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Summertime impacts of climate change on dwellings in Wales, UK

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ABSTRACT

Wales's climate is predicted to be warmer and wetter, and 'hot' summers are expected to become more commonplace by the middle of this century. Whilst the focus of climate change adaptation in Wales has been wintertime decarbonisation through the introduction of energy efficiency measures, Welsh Government now want to understand the summertime impacts of climate change on the occupants of Welsh housing. The aim of this project was to test the hypothesis that summertime indoor housing conditions in Wales will diminish as a consequence of climate change. A six-week period from 22nd July–31st August was modelled using UK 2018 local climate projections, baseline, 2030 and 2070 respectively. The results reveal increased incidences of summertime overheating in a majority of dwellings. The poorest performing dwellings were post 1990 dwellings, flats and properties with internal wall insulation. The results show that cooling strategies to reduce indoor air temperature will increasingly be required. The other indoor vulnerability modelled was that of moisture. Results demonstrate the potential for poorer indoor environmental quality due to increased relative humidity. Every location will experience increases in relative humidity regardless of dwelling typology. Relative humidity will be highest in pre-1919 dwellings and dwellings with solid stone walls. The results show that ventilation strategies to improve the extraction of moisture-laden air, whilst diluting the concentration of pollutants that are present indoors, are required if these dwellings are to avoid increased incidences of condensation, damp, and mould growth, and adverse impacts from other allergens, particles and pollutants.

1. Introduction

Wales is one of the UK's four countries, and as such it lies within the north temperate zone. It is bordered by England to the east, the Bristol Channel to the south, and the Irish Sea to the north and west, and consequently has a changeable, maritime climate. Wales has a total area of 8023 square miles with over 1680 miles of coastline and is largely mountainous with its higher peaks in the north and central areas. With an estimated population of 3.17 million, it is the third most populous country after England and Scotland. Wales's climate is predicted to be warmer and wetter, and 'hot' summers are expected to become more commonplace by the middle of this century.

The Welsh Government, Wales's devolved, unicameral legislature, is required to address the challenges of Climate Change under the UK Government's Climate Change Act of 2008 [1]. Indeed, with the introduction of "The Well-being of Future Generations (Wales) Act 2015", Wales's Sustainable development Law, there is a clear mandate for climate resilience planning and action for communities across Wales. In fact, Wales became the first parliament in the world to officially declare a climate emergency, when on May 1, 2019 the Senedd Cymru (Wales's national parliament) approved the declaration. As a government with devolved powers, Welsh Government have a responsibility to ensure policy is resilient to future change including threats to health, economy, infrastructure, and natural environment. This requirement is set out in the well-being goal of "A Resilient Wales", within the *Wellbeing of Future Generations (Wales) Act 2015* [2].

One important aspect of the country's resilience is the health of its building stock. However recent reports by the Committee on Climate Change suggest that buildings, and in particular an aging housing stock, are "not fit for the future" [3] (p.9). Not only have greenhouse gas emission reductions for buildings stalled, but efforts to adapt buildings for higher temperatures, flooding and water scarcity are falling far behind the increase in risk from Climate Change. The quality, design, and operation of all buildings (schools, hospitals, municipal buildings,

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public and private housing) across the UK must be improved now to address the challenges of Climate Change, specifically higher temperatures, flooding and water scarcity; but this is particularly pertinent in Wales, where there is a highest proportion of ageing housing stock, 26% of all dwellings are more than 100 years old. Climate adaptation is "anticipating the adverse effects of climate change and taking appropriate action to prevent or minimise the damage they can cause or taking advantage of opportunities that may arise. It has been shown that well planned, early adaptation action saves money and lives later" [4]. Climate adaptation therefore aims to improve health, wellbeing, and comfort.

As the most common of all building typologies in Wales, housing has been and will continue to be subject to significant developments to meet climate mitigation targets, such as those aimed at improving energy efficiency to reduce carbon emissions. However, as evidenced in the literature, for example, in work by Mulville and Stravoravdis [5] meeting climate targets e.g., through additional insulation, whilst maintaining healthy indoor environments, is a major challenge. The Welsh Government therefore want to understand the wider impacts of climate change on the occupants of Wales's housing stock, more than 90% of which are predicted to remain in-use in 2050.

The focus of climate change action in Wales, up to now, has been melioration, and decarbonsiation through driven by wintertime energy efficiency targets. The aim of this discrete piece of work was to focus on the impacts of climate change on buildings during the summertime and test the hypothesis that summertime indoor housing conditions in Wales will diminish as a consequence of climate change. In order to answer this research question, a climate vulnerability modelling methodology was developed and modelling results for a six-week period, representing the height of the Welsh summer, are reported in this paper.

2. Material and methods

A climate vulnerability modelling methodology was developed in order to test the hypothesis that summertime indoor housing conditions in Wales will diminish as a consequence of climate change. This was accomplished using UK climate projections, indoor environment calculations and building typology data, as outlined below.

2.1. Climate data sets

The climate vulnerability modelling utilised the UK Climate

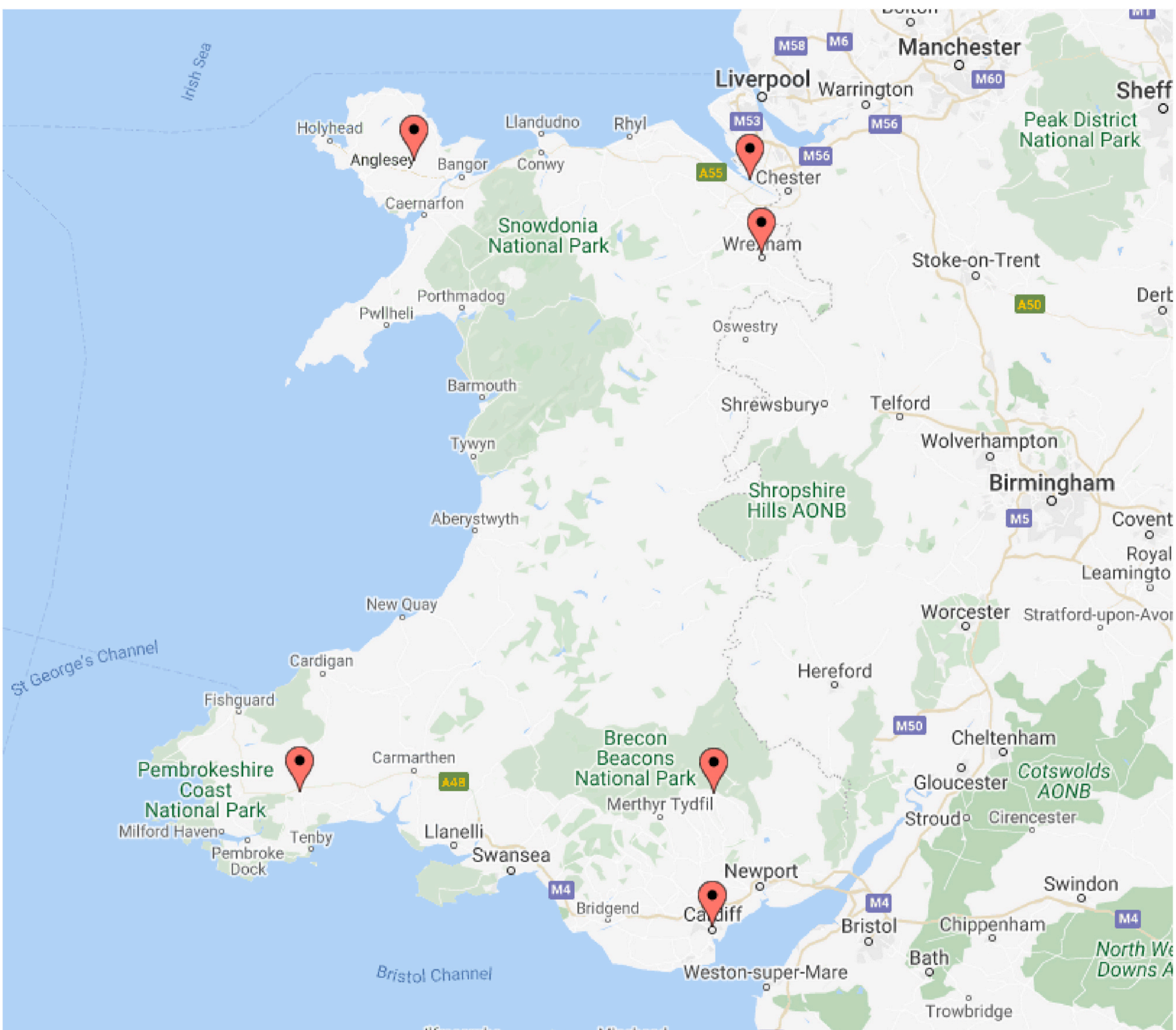

Fig. 1. Locations in Wales, clockwise from the top left [Llangefni, Shotton, Wrexham, Brynmawr, Cardiff, and Narberth].

Projections 2018 (UKCP18) local (2.2 km) projections for 12 Met Office Hadley Centre models (HadGEM3-GC3.05) under Representative Concentration Pathway (RCP) 8.5 (Centre for Environmental Data Analysis, 2021). Variables used included daily temperature (average, maximum and minimum), daily specific humidity (average), daily relative humidity (average), daily precipitation (average) and daily solar flux (average). The 1981–2000 time period was used as the baseline, whilst the 2021–2040 and 2061–2080 time periods were used for 2030 and 2070 projections, respectively. Results were generated for six locations throughout Wales, namely: Cardiff, Wales's capital and most populated city; the town of Narberth on the southwest coast in Pembrokeshire; Brynmawr in the Brecon Beacons; Llangefni on the Ise of Anglesey in the north, Shotton, on the river Dee, which borders England, and the market town of Wrexham.

The locations were chosen to reflect a range of human settlement forms, for their geographic spread, as well as differences in for example, elevation and coastal proximity (see Fig. 1).

2.2. Indoor environment calculation

One of the aims of this study was to quantify the change in indoor temperature and relative humidity as a result of projected changes in outdoor temperature and humidity. A building's indoor environment will influence the health and comfort of its occupants. As the outdoor environment changes, so too will the indoor environment, if there are no mechanical systems to provide cooling or ventilation. For the purposes of this study, the relationship between outdoor temperature and indoor temperature, shown in Fig. 2a and b, was based on a monitoring study of 193 free-running dwellings, in other words without heating or cooling, located throughout England (Beizaee et al., 2013; CIBSE, 2015) [6,7]. The study reports mean and maximum hourly indoor temperature across all monitored dwellings for the 41-day period from July 22nd to August 31st; the height of the UK summer as shown in Table 1. The average outdoor temperature was also reported across England and for two of England's Government Office Regions.

