteed for many hours over the year.

These results suggest that policymakers need to change the methodology in order to consider more flexible winter and summer periods due to higher temperature levels and should also allow for a more flexible availability of the heating and cooling thermostat on a daily basis to avoid discomfort hours.

Next, we look into the geographical areas more expose to climate change. To do so, we classify the territory into three main climates: Mediterranean, Atlantic and Continental as proposed by [42] (Fig. 6).

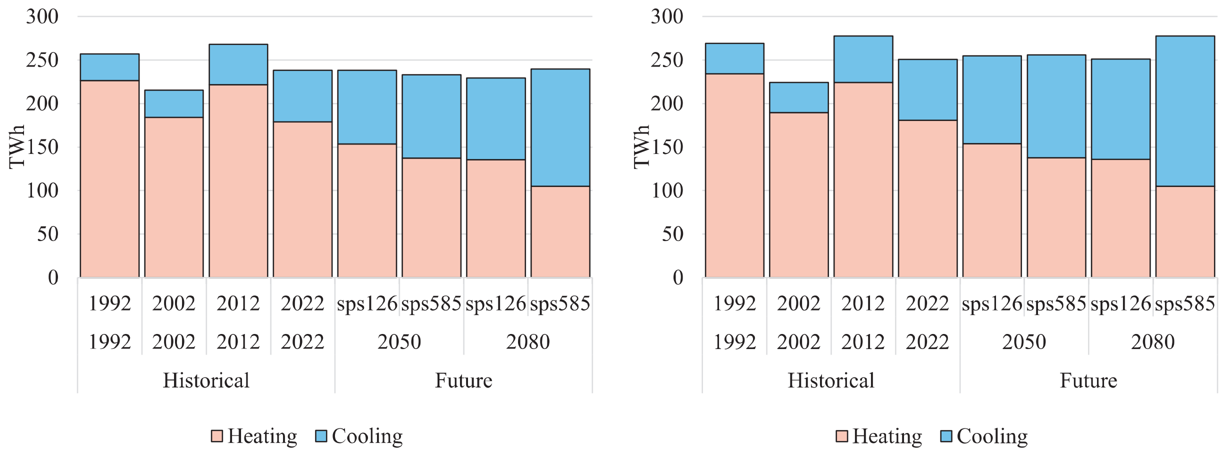


Fig. 4. Aggregated heating and cooling demand for the Spanish residential building stock in the certification (left) and simulation (right) mode.

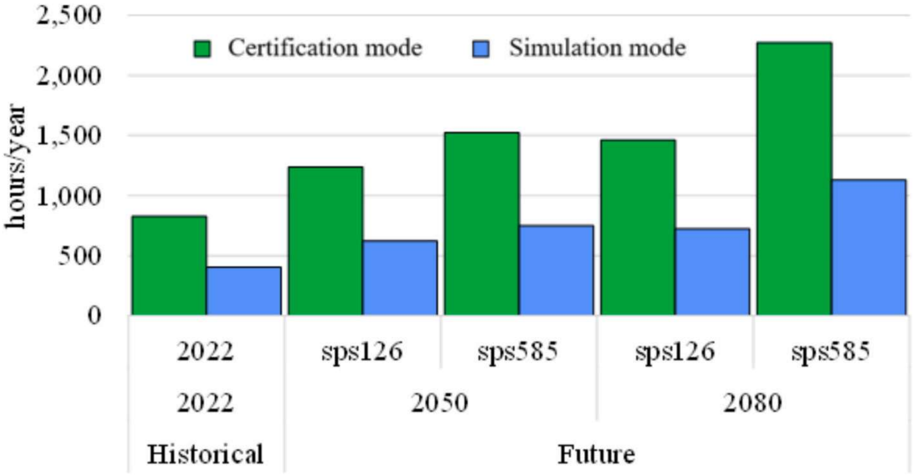


Fig. 5. Number of hours of discomfort per year (T > 26 °C).

