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Ten questions concerning residential overheating in Central and Northern Europe

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A B S T R A C T

Rising global temperatures and more frequent heatwaves due to climate change have led to a growing body of research and increased policy focus on how to protect against the adverse effects of heat. In cold and temperate Europe, dwellings have traditionally been designed for cold protection rather than heat mitigation. There is, therefore, a need to understand the mechanisms through which indoor overheating can occur, its effects on occupants and energy consumption, and how we can design, adapt, and operate buildings during warm weather to improve thermal comfort and reduce cooling energy consumption. This paper brings together experts in overheating from across Europe to explore 10 key questions about the causes and risks from overheating in residential settings in Central and Northern Europe, including the way in which we define and measure overheating, its impacts, and its social and policy implications. The focus is not on summarising literature, but rather on identifying the evidence, key challenges and misconceptions, and limitations of current knowledge. Looking ahead, we outline actions needed to adapt, including the (re)design of dwellings, neighbourhoods, and population responses to indoor heat, and the potential shape of these actions. In doing so, we illustrate how heat adaptation is a multi-faceted challenge that requires urgent and coordinated action at multiple levels, but with feasible solutions and clear benefits for health and energy.

1. Introduction

The Earth is warming at a rate that is unprecedented in tens of millions of years [1]. In Europe, the mean annual average temperature has already increased by 1.7–1.9 °C, relative to the pre-industrial period [2], and the last ten years (2013–2022) all rank amongst the eleven warmest years on record [3]. These changes are resulting in more frequent periods of warm and hot weather, and an increased frequency and severity of heatwaves. This trend is set to continue, with the amount of warming dependent on how global society, demography and the economy develop over the coming decades, as described using Shared Socioeconomic Pathways (SSP) [4,5]. For example, under SSP1 (where global emissions are reduced and reach net zero by 2050), European land temperatures will rise on average by 1.2–3.4 °C (95% CI) relative to 1981–2010, whereas under SSP5 (fossil-fuelled development) temperatures are projected to increase by 4.1–8.5 °C (95% CI) (Fig. 1) [6]. Further increases in average summer temperatures and heatwaves are inevitable, but the magnitude of change depends on the success of global mitigation efforts.

Future elevated temperatures pose risks to health and wellbeing, will increase energy consumption for space cooling, and may reduce productivity [7]. This has led to increased concern about heat, and how to prepare for and adapt to it. People in Europe spend around 90% of their time indoors [8], and thus buildings are important locations for heat risk mitigation. Historically, dwellings in cold and temperate climates have been constructed with the aim of retaining heat during the winter and are not typically prepared to cope with hot weather. However, buildings designed without consideration for heat are at risk of summertime overheating, especially during heatwaves. Other trends exacerbate the problem. For example, dense and extensive urban development creates

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Urban Heat Islands (UHI), further increasing temperatures in urban locations, particularly at night. To reduce the risks of overheating, changes to the housing stock are necessary, both in retrofitting existing dwellings and in more stringent regulations for new buildings.

Despite the risk of overheating, research understanding and policy action in cold and temperate Europe remains limited. There is also a lack of 'tacit' knowledge - in dwelling design and occupant behaviours - that exists in other, warmer, parts of the world. Existing research on overheating often convolutes built form, construction design detail and energy efficiency, and conflicting findings can lead to confusion and a lack of nuanced understanding of overheating risk. Guidelines and standards for the housebuilding industry, and evidence on which to base national and regional heat mitigation policy, is weak. As a result, there is significant variation in the policy responses to overheating throughout Central and Northern Europe.

A critical examination of overheating in dwellings in cold and temperate climates is needed to appreciate its causes and impacts, possible mitigation measures, the way in which we define and assess overheating, and how different policies and compliance criteria will influence the future of housing. This is achieved by answering 10 key questions: Questions 1–3 provide contextual background, why overheating occurs and the impacts of it; Questions 4–7 describe how overheating risk is calculated and predicted and methods of mitigation; and Questions 8–10 discuss the policy and social implications of overheating. The answers to the questions are based on the authors' collective knowledge and expertise, underpinned by a synthesis of existing literature. The work highlights priorities for policymakers, researchers, planners, developers, and other practitioners.

2. 10 Questions on overheating

2.1. Question 1: What is overheating in buildings?

Overheating in cold and temperate regions occurs predominantly during the summer due to high outdoor temperatures and solar heat gains, possibly accompanied by excessive internal heat gains from within the dwelling or adjacent spaces. Overheated dwellings can cause thermal discomfort leading to diminished wellbeing and may become a detriment to health if hot conditions persist. In extreme conditions, elevated temperatures can cause thermal stress, which can rapidly lead to physiological strain and ultimately to morbidity and potentially mortality. In addition, in some buildings, uncontrolled heat gains and an inability to remove excess heat can cause chronic overheating, i.e., overheating that persists throughout much of the year [9]. Such cases highlight the fact that climatic change is not the sole cause of overheating. However, this paper will focus on summer time overheating since it is far more prevalent.

People respond differently to high temperatures (see Q3). Older people and some people on medication or with underlying health conditions do not sense temperature well and so may be unaware that it is hot. Older people and young children may also be less able to take effective adaptive action during hot weather and so they are the most vulnerable to heat. These are also the very people for whom the health risks of elevated temperatures are greatest. Responses to elevated temperature are also likely to differ with gender (e.g. Ref. [10]) and culture (e.g., Ref. [11]). The scale of these effects and how they relate to questions around summertime overheating and dwelling design are, however, currently unresolved.

Elevated outdoor temperatures combined with solar radiation (UVA and UVB) play a catalytic role in the formation of ground level ozone, as atmospheric pollutants interact in the presence of sunlight. Ozone is known to trigger asthma and aggravate other respiratory illnesses, including pneumonia and bronchitis and particulate matter (PM_{10}) and common gaseous pollutants (SO_2 and NO_2) have been linearly associated with mortality during high temperatures [12] (Q3). Elevated ozone levels were recorded across much of Europe during the extremely hot summer of 2022 [13]. The presence of such confounding factors points to the need to view heat-induced morbidity and mortality more broadly, as evidenced during the EuroHEAT project [12].