Applying the study data, a relationship was developed between average daily outdoor temperature and average daily indoor temperature, as well as between average daily outdoor temperature and maximum daily indoor temperature, each for the 41-day monitoring period.

An hourly temperature profile was generated, assuming a 12-h linear relationship between the maximum and minimum daily temperatures, for each day in the analysis period. Minimum daily indoor temperatures were calculated by subtracting the difference in maximum and average daily temperature from the average daily temperature.

Temperatures were monitored and reported in dwelling living rooms and bedrooms separately, with average and maximum temperatures in

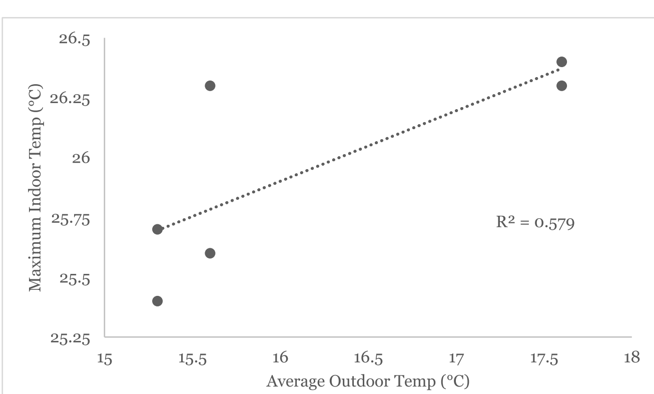

Fig. 2a. Indoor-outdoor maximum temperature relationship based on monitored temperature data points.

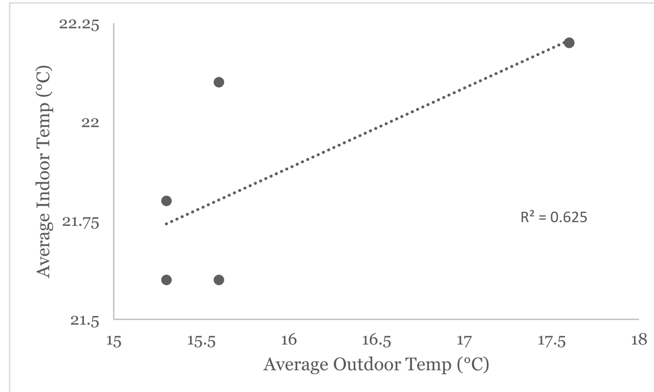

Fig. 2b. Indoor-outdoor average temperature relationship based on monitored temperature data points.

Table 1
Monitored temperatures used in formulation of indoor-outdoor temperature relationship.

Monitored Temperature					
Location	Monitoring Period	Room Type[a]	Average Indoor	Average Maximum Indoor[b]	Source
England	Jul 22nd - Aug 31st	LR & BR Avg	21.7	25.6	Beizaee et al. [6]
London	Jul 22nd - Aug 31st	LR & BR Avg	22.2	26.4	
Southeast	Jul 22nd - Aug 31st	LR & BR Avg	21.9	26.0	

[a] LR = Living Room, BR = Bedroom.
[b] Average maximum temperature across all monitored spaces (LR and BR) used to get a full day picture of each monitored space within the dwelling. Using only living room temp would give a higher maximum temperature but only of one space in the dwelling.

living rooms reported from 8:00–22:00 and bedrooms from 23:00–7:00. To allow analysis of a full 24-h days' worth of data, and to capture the internal temperature profile across multiple room types, the living room and bedroom monitoring data were averaged. The averaged values demonstrated better correlation with outdoor temperature values than they did individually. While using only living room data for daily maximum temperature would have resulted in a higher value, it would have only reflected one space in the dwelling.

A similar method was used to calculate indoor humidity from outdoor humidity. The relationship between indoor and outdoor humidity depends heavily on the type of humidity. Relative humidity, which is the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the given temperature, shows a poor correlation between indoor and outdoor levels as identified by Tamerius et al. [8]. Conversely, as recognised in work by Nguyen and Dockery [9], with specific humidity (which is the mass of water per unit mass of air and does not depend on temperature), indoor measurements track well with outdoor measurements across seasons, diverse climates, and a wide range of outdoor temperatures. Specific humidity data is also available as part of the UKCP18 climate data. For these reasons, specific humidity was used as the meteorological metric for the relationship between indoor and outdoor humidity.

Linear regression relationships as reported in three previously published monitoring studies were used as the basis for the relationship between average daily indoor and average daily outdoor specific humidity (Table 2) [8,9,43]. These studies feature monitored specific humidity data from six global locations sourced from a variety of building types (although mostly from dwellings) of different age, type,

Table 2
Linear regression relationships used to model the indoor-outdoor specific humidity relationship.

Specific Humidity Relationships			
Location	Slope	Intercept	Source
Athens, GRC	0.82	1.88	Nguyen et al. [9]
Boston, USA	0.86	1.75	Nguyen et al. [9]
Dublin, IRL	0.76	2.09	Nguyen et al. [9]
Nuuk, ISL	0.54	4.32	Nguyen et al. [9]
New York City, USA	0.60	2.58	Tamerius et al. [8]
Kent, GBR	0.93	0.50	Lankester [43]

construction, and levels of conditioning (heating, cooling and neither). Despite differences in building characteristics, it is assumed that the relationship between indoor and outdoor specific humidity established by these studies holds true in Welsh dwellings.

Using psychrometric equations, with inputs of indoor dry bulb temperature and specific humidity, the indoor relative humidity was calculated. It was assumed that maximum daily relative humidity occurs simultaneous to the minimum daily temperature and minimum daily specific humidity. Similarly, it was assumed that the average daily relative humidity occurs simultaneous to the average daily temperature and average daily specific humidity.

Use of monitored temperature and humidity data have several benefits and limitations when compared to thermal simulation modelling. While modelled data simulates indoor heat gain from occupants, equipment, lighting and others based on pre-defined typical schedules, monitored data has the ability to capture indoor condition fluctuations occurring as a result of behaviours and gains that are specific to the given dwelling or dwellings. Modelling does excel in the ability to evaluate differences in internal conditions due to many combinations of building characteristics such as insulation type, orientation, window area and others. It is also possible to model the climate specific to any location for present day or future climate projections. Monitored data is limited in its feasibility by the logistics of sensor deployment and in its applicability to the characteristics and locations of the dwellings within which sensors are installed.

In practice, whether a monitoring and modelling approach is employed, it is important to note the differences in a country-wide analysis, as is described in this paper, and a dwelling-scale analysis. The methodology described in this study informs broader country-level adaptation strategies, whereas a dwelling scale analysis will describe the vulnerabilities, and inform the climate adaptation strategies, specific to the dwellings in question. The most tailored and suitable adaptation plan will be based on monitored temperature and humidity data from, or a dynamic thermal model based on, the specific dwellings for which adaptation strategies are to be employed.

Climate vulnerability modelling limitations have been further outlined later in the paper.

2.3. Building typologies

To ensure the climate vulnerability modelling would be relevant to, and representative of, the housing stock of Wales, an analysis of the breakdown of dwelling typologies across Wales was undertaken. Consequently, the results for internal overheating risk and indoor air quality are reported for eleven distinct dwelling classes, which seek to represent the most common Welsh dwelling types. Some of these classes include more than one dwelling type, e.g., solid and cavity brick; properties aged between 1919 and 1990; and terraced and semi-detached dwelling forms. These have been grouped together into single classes because Beizaee et al.'s study [6] revealed that these groups behaved equivalently, and therefore the °C adjustment was the same.

The temperature adjustments listed in Table 3 are applied to the indoor temperature calculation discussed in the previous section, which

Table 3
Building classes with associated temperature adjustments.

Welsh Housing Building Classifications			
Building Classes		Adjustment (°C) Add to calculated internal temp	
		Mean	Max
Age	Pre 1919	−1.0	−1.8
	1919–1990	0.1	0.2
	Post 1990	0.8	0.8
Wall Construction	Timber Frame	0.0	−0.3
	Solid - Stone	−1.6	−2.1
	Solid - Brick & Cavity	0.0	0.2
Dwelling Type	End Terrace & Mid Terrace & Semi Detached	0.1	0.2
	Detached	−0.4	−0.4
	Flat	0.7	0.8
Insulation	Internal Wall Insulation	0.4	0.6
Window	Double Glazing	−0.4 (−1.4)	−0.6 (−2.4)

is based on data from 193 free-running dwellings in the English monitoring study by Beizaee et al., 2013 [6]. The age, wall construction, and dwelling type temperature adjustments come from this same monitoring study, which reported separate dwelling temperature data for six different dwelling age bands, four different external wall types, and five different dwelling types. This data formed the basis for nine of the eleven Welsh dwelling categories.

Results from a study by Mavrogianni et al. [11], which used *Energy Plus* thermal simulations to model temperature conditions within London dwellings, were used to inform Internal wall insulation (IWI) and double-glazing building class temperature adjustments. Increase in average and maximum temperature due to wall or window retrofit was reported by the study. These values were then directly applied as the building class adjustments for internal wall insulation and window type.

Welsh Government were particularly keen to understand the impacts of internal wall insulation, as there has been significant investment in insulation retrofits through an Optimise Retrofit Programme. In Mavrogianni et al.'s study [11], exterior walls that are retrofitted with additional insulation were found to increase mean daytime living room temperatures by 0.38 °C (95% C.I. 0.25–0.51 °C) and maximum daytime living room temperatures by 0.61 °C (95% C.I. 0.36–0.85 °C). It is worth noting that, while most walls in the study were insulated internally, some walls were modelled as cavity walls with varying air gap sizes. On the contrary, glazing retrofit was associated with a decrease in mean daytime living room temperature of 0.39 °C (95% C.I. 0.25–0.51 °C) and a decrease in maximum daytime living room temperatures of 0.61 °C (95% C.I. 0.36–0.85 °C). Glazing retrofit was modelled as an improvement to thermal conductivity and U value, which was labelled as double glazing for the purposes of the building classes in this study. It is important to note that a standard daytime-only window opening schedule was included in the models.

The Welsh housing survey [12] found that all dwellings built after 1919 have already been retrofit with double glazing. The same is assumed to hold true for the dwellings in the Beizaee et al. [6] monitoring study, since glazing properties were not specified as part of the study. Therefore, the double-glazing temperature adjustment and associated results are only applicable to pre-1919 dwellings in this study.