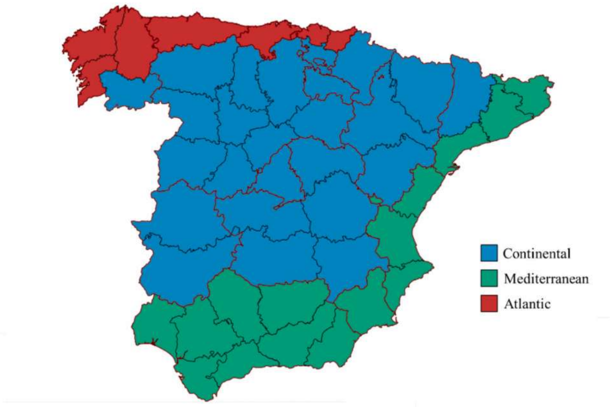


Fig. 6. Distribution of macro-climates in Spain [42].

Heating and cooling demand per surface area under simulation mode conditions are presented in Fig. 7. The Mediterranean area is the most exposed to climate change. In all future scenarios, demand increases from 5% in the SSP1-2.6–2050 to 17% in the SSP5-8.5–2080. For this last scenario, heating decreases by 41% while cooling increases by 138%. In the case of the continental area, total heating and cooling demand decreases in all scenarios driven by the reduction of heating and its weight on the total demand (heating represents 82% of the energy needs in 2022). The Atlantic macro regions is expected to experience significant total demand reduction of 28.4% driven by a heat demand of roughly 40%. As a result, the mediterranean region which concentrates half of the national residential building stock, is the most vulnerable if future projections materialise.

Another important aspect of our analysis is the assessment of climate change preparedness for climate change. In Fig. 8, we present the relation between heating and cooling demand to the dry bulb temperature per type of building and construction year. Overall, the cooling demand is growing and heating decreasing in all cases regardless the climatic zone.

If we compare the cooling slope to the average temperature evolution, the older buildings are more exposed to global warming. As an example, a SFH located in the climatic zone A4, the warmest, shows a correlation of 13.2 kWh/m^2-°C. For the same dwelling built in 2008, the correlation decreases to 12.5 kWh/m^2-°C (5% reduction). However, the exposure to climate change is largely driven by the climatic zone and not by the construction year. The same SFH, built in 2008 and located in climate zone E1, the coldest, shows a correlation of 5 kWh/m^2-°C, a more than 50% reduction. Looking across building typology, differences are not as relevant as climate. LFH are less exposed compared to SFH and LMFH slightly improves compared to LFH. Therefore, in order to prioritise the renovation of residential building stocks, SFH in warm climates should be prioritised.

The last element of the analysis has to do with the adequacy of U-values requested by the CTE and previously introduced in Table 4. We have compared a hypothetical scenario in which all national residential building stock has been renovated with the existing stock based on future scenarios. As observed in Fig. 9, the full renovation of the residential building stock achieves significant improvements, reducing thermal demand per surface area by more than half in all scenarios. Thus, for the SSP5-8.5 2080 thermal demand per surface area decreases from 126 to 53 TWh.

However, the benefits achieved are uneven across regions. In the E1 climatic zone, the coldest in the country, thermal needs are reduced by 72%, heating is reduced by 88% and cooling by 14% while in the warmest region (A4) the improvement reaches 20%, being the heating demand almost negligible (100% reduction) and the cooling demand reduced by 14%.

Another important effect of future climate scenarios relates to the peak demand loads and how they will shift from winter to summer period. Previous works such as [43,44] have dealt with the effect of climate change on the electricity grid. Here, we do not aim to go in such level of detail but contribute to the discussion by reflecting on how the electricity grid will need to cope with higher peak demands in the summer period for the Spanish case.

In Fig. 10, we present the load duration curves of the hourly heating and cooling demand for a SFH built before 1940 in the warmest climatic zone (A4). As observed, under the current status, the peak heat demand will not significantly decrease ranging from 8.6 kW to 10.5 kW. However, cooling will almost double from 2022 to 2080 under the SSP5-8.5 scenario. In the case of the fully renovated scenario, the heating demand is limited to 2 kW and cooling demand is half the one for the non-renovated scenario. Overall, results show that heating demand would play a minimum role if the residential building stock were retrofitted. In the full renovated situation in the SSP5-8.5–2080 scenario, the cooling demand is similar to the observed in the 2022 with no renovation. This means that if we want to keep cooling peak demand on todaýs level we need to pursue the insulation levels advocated by the CTE. If buildings are not renovated, the cooling supply that largely rely on electricity will add strong pressure to the electricity grid which already today shows high levels of congestion [45]. Our work sets the basis to further explore on this matter, but it calls for a separate and deeper analysis. Yet, we wanted to illustrate that the consequences for the national energy systems will be of great importance in the years to come.