The desire to design dwellings that provide thermal comfort, whilst using as little (cooling) energy as possible, means that European design guidelines, standards and regulations have been developed on the basis of maintaining thermal comfort, or at least avoiding extended discomfort (see Q6). Applying adaptive comfort standards (e.g. Ref. [14], see Q6), the indoor threshold temperature above which overheating is deemed to occur can be 29 °C, or more during heatwaves. In some dwellings, such conditions can be so hot that they lead to heat stress [15]. This occurs when the body's core temperature rises, and the heart rate increases. The severity of the conditions can be estimated using the Canadian Humidex index [16] or the US Heat Index [17]. These metrics account for relative humidity, the physiological effects of which are more pronounced at higher air temperatures. Heat stress metrics are represented as an effective temperature, wherein the Heat Index advises 'extreme caution' at effective temperatures over 32 °C and 'danger' at

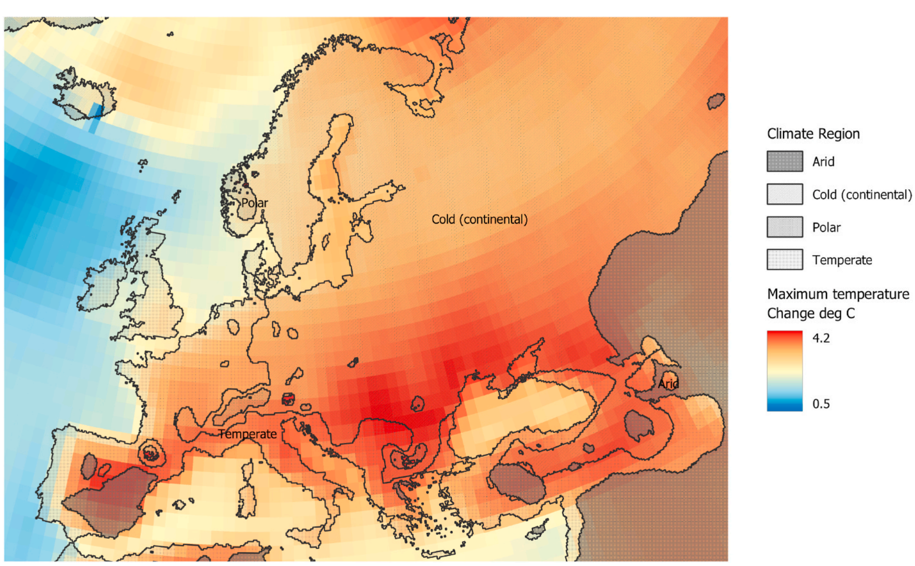

Fig. 1. Maximum summertime temperature change (deg C) by the 2050s (SSP2-4.5) relative to 1961–1990, CMIP6 [6], and Koppen temperature zones. This paper focuses on cold and temperate areas in Europe.

temperatures over 41 °C.

The timing as well as the magnitude and duration of elevated temperatures matters. If high temperatures persist through the night, the quality of sleep is diminished, which, over successive nights, can be debilitating, and detrimental to health, daytime performance and productivity [18]. Cooler nights provide respite from daytime heat and ventilation with night-time air can reduce indoor temperatures and remove the heat stored in the building fabric, which provides resilience to the heat of the forthcoming day. It is the elevation in night-time temperatures caused by the UHI effect, where temperatures are higher in urban centres relative to surrounding suburbs and rural areas (see also Q2), that contributes to the greater prevalence of overheated dwellings in cities than elsewhere [19]. There remains much to do to understand the relationships between heat, sleep quality and health (see Q3).

Understanding the causes, future prevalence, and human impacts of overheating in dwellings requires research contributions from social and behavioural scientists, meteorologists, clinicians, and many others. Their work is essential if building engineers and architects are to effectively design new dwellings, and redesign existing dwellings, so that they are resilient to hotter summer weather.

2.2. *Question 2: What are the causes of overheating?*

Buildings overheat when heat gains from the outdoors and/or generated indoors are greater than heat losses for a prolonged period. Outdoor environmental conditions, the design of the building, internal production of heat, and occupant behaviour all influence the magnitude and extent of overheating.

Overheating risk in cold and temperate climates is influenced primarily by the outside air temperature and solar radiation, but also by humidity and wind speed. The UHI may elevate temperatures, especially at night, and the local microclimate immediately around buildings is influenced by shading from other buildings and trees, surface materials, and the ability of wind to remove excess heat. The temperature difference from the UHI effect can be around 2–4 °C hotter than the surrounding rural areas, and in extreme cases up to 5–10 °C [20]. Often, the effects of the UHI and microclimate are left unaccounted for in dwelling design.

The outdoor climatic conditions interact with dwellings' characteristics and occupant behaviours to influence overheating risk (Fig. 2). Dwelling design impacts heat transfer from the outdoors and the retention of accumulated heat. Solar heat gains through windows, conduction through the opaque building fabric, and the ventilation movement of hot air into the building from outdoors or adjacent spaces, all increase indoor temperatures. At higher latitudes, the importance of solar radiation is increased because long summer days and low angle sunlight results in increased solar gains [21]. Heat may accumulate in the fabric of the building, such that in dwellings with high thermal mass air temperatures may rise and fall more slowly reducing the peaks in indoor temperature [22,23]. High levels of heat generated indoors from cooking, electrical equipment, or poorly insulated hot water pipes, can also contribute to overheating. Spaces particularly at risk of overheating are those with large areas of glazing facing within 90° of South and rooms immediately below the roof, especially an uninsulated roof.

Solar heat gain can be prevented most effectively by static or moveable external shading; the use of low g-value glazing and internal window shading is also beneficial. Heat can be removed through ventilation involving natural and/or mechanical extraction of hot air. Passive ventilation with cooler outside air, especially at night, is generally the primary passive mechanism for removing heat. Ventilation is usually through windows, but often the opening areas are too small and air flow may be blocked by window restrictors or curtains - especially at night. More inventive ventilation strategies are likely to be needed in some dwellings (Q5).

The effective use of movable shading and ventilation relies on occupant behaviour as does the use of mechanical ventilation and cooling systems. Overheating is therefore a sociotechnical problem, resulting from a combination of occupant behaviour and physical and technological factors (see Q5). The role of occupant behaviours, while critical for heat mitigation, are comparatively less well studied than physical mitigation measures.