The study does not include building class adjustments for specific humidity due to a lack of monitoring data by building class type. However, indoor temperature for each building class is combined with specific humidity values representative of all dwellings, which results in an adjusted relative humidity for each building class.

2.4. Modelling parameters

Two climate vulnerabilities were modelled in this study. Those that pertain to indoor environmental quality, namely overheating and moisture risks, are based on the indoor temperature and specific humidity calculations detailed in the previous section.

Temperatures inside of free running dwellings are heavily influenced by the outside air temperature. Therefore, rising outside temperatures associated with climate change lead to a risk of increased internal temperatures. Overheating in dwellings can lead to issues for occupants ranging from thermal discomfort, to heat stress, to more severe heat related illnesses. While the threshold that constitutes overheating varies from person to person and dwelling to dwelling, an operative temperature of 26 °C was used as the threshold in this study. This is consistent with the Chartered Institution of Building Services Engineers (CIBSE) Technical Memoranda 59 (TM59) section 4.3 which defines an operative temperature of 26 °C as the static overheating threshold that should not be exceeded for more than 3% of occupied hours for dwellings without sufficient opportunities for natural ventilation (insufficient window area or unfavourable conditions for open windows) [13].

TM59 also formalises a criterion for dwellings with sufficient opportunity for natural ventilation, called the adaptive criterion, where the acceptable indoor temperature fluctuates according to the outdoor temperature [13]. Such an adaptive criterion is based on the idea that people adapt to their environment and so may find higher indoor temperatures comfortable as outdoor temperatures rise. Future research opportunity exists to evaluate how thermal comfort in Welsh dwellings may change as a result of climate projections using the adaptive thermal comfort definition, but this was outside of the scope of this study.

While the overheating temperature threshold used in this study is consistent with the TM59 static threshold, it is important to note that this study is not an application of the TM59 methodology. The TM59 methodology is intended to be utilised by designers as a pass or fail test for an individual home's overheating risk using hourly dynamic simulation modelling software. Such an application is outside of the scope of this study and the results of this study should not be taken as a pass or fail overheating assessment of the Welsh housing stock. This is especially significant to keep in mind since this study is for 41 days of the cooling season, rather than the entire year as is standard in the TM59 overheating criteria.

As noted above, the thermal comfort criteria is based on the operative temperature, which is assumed to be equal to the air temperature. CIBSE TM52 confirms this assumption by noting that in well-insulated buildings and away from direct radiation from the sun or from other high temperature radiant sources, the difference between the air and operative temperature is small [13]. Therefore, the thermal comfort results presented in this study are only applicable so long as this assumption holds true. If conditions in a given dwelling are such that the operative temperature differs from the air temperature (direct solar radiation, high air speeds, etc.) then overheating risk may vary from that presented here.

The next vulnerability metric assesses the impact of humidity levels on the air quality inside of dwellings. High levels of relative humidity have been shown to contribute to increased levels of mould and fungus, bacteria, viruses, and mites as identified by Arundel et al. (1986), the World Health Organisation (2009), and Lankester (2013), amongst others [14,15]. A relative humidity range of 40%–60% was found by Arundel et al. [14] to be the ideal range for favourable indoor air quality across all categories studied. This current study looked at days with average or maximum relative humidity greater than 60% to quantify the change in risk to poor air quality. While low relative humidity can also have negative consequences, it was not assessed in this study since indoor relative humidity levels are projected to increase. The climate in Wales is also such that low relative humidity is typically not the prevailing issue.

3. Results

The results of the climate vulnerability modelling are reported for all six of the aforementioned locations (see Fig. 1), with daily average and maximum temperatures projected to increase from baseline (1981–2000) to the projected periods of 2030 (2021–2040) and 2070 (2061–2080).

3.1. Projected temperature trends

Projected temperature trends are evidenced in Fig. 3, which shows an annual profile of daily average outdoor temperatures for the baseline, 2030 and 2070 time periods in Cardiff. A similar trend can be seen in the other five locations as well, with temperatures increasing across all months of the year, but with the most pronounced increase in the summer. In Cardiff, the average daily change from baseline to 2070 is 3.6 °C and the maximum daily change from baseline to 2070 is 6.0 °C. The period with the most pronounced temperature changes also corresponds to the 41-day monitoring period from July 22nd to August 31st that dictates the analysis period for all of the indoor temperature portions of this study.

3.2. Indoor and outdoor temperature profiles

Daily average indoor and outdoor temperatures for the analysis period are shown in Fig. 4a. The increase in outdoor temperatures illustrated in the annual profile in Fig. 4b can be seen, with temperatures in all locations steadily increasing from baseline to 2030 and 2070. Changes in outdoor temperature are further illustrated in Fig. 4b, where there is an average increase of 2.1 °C from baseline across all locations in 2030, but that by 2070 the change in temperature starts to vary between locations by more than a degree, from 4.7 °C to 5.8 °C. Two of the most northern and coastal locations, Llangefni and Shotton, exhibit the lowest rise in temperature by 2070.

Less pronounced is the change in indoor temperature, which is projected to increase by an average of 0.4 °C by 2030 and by 1.0 °C by 2070 across all locations as shown in Fig. 4c.

As demonstrated by Fig. 5a, the average daily maximum indoor temperature is greater than the average daily maximum outdoor temperature by an average of 6.1 °C in the baseline time period, but this difference diminishes to 4.4 °C by 2030 and to 1.9 °C by 2070. One potential cause of this is the thermal mass of a typical dwelling, and the heat-generating activities within, which keep internal temperatures from swinging as severely as the exterior temperature. Temperatures under consideration in this section reflect the average dwelling. However, interior temperatures vary by dwelling type, such as in the case of flats (apartments) and dwellings built after 1990, which demonstrate higher interior temperatures than average.

Like the daily average outdoor temperature, the average daily maximum outdoor temperature shows steady increases across all locations from the baseline to 2030 and 2070 (Fig. 5b). Projections show a slightly larger increase in maximum temperatures than were seen with average temperatures. Whereas the increase in average temperature by 2030 across all locations averages 2.1 °C, the average increase in maximum temperature across all locations by 2030 is 2.4 °C, ranging from 2.0 °C to 2.7 °C. Similarly, by 2070 average temperatures show an increase of 5.2 °C, while maximum temperatures increase by 6.0 °C, ranging from 5.2 °C to 7.0 °C. The two most northern locations again show the lowest rise in maximum daily temperature by 2070.

The projected increase in indoor maximum temperature is less pronounced than outdoor maximum temperature, with indoor maximum temperature projected to increase by an average of 0.6 °C by 2030 and by 1.5 °C by 2070 across all locations as shown in Fig. 5c.

Hours above the 26 °C overheating threshold were tallied as identified in Fig. 6. It is worth noting that in a dwelling with sufficient opportunity for natural ventilation, and so one that may follow the adaptive thermal comfort criterion, the thermal comfort threshold may exceed 26 °C. In such a case, overheating may not occur even at the maximum temperature values seen in Fig. 5. Similarly, the percent of

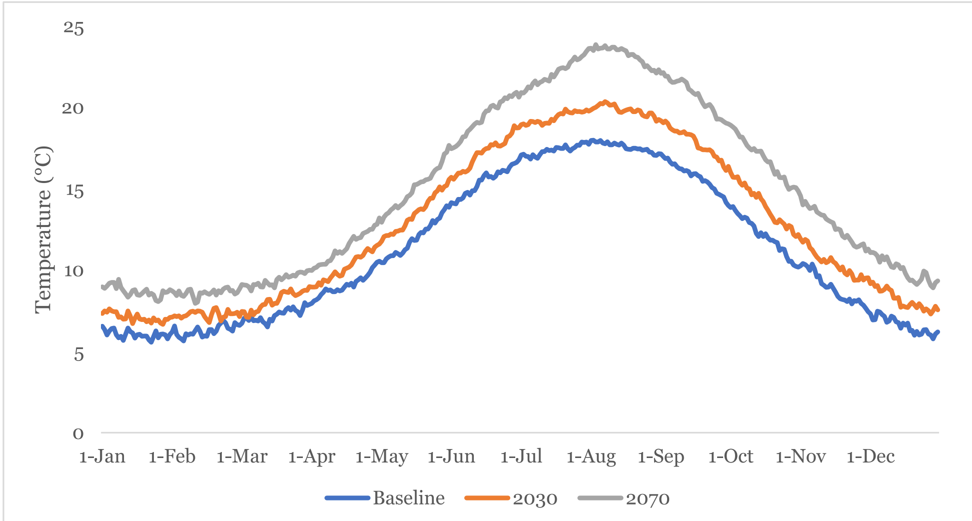

Fig. 3. Annual profile of daily average outdoor temperature in Cardiff for baseline, 2030 and 2070.

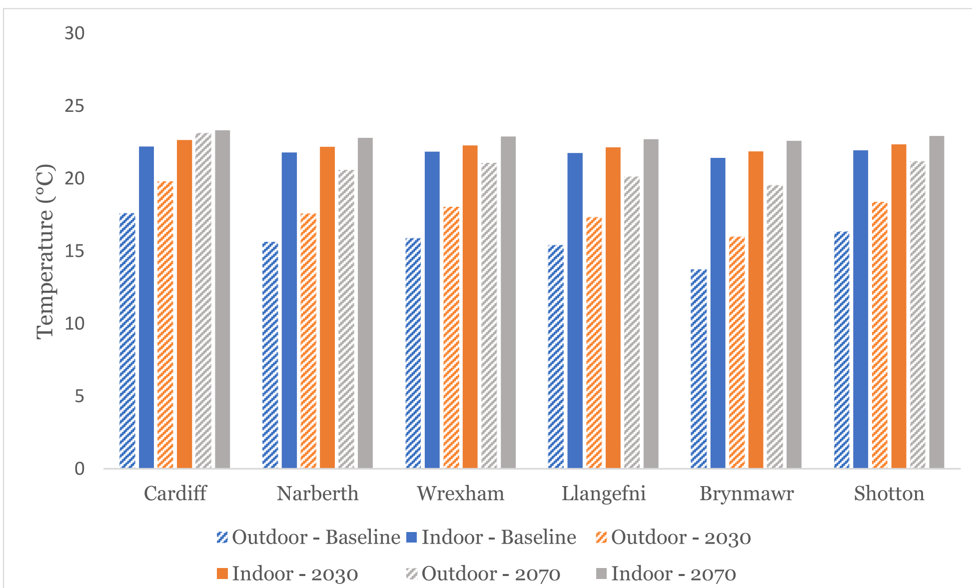

Fig. 4a. Indoor and outdoor daily average temperature averaged over the study period.

hours that exceed the thermal comfort threshold may decrease from what is shown in Fig. 6.