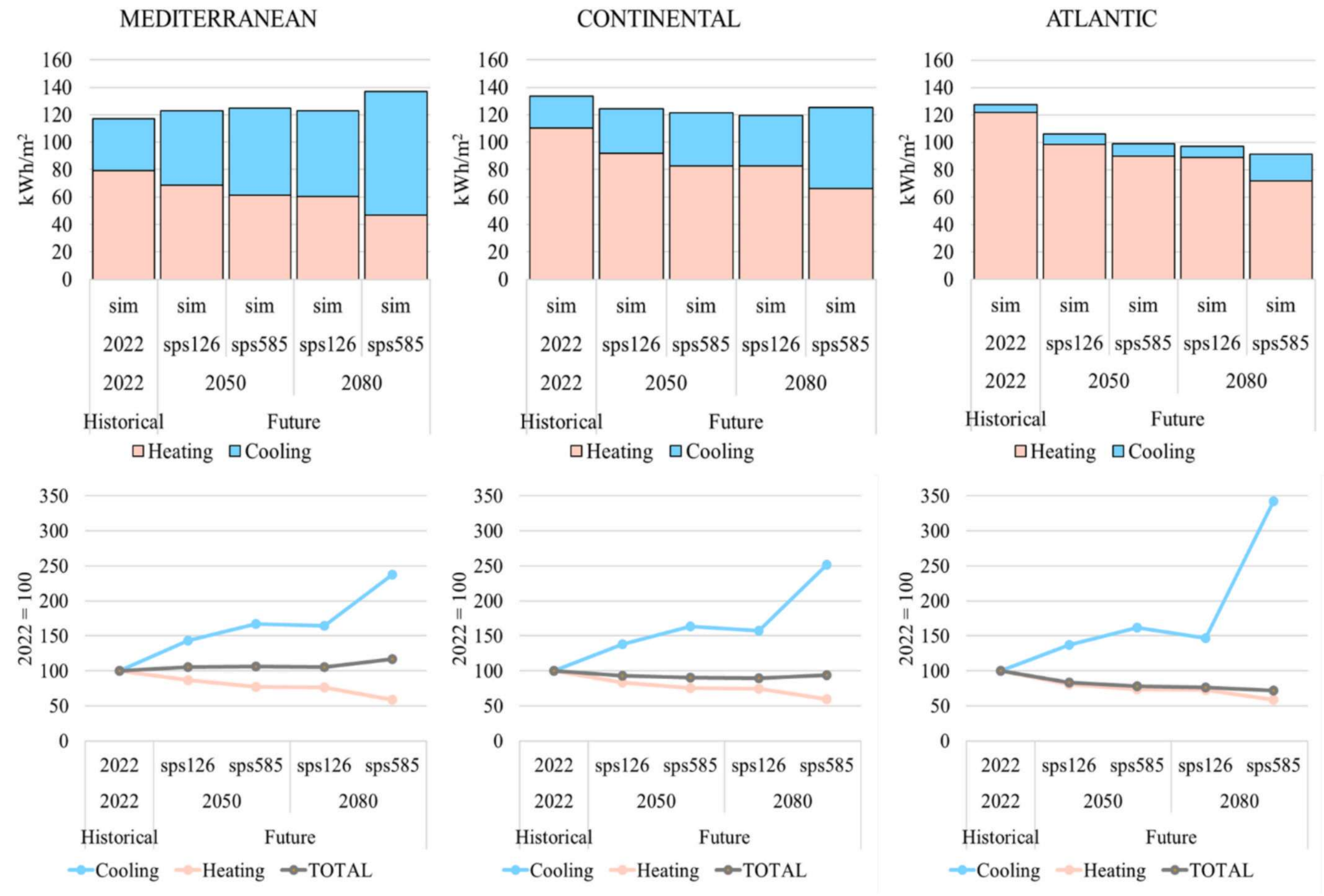


Fig. 7. Heating and cooling demand per surface area for the three climatic groups.