Dwellings in cold and temperate Europe are constructed for a heating dominated climate with little, if any, consideration given to design for mitigating the risk of summertime overheating. Whilst the social culture around space-heating is very well developed, tacit knowledge within individuals and society about managing overheating is poorly developed but evolving.

2.3. *Question 3: What are the impacts of overheating?*

While indoor temperatures are generally described in terms of 'discomfort', excess heat has much wider implications for human health, the productivity of occupants, space cooling, energy consumption (and associated carbon emissions) and the energy supply infrastructure.

Humans regulate their internal body temperature within a narrow range (between 36 °C and 38 °C, at rest), balancing between metabolic heat production, heat loss, and heat gain from the environment. This heat balance is often described mathematically using human thermophysiology models, which form the basis for many thermal comfort criteria (see Q6). Heat stress occurs when the body cannot remove excess heat, resulting in increased core temperatures and potentially leading to acute heat-related illnesses, such as cramps and heat stroke. At the

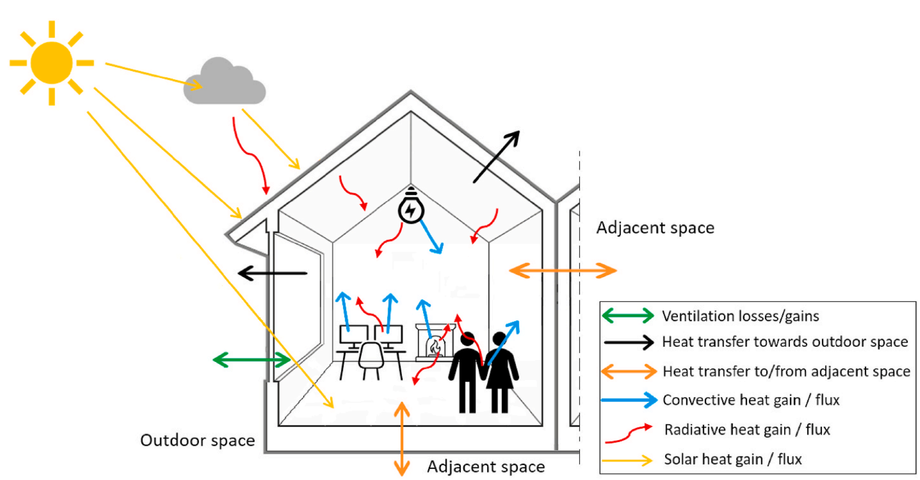

Fig. 2. Mechanisms of heat accumulation in buildings.

population-level, elevated ambient temperatures are associated with increased deaths from all causes [24,25], including cerebral and cardiovascular causes [26]. Population health impacts can be significant: for example, the 2003 European heatwave led to an estimated 70,000 excess deaths across Europe [27], while the recent 2022 heatwave in Europe is estimated to have led to over 15,000 excess deaths [28]. However, most excess deaths may be due to more frequent warm and hot days, rather than occasional heatwaves [29]. Evidence suggests night temperatures, which disrupt sleep, may be particularly detrimental for health [30], and other confounding factors such as increased ozone levels and particulate air pollution (Q1) can also exacerbate health risks. High ambient temperatures have also been associated with increases in mental health problems [31] and domestic violence [32]. The impacts of the warming climate on health can already be seen (Fig. 3), with the six year moving average of heat-related deaths increasing by 33% (to an estimated 104,000) in Europe in 2019, relative to 2005 [33].

Health risks from heat are not evenly shared, with older people, the very young, those with pre-existing cardiovascular and respiratory diseases, and the socially isolated being more vulnerable [34]. Older individuals are particularly at-risk because they sense heat poorly and are thermo-physically less able to ameliorate the effects (see Q1). The European population is aging, and between 1990 and 2019 the heat-vulnerable population increased by 6% across all European regions [35].

Much more work is needed to understand how dwelling characteristics impact heat-related health outcomes. Most epidemiological evidence relies on *outdoor* rather than *indoor* temperatures, and studies based on measured indoor temperatures or housing characteristics are relatively rare in Europe. In hotter climates, the absence of air-conditioning (A/C) is often included as a risk factor [36], while living under a poorly insulated roof is a known risk factor as revealed most clearly in a Paris-based study [37]. Epidemiological studies that do include dwellings (e.g. Ref. [38]) often rely on spatially aggregated housing data that fails to account for significant temperature variation between individual dwellings within a spatial unit. Some studies estimate the effectiveness of different dwelling adaptation scenarios using heat-related mortality calculations (e.g. Refs. [39–41]), assuming that the temperature-mortality relationship is the same indoors as it is outdoors, but it is unclear if this is the case in reality. It is worth noting, however, that despite the increasing exposure to heat, heat-related mortality in Europe is a fraction of that from cold, and this is expected to continue into the future [42–44].

Increasing temperatures will also impact on energy consumption. While increasing winter temperatures may cause a small reduction in winter heating demand, higher summertime temperatures are increasing the uptake of active cooling systems. The IEA estimates that the number of A/C units in Europe increased from 44 million in 1990 to 97 million in 2016, with a projected growth to 270 million by 2049 [45]. Depending on the carbon intensity of electricity generation, this could lead to greater greenhouse gas emissions, and energy infrastructures will need to be resilient to the increased cooling demands. The use of cooling systems is likely to lead to increased household costs for installation, maintenance, and operation, which some may be unable to afford (see Q8).

In hotter climates, heat-related mortality occurs at higher outdoor temperatures than in cold and temperate Europe [46]. This difference is often attributed to the adaptation of people in hotter climates physiologically and behaviourally, as well as through more appropriate building design and infrastructure [47]. There is mixed evidence regarding whether climate-related heat acclimatisation in Europe is occurring [47,48]; which mechanisms are driving possible adaptation; whether this will continue; and whether all segments of the population can adapt equally (see Q8).