Differences in thermal comfort and overheating by building class are immediately apparent, with higher fabric heat loss likely correlating to lower overall temperatures. The older dwellings generally exhibited lower temperatures, especially those built before 1919, typically built with solid wall construction. Indeed, homes with solid stone walls, correlate with pre-1919 homes, and demonstrate markedly cooler temperatures than dwellings with timber frame, solid brick, and cavity walls. This is likely due to the greater amount, and increased effectiveness, of insulation used in the construction of newer homes and the increased insulative performance of the latter three wall types. Similarly, flats demonstrated the highest temperatures of any dwelling type. This may be attributed to the modern construction techniques in the construction of flats. It may also be due to the low ratio of external wall to volume that they typically exhibit in comparison to the other two housing types, although, as identified by Beizaee et al., flats on the top level of buildings typically demonstrate a greater tendency to exceed overheating thresholds than flats on lower levels [6]. Along these same lines, Mavrogianni et al. note that homes retrofitted with internal wall insulation experience increased temperatures from the average home, which may also be due to the reduced fabric heat loss after installation [17].

The focus of climate change mitigation in the UK is currently on reducing heat loss for wintertime energy savings, which may also be exacerbating the risk of summertime overheating, especially in the dwelling types discussed above. Further study is suggested to verify the cause of elevated heat levels in these dwelling types, and such study should be taken into consideration by the UK and Welsh government decarbonisation policies and programmes.

3.3. *Indoor and outdoor humidity profiles*

Like indoor temperature, the indoor relative humidity for the study period (July 22nd – August 31st) is projected to increase across all six study locations from baseline levels into the 2030 and 2070 time periods (Fig. 7). While the Northwest and Southwest locations of Llangefni and Narberth have the highest baseline daily average relative humidity, at

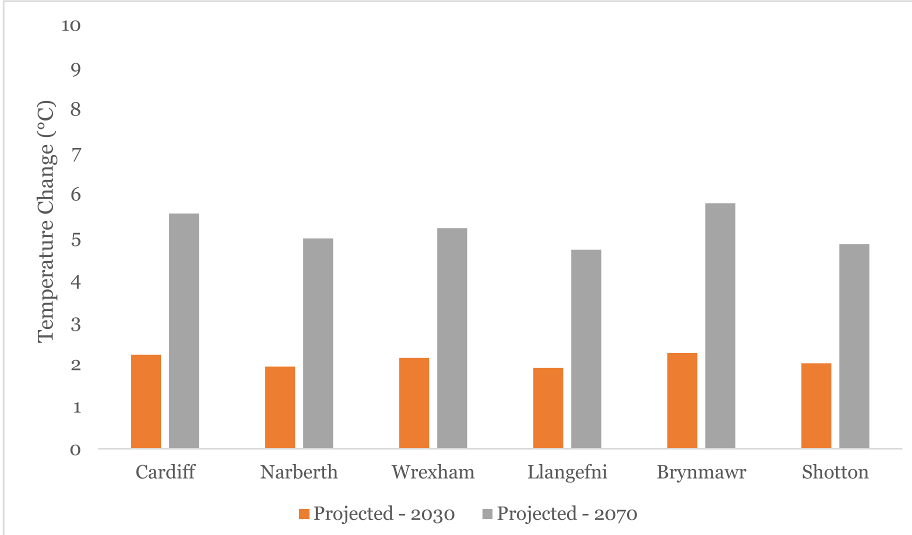

Fig. 4b. Change in outdoor average daily temperature averaged over the study period for 2030 and 2070.

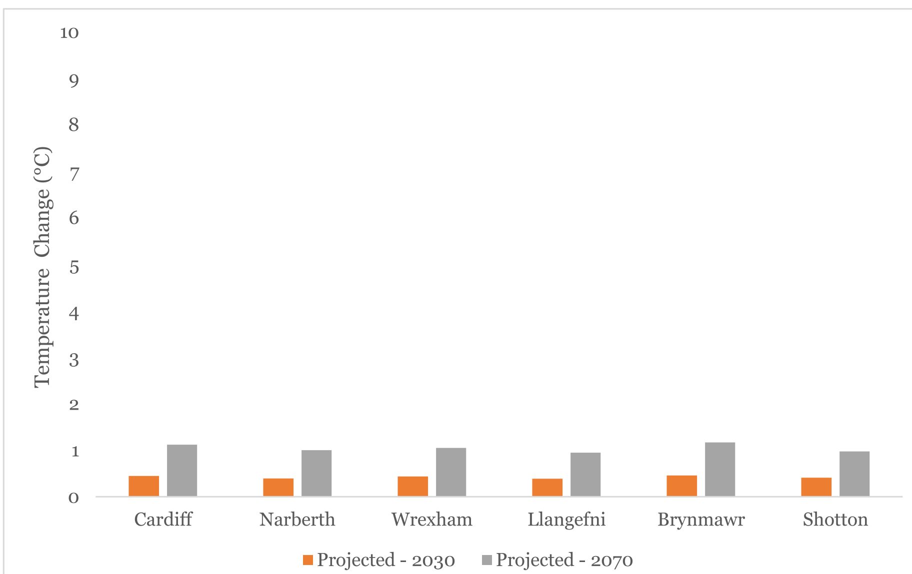

Fig. 4c. Change in indoor average daily temperature averaged over the study period for 2030 and 2070.

53.6% and 53.9%, respectively, it is Llangefni and Shotton that are projected to experience the greatest increase in relative humidity by 2070 (7.2% and 6.9%, respectively). Average daily maximum relative humidity values are also projected to increase across all six study locations, although by a larger margin (Fig. 8). Whereas daily average relative humidity is projected to increase by an average of 2.5% by 2030 and 5.9% by 2070 across all locations, daily maximum relative humidity is projected to increase by an average of 4.2% by 2030 and 10.0% by 2070.

In the context of the 60% relative humidity threshold, even by 2070 only two building classes in Cardiff are projected to have daily average indoor relative humidity levels breach this threshold. This is illustrated in Fig. 9a. The same cannot be said for daily maximum indoor relative humidity, which breaches the 60% threshold for ten out of eleven building classes by 2030 and for all building classes by 2070 (Fig. 9b).

By age, occupants of newer homes, built after 1990, are predicted to experience the lowest relative humidity. Timber frame homes and flats also perform well in their respective building class categories. These results are contrary to those for temperature. In general, dwelling classes that demonstrated the highest temperatures are the same that demonstrate the lowest relative humidity levels. To a certain extent, this is because all building classes have the same specific humidity (since there are no building class adjustments for specific humidity) input into the psychrometric equation, with building-class-specific temperature, to reach the internal relative humidity values shown. Due to psychrometric relationships, one specific humidity value at a lower temperature will result in higher relative humidity, and vice versa.

The relative humidity levels presented here do not reflect prevalence of ventilation any more than is inherently present in the temperature and humidity monitoring data. As discussed above, the variation is primarily due to the temperature differences between the building classes. These values also correspond to the average dwelling in each category.

In the case of mould growth, relative humidity is only one precursor. Additional factors that play a role include moisture, temperature, and duration of favourable conditions. Predicting mould growth is an

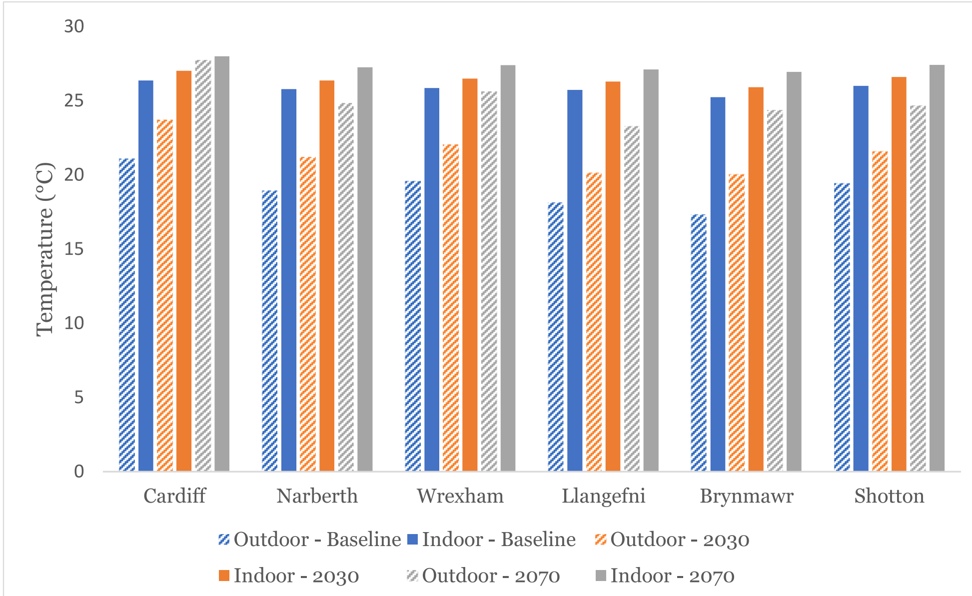

Fig. 5a. Indoor and outdoor daily maximum temperature averaged over the study for baseline, 2030 and 2070.

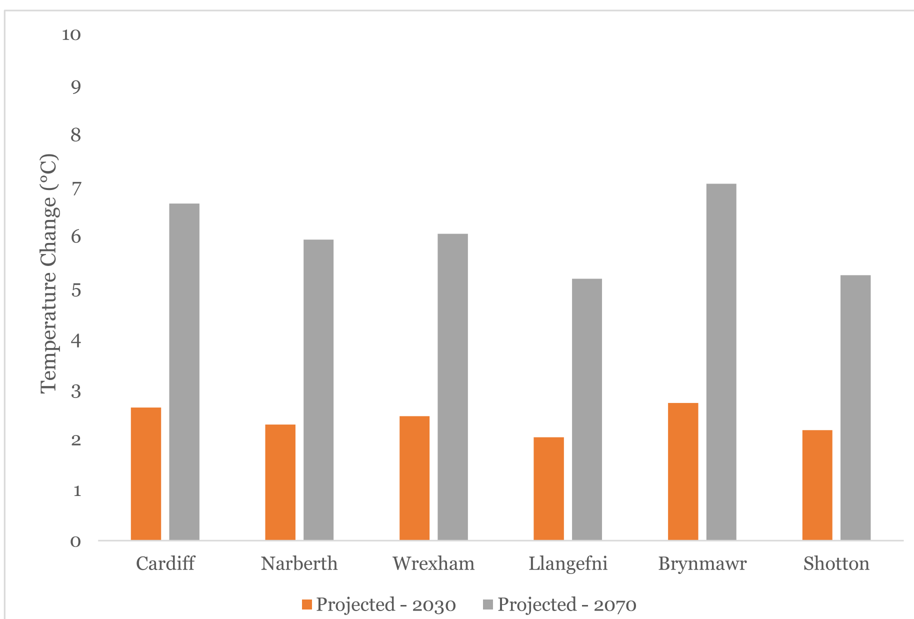

Fig. 5b. Change in outdoor maximum daily temperature averaged over the study for 2030 and 2070.

imperfect science as acknowledged in multiple studies, for example work by Abuku et al. (2009), Isaksson et al. (2010), Johansson et al. (2010, 2014, 2021), and Sedlbauer (2002) [18–23], partially due to the number of factors involved and the inhomogeneous nature of conditions from dwelling to dwelling and even from room to room. However, if exceedance of the relative humidity threshold is projected as in Fig. 10, it indicates elevated relative humidity for longer periods of the day, resulting in conditions more favourable for mould growth and other indoor environmental quality issues. The actual presence of mould in any given dwelling would depend on actual relative humidity levels, duration at favourable relative humidity levels, temperature, ventilation rates, the level of occupant generated moisture, and other factors.

