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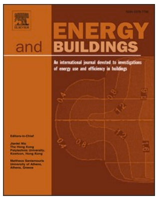

Overheating calculation methods, criteria, and indicators in European regulation for residential buildings

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ABSTRACT

With the ongoing significance of overheating calculations in the residential building sector, building codes such as the European Energy Performance of Building Directive (EPBD) are essential for harmonizing the indicators and performance thresholds. This paper investigates Europe's overheating calculation methods, indicators, and thresholds and evaluates their ability to address climate change and heat events. The study aims to identify the suitability of existing overheating calculation methods and propose recommendations for the EPBD. The study results provide a cross-sectional overview of twenty-six European countries. The most influential overheating calculation criteria are listed the best approaches are ranked. The paper provides a thorough comparative assessment and recommendations to align current calculations with climate-sensitive metrics. The results suggest a framework and key performance indicators that are comfort-based, multi-zonal, and time-integrated to calculate overheating and modify the EU's next building energy efficiency regulations. The results can help

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Abbreviations: ANSI, American National Standards Institute; ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers; CEN, European Committee for Standardization; CIBSE, Chartered Institution of Building Services Engineers; CCD, Cooling Degree-days; EEA, European Environment Agency; EPBD, Energy Performance in Buildings Directive; EPC, Energy Performance Certificate; EU, European Union; HDD, Heating Degree-days; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; ISO, International Standardization Organization; nZEB, nearly Zero-Energy Building; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; UK, United Kingdom; WWR, Window to wall ratio.

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policymakers and building professionals to develop the next overheating calculation framework and approach for the future development of climate-proof and resilient residential buildings.

Nomenclature

A_G	Net floor area [m^2]
A_{util}	The useful area of the living spaces following the definition of section 4.6 of HE0 (Spain regulation)
$A_{w,p,k}$	Area of the opening k [m^2]
$A_{W,j}$	Window area of zone j [m^2]
$F_{sh,obst,k}$	Reduction factor for shading by external obstacles (includes all the elements outside the window gap such as overhangs, lateral protections, setbacks, obstacles, etc.), for the month of July, of the gap k
FF_k	Frame fraction of the gap k (in a simplified way, the value of 0.25 can be adopted)
$g_{tot,j}$	Total energy transmittance of the glazing, including sun protection zone j
$g_{tot,sh,wi,k}$	Total solar energy transmittance of the glazing with the mobile shading device activated (closed) for the month of July and for gap k
$H_{C,D,juli,or,zi}$	Direct heat transfer coefficient by transmission between the heated space and the outdoor air except for the ground floor for orientation or in zone zi [W/K]
$H_{C,ve,juli,or,zi}$	Direct heat transfer coefficient through ventilation for orientation or in zone zi [W/K]
$H_{gr,an,juli,or,zi}$	Direct heat transfer coefficient by the transmission for building elements in thermal contact with the ground for orientation or in zone zi [W/K]
h_{juli}	Total time over the month of July
$H_{sol,juli}$	Average accumulated solar irradiation for the month of July (kWh/m^2 month) in the studied location considering the inclination and orientation of the opening k
$H_{T,\ overh}$	Conduction heat transfer coefficient [W/K]
$H_{V,\ overh}$	Monthly ventilation heat transfer coefficient [W/K]
i	Recursive index in a summation
in	Indoor
m	Recursive index in a summation for the month of the year
out	Outdoor
$Q_{C,HP,juli,or,zi}$	Extract energy from the cooling unit by the booster heat pump for orientation or in zone zi [kWh]
$Q_{C,nd,juli,or,zi}$	Cooling demand for orientation or in zone zi [kWh]
$Q_{g,\ overh,m}$	Monthly solar and internal heat gains [MJ]
$Q_{sol,juli}$	Solar gains for the month of July of the windows and openings of the thermal envelope with its mobile solar protections activated (closed) [kWh]
T_{op}	Temperature operative [°C]
$T_{Setpoint,i}$	Set point temperature
up	Upper limit of comfort/heat-balance range
wf_i	Weighting factor (dimensionless)
$\eta_{util,\ overh,m}$	Utilization factor depending on the ratio between the monthly heat loss and heat gain

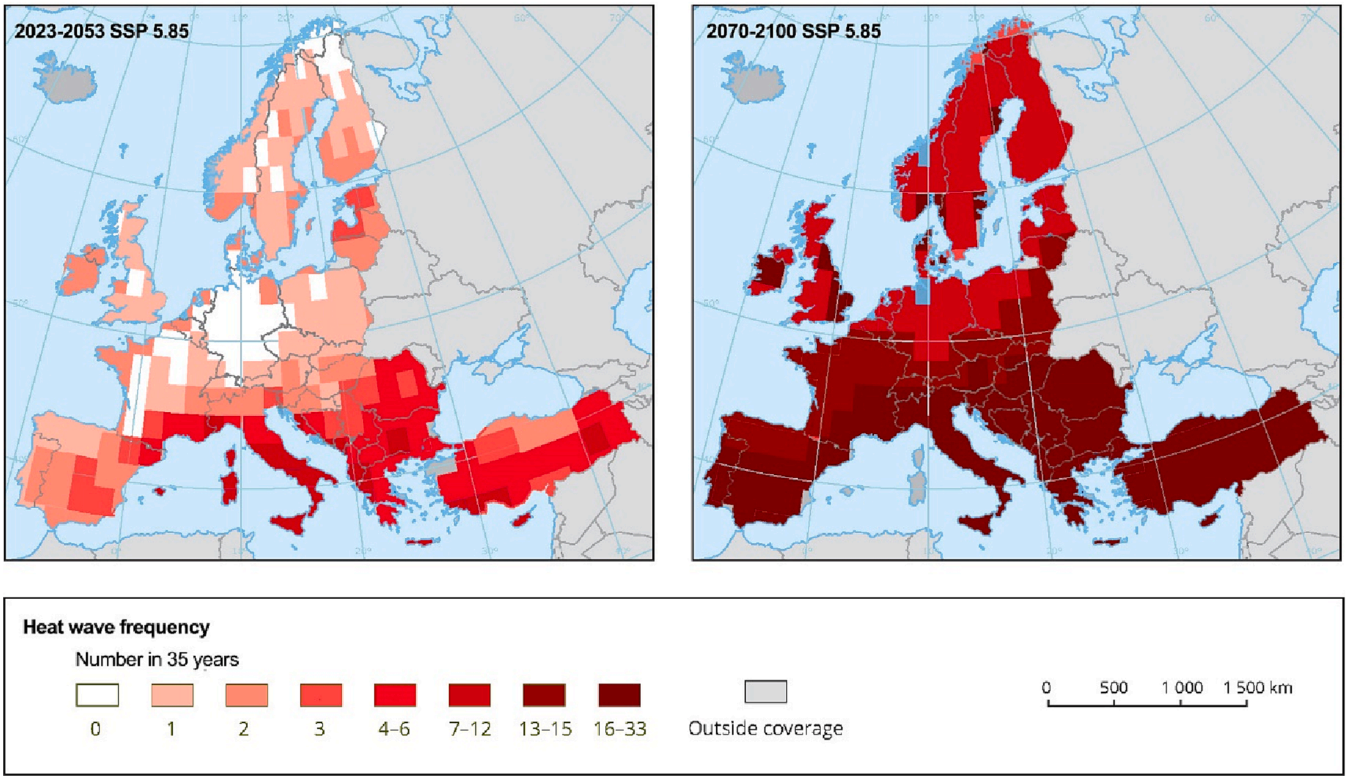

Fig. 1. Number of extreme heat waves in future climates under the SSP 5.85 forcing scenarios based on the EEA data [4].

1. Introduction

Climate change is expected to drive an increasing frequency of heat waves, which can cause significant morbidity and mortality [1]. High ambient temperatures in cities are associated with many health risks, including the increase in premature mortality of the senior population [2]. According to the European Environment Agency (EEA), mortality risk increases by 0.2 and 5.5 % for every 1 °C increase [3]. For example, the excess mortality in the EU climbed to +16% in July 2022 from +7% in June and May. According to the EEA and Eurostat statistics on excess mortality, Europe might reach an annual +60.000 to 165.000 premature death by the end of the 2080s, with the highest impact in Southern Europe [3,4].

With the increase and repetition of heatwaves, dwellings are at risk of overheating and potentially increase of cooling demand. Fig. 1 indicates the number of extreme heat waves in future climates under the SSP 5.85 forcing scenarios of the IPCC AR6. SSP 5.85 refers to the Shared Socio-economic Pathway describing the socioeconomic trends underlying the Fossil-Fueled Development scenario in the year 2100 [5]. The pattern of heatwaves frequency and intensity [4] and the increase in tropical nights [6] indicates the likely occurrence in the near and long future. Therefore, peak and mean summer temperatures will increase by 10 °C across most European capitals by 2080. The trapping of internal and external heat gains causes overheating, and the latter is expected to worsen with further urbanization and climate change.