Despite uncertainties in predicting future heat-health impacts, there is clear need for further research on how to adapt cold and temperate European dwellings to be more resilient to summer heat. This is particularly challenging when considered against the concurrent need to reduce emissions and energy demands. Energy efficient retrofits may change how buildings respond to summer-heat (Q4), while the current, largely unrestricted, growth in active cooling systems presents challenges for energy reduction.

2.4. Question 4: Do low-energy dwellings overheat more than dwellings with less energy efficient fabric?

There is an urgent need to improve the energy efficiency of buildings in Europe and understand the relationship between energy efficiency and overheating risk. A common narrative is that energy efficient buildings are more vulnerable to overheating than conventional buildings, and that overheating is an unintended consequence of energy efficiency. The situation is more nuanced, and such narratives risk discouraging urgently needed energy efficiency improvements.

The main differences between low-energy and conventional dwellings (from an overheating perspective) is generally related to the degree of air tightness (or uncontrolled air exchange), the depth of insulation used, and, dependent on the construction typology, possibly the thermal

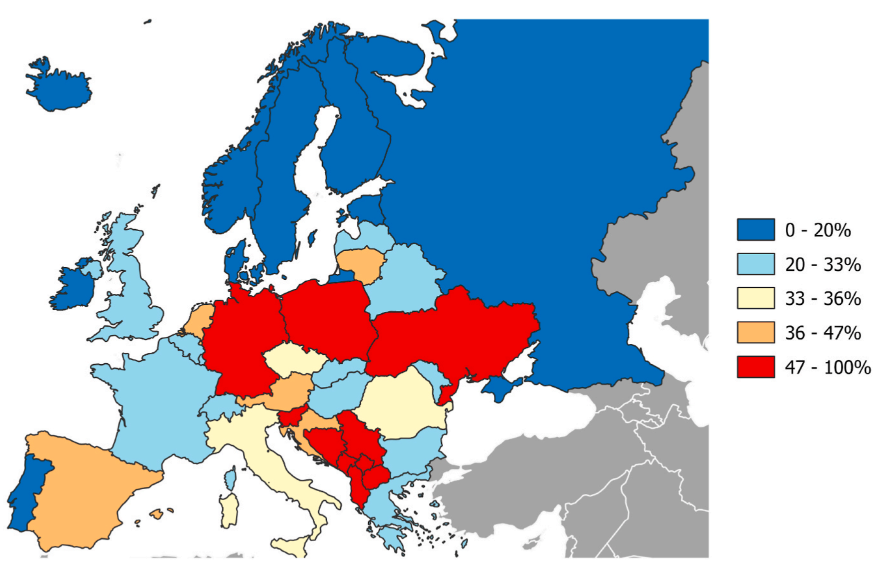

Fig. 3. *The % increase in deaths (6 year moving average) attributable to heat amongst those over 65 in 2019 relative to 2005 baseline. Adapted from* Ref. [35].

mass and orientation. The theory, from a physics perspective, is that well insulated and airtight dwellings retain heat from internal and solar gains, both in the winter and summer. And while various modelling and monitoring studies have shown that modern housing can overheat more than older housing, evidence that low energy dwellings will inevitably overheat more than conventional dwellings is – in fact - far from conclusive.

In the UK, monitoring studies of existing homes are beginning to reveal a consistent picture. A national overheating survey in the English housing stock during one of England's hottest summers found no significant differences in the measured prevalence of overheating in either living rooms or bedrooms due to any single energy efficiency measure (wall insulation, glazing type, depth of loft insulation), or the total number of energy efficiency measures [19]. Conversely, increasing roof insulation appeared to significantly reduce overheating. Other studies have shown a higher prevalence of overheating in dwellings with a better overall energy performance rating [49], however, the more efficient homes were more likely to be apartments - a built form at inherently greater risk of overheating. Experiments in matched-pair test houses with synthetic occupancy have shown that internal wall insulation can increase room temperatures by up to 2 °C [50]. However, with night ventilation and daytime curtain shading in both homes there was no difference in bedroom temperature and only about 1 °C difference in living room temperatures.

Modelling studies (with caveats, see Q7) have shown a reduction in overheating from roof insulation [51,52] and external solid wall insulation [53], small increases in overheating from internal wall insulation, and larger increases in overheating due to reduced ventilation following air tightening (without compensatory purpose-provided ventilation) [40,52] – with the magnitude dependent on the dwelling typology. A modelling study of a London terraced house indicated a 1 °C reduction in the maximum operative temperature for Passivhaus energy efficiency when compared with building regulation compliant efficiency [54].

The prevailing evidence is that overheating is not an inevitable consequence of energy efficient or 'super-insulated' dwellings, but rather a potential consequence of design decisions about glazing area, orientation, provision of summer solar shading, the position of wall insulation, and ventilation (see Q1). Design to minimise peak heating loads rather than annual heating energy demand can ensure compliance with advanced performance standards such as Passivhaus, without necessitating high South-facing glazing ratios [55,56]. Well insulated buildings may be more sensitive to elevated outdoor temperatures, but they seem also to be more responsive to mitigation measures [48]. Small increases in summertime temperatures following certain retrofits may thus be easily mitigated by adequate ventilation and shading [39,50]. The health benefits of reduced winter cold exposure following energy efficiency improvements are likely to vastly outweigh any small increases in summertime temperatures [43].

Further research is required into the effects of energy efficient design on overheating in different contexts and with different occupant behaviour patterns. However, current evidence suggests that heat-sensitive design matters far more than thermal efficiency, and if active cooling becomes necessary, high thermal efficiency with heat recovery ventilation can offer tangible energy savings [56]. Equating increased overheating with improved energy efficiency will slow progress towards a resilient, efficient and healthy housing stock.

2.5. Question 5: How to prevent summertime overheating?

In Q2 and Q4 the causes of indoor overheating were discussed, and possible mitigation measures noted. This question considers the actions required to mitigate overheating at different scales in more detail.

At the regional or citywide scale, a key objective is to reduce the amplitude and extent of the UHI, since cities are where the worst impacts of overheating are experienced. Urban design strategies, including large-scale greening and extended ventilation corridors promote cool air pathways [57]. Similarly, at the *neighbourhood* level, green and blue infrastructure including tree-lined streets, parks, ponds, canals, and water permeable surfaces can reduce ambient temperatures and provide places for respite during warm weather. The micro climatic cooling effect of urban greening decreases with distance from green space however [58,59], and thus cannot replace the need for individual dwelling level solutions. Protection of citizens during hot weather can be assisted by the provision of places in which people can escape the heat, e.g., cool, shaded outside spaces, balconies and perhaps 'safe havens' indoors [60].