Another way to look at the relative humidity projections is by the percent of days over the course of the study period during which the average and maximum daily relative humidity exceeds the indoor air quality threshold of 60%. Fig. 10a gives an indication of the duration over the study period that average relative humidity levels stay in the range favourable for mould growth. As noted previously, duration of favourable conditions is a key factor in mould growth.

While the average and maximum relative humidity values averaged across the duration of the study period may not exceed the 60% indoor environmental quality threshold until 2070, Fig. 10b illustrates the prevalence with which the threshold is exceeded even in the baseline time period by all building classes. For example, while the baseline average daily relative humidity for timber frame buildings is only 51.1% across the study period, the daily average relative humidity does still exceed 60% for 6% of days in the baseline period, and for 30% of days by 2070. Continuing with timber frame buildings, while their baseline maximum daily relative humidity for the entire study period is 57.4%, their daily maximum relative humidity exceeds 60% for 36% of days in

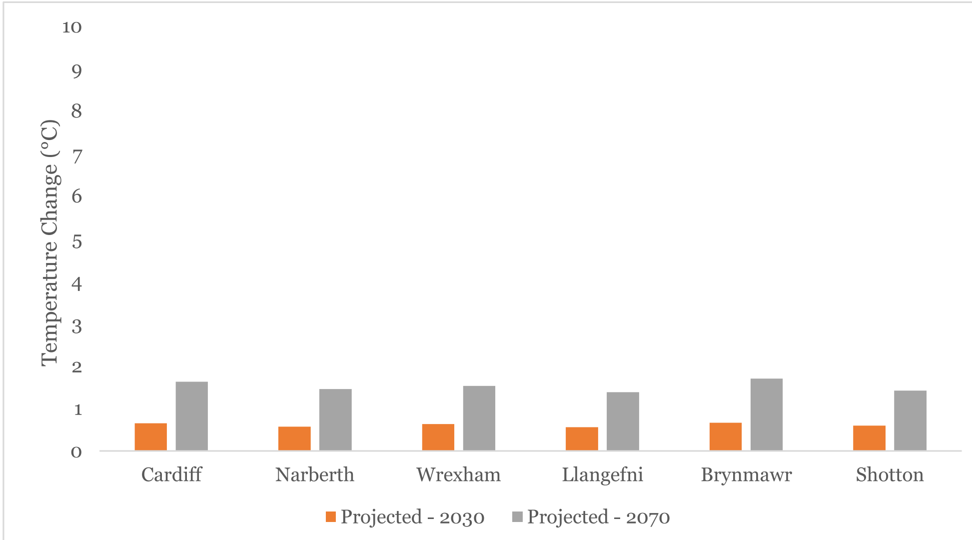

Fig. 5c. Change in indoor maximum daily temperature averaged over the study period for 2030 and 2070.

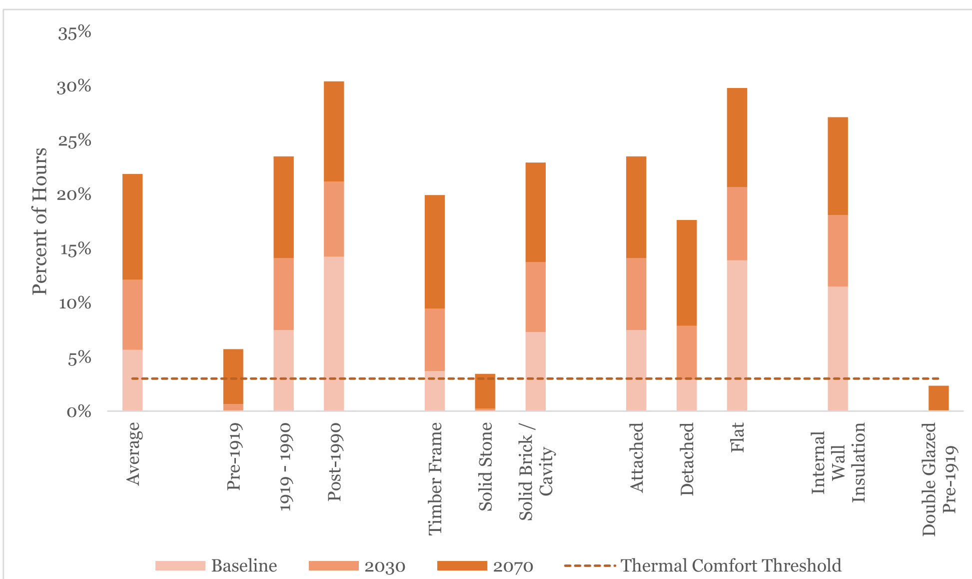

Fig. 6. Percent of hours in the study period over 26 °C threshold for thermal comfort [3% of occupied hours threshold shown for reference].

the baseline period, and for 73% of days by 2070. This may indicate a risk for mould growth but also for more acute indoor environmental quality related problems that do not depend on extended durations of favourable conditions.

3.4. Climate adaptation

The results of the climate vulnerability modelling were shared with representatives from across Welsh Government as well as other invited non-government public bodies, and a series of workshops convened between August and October 2021 to discuss the challenges associated with summertime overheating and higher indoor humidity levels expected for Welsh dwellings, including the co-creation of adaptations that could be adopted to improve indoor environmental quality in Welsh dwellings, comprising climate-responsive behavioural changes (making small but significant behavioural adjustments to the way occupants live in their homes), internal fit-out alterations, and building fabric modifications (Fig. 11). One of the intentions of the workshops was to co-create a prioritisation index for dwelling adaption. However, it became evident, during these conversations, that distinct adaptation recommendations and how they should be prioritised, would need to be separately devised for different building typologies and separate geographical locations. The implications of this are discussed below.

4. Discussion

4.1. Climate mitigation versus adaptation

Climate change is and will undoubtedly continue to impact the indoor environmental quality of Welsh dwellings. In general terms, due to increasing temperatures, heating loads in Wales will decrease in winter, while in summer, occupants will experience more uncomfortable conditions across the board. The climate vulnerability modelling reported in this paper has revealed that residents of pre-1919 and solid stone

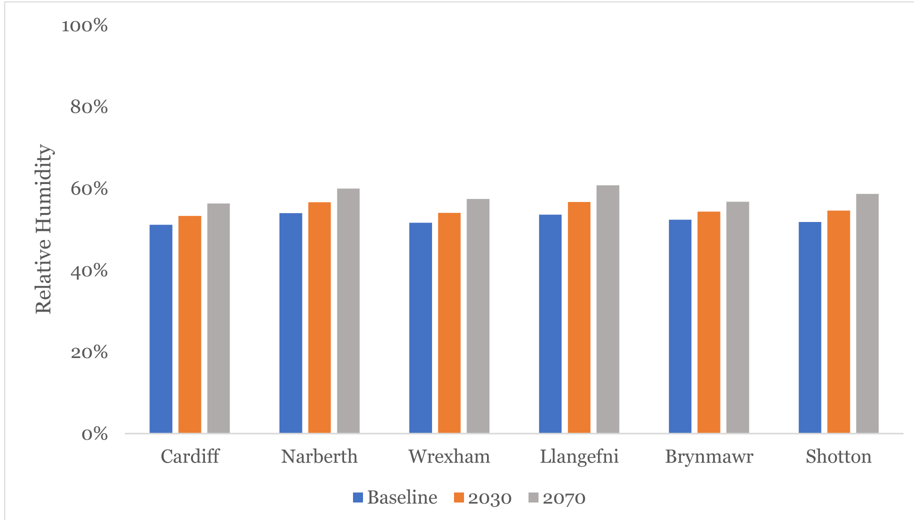

Fig. 7a. Indoor daily average relative humidity averaged over the study period for baseline, 2030 and 2070.

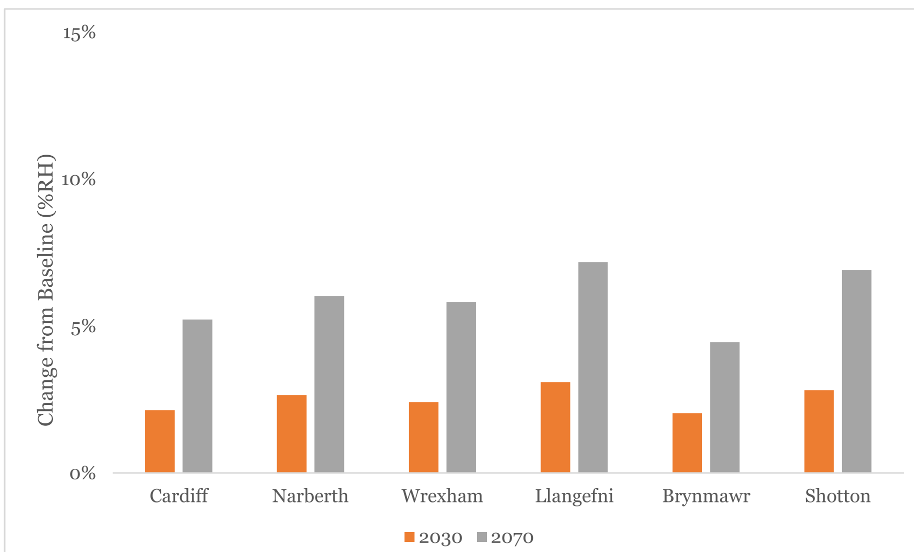

Fig. 7b. Change in indoor average daily relative humidity averaged over the study period for 2030 and 2070.

dwellings will be less affected by overheating, assuming, for example, that their properties have not been subdivided into e.g., single-aspect flats or retrofitted with e.g., internal wall insulation. Wetter weather and associated wind-driven rain across most of the country will also bring its challenges, both for building upkeep and associated indoor moisture levels.