Indoor overheating has already been identified in European dwellings [7]. Most studies found in the literature confirm the like hood of overheating risk increase and discomfort in households due to global warming [8,9]. The contemporary construction of highly insulation nearly-zero and net-zero energy buildings (nZEB and NZEB) across Europe results in periodic overheating in today's climate in Southern Europe [10], Eastern Europe [11], and even in Western and Northern Europe [12]. The Energy Performance of Energy Directive (EPBD) was strongly influenced by the Passive House Standard principles [13,14]. During the last ten years, the focus of the EPBD has been mainly on closing the energy efficiency gap [15]. However, the new EPBD recast of 2021 made special attention to thermal comfort [16]. More importantly, the 2023 recast is expected to address climate change and overheating more appropriately. All member states must revise their national energy calculation methods and address discomfort problems under climate change scenarios by the end of 2025.

In this context, the International Energy Agency (IEA), through Annex 80 on Resilient Cooling in Buildings, reviews existing standards and regulations on overheating calculation methods, criteria, and indicators. The preliminary findings indicate disparities between the methods and the lack of common and consistent calculation methods. Standard CEN 13790:2008 (or ISO 52016–1:2017) for energy performance calculation of buildings is the basis of overheating calculation in Europe. The standard is under serious critique because it adopts an old heat balance approach [12] and does not consider the modern thermal comfort estimation approach based on the six thermal comfort parameters [17].

Overheating refers to high indoor temperatures and affects occupants' health and productivity. Therefore, the overarching aim of this paper is to improve the well-being of residential buildings in European countries. Epidemiological studies have shown that heat wave vulnerability occurs at night in nursing and residential homes [18]. According to the Lancet Countdown Report of 2019, exposure to extremes of heat results in a range of health consequences. With Europe's aging populations, the effects of heat waves are increasing. The study focuses on residential buildings where the risk of heat stress and heat stroke is the highest during heat waves. Improving well-being requires preparing and adapting new and existing buildings to be climate-proof against future extreme scenarios [19]. Also, we excluded other types of buildings because residential buildings have a specific occupancy density, occupation schedules, and, more importantly, a different architecture than office buildings or other commercial buildings.

In this context, we identified a need to provide an overview of overheating calculation methods, criteria, and indicators in European regulation for residential buildings. The objective of this paper is an attempt to respond to the following research questions:

- What are the methods and criteria to assess thermal comfort and overheating in European building codes based on the EPBD?
- How to characterize and compare different methods and criteria?
- What is the main difference that distinguishes different methods? What is the unique overheating national method?
- What factors should be considered to advance the overheating assessments in future revisions of building regulations?

By answering the questions above, this paper provides a critical overview of assessment methods used for overheating based on thermal comfort criteria. The paper's novelty is an exhaustive and longitudinal study that continued over three years as part of the IEA Annex 80 activities. 26 EU member and non-member states, including the UK and Switzerland, were investigated. A comprehensive review report was developed. Representative publications and standards screening were performed, and available experts were interviewed and surveyed. To the best of our knowledge, this is the first paper that provides relevant information on overheating calculation methods and key performance indicators to tackle discomfort during summer in the European continent. The originality of the paper is twofold. First, the paper compares overheating calculation methods and indicators regarding nearly and net zero energy buildings in compliance with EPBD, ISO, and CEN. Secondly, the paper identifies key overheating calculation methods and indicators considering climate change and heat waves. The paper identifies the overheating indicators and calculation approach within a thermal resistance and resilience paradigm [20]. Finally, the paper provides a concrete set of recommendations that can be considered in the next EPBD recast towards a consistent and unified calculation approach that caters to the climatic and socio-economic variability of people of the continent.

2. State of-the-art

Overheating is excess heat in living, sleeping, and working spaces [21]. European public health stakeholders raised concerns about heat-related death and called for preventive measures [22]. Many factors affect overheating in dwellings, including dwelling characteristics, environment and urban climate, and dwelling design [7]. Nevertheless, the calculation of overheating remains one of the major challenges. The calculation of overheating can influence the passive and active design measures. In Europe, the prevalence of active cooling (AC) is low, where 15% to 30% of residential buildings have AC. Depending on the overheating calculation methods and thermal comfort thresholds, AC demand will increase drastically, increasing the energy demand and GHG emissions.

There is somewhat less research applicable to the European context on overheating because past research has been conducted on the assumption of broadly stable climate and heating-dominated regions.

Several studies have aimed to document the overheating phenomena in European residential buildings [23]. The first group of studies investigated the global causes and effects of overheating in European dwellings and recommended directions for adaptation and mitigation. The recent work of Alrasheed and Mourshed (2023) critically reviews the factors that influence the overheating risk in dwellings and presents state-of-the-art on possible mitigation strategies [7]. The study developed a framework that illustrates the effect of overheating factors on the cooling efficacy of passive strategies. In 2019, Chen presented an editorial article on the challenges and opportunities of overheating in residential buildings [8]. Next, the work of Lomas et al. (2017) aimed to describe this phenomenon and its causes [21]. Also, the work of

Santamouris and Kolokotsa discussed issues related to the impact of urban overheating on vulnerable populations in Europe [22]. More recently, Santamouris presented the risk factors arising from urban overheating in a holistic and integrated way[24]. The study described the current and future impact of urban overheating on the urban population.

The second group of studies aimed is case study-based that modeled overheating and focused on the calculation approach and indicators choice [25]. In an earlier study, Robert et al. (2013) estimated the future performance of UK dwellings built in compliance with the Passivehaus standard requirements. The study confirmed that the super-insulated Passivehaus dwellings at already at risk of overheating in the UK and Northern Europe [26]. The study is ten years old but provided valuable insights into the overheating phenomena. Four years later, Figueiredo et al. (2016) performed a sensitivity analysis for a Passivhaus in Portugal and found a long period of overheating during summer. The study complied with the Passivhaus thermal comfort criteria and proved the ability to avoid active cooling through improved building envelope design and operation. Also, in 2016, Mulville and Stravoravdis (2016) simulated a typical UK case study in free-running mode and applied the UK national calculation method [27]. They proved that the current overheating calculation methods are out of order and not fit to purpose. Then, the work of Brotas and Nicol looked at the criteria from CIBSE TM52 and discussed their applicability to a single UK dwelling archetype [28].

Another example is the work of Simson et al. (2017) modeled overheating in five Estonian apartments and investigated the impact of thermal zoning on the simulation-based overheating assessment calculation [29]. The study suggested a temperature measurement-based approach for pre-assessing overheating as part of the regulations compliance process. Then, Narozny et al. (2016) applied a post-occupancy evaluation method to understand the influence of occupants on overheating and their ability to interact with cooling and ventilation systems [30]. Similarly, Morgan et al. (2017) monitored 26 new homes and documented the overheating causes, including the high insulation and occupants' behavior [31]. The study reported the significant influence of occupants on mitigating overheating.

Sepulveda et al. (2020) published a recent case study that simulated the overheating risk in a Spanish residential unit. The study applied the Spanish regulations and focused on reducing the overheating risk by manipulating the window-to-wall ratio and night ventilation [32]. In Sweden, Tettey and Gustavsson (2020) explored the climate change implication on a renovated housing unit [33]. The study confirmed that with climate change, the space heating demand would decrease significantly in Sweden, and the space cooling demand would increase remarkably. Attia and Gobin modeled a Passivehaus case study for timber construction under climate change in Belgium. The study indicated the high risk of overheating associated with newly constructed timber construction [34]. Dartevelle et al. investigated the overheating risk in nZEB and applied the European EN 16798 [35] and CIBSE standards [36]. They proved the difficulty of mainlining comfortable thermal conditions in nZEB houses despite the temperature climate of Belgium.

The third group of studies comprises an article that reviewed and compared the calculation methods and indices for overheating in buildings. The work of Carlucci et al. (2018) is a review paper on adaptive thermal comfort models in regulatory documents [37]. The paper focused on comparing the standards from an international perspective, including ISO 17771–2 [38], EN 16798 [35], ASHRAE 55, Dutch ISSO 71, and the Chinese thermal comfort standard. The study focused mainly on adaptive thermal comfort and provided general recommendations for commercial buildings. The authors recommended that a harmonized method for multi-zone models, which can include multiple indices, should be found to improve regulations. More recently, Rahif et al. [39] reviewed time-integrated overheating evaluation methods for residential buildings. The study focused on residential buildings and was limited to Western Europe. The study looked into five national building codes based on the Energy Performance of Building Directive (EPBD) in Belgium, France, Germany, the UK, and the Netherlands.

Among the three groups of studies, the last group on review articles appeared the most interesting. Additional screening and filtering pinpointed three outstanding indicators that quantify overheating duration and intensity in buildings. Some of the three indicators are found in existing standards, and one is only used in scientific research studies. The summary below frames the literature review outcomes and provides a profile of the unique overheating-related found in the literature:

1. Percentage of occupied hours when an operative temperature exceeds a certain threshold of the annual occupied hours based on a PMV/PPD or adaptive comfort model for a specific comfort category (I, II, III or IV) (ISO 17772). The indicator is used by many European standards that address overheating calculation, including CIBSE (Guide A, TM52, and TM59), The Passive House Standard, CEN 16789, and ISO 17772.
2. Standard Effective Temperature (SET) is a commonly used index in thermal comfort evaluation. It was established based on a two-node model reflecting the thermal regulation process of the human body based on the six thermal comfort parameters: air temperature, radiant temperature, air velocity, humidity, clothing, and metabolism. The SET has been reintroduced into the ASHRAE 55 calculations to determine the cooling effect of air movement. Moreover, the United States Green Building Council (USGBC) RELI rating system has used the SET indicator as a thermal resilience indicator.
3. The Indoor overheating Degree (IOD), Ambient Warmness Degree (AWD), and overheating escalation factor ($aIOD = AWD$) were developed by Hamdy et al. (2011) [40]. The Indoor Overheating Degree (IOD) index is the summation of the temperature difference between the indoor operative temperature and a preferred comfort temperature. The difference is averaged over the total number of zonal occupied hours. The three indicators are used by several studies and recommended by the IEA Annex 80.