At the building-level, lessons can be learnt from traditional heat management practices adopted in architecture and urban design in warmer climates. These include use of intermediary shaded spaces at the indoor/outdoor interface (such as balconies, see Fig. 4), courtyards and shaded walkways, light coloured and high albedo surfaces and reduced glazing apertures, especially within 90° of South [53,61–64]. Exposed thermal mass, to absorb heat during the daytime and release it during the night, is a widely adopted passive cooling strategy in hot and dry climates [23]. Caution is needed however, when high thermal mass strategies are proposed in heavily glazed dwellings, especially where night ventilation is restricted. Although thermal mass may help reduce daytime temperature peaks, stored heat released into bedrooms can elevate night-time comfort temperatures at the time when occupants are most heat-sensitive [65].

In temperate and cold climates, households have traditionally relied upon natural ventilation to *purge* warm indoor air. Noise, pollution, safety and privacy are, however, barriers to the use of windows or other natural ventilation inlets [66,67]. Vented side panels, especially if acoustically lined, are a potential solution to such concerns. Inward opening tilt and turn windows can be left securely open at night

Fig. 4. Light coloured surfaces, planting, overhangs and side-fins, that shade glazing, mitigate overheating risk in these East-facing apartments. Architect: John McAslan + Partners. Photo: Joe Clark (http://joeclark.photo/).

(especially at high levels) when used in conjunction with external shutters, whereas outward opening windows may be difficult to secure and shade. Window restrictors are commonly applied to reduce falls from floors above ground level but can severely limit ventilation. Many European dwellings also incorporate, by design or custom and practice, a combination of other passive cooling components. Low-cost but effective examples include fixed shading devices (e.g., reveals, overhangs) and moveable devices (such as awnings and external shutters). Consideration must be given to the functionality of movable devices (including full-height doors and windows) since they must be useable by all potential dwelling occupants. However, the impact of static adaptations on year-round thermal performance cannot be neglected in heating-dominated Central and Northern Europe.

Issues with overheating in Passivhaus dwellings in warmer climates can also provide lessons in heat mitigation. A study of an end-terrace Passivhaus in Marseille (with triple glazing and heat recovery) showed that all dwelling variants in the study required active cooling to comply with the overheating criteria, but around 35% less useful cooling energy was required to maintain summertime thermal comfort in the Passivhaus dwelling [68]. For such dwellings, solar control, and a summer bypass on the mechanical ventilation is important. Even in cold and temperate climates, there are lessons to be learned from highly insulated Passivhaus buildings about the consequences of not controlling summertime heat gains. An example in Denmark overheated for 40%–60% of July [69], while in Swedish cases 56% of residents stated they were too warm in summer [70,71] and peak summertime temperatures exceeded 29 °C in some cases [72]. The year-by-year changes in overheating and the inter-dwelling variations in summer temperatures illustrate the sensitivity of well-insulated homes to hot weather and internal heat gains (see also Q4) but also the importance of occupant behaviour, enabled by heat mitigation devices, in maintaining comfort [71,72]. However, year-round thermal performance cannot be neglected in Central and Northern Europe since they are heating dominated regions.

Reducing internal gains is an important heat mitigation strategy. At the design stage this implies reducing or eliminating heat from communal heating and hot water distribution systems (often located in the corridors and risers in apartment buildings) as well as minimising the need for domestic hot water storage in individual apartments [9]. Decentralised mechanical (supply and extract) ventilation systems should be designed to ensure that the fresh supply is not inadvertently pre-heated via extended or poorly insulated duct runs.

At the household level, behavioural adaptations can reduce overheating. Such measures may include using smaller and/or more energy efficient appliances and switching off appliances when not needed. Use of non-essential, high power household appliances (such as vacuum cleaners and washing machines) should be undertaken at cooler times of the day. More important is the use of shading, be this internal curtains or external devices, and appropriate ventilation to take advantage of periods in the day when it is cooler outside than in. Fans should perhaps be promoted more strongly in Europe, as they can be surprisingly effective at improving thermal comfort [73,74], however at very high temperatures and with dry air they may actually increase heat stress [75]. Personal behavioural strategies such as wearing cooler clothing, resting during the hottest parts of the day, and the use of portable mist-sprayers (to promote evaporative cooling) can all help to improve thermal comfort and combat heat stress. Information and training can assist in encouraging the diligent and effective use of household-level cooling strategies.

Active cooling systems are sometimes needed, but A/C and district cooling increases energy costs, and in the absence of clean energy sources, greenhouse gas emissions. In urban areas, waste heat from A/C systems can exacerbate the UHI [76,77] unless deployed in conjunction with ground source heat pumps [78]. However, there are limits on the maximum energy density that can be extracted from shallow bore-hole systems in dense urban areas due to the induced summertime ground warming [79,80]. Relative to conventional heat pumps and chiller systems, direct ground cooling systems require minimal electricity to circulate a working fluid between the building and the ground and consequently achieve very high seasonal performance factors. However, such systems can only be used effectively in very energy efficient buildings [81]. Moreover, all active systems are reliant on a resilient energy supply, and if housing is not designed for 'passive survivability' they may become uninhabitable if the power supply fails [82].

2.6. *Question 6: What is the role of compliance criteria?*

Evaluating the degree of overheating requires an appropriate metric and criteria with which dwellings should comply. Several different overheating assessment methods and criteria have been used. Contemporary European standards set an indoor temperature threshold above which overheating is deemed to occur, and an allowable exceedance (a limit on the number of hours that this threshold can be exceeded during periods of room occupancy). The temperature thresholds are based on considerations of human thermal physiology or comfort and may be fixed or variable. Variable thresholds are based on an adaptive thermal comfort approach, which acknowledges that people can adapt to higher temperatures over time.