Nevertheless, in the UK as a whole, there is still a focus on climate change mitigation, reducing energy consumption associated with heating, driven by UK and Welsh government decarbonisation policies and programmes. Although the current drive to reduce heat loss is not without obvious merit, as levels of insulation increase and air infiltration decreases, there is an increasing risk of summertime overheating linked to climate change, particularly in urban areas [5]. This risk is reported in other countries too. For example, a French study undertaken by Moreau-Guigon and colleagues found that the emphasis on energy-efficiency in housing has resulted in retrofit solutions, such as increased insulation, that do not always allow for the effective exchange of air between the indoors and outside [24]. Certainly, Carmichael et al. (2020) [25] have recognised that whilst wintertime thermal comfort is improved through energy efficiency measures, problems with damp, mould, overheating, and adequate ventilation that are frequently exacerbated due to increased insulation and air-tightness levels, will become more prevalent. Therefore, it is suggested that the findings from these, and this current research project, should be taken into consideration before any future retrofit decision-making. Additionally, as mentioned above, the most appropriate adaptation strategies for an individual dwelling will be based on the dwelling's specific characteristics and resulting internal conditions, which will vary from those presented here since the methodology described in this study is intended to inform broader country-level adaptation strategies.

4.2. Overheating

Overheating in residential buildings is acknowledged in the wider UK-context and its significance to Wales validated by the results of the climate vulnerability modelling, which demonstrates that cooling strategies to reduce indoor air temperature will increasingly be required. This is in line with other studies, where real-time overheating has been identified. For example, Mavrogianni et al. [11], who undertook a pilot monitoring study of 36 London dwellings during the summer of 2009,

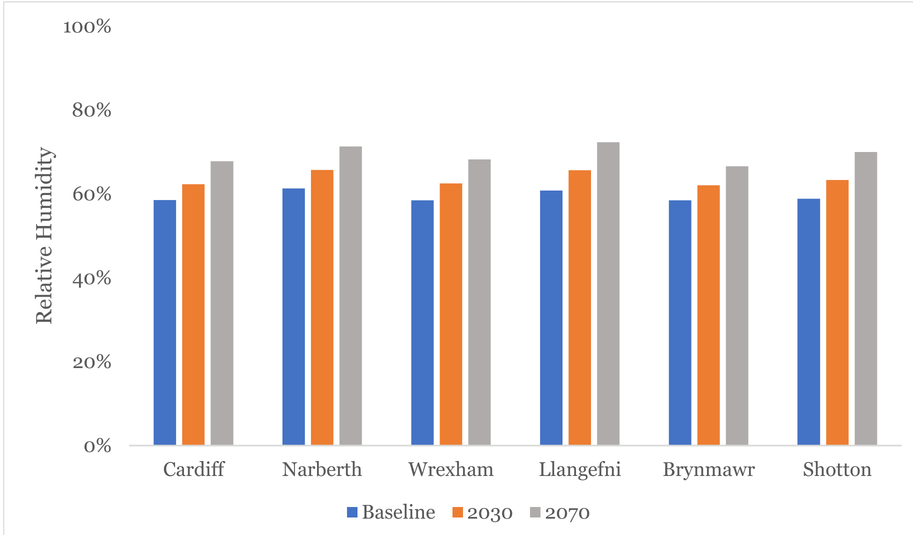

Fig. 8a. Indoor daily maximum relative humidity averaged over the study period for baseline, 2030 and 2070.

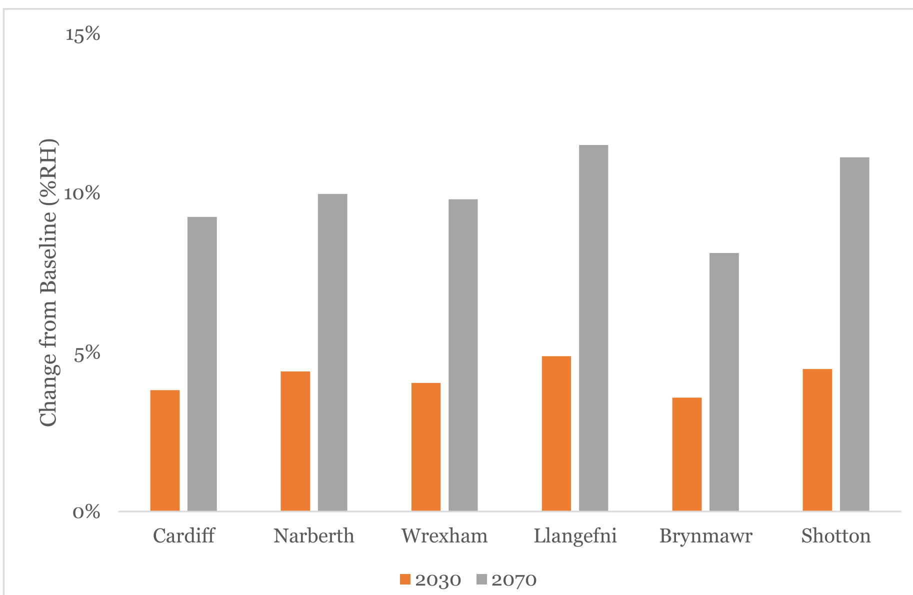

Fig. 8b. Change in indoor maximum daily relative humidity averaged over the study period for 2030 and 2070.

found that 42% of bedrooms monitored failed the CIBSE overheating criteria, a large proportion of which were in purpose-built flats. In addition, it was purported that sleep impairment was experienced in 86% of the monitored bedrooms. Evidence points to construction type as well as site-specific microclimatic conditions as determinant factors for overheating. Meanwhile, Baborska-Naroznya and Grudzinska [26] looked at overheating in a high-rise retrofit apartment block in Leeds, in the north of England, and established that overheating might have been avoided if shading measures such as blinds had been introduced to prevent excessive solar heat gains [11]. D'Ippoliti et al. [26] looked at the impact of heat waves on mortality in nine European cities, including London, with a view to preparedness for more extreme climate events. Their research suggests that prevention programmes should specifically target the elderly, especially women, and those suffering from chronic respiratory disorders, in order to reduce the future burden of heat-related mortality, which is set to become a relevant threat even in areas usually not exposed to extreme hot temperatures. Many other researchers concur that energy demand associated with cooling will increase in the future as a direct result of thermal discomfort due to an increase in the number of days where cooling is a necessity [27–36].

Occupant behaviour can also have a significant impact on overheating, and a number of the adaptation strategies proposed by key stakeholders are contingent on climate-responsive behaviour change (Fig. 11). Indeed, Coley et al. have previously proposed that physical building adaptation, and behavioural interventions [37]. It was not possible to account for occupant behaviour in the results of the monitoring study, however the role of occupant behaviour has been acknowledged in the research and recognised as impacting on incidence of indoor overheating, as well as humidity fluctuations and the need for ventilation strategies. One further note of caution, it is acknowledged that more needs to be done to engage building owners and occupiers in developing and sustaining climate-responsive behavioural adaptations. Individuals cannot be expected to make changes to their behaviours in isolation, and investment will need to be made to establish, secure and sustain climate-responsive behaviour change.

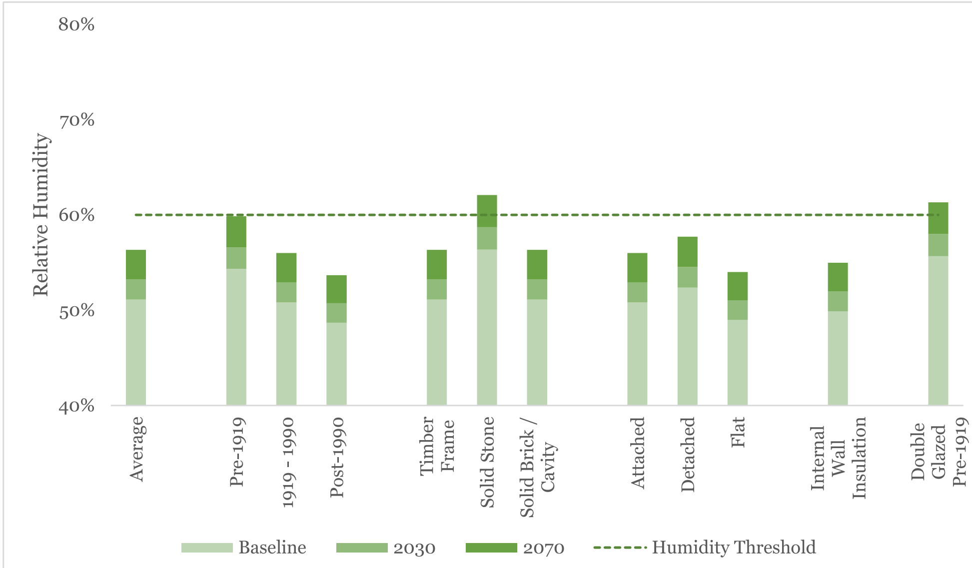

Fig. 9a. Indoor daily average relative humidity averaged over the study period in Cardiff [60% relative humidity threshold shown for reference].

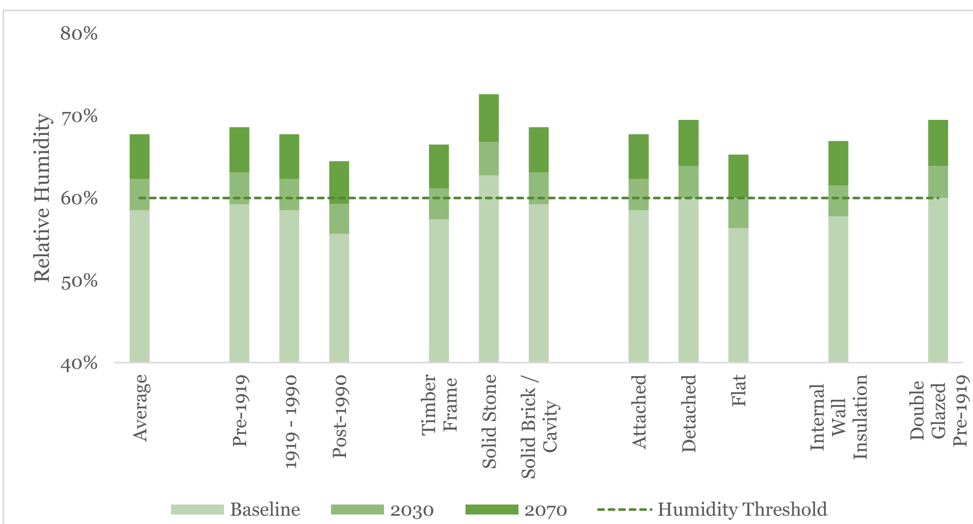

Fig. 9b. Indoor daily maximum relative humidity averaged over the study period in Cardiff [60% relative humidity threshold shown for reference].