Despite the three groups of studies found in the literature to date, no study provides a comprehensive review of overheating calculation methods in the EU regulatory documents. Several studies have focused on the UK and addressed CIBSE Guide A (2006), CIBSE TM52, CIBSE Guide A (2015), CIBSE TM59, and Passive House standards. A comparative approach is lacking for analyzing overheating calculations for residential buildings in the EPBD. Most investigated studies did not address long-term climate change impacts and short-term heat wave effects. In addition, the impact of the urban heat island effect on the overheating risk is almost not addressed in the reviewed studies concerning thermal comfort in residential buildings.

Therefore, the objective of this study is to bridge this knowledge gap, analyze, and compare overheating calculations for residential buildings in the EPBD regulatory in twenty-six countries: Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Spain, Sweden, Switzerland, the United Kingdom (UK), and the Netherlands. The study is part of the International Energy Agency (IEA) Annex 80 on Resilient Cooling in Buildings. The study builds upon previous work as part of Annex 80, reviewing the overheating indicators [39] and the overall discomfort parameters, including humidity in residential buildings [41]. Therefore, the study provides a valuable guide to developing the EPBD and a comprehensive list of recommendations and conclusions to address overheating in the regulations of the residential sector in Europe and Worldwide.

3. Methodology

The research methodology is qualitative, similar to previous studies

[10,42], and comprises three main stages. Fig. 2 illustrates the study's conceptual framework. First, the study goal, scope, and boundary conditions were defined to have a practical set of questions to guide the investigation of thermal comfort and overheating calculations in each country. This step included selecting representative experts from EU member and non-member states. Also, an initial questionnaire was created and tested through a pilot study for validation. Secondly, the data collection process was conducted through one-to-one interviews and a literature review. Finally, the analysis of interview results and comparison of the calculation methods took place. At this stage, the analysis of the results through focus group discussions allowed us to select the most outstanding calculation methods, criteria, and indicators and develop a set of refined recommendations to be integrated into the regulation of each country and more globally in Europe through the Energy Performance of Buildings Directive (EPBD). In the following paragraph, we explain in detail the research methodology.

3.1. Boundary conditions

26 European countries were selected, namely Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden, Norway, Switzerland, and the United Kingdom. The study scope covered residential buildings in European countries and excluded nursing homes and elderly houses. The temporal study period was the summer overheating. The investigation of overheating calculation for heat waves during the shoulder periods was excluded. Also, the study focused on overheating and did not adopt an overall discomfort concept. Humidity was excluded to focus on the thermal aspect of heat, assuming that humidity will be controlled [43]. Countries with no overheating calculation methods embedded in their EPBD were excluded after screening the six countries. Focusing on thermal comfort in residential buildings, the study avoided preference or bias towards overheating calculation methods based on specific resilient technologies, including passive [34] and active solutions [35]. Economic and other social aspects of thermal comfort perception were excluded.

Next, a questionnaire was created and tested through pilot interviews with pseudo-experts. The questionnaire comprised nine key questions focused on new and existing residential buildings. They evolved around one central question mentioned below:

- What are your country's thermal comfort/overheating limits for residential buildings?

The questionnaire is available in an open-access repository (see Appendix 1). Moreover, 31 interviewees were requested to fill in an exhaustive table with specific information about their national regulations. The table comprised five major elements relevant to the overheating calculation. Fig. 3 illustrates the relation between overheating calculation and weather representation, envelope prescriptive or performance-based requirements, simulation model type (static or dynamic), occupancy type, and thermal comfort model—the five elements were translated into questions embedded in the table.

3.2. Target countries' regulation

The study targeted the energy performance of buildings regulation between 2021 and 2023. The focus of the study was residential buildings. The Energy Performance of Building Directive requires all EU

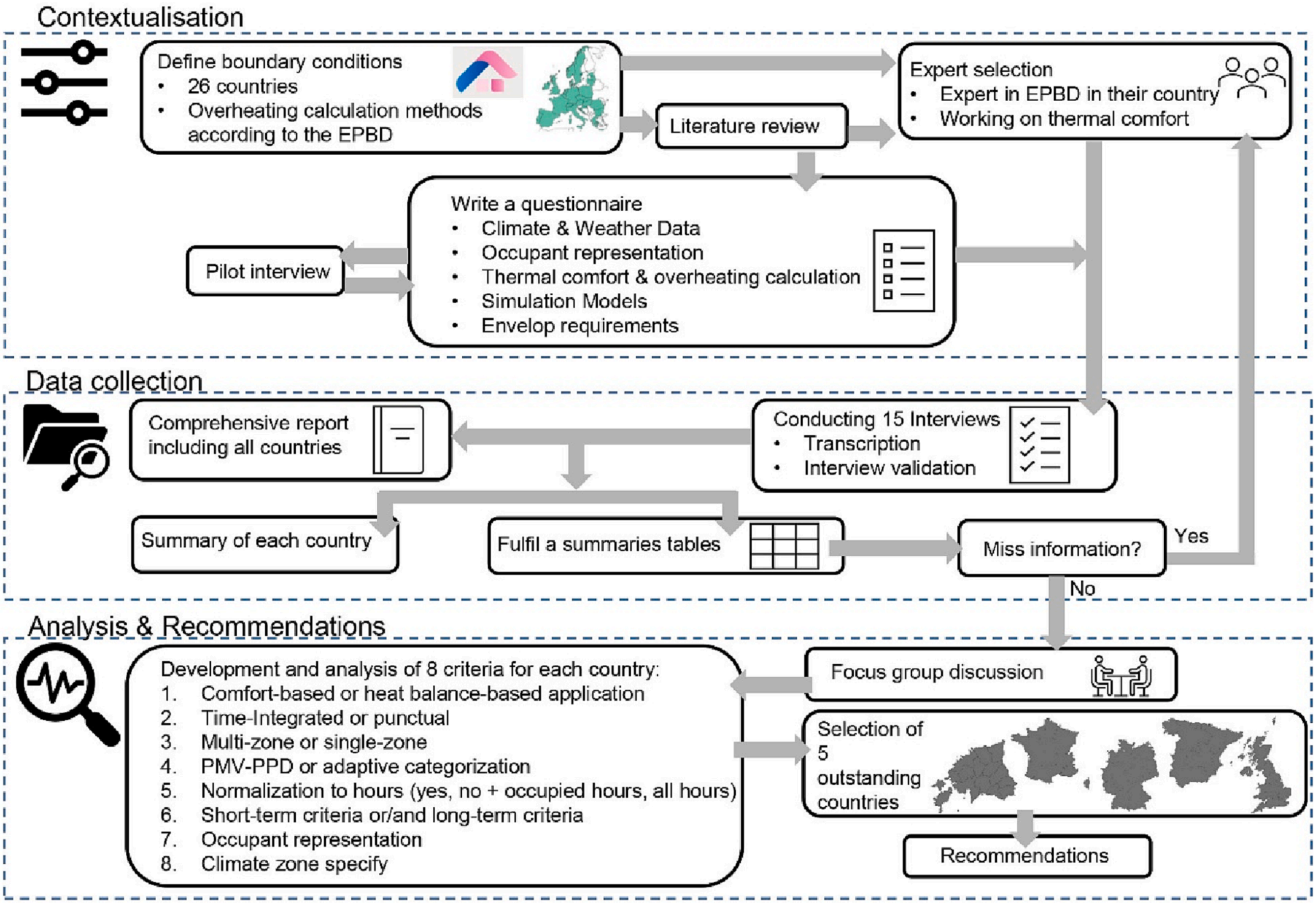

Fig. 2. Study Conceptual Framework.

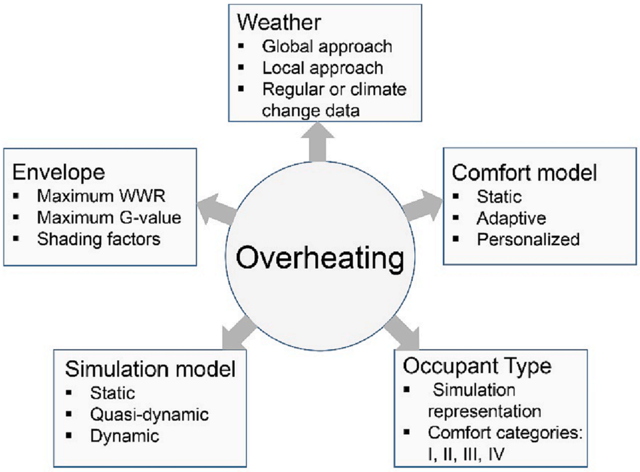

Fig. 3. Key elements influencing overheating calculation in European residential building standards.

member states to develop energy performance certifications and calculations for residential buildings. Therefore, the exclusion criteria were used to narrow the scope of the study except for the UK, Norway, and Switzerland. Twenty-six national experts on thermal comfort (Austria, Belgium, Bulgaria, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Ireland, Latvia, Lituania, Romania, Poland, Portugal, Spain, Sweden, Norway, Slovakia, Spain, Sweden, Switzerland, and the UK) were extensively consulted to validate the data produced during the interview stage. As part of the IEA Annex 80 activities, we contacted experts from the annex and experts who are not associated with the annex to cover the 26 countries. More than 250 articles, standards, reports, and websites were consulted and reviewed based on the input provided by the first authors of two literature review papers [39,41]. We focused mainly on national and international standards and included reports and studies published by the building energy efficiency industry and scientific community.