Overheating criteria, which use fixed temperature thresholds and exceedances, vary by country - or even region within a country [83] – as well as with the perceived vulnerability of occupant groups (Fig. 5). For example, in the Brussels region of Belgium, there is a static limit of 5% of annual hours over 25 °C, with no more than a 5 °C difference between indoor and outdoor temperature; in Germany the recommended threshold varies with geographic region, between 25 °C and 27 °C [84]; and in Finland, there is a limit of 150°-hours above 27 °C [85].

Since the mid-2000s, adaptive thermal comfort criteria [86] have become more common. The approach recognises that, in free-running buildings, people gradually adapt to increasing or decreasing temperatures, through their clothing, behaviours and physiological adaptation. Here, threshold temperatures increase linearly with either the running mean of daily outdoor mean temperatures [87] or the mean monthly temperature [74]. The adaptive approach is recommended for buildings in Europe [14] and is used in the UK for assessing naturally ventilated dwellings and schools (e.g., Ref. [88]). The allowable exceedance of the adaptive threshold might be expressed as a duration (the total hours), heat exposure (total degree hours) or intensity (a limiting absolute temperature difference) or a combination thereof. Adaptive thermal comfort thresholds shape the design of buildings throughout the world via the US ASHRAE standard [70], European Norm EN16798-1 [14], and the UK CIBSE guides TM52 [89] and TM59 [90]. The adaptive threshold might be adjusted to better reflect comfort perceptions in warmer climates [91].

Whilst most standards use operative temperature as the metric of measurement, other environmental factors are also physiologically associated with overheating, including a lack of air movement, elevated relative humidity, and radiant temperature. Humidity is especially important when evaluating the likelihood of heat stress due to very high indoor temperatures.

Overheating criteria were originally developed to interpret the results from dynamic thermal models to assess the likelihood of overheating in new or refurbished buildings and ensure that new homes comply with new overheating mitigation regulations [93]. (see Q7). These criteria have since been adopted by numerous researchers to interpret temperatures measured in existing dwellings. However, many authors [94,95] have demonstrated the sensitivity of analyses to the way overheating is defined, the criteria used, as well as models' input parameters and algorithms (see Q7). The choice of the threshold temperature tends to be the focus of research and debate, however, the allowable exceedance, assumed occupancy period, time frame over which hours are accrued and choice of weather year for modelling also determine whether overheating is or is not measured or predicted. The

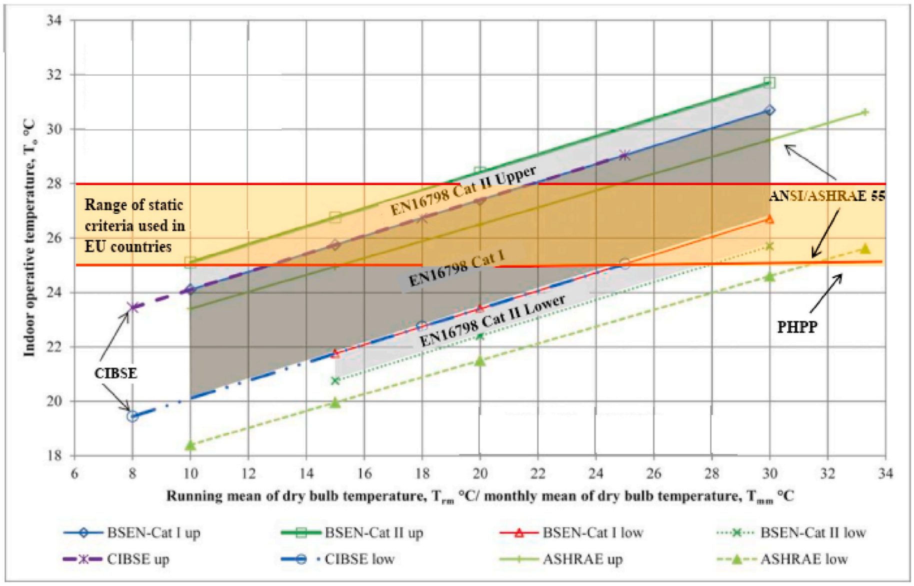

Fig. 5. Adaptive overheating thresholds defined in standards and the range of static criteria adopted in EU counties (adapted from Refs. [74,87,89,92]).

underpinning evidence base for selecting these parameters is weak, and the basis for choosing a particular criterion lacks transparency. In particular, it is not clear that prevailing overheating criteria are applicable to people trying to sleep, not least because the scope for, and nature of night-time heat adaptation is quite different to that for people who are awake and active.

2.7. Question 7: Can we predict overheating risk?

Both steady state and dynamic building physics models may be used to predict overheating risk. Prediction is difficult however, as overheating, its frequency, duration and magnitude is an inherently dynamic phenomenon depending on time-varying boundary conditions, transient thermal heat flows and behavioural interventions. In response, some countries have introduced guidance on the appropriate use of dynamic simulation to standardise modelling approaches, e.g. Ref. [90]. However, while the reliability of models' prediction of overheating has been questioned [94], there remains no alternative way to assess overheating risk at the design stage.

Studies have found that the choice of model and its algorithms, as well as the choice of the overheating criterion (Q6), are important to the outcome of analyses [95,96]. Different criteria may be used for bedroom and living rooms [97], thus the same room temperatures may result in one room being classed as overheated and the other not. Thus, purely because of the criterion used, heat mitigation measures may be deemed desirable for some rooms and not for others.

Modellers also face many choices about input values, and these too can have a significant impact on model outputs. The dominant factors contributing to the performance gap will always be case specific [98]. Occupant behaviour is especially uncertain, for example the production of internal heat gains from appliances or occupants, the use of blinds and opening of windows to purge excess heat [99], and whether behaviours change as occupants adapt to heat. Improved behavioural modelling – including adaptive behaviours [100]– may be one way to improve model predictions. This may require specific models that account for differences in adaptive capacity between people and populations.

Default assumptions embedded in models, which modellers may not change, can affect the reliability of internal temperature predictions; for example the use of fixed air-change rates which deliver air at ambient temperature rather than explicitly modelling infiltration, exfiltration, and internal air flow pathways [101,102]. Building modellers also have a wide range of weather files to choose from, representing anything from typical reference years to probabilistic future data sampled from regional climate models, and extreme heatwave scenarios.