4.3. Ventilation

It is well recognised and reported in international studies by Moreau-Guigon et al. [24], Pegas et al. [38] and Yang et al. [39] that inadequate ventilation accelerates the accumulation of contaminants from both outdoor and indoor sources [38] and is a primary cause of indoor air pollution and is why pollutants rise in homes during the winter [39]. Conversely, suitable ventilation meliorates indoor air quality by both reducing moisture levels (relative humidity) and diluting the concentration of pollutants that are present indoors, introducing fresh air from outdoors and removing polluted indoor air. Occupant behaviour once more can be key to reducing moisture build up; with an awareness and appropriate management of high-moisture generation activities, particularly in kitchens and bathrooms, good passive air exchange practices can be sustained. The climate modelling research outcomes indicate that efficient ventilation (passive or active) will increasingly be required to alleviate moisture build up, especially where indoor relative humidity levels regularly exceed 60%. This will also help alleviate the build-up of indoor pollutants. According to McGill et al. [40], the lack of attention given to indoor contaminants in research to date may be due to the problems associated with measuring pollutants, the intangibility of health and wellbeing, and difficulties in the delivery of quantifiable benefits to improving indoor environmental quality. Furthermore, McGill et al. [40] identify trade-offs between indoor environmental quality and building energy conservation such as ventilation rates and specification of materials, which may be more heavily weighted to energy conservation goals than ensuring satisfactory indoor air quality. It is assumed that the shortage of guidelines or regulatory levels for indoor pollutants is affecting the ability to deliver robust indoor environmental quality criteria. Emphasising the need to monitor indoor environmental quality as a consequence of reported climate change vulnerabilities may prove the precursor for future legislation.

Certainly, climate change and the need to plan for future climate scenarios, is yet to be effectively and consistently integrated or delivered through building policy and regulation. Adaptation advice for building occupants and owners up until now has been unsubstantiated, with

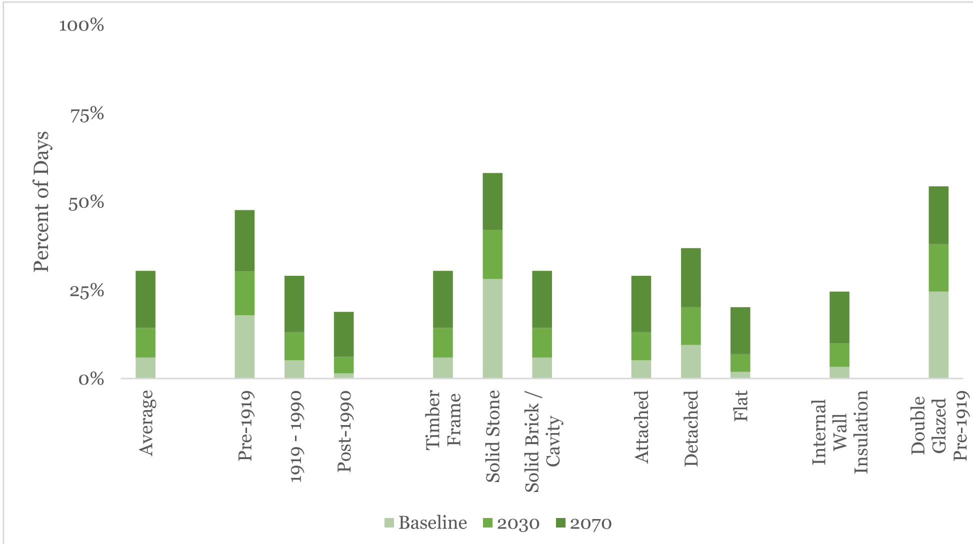

Fig. 10a. Percent of days in the study period with indoor daily average relative humidity above the 60% relative humidity threshold in Cardiff.

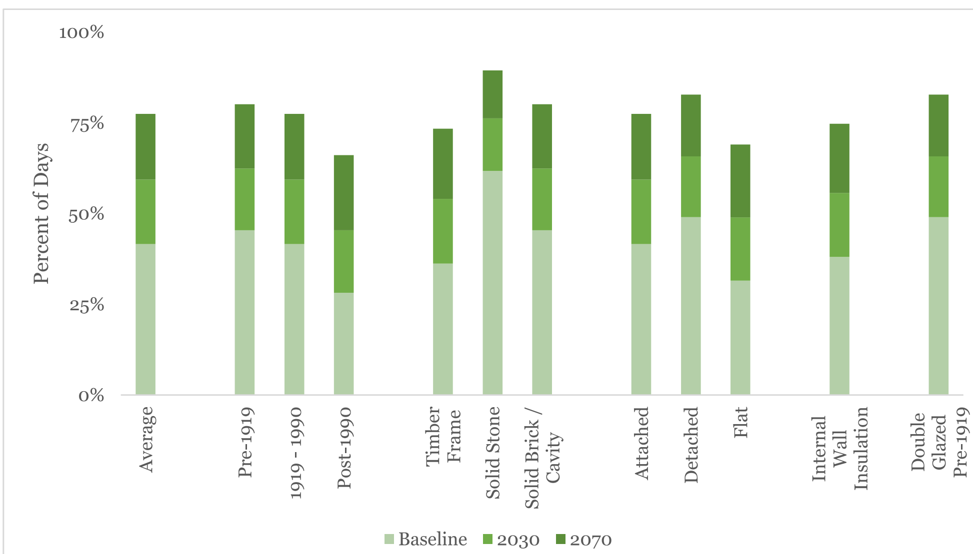

Fig. 10b. Percent of days in the study period with indoor daily maximum relative humidity above the 60% relative humidity threshold in Cardiff.

inconsistent messaging.

Comprehensive climate adaptation decision making is needed now. Back in 2013, Gupta and Gregg [41] stated that adaptation measures implemented at the same time as energy efficiency measures, could significantly reduce the risk of overheating. Whilst Carmichael et al. [25] called for a more holistic policy approach to housing design and construction, with an integrated framework. Certainly, it is now necessary to ensure retrofit approaches align carbon reduction with climate change adaptation, to avoid any maladaptation, such as the unintended consequences, including the inferior indoor environmental conditions (overheating and increased relative humidity) that can be introduced during the application of solid wall insulation, as identified by King for the BRE [42]. The complexities of tackling climate change demand a holistic policy approach to the design, build and planning process, one where strategic foresight can be applied and include risk-based adaptations.

4.4. Risk-based adaptations

The next stage of the current research project is the progression and dissemination of a series of adaptation pathways for housing typologies, which it is anticipated will benefit both the owners and occupants of dwellings in Wales, and more widely, the UK. How this work will be disseminated is still under review.

4.5. Climate vulnerability modelling limitations

This study aimed to inform a deeper understanding of the vulnerability of the Welsh housing stock to summertime climate change impacts. While the methodology described above achieves detailed results that can help inform appropriate adaptation steps, there are limitations of the analysis that stem from a wide range of sources such as data gaps, necessary assumptions, and more. Several limitations have been outlined above, while those that have not been previously covered are discussed in this section.

Indoor temperature calculated as a function of outdoor temperature

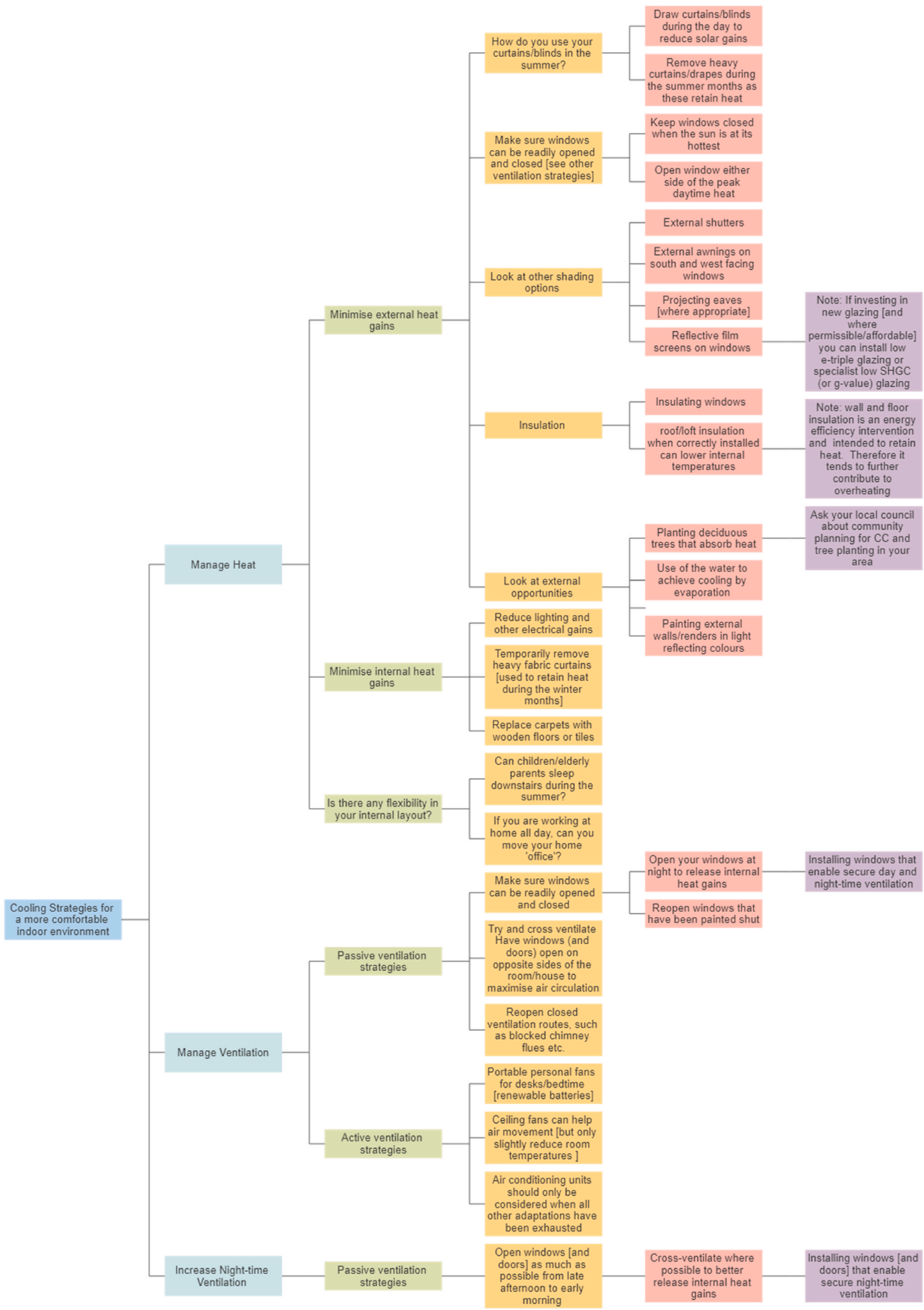

Fig. 11a. Cooling strategies for a more comfortable indoor environment.