4. Discussion

Our analysis yields relevant results that policymakers can utilise to implement measures for enhanced climate adaptation of the residential building stock. First, climate change is expected to significantly increase the demand for sensible cooling while maintaining the total energy demand (heating plus cooling). This swap of roles has implications for the adoption of technology in heating and cooling supply and energy infrastructure. An increase in cooling demand will pave the way for reversible heat pumps, thereby leading to a more electrified building sector that will put pressure on the electricity grid. In this sense, the most vulnerable residential building stock segment in the warmest climatic zone is expected to double the peak cooling load by 2080 under the SSP5-8.5 scenario if no corrective measures are taken. Only by adopting envelope improvements up to the level proposed by the national building code will peak cooling demand remain at todaýs levels.

Another important conclusion stems from the comparison of the certification and simulation modes. Our results show that the current energy certification procedure, which limits winter and summer periods as well as the daily profile use (thermostat availability) of the heating and cooling supply system, fails to capture the real needs associated with a new climate reality. For the year 2022, the certification mode underestimates total demand by 5%, primarily due to larger cooling needs that are underestimated by 18%. These differences are expected to increase in the future climate. For the SSP1-2.6 in 2080, heating declines by 4% but cooling increases by 22.7% (21 TWh). In the case of SSP5-8.5 for 2080, the cooling difference increases by 28% (38 TWh). On the positive side, the U-values requested by the CTE are effective under the SSP1-2.6 and SSP5-8.5 scenarios, considering the simulation mode. Retrofitting the entire residential building stock would reduce total demand by half, while maintaining cooling levels at today's levels.

Lastly, our analysis shows that the most vulnerable segment of the stock is the single-family houses built before 1940 (the oldest of the residential building stock) and located in the Mediterranean area. Thus, the oldest SFH in warm climates (Mediterranean) must be prioritised as they are expected to double their cooling demand by 2080. Therefore, policy instruments for the decarbonisation of the Spanish residential building stock should focus on these buildings to prepare them for the ongoing climate change.

5. Conclusions

This study proposed a detailed bottom-up model of over 200,000 cases to assess the adaptation of the Spanish residential building stock to future climate scenarios (SSP1-2.6 and SSP5-8.5). Our aim was to quantify the impact of climate change on energy demand and to evaluate the adequacy of current energy certification procedures. At national level, main contributions to knowledge are:

- Quantification of policy flaw: the current Spanish energy certification procedure critically underestimates total national residential building energy demand by 5% in 2022, primarily because cooling demand is underestimated by 18%. This discrepancy will escalate dramatically with climate change. This finding provides that the current regulatory assumptions fail to capture the real energy risk and the escalating problem of thermal discomfort.
- Validation of retrofit potential: a policy of universal retrofitting of the entire stock to current CTE U-values is a robust climate adaptation measure. It reduces total national residential building