3.3. Climate zone

The different EU countries' climate disparity and geographical context are part of the study. The study adopted a sensitive approach to cluster and group countries climatically. Overheating calculation and thermal comfort thresholds depend strongly on the local climate and topographical relief. Therefore, the study was inspired by the European Environmental Agency map that divides the continent into four nuanced climatic zones [44]. As shown in Fig. 4, the subtropical climates cover most of the southern part of Europe, including Bulgaria, Cyprus, Croatia,

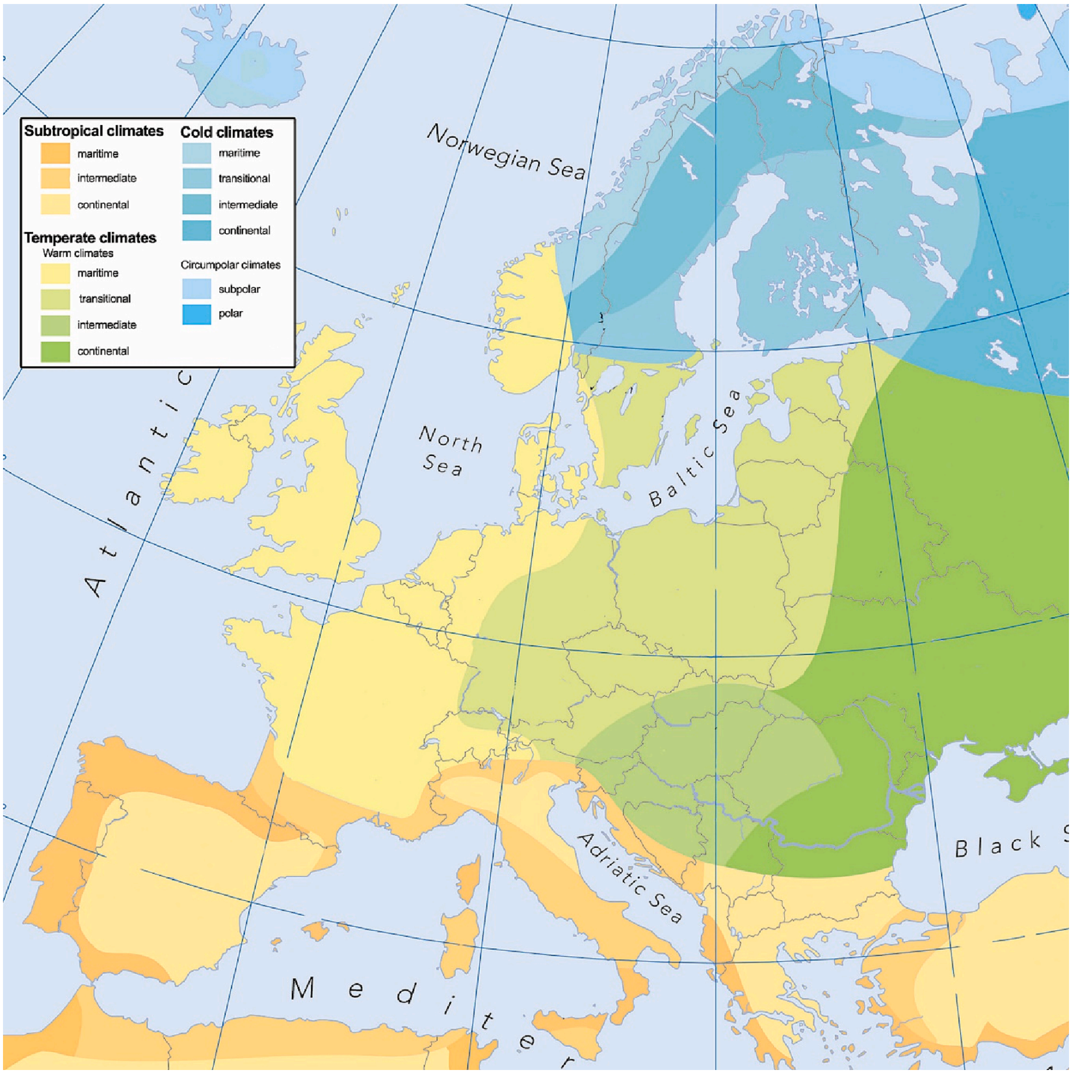

Fig. 4. The four major European climate zones according to the European Environment Agency (EEA) [44].

Italy, Spain, Greece, Portugal, and France. The main characteristics of this climate are dry winter and hot summer. The temperate climate with warm climates covers the East, West, and North of Europe, including Belgium, Czechia, Hungary, Latvia, Lithuania, Norway, Romania, Slovakia, Sweden, Austria, Denmark, Switzerland, Estonia, France, Germany, Netherlands, and Poland. The main characteristics of this climate are without a dry season and warm summer. The temperate climate, with a group of cold climates, covers the extreme north of Europe, including Norway and Sweden. The main characteristics of this climate are cold winter and temperate summer. The circumpolar climates do not concern this study because it is in the extreme North of Europe. Under this classification, the study aimed to generate climate-sensitive recommendations and evaluation the existing calculation methods from a wide pan-European climate perspective, beyond the limit of national approaches.

4. Result

A detailed report (see Appendix 2) was published, including all interview answers and filled-in tables [43]. However, for this paper, we selected the essential outcomes and classified them under five sections, described below:

4.1. Summary of the main regulations on thermal comfort in residential buildings (inventory)

Existing calculation methods and criteria to assess thermal comfort and overheating in 26 European building codes were analyzed based on the national EPBD regulations. Based on Fig. 3, a comparative table with five classification criteria for all investigated countries was created. The table is large and cannot be visible in this article but can be found in Appendix 3. To visualize the comparative table, a representative figure was created. Fig. 5 is an infographic illustration of the comparative table in Table 1 and Appendix 3. The Figure indicates a huge disparity and diversity between the calculation methods found. Almost every country has its calculation method. The calculation methods disparity does not reflect modern and climate change fit methods.

Next, a summary of overheating calculations and indicators in the investigated countries was created. The result of the standards reviews shown in Table 1 lists the equations and parameters of the overheating calculation. Table 1 and Fig. 5 are considered the basic form of the screening results. Table 1 results from the literature review presented in Section 2 and provided a more detailed comparison of overheating calculation methods. Table 1 is one of the early results used as an inventory for the further analysis step presented in the following section.

Country

Climate & Weather Data

- Is comfort dependent on national geographic climate zones? If yes, list them.
- Do you have a specific comfort calculation approach for heat waves?
- Do you take into account the urban heat island effect?
- Does your overheating methodology take into account future climate change weather files with extreme scenarios?

Occupant representation

- Does your method embrace the occupant and building categories (e.g. I, II, III, IV EN15251)?
- How do you represent occupancy presence in the simulation model?

Thermal comfort model & Overheating calculation

- What is overheating provisions period coverage?
- What is the comfort standard?
- Is your comfort model based on an adaptive or static method?
- What are your comfort thresholds?
- What is your overheating indicator?
- What are your overheating thresholds? And according to which standard are those thresholds defined?
- Is there a distinction between naturally ventilated, air-conditioned, and mixed-mode buildings?
- Does your model consider local personalized heating/cooling & ventilation systems (ceiling fans, air-conditioned chairs, electric heating mattresses...)?

Simulation Model

- Is your calculation based on a static/quasi-dynamic/dynamic model? What is the calculation time step?
- Is your overheating calculation based on a single or multi-zone model?
-.Does your calculation distinguish sleeping rooms from other living areas?

Mandatory Envelope Requirements

- Does your method oblige the installation of external shading?
- Does your method oblige the limitation of the window-to-wall ratio? If yes, what is the limit?
- Does your method recommend a g-value? If yes, what is the limit?

Fig. 5. Infographic of the information gathering during interviews.

Table 1
Summary of overheating evaluation methods for each country including the nomenclature.