Given the difficulty of accurately predicting overheating risk, the key question is whether more sophisticated, dynamic tools result in better predictions than simpler methods. For example, the Passive House Planning Package (PHPP), a steady-state spreadsheet used for Passivhaus design compliance [103], is increasingly used for designing airtight low energy buildings without the need for additional cooling systems. However, in low energy housing with large, glazed areas, high insulation levels and complex heating and cooling systems, it is impossible for static models to reliably capture the transient effects, for example peak temperatures, night ventilation cooling rates, thermal mass charging and discharging that dynamic models can accommodate for [54,69]. In overheating assessment, steady-state processes, such as conduction through opaque surfaces, are relatively less important when inside and outside temperature differences are low.

Documented modelling methodologies and standards (such as TM59) seek to reduce the scope for modelling errors and reduce differences in the results obtained by different modellers. In doing so, they may inadvertently mask the sources of model inaccuracy [99]. Although work has been done to compare the prediction of different models and the difference between modelled and measured overheating (e.g. Refs. [97,104]) much more needs to be done. This could take the form of, for example, controlled inter-model comparisons of overheating in housing most at risk of overheating, with weather data to represent chosen countries and regions.

Prediction of overheating risks is not confined to the design-stage, and in the case of existing dwellings, it may be possible to use empirical data to create models. Statistical models have proven very successful in accurately forecasting internal temperatures based on historical measurements and exogenous variables [105]. Such models have the distinct advantage of being able to create accurate forecasts with minimal data inputs, however their accuracy becomes increasingly limited as the forecasting horizon lengthens. Networks of such information based on the real-time monitoring of existing buildings have the ability to provide valuable short-term information which incorporates occupant interventions and behavioural patterns and is thus capable of creating a high-resolution indoor heat health warnings [106]. To date, although only limited work in this domain exists, there is clearly great potential for further advancements.

Modelling plays a valuable role in overheating assessment to inform design, retrofit, and heat and health policy. However, inaccurate model input specification, simplifications of complex processes, and in some cases poor modelling practices can lead to unreliable predictions. Further work is also required to confirm the optimal choice of algorithms and overheating metrics and to better understand how individual households respond to heat to mitigate its effects. An essential component in this process will be the use of large-scale, high-resolution empirical data.

2.8. Question 8: How does housing overheating relate to climate justice?

The quality of an individual's dwelling and surrounding neighbourhood can vary substantially across sociodemographic groups, and this has implications for heat exposure. At the same time, low-income populations may be disproportionately affected by excess indoor heat exposure due to underlying structural vulnerabilities, such as the price of energy, chronic health conditions and co-morbidities, social isolation and inability to adapt, cope and recover from heat [107–109].

At the meso- and microclimate scale, the relationship between green infrastructure, the UHI and socioeconomic variables has long been established. In many cities around the world, less affluent urban neighbourhoods are characterised by lower levels of green or natural surfaces, higher densities, and consequently, higher levels of local temperatures and associated adverse heat-related health risks [110–115].

There is some evidence that disadvantaged households in Europe are more likely to live in housing that overheats [19,108]. This is due to a combination of factors, such as: poor building design; smaller dwellings and so overcrowding [114]; neighbourhoods with higher levels of outdoor air pollution, noise and security fears (which curbs the use for cooling by natural ventilation) [67]; and limited access to cooler communal spaces during hot spells [116]. Disadvantaged households are also less likely to be able to buy, maintain, operate, or repair A/C systems. Studies in hotter climates have shown socioeconomic differences in heat mortality attributable to lower rates of A/C uptake in low-income households (e.g. Ref. [36]) and as the climate warms this may become the case in cold and temperate Europe.

Recent research has broadened the definition of fuel poverty, usually referring to the inability of a household to afford to heat their home in winter, by introducing the concept of summer fuel poverty, which 'addresses the ability of a household to maintain indoor temperatures at safe levels during summer' [117]. With increasing ambient temperatures, and possibly fuel costs, the use of A/C may be limited to households in the upper income bands leading to growing disparities in indoor heat exposure [118].

There is a need to understand the current and potential future disparities in heat exposure and identify affordable solutions to heat mitigation. Participation in decision making for climate adaptation and resilience should be promoted within marginalised communities and providing social infrastructure such as carer visits and cooling centres to support vulnerable individuals during hot weather is important. Increased development of community cooling solutions such as district or geothermal cooling would help to reduce the cost of cooling and so the risks of summertime energy poverty. Finally, identifying the most cost-efficient overheating mitigation strategies that landlords could introduce in rented properties is crucial. Tighter regulatory standards for housing providers might be used to incentivise landlords to undertake heat mitigation in dwellings where temperatures regularly exceed defined thresholds [119].

2.9. Question 9: What is the role of policy?

Policies to protect citizens from summer heat are desirable, and as the climate warms – essential [120]. However, in cold and temperate climates, there is a lack of knowledge and experience within the construction and housebuilding industries about building for a hotter climate. Relying on voluntary implementation of best practice design is insufficient, and many countries will require enhanced regulatory standards supported by guidelines, as well as upskilling of the work force. At the EU-level, the Energy Performance of Buildings Directive (EPBD) states that passive measures are preferable to active solutions for reducing overheating [121]. However, this is not always reflected in compliance criteria, which are decided nationally or sub-nationally, and vary significantly across Europe (Q6). For example, until recently, passive cooling was not prioritised in the UK due to the lack of regulations. Standardised modelling criteria (Q6) can influence the overheating measures used in construction. An example is the Finnish regulations for new housing, where compliance modelling standards permit closed blinds and increased mechanical ventilation without window opening, therefore promoting active ventilation and less opportunity for adaptive thermal comfort. Both static and adaptive thermal comfort criteria may neglect the potential of hybrid buildings, where housing is allowed to be free-running up to a certain high indoor temperature (for example 30 °C). However, more evidence is needed to demonstrate whether hybrid strategies work in homes in practice.