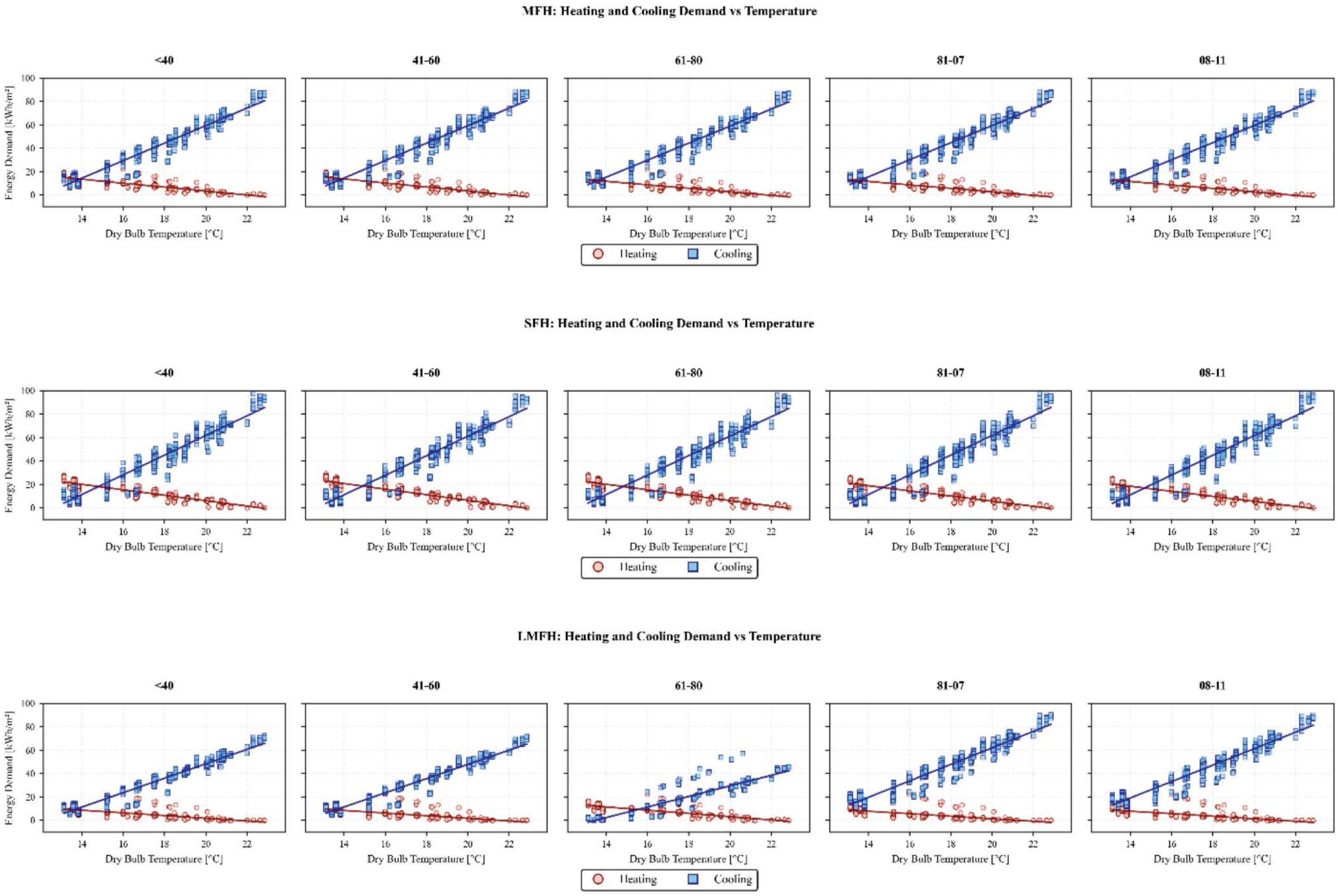


Fig. 8. Heating and cooling demand vs dry bulb temperature per typology and year of construction.