Country	Overheating indicator	Equation
Austria	Daily maximum of the hourly operative temperature of the room (DM)	$DM = max_{day}(T_{op,i,})$ Where $i = 1am\,to\,12pm$
Belgium (Brussels)	Percentage of hours outside the range (%PhOR)	$\%\mathrm{PhOR} = \frac{\sum_{i=1}^{occupiedhours} wf_i.h_i}{\sum_{i=1}^{occupiedhours} h_i} \times 100$ Where $\begin{cases} wf_i = 1;\ T_{a,i} > 25^{\circ}C \\ wf_i = 0;\ T_{a,i} \leq 25^{\circ}C \end{cases}$
Belgium (Flanders and Wallonia)	Time-integrated overheating index (I_{overh})	$I_{overh} = \sum_{m=1}^{12} Q_{excessnorm,m}\,[Kh]$ With $Q_{excessnorm,m} = \frac{(1-\eta_{util,\,overh,m}).Q_{g,\,overh,m}}{H_{T,\,overh} + H_{V,\,overh}}.\frac{1000}{3,6}$
Bulgaria	Operative temperature	T_{op}
Croatia	Operative temperature	$T_{op} + T_{SolarRadiationGains}$
Czechia	Maximum daily indoor air temperature in the critical room (DM_{cr})	$DM_{cr} = max_{day}(T_{op,i,criticalroom})$ With $i = 1am\,to\,12pm$
Denmark	Operative temperature	T_{op}
Estonia	Hours of exceedance of the indoor temperature (He)	$He = \sum_{m=June}^{August}\sum_{i=1}^{24h} wf_{i,m}.h_{i,m}$ Where $\begin{cases} wf_i = 1;\ T_{op,i,m} \geq 27^{\circ}C \\ wf_i = 0;\ T_{op,i,m} < 27^{\circ}C \end{cases}$
Finland	Air temperature	T_{air}
France	Statistical summer discomfort duration: degree hours (Dh)	$Dh = wf_i\sum_{i\in occupiedhours}.T_{op,i} - T_{Setpoint,i}$ Where $\begin{cases} wf_i = 1; \begin{cases} T_{op} \geq 26^{\circ}C to 28^{\circ}C(day) \\ T_{op} \geq 28^{\circ}C(night) \end{cases} \\ wf_i = 0; \begin{cases} T_{op} \leq 26^{\circ}C to 28^{\circ}C(day) \\ T_{op} \leq 28^{\circ}C(night) \end{cases} \end{cases}$
Germany	Solar transmittance index (S_{vorh})Hours of exceedance of the indoor temperature (He)	$S_{vorh} = \frac{\sum_j (A_{W,j} + g_{tot,j})}{A_G}$ and $S_{zul} = S_1 + S_2 + S_3 + S_4 + S_5 + S_6$ and $S_{vorth} \leq S_{zul}$ $He = \sum_{year}\sum_{i=1}^{24h} wf_i.h_i$ Where $\begin{cases} wf_i = 1; \begin{cases} T_{op} \geq 25^{\circ}C(climateA) \\ T_{op} \geq 26^{\circ}C(climateB) \\ T_{op} \geq 27^{\circ}C(climateC) \end{cases} \\ wf_i = 0; \begin{cases} T_{op} < 25^{\circ}C(climateA) \\ T_{op} < 26^{\circ}C(climateB) \\ T_{op} < 27^{\circ}C(climateC) \end{cases} \end{cases}$
Greece	Operative temperature	T_{op}
Hungary	Average internal heat (qb)Average temperature difference between indoor and outdoor (Δtb)	$qb = \frac{\sum_{i\in ocuupied\ hours} Q_i}{A_{floorbuilding}\sum_{i\in ocuupied\ hours} i}\Delta tb = \frac{\sum_{i\in dhoursday} T_{in,i} - T_{out,i}}{\sum_{i\in hoursday} i}$
Italy	No overheating criteria only operative temperature	T_{op}
Latvia	Hours of exceedance of the operative temperature (He)	$He = \sum_{m=May}^{September}\sum_{i=1}^{24h} wf_{i,m}.h_{i,m}$ Where $\begin{cases} wf_i = 1;\ T_{op,i,m} \geq 27^{\circ}C \\ wf_i = 0;\ T_{op,i,m} < 27^{\circ}C \end{cases}$
Lithuania	Average indoor temperature (At)	$At = \frac{\sum_{i\in non-heating\ season} T_{op,i}}{\sum_{i\in non-heating\ season} i}$
Netherlands	Cooling demand and heat transfer coefficient index ($TO_{Juli;or,zi}$) Hours of exceedance of PMV by + 0.5 (GTO)	$TO_{Juli;or,zi} = \frac{(Q_{C,nd,juli,or,zi} - Q_{C,HP,juli,or,zi}) \times 1000}{(H_{C,D,juli,or,zi} + H_{gr,an,juli,or,zi} + H_{C,ve,juli,or,zi}) \times h_{juli}} GTO = \sum wf_{i,NTA8800}$
Norway	Hours of exceedance of the outdoor temperature (He_{out})	$He_{out} = \sum_{m(1year)}\sum_{i=1}^{24h} wf_i.h_{i,\,out}$ Where $\begin{cases} wf_i = 1;\ T_{op,i,m} \geq 26^{\circ}C \\ wf_i = 0;\ T_{op,i,m} < 26^{\circ}C \end{cases}$
Romania	PMV indices	PMV indices of ISO 7730 and $-0,5 < PMV < +0,5$
Slovakia	Operative temperature	T_{op}
Spain	Solar gains indicator ($q_{sol,jul}$)Percentage of exceedance hours (%He)	$q_{sol,jul} = \frac{Q_{sol,,juli}}{A_{util}}$ Where $Q_{sol,,juli} = \sum_k F_{sh,obst,k}.g_{tot,sh,wi,k}.(1 - FF_k).A_{w,p,k}.H_{sol,juli}$ $\%He = \frac{\sum_{m=June}^{September}\sum_{i\in hours} wf_i.h_{m,i}}{\sum_{m=June}^{September}\sum_{i\in hours} h_{m,i}} \times 100$ Where $\begin{cases} wf_i = 1; \begin{cases} T_{op} > 25^{\circ}C, i \in [3:00;10:59]pm \\ T_{op} > 27^{\circ}C, i \in [11:00\mathrm{pm};6:59\mathrm{am}] \end{cases} \\ wf_i = 0; \begin{cases} T_{op} \leq 25^{\circ}C, i \in [3:00;10:59]pm \\ T_{op} \leq 27^{\circ}C, i \in [11:00\mathrm{pm};6:59\mathrm{am}] \end{cases} \end{cases}$
Sweden	Operative temperature	T_{op}
Switzerland	Operative temperature	T_{op}
UK	Percentage of exceedance hours (%He) Percentage of sleeping hours outside the range (%$PShOR$)	$\%He = \frac{\sum_{i=1}^{occupiedhours} wf_i.h_i}{\sum_{i=1}^{occupiedhours} h_i} \times 100$ Where $\begin{cases} wf_i = 1;\ T_{op,i} - T_{op,i,up} \geq 1^{\circ}C \\ wf_i = 0;\ T_{op,i} - T_{op,i,up} < 1^{\circ}C \end{cases}$ $\%PShOR = \frac{\sum_{d=1}^{d=365}\sum_{10pm}^{7pm} wf_i.h_i}{\sum_{d=1}^{d=365}\sum_{10pm}^{7pm} h_i} \times 100$ Where $\begin{cases} wf_i = 1;\ T_{op,i} > 26^{\circ}C \\ wf_i = 0;\ T_{op,i} \leq 26^{\circ}C \end{cases}$

4.2. Develop a set of criteria for overheating calculation in Europe

In this section, the focus is on the evaluation and comparison of the methods, criteria, and indicators for detecting and characterizing overheating. A set of criteria can be used to assess different overheating evaluation methods. Some of these criteria have been developed in previous studies [45], while others are newly defined. It is important to note that the specific criteria used in the evaluation may vary depending on the specific application or context. However, having a set of universal criteria can provide a useful starting point for evaluating different methods and comparing their effectiveness. Eight criteria are used that are described below as a result of analyzing the inventory presented in Section 4.1.

1. **Thermal comfort-based or heat balance-based:** This criterion assesses whether the method is based on comfort parameters or the heat balance between indoor and outdoor environments. Comfort parameters refer to variables that affect human comfort, such as air

temperature, radiant temperature, relative humidity, air velocity, metabolic rate, and clothing factor. Methods based on comfort parameters typically aim to maintain a comfortable indoor environment for people by controlling these variables. In contrast, a heat balance approach considers the thermal behavior of the indoor and outdoor environments. This approach considers factors such as the building envelope, ventilation, and solar gains and aims to maintain an overall balance between the heat gains and losses in indoor and outdoor environments [46].

2. **Time-Integrated or punctual:** This criterion assesses whether the method is time-integrated or punctual. Time-integrated methods quantify overheating over a span of time, giving a more thorough picture of thermal performance over a given period. Punctual methods, however, are *"right now"* and *"right here"* approaches to limit instant overheating in buildings.
3. **Multi-zone or single-zone:** This criterion evaluates whether the method considers building a single-zone or multi-zone environment. A single-zone approach assumes the building is a single space with uniform thermal conditions. In contrast, the multi-zone approach recognizes the differences in thermal conditions between different parts/zones of the building [47].
4. **Static and/or adaptive thermal comfort model:** This criterion assesses whether the method relies on a comfort model and, if so, what model is used. Static and adaptive thermal comfort models are two main categories [48], with the former using fixed parameters to provide comfortable conditions and the latter using real-time data to adjust comfort limits [49] based on changing outdoor weather conditions [50].
5. **Normalization to occupied hours:** This criterion assesses whether the index of a method is normalized to occupied hours. Normalized indices allow for the possibility that different buildings may have varying occupancy profiles and thus have varying cooling/heating requirements at different times. Normalizing the index to the occupied hours makes it possible to compare different buildings with varying occupancy profiles more meaningfully. This enables the fair comparison of buildings with different usage patterns, leading to more accurate and credible overheating risk assessments.
6. **Short-term criteria or/and long-term criteria:** Short-term and long-term criteria are used to set threshold values for limiting overheating in buildings during different time scales [51]. Short-term criteria focus on hourly, daily, or weekly periods to prevent overheating during resiliency events [52], such as heatwaves and power outages, which can lead to sudden impacts on the thermal comfort of building occupants. The role of thermal mass and heat storage of the building structure and surfaces is essential. In contrast, long-term criteria limit extensive overheating over longer periods, such as monthly, seasonal, or annual, and consider the cumulative effects of temperature increases over time [53]. Both indicators and metrics are needed to increase the thermal resilience of residential buildings during heat events [54].
7. **Occupant representation:** This criterion examines, if it exists, the occupant representation model defined for overheating simulations/calculations. The occupant representation describes the behavior of the occupants in the building, which includes the number of occupants, the use of spaces, etc. Stochastic and deterministic models are the two principal models for occupant representation. The stochastic models are based on statistical data to establish random occupant behavior, whereas the deterministic models are more detailed and accurate.
8. **Climate zone-specific:** This criterion evaluates whether the method is tailored to the specific climate conditions of a particular region. The methods or criteria that are effective in one climate zone may not be effective in another and may lead to overestimation/underestimation of overheating incidents.