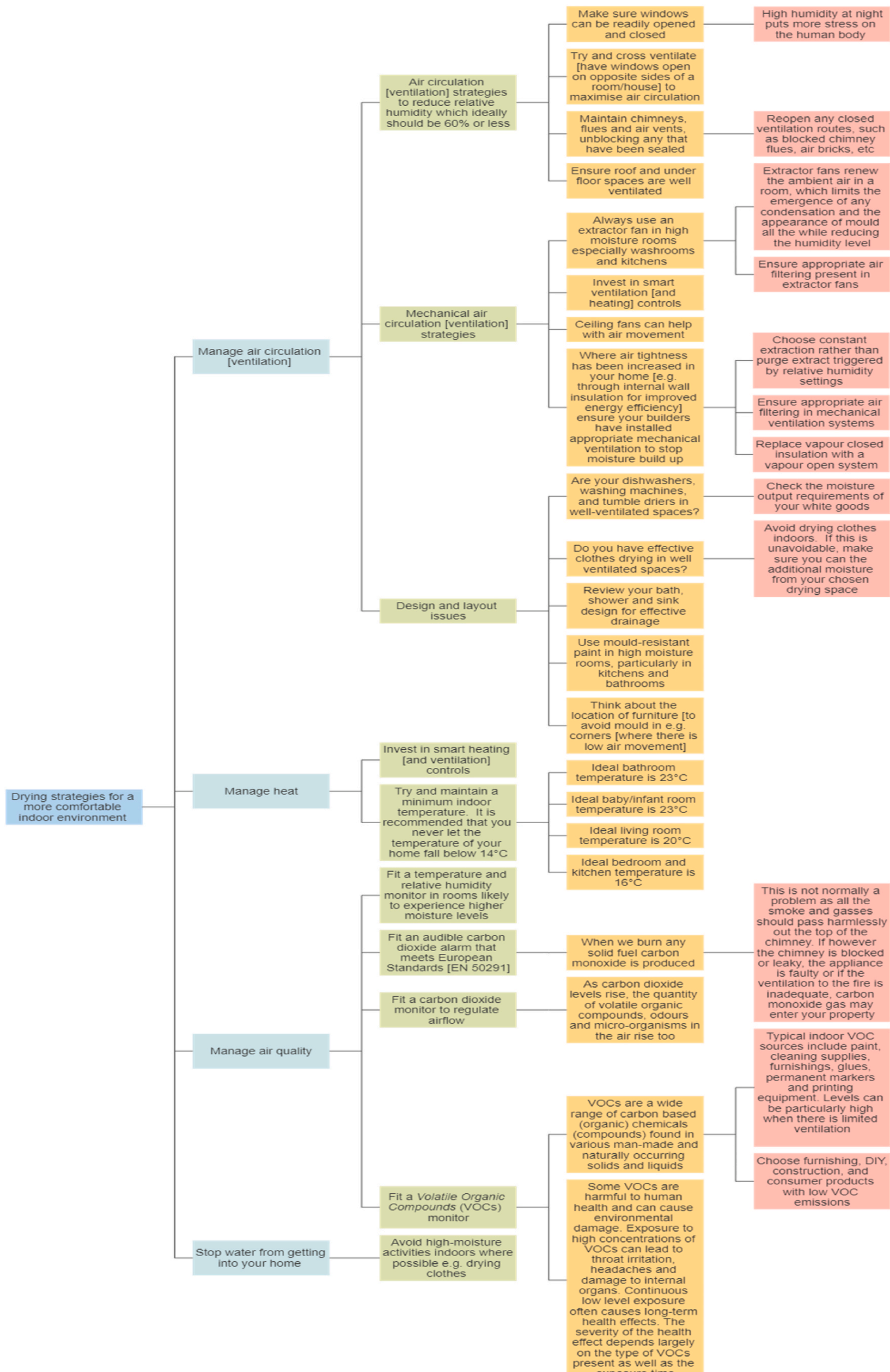

Fig. 11b. Drying strategies for a more comfortable indoor environment.

is an input to both the overheating and indoor air quality vulnerability metrics. One limitation of the indoor temperature calculation is the monitoring data from which it is based. First, the monitored temperature data is from a study of English homes for which the only dwelling characteristics known are type, age band, and external wall type. From this it is only possible to determine temperature differences between a single one of these pre-defined dwelling characteristics. Tailored temperature calculations cannot be performed for a dwelling's specific combination of construction materials, wall types, etc. since temperature adjustment for a combination of these characteristics is not possible. Additionally, the monitoring study only reported three outdoor average temperature values across the monitoring period: one for all of England, one for London, and one for Southeast England. The indoor-outdoor temperature relationships may be enhanced by the inclusion of additional paired data points for average outdoor temperature and indoor temperatures. A second limitation of the indoor temperature calculation is that hourly temperature is assumed to change linearly over a 12-h period between minimum and maximum daily temperature. Likewise, the relationship between indoor and outdoor specific humidity is the result of a set of global monitoring studies that do not allow for the differentiation of specific humidity values based on building characteristics. Information on humidity fluctuations as a result of occupant behaviour was not included in the monitored data and so is not included in this analysis. Instead, the indoor specific humidity fluctuation pattern mimics that of the outdoor specific humidity.

In both cases a more tailored result could be achieved if whole-year hourly monitoring data existed amongst a wide range of Welsh dwellings, with temperature and humidity differences tracked between numerous combinations of building and occupant characteristics. Not only would this improve the data on each building class, but it would also allow for actual daily indoor specific humidity ranges to be calculated. This in place of using the daily specific humidity range coinciding with the typical design day. Indoor relative humidity is calculated using calculated indoor temperature and indoor specific humidity values. Again, actual monitored indoor relative humidity values may lead to results that are more accurate for any given building, since this would capture the actual occupant generated humidity and would not rely on an assumed daily specific humidity fluctuation.

5. Conclusions and recommendations

The urgency and likely impact of climate change on our weather systems has been thoroughly assessed by scientists, the results of which are now widely published in academic literature and regularly reported in the mainstream media. In Wales, the climate is predicted to be warmer and wetter, and 'hot' summers are expected to become more commonplace by the middle of this century. The aim of this research project was to understand one of the direct impacts of climate change on the occupants of Wales's housing stock, by testing the hypothesis that summertime indoor housing conditions in Wales will diminish as a consequence of climate change. In order to answer this research question, a climate vulnerability modelling methodology was developed, and modelling was completed for a six-week period, representing the height of the Welsh summer.

The climate vulnerability modelling outcomes, outlined in this paper, reveal that the owners and occupiers of Welsh dwellings will certainly experience significant challenges, potentially compromising their experiences of comfort, and conceivably their physical health. The modelling measured vulnerabilities to indoor environmental quality, specifically thermal comfort and moisture. UKCP18 local (2.2 km) projections were used, under an emissions scenario of RCP 8.5. Three time periods were modelled, named 'baseline' (1981–2000), '2030' (2021–2040), and '2070' (2061–2080). 12 HadGEM3-GC3.05 models were used, and the results presented in the report are for six distinct geographical locations across Wales, namely Cardiff, Brynmawr, Narberth, Wrexham, Shotton, and Llangefni.

The derived relationship between outdoor temperature and indoor temperature was based on a previous study that monitored 193 free-running dwellings, without heating or cooling [6]. Eleven separate building classes were identified, which aimed to represent the variety of dwellings found across Wales according to building age, construction and dwelling type (detached, semi-detached, bungalow, flat, etc).

To understand the impact of climate change on the indoor environmental quality of dwellings in Wales, a six-week period from 22nd July – 31st August was modelled. The results reveal increased incidences of summertime overheating in a majority of dwellings across Wales, as identified by the number of hours exceeding the overheating threshold of 26°C. The best performing dwellings were pre 1919 dwellings and dwellings with solid stone walls. The poorest performing dwellings were post 1990 dwellings, flats and properties with internal wall insulation. The later was of particular interest to Welsh Government who fund an ongoing optimise retrofit programme. The results show that cooling strategies to reduce indoor air temperature will increasingly be required. The other indoor vulnerability modelled was that of moisture. There is an optimal range of between 40 and 60% relative humidity for human health and comfort. Anything beyond 60% is deemed too moist. Results demonstrate the potential for poorer indoor environmental quality in the summer due to an increase in relative humidity. All locations will experience increases in relative humidity regardless of dwelling typology. Relative humidity will be highest in pre-1919 dwellings and dwellings with solid stone walls regardless of location. The results show that ventilation strategies to improve the extraction of moisture-laden air, whilst diluting the concentration of pollutants that are present indoors, are required if these dwellings are to avoid increased incidences of condensation, damp, and mould growth, and adverse impacts from other allergens, particles and pollutants.

A review of recent and emerging research and published academic literature indicates that climate change mitigation and carbon reduction targets continue to be the main climate change goal for the design and construction industry; certainly, this has been the case in the UK and Wales. However, the results of this research verify that summertime indoor housing conditions in Wales will continue to diminish as a consequence of climate change. Therefore, it is recommended that comparable motivation is now required to oversee the climate adaptation of existing buildings, with particular emphasis on improving the indoor environmental quality of Wales's buildings. Going forwards, housing decarbonisation strategies should be combined with climate adaptation actions, which it is hoped will avoid activities that may lead to increased risk of adverse climate related outcomes, increased vulnerability to climate change, or diminished occupant health and wellbeing, now or in the future.

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CRediT authorship contribution statement

Carolyn S. Hayles: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Matt Huddleston:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paul Chinowsky:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Jacob Helman:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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