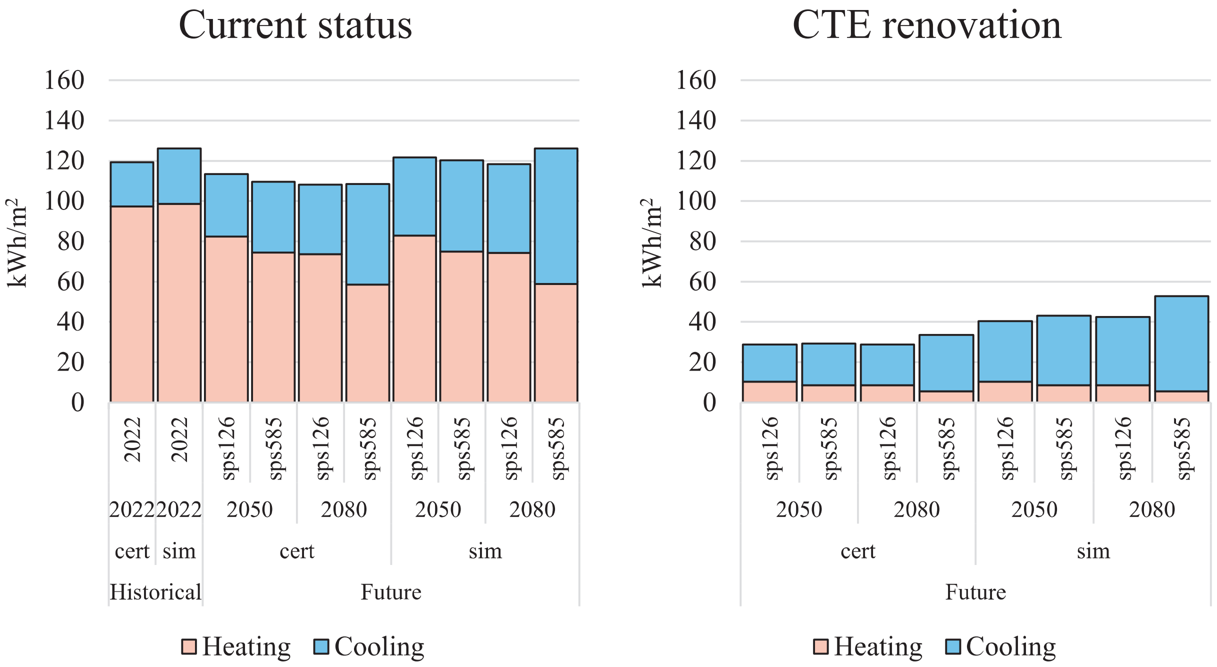


Fig. 9. Heating and cooling demand per surface area for the current status of the national Spanish residential building stock (left) and for the fully renovated residential building stock according to the U-values set by the technical building code (CTE) (right).

energy demand by half, while maintaining cooling needs at today's levels.

— Uneven impact across the territory, typologies, and construction years: out of the three macro-regions defined, the Mediterranean