4.3. Classify and categorize regulations according to similarity (classification)

Table 2 and Fig. 6 identify the main difference that distinguishes the overheating calculation methods. Table 2 compares each country's overheating calculation methods and requirements based on the eight criteria listed in Section 4.2. Fig. 6 illustrates and compares the studied countries spatially. Based on the study report [43], 26 countries were analyzed.

4.4. Selection of six outstanding countries (selection)

This section aimed to identify the most outstanding overheating national calculation method based on the eight study criteria explained in Section 4.2. The eight criteria represent the state-of-the-art for evaluating overheating in residential buildings based on comfort-based and multi-zonal modeling. Table 3 presents a summary of the mapping results. The following paragraph lists and describes six European countries' most outstanding overheating calculation methods.

Switzerland:

The Swiss comfort calculation is based on a specific summer period definition. The calculation utilizes a Design Reference Year that includes average heat waves in the Swiss climate. Future climate change scenarios will be incorporated into the standard, with two scenarios for 2035 and 2050. The future weather files available can be used in the calculation. The thermal comfort calculation is based on operative temperature and adaptive comfort limits diagrams that define thresholds for naturally ventilated and air-conditioned buildings [55]. For naturally ventilated buildings, the maximal upper-temperature limit is higher than for actively cooled residents. The calculation methods allow for personalized local cooling and consider the proximity of occupants to heating, cooling, and ventilation systems. Also, the standard has specific occupancy schedules. The simulation is fully dynamic, and its calculation varies between one hour to a few seconds. The overall building thermal model is multi-zonal.

Spain:

The Spanish overheating calculation method is based on a detailed climatic zoning approach. The calculation method follows a heat balance approach. The country is divided into twelve parts and has five levels of winter from the most temperate zone A to the coldest E and three levels of summer from the mildest 1 to the warmest 3. The overheating calculations are only mandatory for the summer climate zone and are based on the data file of 2005. Solar gains are calculated assuming that solar radiation during July must not exceed 2.00 kWh/m^2.month for any opening; otherwise, the heat gain must be reduced through shading systems, WWR reduction, and the modification (lowering) of the g-value. Between June and September, temperatures in living and sleeping rooms must not exceed more than 4% of the total annual hours for new constructions and newly renovated buildings. The operative overheating temperature is at 27 °C (from 11:00 pm to 6:59 am -> have night limitation) and 25 °C (from 3:00 pm to 10:59 pm) [10]. The calculation method is based on a dynamic simulation model with a 1-hour calculation time step. The modeling approach allows for single-zone and multi-zone models based on pre-set hourly schedules.

Estonia:

Estonia's overheating calculation method is based on a dynamic model with hourly occupancy profiles. Indoor air temperature is used as the overheating indicator. Residential buildings should comply with 150 Kh above 27 °C for the indoor temperature (long-term criteria). The calculation model considers local, personalized heating/cooling & ventilation systems. The calculation approach allows adopting an adaptive thermal comfort approach based on CEN 16798; the cooling systems are sized with static thermal comfort requirements. Four major prescriptive requirements must be met in living rooms and bedrooms regardless of the simulation results: 1) the limitation of the WWR ≤ 0.4; 2) window-to-floor ratio ≤ 0.15; the presence of effective openable

Table 2
Characterization by the criteria of overheating calculation methods.

Country	1: Comfort based or heat-balance based calculation	2: Time-integrated or punctual calculation	3: Multi or single zone calculation	4: PMV-PPD or adaptive thermal comfort model	5: Normalization to occupied hours	6: Short-term or long-term criteria	7: Occupant representation	8: Climate zone-specific
Austria	Comfort	Time-integrated	Single-zone	Adaptive	No	Long-term	Yes	Yes
Belgium (Brussels)	Comfort	Time-integrated	Multi-zone	PMV-PPD	Yes	Long-term	Yes	Yes
Belgium (Wallonia and Flanders)	Heat-balance	Time-integrated	Single-zone	PMV-PPD	Yes	Long-term	Yes	Yes
Bulgaria	Comfort	Punctual	Multi-zone	PMV-PPD	No	No	No	Yes
Croatia	Comfort	Punctual	None	PMV-PPD	No	No	No	No
Czechia	Comfort	Time-integrated	Single-zone	PMV-PPD	No	Long-term	No	No
Denmark	Comfort	Time-integrated	Single-zone	Adaptive	Yes	Long-term	No	No
Estonia	Comfort	Time-integrated	Single or multi-zone	Adaptive and PMV-PPD	No	Long-term	Yes	No
Finland	Comfort	Time-integrated	Multi-zone	PMV-PPD	No	Long-term	Yes	No
France	Comfort	Time-integrated	Multi-zone	Adaptive and PMV-PPD	Yes	Long-term	Yes	Yes
Germany	Both[a]	Both[a]	Single-zone	Adaptive and PMV-PPD	No	Long-term[a]	Yes	Yes
Greece	Comfort	Time-integrated	Single-zone	Adaptive	No	Long-term	Yes	Yes
Hungary	Both[b]	Both[b]	Single-zone	PMV-PPD	Both[b]	Short-term[b]	No	No
Latvia	Comfort	Time-integrated	None	PMV-PPD	No	Long-term	No	No
Lithuania	Comfort	Time-integrated	Single-zone	PMV-PPD	No	Long-term	No	No
Netherlands	Both[c]	Time-integrated	Multi-zone	PMV-PPD	No	Long-term	Yes	No
Norway	Comfort	Time-integrated	Multi-zone	Adaptive or PMV-PPD	No	Long-term	Yes	No
Romania	Comfort	Punctual	Single or multi-zone	PMV-PPD	No	No	Yes	Yes
Slovakia	Comfort	Punctual	Single-zone	PMV-PPD	No	No	No	Yes
Spain	Both[d]	Time-integrated	Single or multi-zone	PMV-PPD	No	Long-term	Yes	Yes
Sweden	Comfort	Punctual	Multi-zone	PMV-PPD	No	Long-term	Yes	No
Switzerland	Comfort	Time-integrated	Multi-zone	Adaptive	No	Long-term	Yes	No
UK	Comfort	Time-integrated	Multi-zone	Adaptive and PMV-PPD	Yes	Long-term	Yes	No

window as a fraction $\geq$0.1; 3) g-value and 4) WWR $\times$ $g \leq$0.2, for single-family [42].

Germany:

The German calculation approach classifies the country into three summer climatic regions. In general, the operative temperature should exceed 26 °C. However, in Regions C, which represents metropolitan areas, upper and the middle Rhine, the operative temperature should not exceed 27 °C. The dynamic calculation method is based on a single-zone model with hourly or fewer calculation time steps. A detailed occupancy schedule is used with an internal gain of 100 $\text{Wh/m}^2_{\text{NFA}}$ for residential buildings [56]. Two calculation approaches are possible: a simplified solar transmittance static indicator method and an adaptive method for the thermodynamic simulation method. Overall the overheating temperature hours per year should not exceed 1200 Kh [57].

UK:

The British overheating calculation methods allow using local weather files for design summer years: DSY1 = the 2020s, DSY2 = 2050s, and DSY3 = 2080. However, the use of those files is not mandatory. The two main calculation indicators are 1) hours of exceedance and 2) the operative temperature. The modeling approach is multi-zonal with an hourly dynamic simulation [58]. The calculation approach distinguished homes that are predominantly naturally ventilated and predominantly mechanically ventilated [59]. For mechanically ventilated households, occupied rooms' operative temperature should be below 26 °C and can only exceed 3% of annual occupied hours.

For naturally ventilated, the exceedance hours (May to September) are set for living rooms, kitchens, and bedrooms. In bedrooms, the operative temperature should stay lower than 26 °C and cannot exceed 1% of annual hours of sleeping between 22:00 to 07:00. The methodology recommends a *g-value* for all external and internal building elements, plus additional shading features. Airspeed in space is considered, assuming the presence of a ceiling fan or other system that can generate air movement. The Maximum sensible heat gain of 75 W/person and a maximum latent heat gain of 55 W/person in living spaces should not be exceeded. An allowance for 30% reduced gain is considered during sleeping [60].