Individual cities may develop their own planning guidance on heat mitigation. In the UK, The London Plan [122] requires all major developments to '*demonstrate how the design, materials, construction and operation of the development would minimise overheating and also meet its cooling needs*'. As part of this, a cooling hierarchy is proposed, prioritising passive solutions and with low carbon active cooling systems as the final option. But conflicting requirements can exist in regulations. For example, the London Plan promotes connection to heat networks and communal heating systems. These typically operate 24/7 year-round at high temperatures to provide domestic hot water, and so release heat from the pipework, which can exacerbate overheating [9].

Financial instruments may be one way to incentivise heat adaptation. Grants, subsidies, energy efficient mortgages, and other instruments are used to encourage energy efficiency measures and could be expanded to support overheating mitigation or post-intervention assessment. There are opportunities for such innovative financial mechanisms to be expanded to fund heat adaptation when undertaken in conjunction with energy efficiency measures. For example, this could include ensuring that new energy efficient windows have integrated shading and provide adequate summertime ventilation. This brings a holistic approach to the mitigation/adaptation conundrum.

Building regulations and financial policies take time to develop. There is therefore a role for short to medium term social and political awareness-raising which can help to shape occupant behaviour. Information campaigns should advise on how to reduce indoor temperatures and stay cool. Public health authorities might also consider the provision of social infrastructure such as cooling centres where the public can seek refuge during heat waves. Thus, there is a useful role for solutions and policies that are not solely technically focused but that also support social justice, inclusivity and human-centric design.

2.10. Question 10: What does the future hold?

The world is already committed to further warming relative to pre-industrial levels regardless of the mitigation actions taken [123,124]. This brings with it inevitable increases in summertime temperatures and more frequent heatwave events. By adapting housing to better contend with excess heat, the rise in the energy demand for cooling can be constrained. This is critical because analysis based on current policies suggest that energy demand for cooling (from residential and non-residential buildings) in the EU-28 is likely to grow by 210% (from 2021 to 2050) to comprise 8% of the final energy demand from the built environment sector [125].

Planning for a warmer future requires a coordinated approach linking planning, policy and implementation. This implies harmonised policy development covering the full range of legislative issues and actors, addressing diverse building typologies and tenure models. Lack of capital to carry out refurbishment work in households affected by energy poverty (see Q8) has been identified as key barrier to the uptake of renovation activities. Thus, regulatory approaches must be linked with economic incentives and tailored advice to increase uptake and leverage maximum benefit from refurbishment opportunities [125]. Building and development level policies must interface with heat prevention planning at the community and district level (see Q5) to ensure the provision of effective warning systems, communal respite areas and to mitigate the growth of UHIs.

Uncertainties in global economic pathways, demographic changes, and potential physiological adaptation to heat contribute to uncertainties in future temperatures, cooling demand, and health outcomes [126]. Regardless of future trajectories, various studies (e.g. Refs. [127,128]) indicate that passive solutions alone are unlikely to meet thermal comfort criteria even when installed in existing urban dwellings. Notwithstanding the uncertainty in predicting the future, it is clear that there is significant scope for the adaptation of European dwellings, and that adaptation will bring multiple benefits. In particular, by targeting measures at the homes of vulnerable people (see Q3 & Q8), those most susceptible to heat, and least able to protect themselves will benefit and the burden on health care services reduced. There are clear opportunities for affordable housing providers, public health officials, carers, and social services to collaborate with building scientists to develop evidence-based practical tools that allow lay users to assess indoor temperature risks and mitigation opportunities tailored to specific dwellings.

Addressing overheating in dwellings therefore requires coordinated action at multiple levels. At the occupant-level, it requires an understanding of the actions that can reduce high indoor temperatures as well as methods to cool down the surface and core temperatures of overheated occupants. Housing designers and builders need to integrate overheating prevention measures into their new and retrofit homes, shaped by official design criteria and with the skills and knowledge to implement effective adaptations. Urban planners need to be aware of the risks posed by buildings with limited solar shading and high internal heat gains, including unintended consequences arising from poorly designed communal heating and building services. Guidelines and criteria for overheating prevention need to come from policymakers, informed by building and urban physicists, recognising that these criteria influence the types of cooling measures introduced, and that reliance on active systems will necessitate a resilient and zero carbon energy system.

The current response to overheated homes is not future-proof and remains disjointed across sectors and between key actors, but it is not too late to enact coherent policies which will reduce heat risks in cold and temperate Europe. To ensure this happens overarching legislation, policies and frameworks, such as the European framework for sustainable buildings ‘Level(s)’, need to mandate overheating prevention strategies as a fundamental tenet of climate resilience.

3. Conclusions

This paper has presented 10 key questions on overheating in dwellings in cold and temperate Europe, where a changing climate means that homes traditionally designed to retain heat during winter also need to be adapted to reduce summertime indoor temperatures. This changing climate is occurring in parallel with a growing heat-vulnerable population and the need to make large-scale energy efficient retrofits to the housing stock to achieve global net zero emissions.

The increasing risk from overheating urgently requires the implementation of heat management strategies in housing in Northern and Central European countries. Homes can no longer be constructed for a historical climate but need to be designed or adapted to be fit for the future, with lessons taken from heat mitigation practices in other climates and research. Engineered or technical solutions to mitigate overheating only address part of the problem, with occupants and their behaviours playing a significant role. Thus, in parallel with changes to planning and building regulations, there needs to be a shift in public understanding of how to respond to heatwaves.

With continual growth in the uptake of air conditioning devices, there is an imperative to ensure that future cooling loads are minimised, and even capped, at the design stage. Policies and regulations are key in shaping our response to the growing heat challenge, for example how we define overheating and demonstrate compliance, the methods we use to predict overheating in new buildings, the ways in which buildings are designed and constructed to meet key-criteria, and the different heat adaptation pathways followed. Excess heat is an identifiable threat for health, energy, and equity in Europe, and it is imperative that we change how homes and cities are planned, built, operated and adapted. Fortunately, the necessary changes are feasible, potentially low-cost, and supported by a growing foundation of evidence.

CRediT authorship contribution statement

Jonathon Taylor: Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **Robert McLeod:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Giorgos Petrou:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Christina Hopfe:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Anna Mavrogianni:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Raúl Castaño-Rosa:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Sofie Pelsmakers:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization. **Kevin Lomas:** Writing – review & editing, Writing – original draft, Methodology, Investigation.

Declaration of competing interest

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Data availability

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