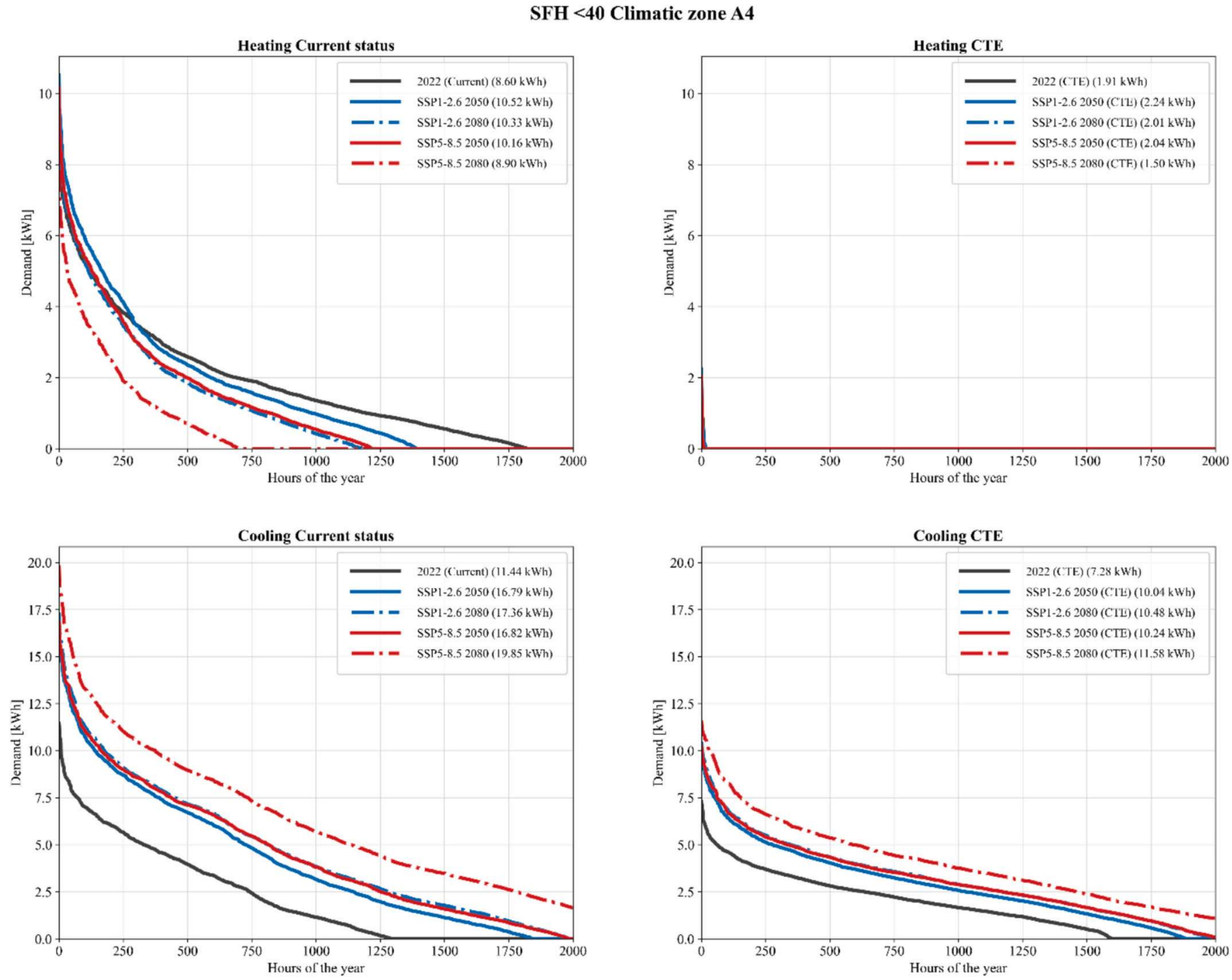


Fig. 10. Load duration curves for the heating and cooling demand of a SFH in climatic zone A4 under the different scenarios considered. (NB: values in parenthesis indicate the peak demand load).

is the most affected by future climate trends due to a growing cooling demand that surpasses heating reductions. Conversely, the stock in the Atlantic region experiences a net reduction, while the Continental region falls in between the two. Beyond climate factors, the oldest SFH (SFH < 40) are the most vulnerable.

- Identification of a prioritized policy target: the oldest single-family homes (built pre-1940) in the Mediterranean region are the most vulnerable segment, facing a projected doubling of cooling demand by 2080. This finding is a baseline projection and is likely conservative, as the real-world risk in densely populated urban centres will be significantly exacerbated by the Urban Heat Island (UHI) effect. This provides a clear, geographically and typologically specific target for urgent policy instruments aimed at climate adaptation.
- Electrical grid load implications: results show the complete shift in the energy balance, which will enforce rapid electrification through heat pump adoption. Crucially, we highlight that the most vulnerable segments face a projected doubling of peak cooling demand by 2080, signalling an imminent challenge for electricity grid resilience and demanding proactive planning for demand-side management strategies in the summer.

In summary, current Spanish energy policy is fundamentally flawed due to restrictive assumptions that underestimate the scale of the cooling challenge and fail to identify the most critical building segments at risk. An immediate and renovated strategy is necessary to ensure effective climate adaptation, prevent a crisis of thermal discomfort, and mitigate the risk of grid overload. Overall, a review of current assumptions of the energy certification methodology of building is proven necessary to better define energy policies that enables a more effective adaption to climate change that, at the same time, ensures the decarbonisation of the residential building stock.

6. Future lines of work

Based on the results obtained in this work, and given the capabilities of the CERMA tool, the authors consider that analysing the impact of demand shifts on the grid infrastructure is timely and of great relevance. Building upon the present methodology and hourly analysis of demand could provide valuable insights into the electricity demand for the national building stock and help inform better grid infrastructure planning in the years to come. To do so, authors aim to perform a calibration analysis to match the estimated demand with real national energy consumption, moving from a dwelling-based analysis to a household-based analysis.

CRediT authorship contribution statement

Juan-Pablo Jiménez-Navarro: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Emilio-José Sarabia-Escriva:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Víctor-Manuel Soto-Francés:** Writing – review & editing, Validation, Supervision, Conceptualization. **José-Manuel Pinazo-Ojer:** Supervision, Software, Conceptualization.

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.

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Data availability

Data will be made available on request.

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