France:

The French overheating calculation is based on climatic zoning that divides the country into eight geographic zones. Heat waves are considered a basic event in all simulations' weather files. The calculation is based on a normalized indicator of occupied hours overheating as degree hours that should not exceed 2600 °C.h per year. A distinction between naturally ventilated and air-conditioned buildings are made. The modeling approach is multi-zonal with a schedule representation of occupancy presence. The Predicted Mean Vote – Percentage of People Dissatisfied (PMV-PPD) model is used during the night, where the operative temperature should not exceed 26 °C (20:00 to 07:00). This is a mandatory requirement in naturally-ventilated households. An adaptive thermal comfort model based on CEN 16798 is applied during the day. The operative temperature threshold falls between 26 °C and 28 °C, considering the occupant's capacity for adaptation [61]. The model is dynamic, with a time step of at least one hour. The designer must install an active cooling system if the building cannot meet the thermal comfort in any thermal zone [10].

In summary, the study findings (Table 3) pointed out France as a European country with one of the most advanced overheating calculation methods. The French calculation method is based on a bioclimatic approach with highly ambitious energy efficiency requirements (10 $\text{kWh/m}^2\text{/year}$), sometimes exceeding the PassiveHaus standard [14]. On the other hand, the French calculation approach allows the application of static (PMV/PPD) or adaptive thermal comfort models. More

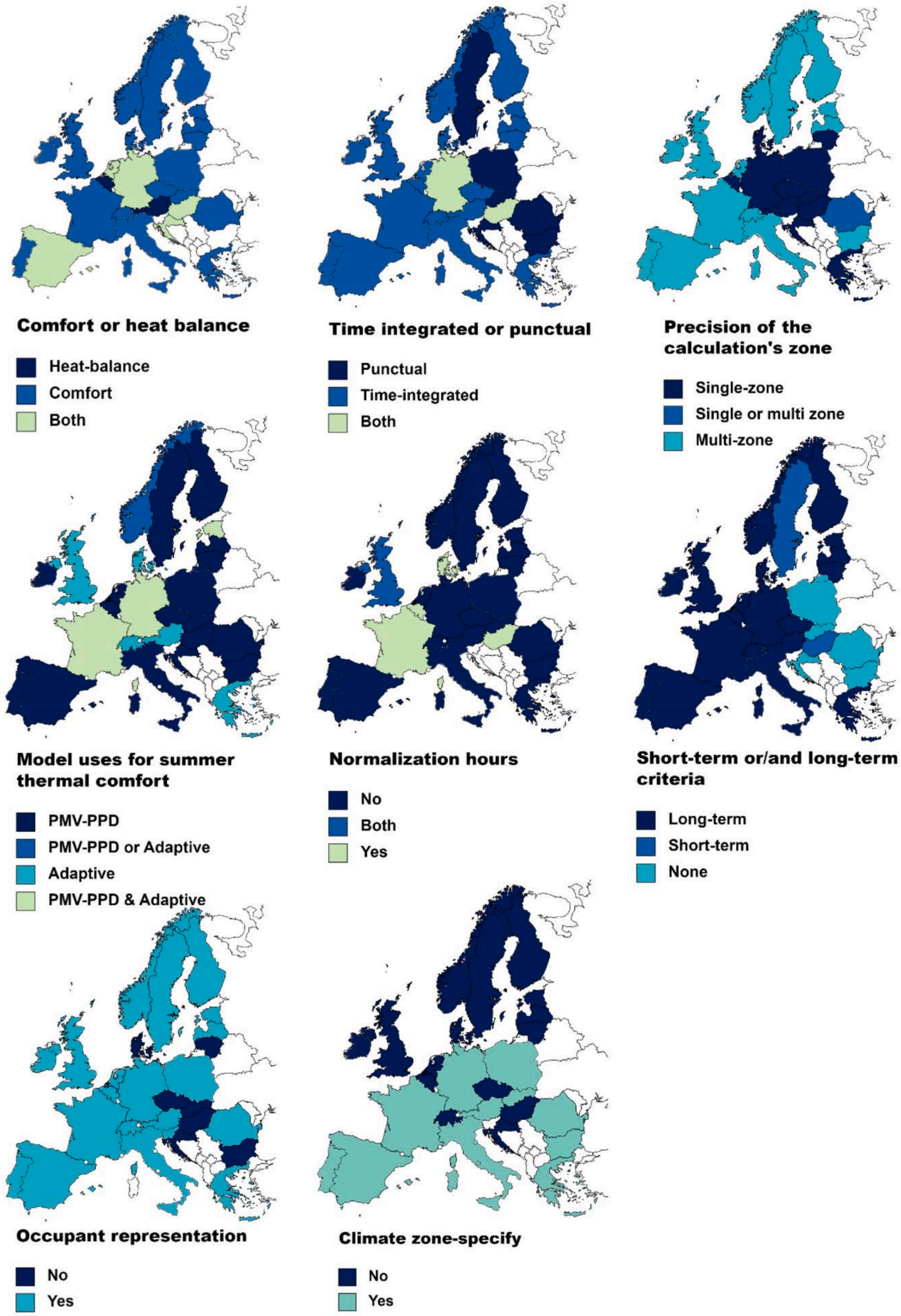

Fig. 6. Mapping of overheating calculation methods across Europe.

importantly, the RE2020 protects occupants and requires a mixed/mode operational model for naturally ventilated households, where the operative temperature should not exceed 26 °C (20:00 to 07:00) in sleeping rooms. This is the first standard in Europe that adopts a mixed-mode approach for overheating calculations.

4.5. Propose factors that should be considered to advance the overheating assessments in future revisions of building regulations (future criteria)

Finally, the analysis and discussions taken in this study on overheating calculation methods highlighted the key factors that should be

Table 3
Classification by the eight criteria from the more advanced to the less advances overheating calculation methods.

Country	Score	Criteria	Categories	Weighted point
France	**9**	1: Comfort based or heat-balance based calculation	Heat-balance	0
UK	**8**		Comfort	1
Germany	**7**		Both	1
Estonia	**6**	2: Time-integrated or punctual calculation	Punctual	0
Spain	**6**		Time-integrated	1
Switzerland	**6**		Both	1
Austria	6	3: Multi or single zone calculation	Single-zone	0
Greece	6		Single-zone or multi-zone	0
Belgium (Brussels)	6		Multi-zone	1
Belgium (Wallonia and Flanders)	5		Single-zone and multi-zone	1
Denmark	5	4: PMV-PPD or adaptive thermal comfort model	PMV-PPD	0
Finland	5		PMV-PPD or Adaptive	0
Netherlands	5		Adaptive	1
Norway	5		PMV-PPD and Adaptive	2
Hungary	4	5: Normalization of hours	No	0
Sweden	4		Yes	1
Bulgaria	3	6: Short-term or/and long-term criteria	Short-term	1
Czechia	3		Long-term	1
Latvia	3	7: Occupant representation	No	0
Lithuania	3		Yes	1
Romania	3	8: Climate zone-specific	No	0
Slovakia	2		Yes	1
Croatia	1			

considered to advance the overheating assessments in future revisions of building regulations. Experts intensively pinpointed the following topics:

- Climate change and more current historical data and future climatic scenarios are essential in future calculation approaches.
- Consideration of the urban heat island effect and limitation of night cooling is needed. There is a need for the use of local weather files to quantify the effects of ventilative cooling [62,63]. Addressing heavily populated areas must be brought into calculation methods.
- There is a need for short-term criteria or/and long-term criteria to prepare a building for thermal resilience and not only thermal resistance.
- There is a need to use a common language for calculation (ISO 52000–1 2017 [64] and CEN 13790 [65]) and push the concept of symmetry. By symmetry, we mean conducting calculations for the summer and winter. The winter season must be considered in any future overheating calculation approach.
- There is a need to refine the calculation methods and introduce multiple parameters based on real measurements, including wind speed, radiant T°C, and humidity…
- Despite the importance of the performance-based approach, there is a need to define prescriptive requirements for imposing building envelopes (external shading, WWR limits, and maximum *g-values* …)
- There is a need to explore the operation of buildings in mixed modes using PMV-PPD and adaptive models directly related to occupants' health and well-being, especially in sleeping rooms [66].

5. Discussion

This study provides a cross-study to identify the difference in the overheating calculation in European regulation. It provides recommendations for harmonizing and improving the Energy Performance of Buildings Directive. In the following section, we present the key study finding and recommendations. The strength and limitations of the paper are discussed, followed by a discussion on the implication on practice and future scientific research.

5.1. Study findings

The situation of overheating calculation methods is very complex in Europe. There is a huge disparity between countries and almost no common approach to addressing overheating in residential buildings [40] rigorously. For this study, we compared the regulations, indicators, and thresholds in 26 countries over three years to understand the different calculation methods and to be able to distinguish them. We understand that a huge continent like Europe has different climates and behavioral thermal adaptation measures [67]. However, none of the investigated countries dedicated enough resources to develop an optimum climate change-sensitive approach that fits Europe's aging population. Most of the current calculation methods are outdated and do not fit the purpose of well-being [68]. Most countries rely heavily on a PMV-PPD model that requires active cooling systems, models households as single zones and does not distinguish between living and sleeping rooms. Therefore, there is a need to join forces and address overheating collectively.

Out of 26 countries, the study findings pinpointed Switzerland, Spain, Estonia, Germany, the UK, and France as leaders in evaluating overheating in the domestic sector. Based on Table 3, France has been ranked as the most consistent and climate-sensitive calculation approach. Other investigated countries have already revised their calculation methods addressing different climate comfort models and thermal zone. However, the pace of change is still slow and does not address the issues raised by experts in Section 4.5. Thus, there is no solid or comprehensible distinction between air-conditioned, naturally ventilated, and mixed-mode building operations. In our opinion, the lack of standards on the mixed-mode operation of the residential building is one of the key challenges to a suitable calculation method.

Our review indicates three key indicators that quantify overheating duration and intensity in buildings. Firstly, the percentage of occupied hours when an operative temperature exceeds a certain threshold of the annual occupied hours based on a PMV/PPD or adaptive comfort for a specific comfort category (I, II, III or IV). The indicator is used by many European standards that address overheating calculation, including CIBSE (Guide A, TM52, and TM59), The Passive House Standard, CEN 16789, and ISO 17772. Table 4 provides example of the exceedance hours indicators in existing thermal comfort standards. Secondly, the Standard Effective Temperature (SET) is based on the six thermal comfort parameters: air temperature, radiant temperature, air velocity, humidity, clothing, and metabolism. Regardless of the thermal comfort (PMV/PPD or adaptive) model used, we urge using more flexible indicators that consider the effect of airspeed and humidity. Thirdly, the Indoor overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), and overheating escalation factor ($aIOD = AWD$) developed by Hamdy et al. (2011) [68] and adopted by the IEA Annex 80 [69].

Finally, the paper proposes eight overheating calculation criteria

Table 4
Examples of exceedance hours thresholds in existing thermal comfort standards.

Standard	Temperature threshold	Exceedance hours threshold
ISO 17772–2 CEN 16798–2	26 °C (Cat. II)	6% (annually) – 25% (monthly) – 50% (weekly) during occupied hours
Passive House Standard	25 °C	10% (Annually) all hours (not only occupied hours)
CIBSE Guide A (2019)	=>27 °C (Cat. II)	Mechanically heated and cooled 3% (annually) during occupied hours
CIBSE TM52	=> 27 °C (Cat. II)	Free running buildings – 3% during occupied hours during Typical non-heating season (1 May to September)

presented in Section 4.2 that can help designers and practitioners to compare and select an appropriate methodology for climate-proof building design. New criteria and metrics for the thermal resilience of residential buildings are needed during heat events. In a changing climate, there is increasing concern about the risk of overheating in EU domestic buildings. A consistent and unified approach to overheating calculation in buildings is needed. This paper identifies key performance indicators to develop a consistent and appropriate overheating calculation methodology for the EPBD within a resilience paradigm [20]. The indicators can be elaborated and extended through performance thresholds and prescriptive requirements to form a common framework for future Europe calculation approaches.

5.2. Study recommendations

Therefore, we strongly recommend developing a common climate-sensitive calculation framework based on European standards for overheating estimation and thermal autonomy [70]. Eight parameters related to the overheating calculation are recommended: Time-Integrated or punctual to quantify overheating over a while, multi-zone or single-zone, static and adaptive thermal comfort model, normalization to occupied hours, short-term criteria or/and long-term criteria, occupant representation, and climate zone-specific. Based on the study findings, we recommend a set overheating indicator including the Indoor overheating Degree (*IOD*), Ambient Warmness Degree (*AWD*), overheating escalation factor ($aIOD = AWD$), and Standard Effective Temperature.

The study indicates that the French regulation is the most advanced regarding the overheating calculation in Europe according to the eight criteria reported in Sections 4.2 and presented in Section 4.4. The French Standard RE2020 fixes a maximum temperature of 26 °C in sleeping rooms at night. It requires an adaptive thermal comfort model based on CEN 16789 that allows the operative temperature to fluctuate between 26 and 28 °C in other housing zones. However, the upper limit of operative temperature can be further pushed to higher ranges if air velocity and humidity change. Therefore, we strongly recommend using the Standard Effective Temperature (SET) as an additional indicator to allow for higher upper operative temperatures during heatwaves in households while increasing the air velocity (beyond ASHARE 55 [72, p. 55]) and controlling humidity.

Also, there is a need for a constantly updated climate classification map that includes recent heating-degree days (HDD) and cooling-degree days (CDD) data provided by the European Union (EU). Without a detailed climatic and topographic standard map for Europe, we will fall under national climatic classifications that impede any unified calculation approach [72]. Next, a set of thermal comfort criteria with commonly acceptable thresholds for minimum comfort must be defined concerning the climate specificity represented in HDD and CDD. Also, issuing Energy Performance Certificates (EPC) must include a design review step associated with a post-construction inspection to address overheating risk for building design and renovation [73]. The variation in thermal performance of the building with the same EPC is any more acceptable [58]. EPC should make overheating calculations across member states more comparable.

Moreover, there is a need for mandatory prescriptive requirements for the WWR and g-values. More importantly, external shading protection must be mandatory in cooling-dominated, and overheating risked households. It is time that Europe introduced mandatory envelope requirements. Finally, an advanced dynamic simulation approach must be generalized in all countries to test future climate scenarios and extreme heat wave events and allow for a multi-zonal approach that distinguishes sleeping rooms. For further details, see Section 4.5.

5.3. Study strengths and limitations

In this study, we created a cross-sectional study that provides a snapshot and advice for overheating calculation methods across Europe. We gathered detailed information on 26 Europe countries in a systemic ay involving more than 15 national experts. The study included experts on the IEA Annex 80 on Resilience Cooling in Buildings. It was developed in close consultation with the annex activities as part of Group D [74]. To the best of our knowledge, no existing study compared overheating calculation methods comprehensively in Europe like this study [46]. The implications of this study can benefit countries beyond the EU, allowing the exploration of different indicators and thresholds. Also, the study succeeded in proposing an updated and detailed study report, in line with the EPBD, that pinpoints the weaknesses and strengths of the current regulatory landscape.

At the same time, we know the study is qualitative and could have been more valuable if it had adopted a quantitative modeling approach. Also, once published will be considered outdated due to the continuous modifications introduced in the regulations of 26 member and non-member states and the new EPBD recast that should be published in 2023 or 2024. However, the study remains highly valuable because it presents a snapshot and comparison of Europe’s current overheating calculation methods. This is the first study that provides such an exhaustive comparison and dataset that is the first step to conducting quantitative analysis afterward. More importantly, the study presents constructive and futuristic recommendations of utmost utility and benefit for the future EPBD recast.

5.4. Implications for practice and future research

There is a need to revise the EPBD calculation framework and calculation method approach. Soon, European environmental regulations will require building with timber and bio-based materials. As a consequence, the risk of overheating risk in lightweight construction is increasing [34]. Overheating is a critical problem that will be manifested across European households during this century. The current calculation methods require more accurate ways to help the designer to adapt buildings and renovate beyond the current overheating calculation methods’ limitations. There is a need for funding projects that allow the development, testing, and implementation of novel methods of overheating calculation. The direct implication of such development is enabling architects and engineers to design climate-proof buildings that can consider future weather scenarios.

Future research should compare the different calculation methods for benchmarking purposes. Researchers should seek to develop calculation methods in mixed-mode operations [75]. There is a need to learn from similar studies on thermal resistance and resilience calculations in other regions [76]. Modeling resiliency events such as power outages and extreme heat waves requires further investigation [77]. Also, experimental validation of simulation and measurement-based overheating assessment approaches for residential buildings is needed [78]. Monitoring summer indoor overheating in cities is essential. More case studies should be presented to test the different control logic [79] and strategies [80], overheating indicators, and thresholds concerning public health and mortality rates. The next step of this research is to test the different overheating calculation methods through a quantitative approach that involves building modeling for benchmarking.

6. Conclusion

The suitability of existing overheating calculation methods in the EPBD was investigated and compared against new and emerging methods [69,81]. Eight parameters related to overheating calculation were selected: Time-Integrated or punctual, multi-zone or single-zone, static and/or adaptive thermal comfort model, normalization to occupied hours, short-term criteria or/and long-term criteria, occupant representation, and climate zone-specific. This comprehensive study indicates a need for more research and deeper investigation – particularly regarding the following areas and possible recommendations for which the current study indicated significant gaps between the EPBD and the best available calculation methods [74].

- Considering climate change and the urban heat island effect using more current historical data and future climatic scenarios is essential in future calculation approaches.
- Adopting short-term and long-term indicators prepares a building for thermal resilience and not only thermal resistance.
- Refine the calculation methods to use a comparative calculation approach based on existing standards such as ISO 52000–1 2017 [64] and CEN 13790 [65]) and allow for mixed-mode operation [82].
- In parallel to the performance-based approach, define prescriptive requirements for imposing building envelopes (external shading, WWR limits, and maximum g-values …).
- Explore the operation of buildings in mixed modes using PMV-PPD and adaptive models directly related to occupants' health and well-being, especially in sleeping rooms [66].

Planned future work should develop calculation methods in mixed-mode operations. Also, simulation studies on European home models should be further developed to incorporate the concepts of thermal resistance and resilience for climate-proof buildings.

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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Appendix 1. Questionnaire

To download the questionnaire: https://doi.org/10.7910/DVN/LCBTNX.

Appendix 2. Report

To download the study report: https://doi.org/10.7910/DVN/LCBTNX.

Appendix 3. Countries table

To download the comparative table of countries: https://doi.org/10.7910/DVN/LCBTNX.

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