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How resilient are buildings in the UK and Wales to the challenges associated with a changing climate?

Practical recommendations for risk-based adaptation

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Project Synopsis

Climate research fellowship

1. **Aim:** The aim of this year-long research fellowship was to answer the question "how resilient are buildings in the UK and Wales to the challenges associated with climate change projections?", with the intention of making practical recommendations for risk-based adaptation, where deemed necessary (see Chapter 1).

2. **Motivation:**
    a. The urgency and likely impact of climate change has been thoroughly assessed by scientists, the results of which are now widely published in academic literature and regularly reported in the mainstream media (see Chapter 2).
    b. Together with projected temperature increases, extreme climate events are expected to occur more frequently, for example heavy precipitation events are likely to become more commonplace in Wales.
    c. Current decarbonisation efforts are unlikely to hold global warming to 1.5˚c. Consequently, we need to prepare for warmer, wetter, and more extreme weather patterns.

3. **Rationale:** In addition to UK and Welsh government-lead decarbonisation programmes aimed at reducing our reliance on fossil fuels within the built environment, *it is now more important than ever to start to look at how we adapt our buildings to address the challenges caused by a changing climat**e*** (see Chapter 3).

4. **Activities:** Extended desk study, climate vulnerability modelling, stakeholder engagement and dissemination.
    a. *Desk Study*: The desk study aimed to establish research and evidence currently available, to inform climate change risks to buildings (current and future). This was achieved by scrutinising existing research, evidence and datasets (Chapter 4), examining current mandatory and voluntary Welsh building regulations and related national reference standards (Chapter 5), and evaluating UK-based case studies (Chapter 6) to determine how they can be brought together to assist with the identification and understanding of risks and vulnerabilities, to advance decision-making capability relating to building repair and maintenance practices and adaptation plans.

b. *Climate vulnerability modelling*: The climate vulnerability modelling (Chapter 7) aimed to provide Welsh Government with quantifiable and measurable climate vulnerabilities. Vulnerabilities were identified through the climate impact analysis for an agreed sample of residential dwellings typologies in Wales. Adaptation, repair and maintenance strategies and proposals for specific implementation measures were developed, based on the results of the climate vulnerability modelling (Chapter 8).

c. *Stakeholder engagement:* Stakeholder engagement activities including facilitated workshops (Chapter 9) and seminar/conference presentations provided opportunities to share research findings and discuss adaptation strategies.

Desk study - Literature review findings

1. **Climate change mitigation and carbon reduction:** A review of recent and emerging research and published academic literature confirms that climate change mitigation and carbon reduction targets continue to be drivers within the industry. The energy efficiency gains from retrofitting buildings in general, has accelerated the implementation of additional insulation for the most energy inefficient of existing housing stock (Chapter 4).
2. **Unintended consequences of climate mitigation:** As demonstrated in many of the case study examples outlined in the desk study (see Chapter 4), the addition of internal wall insulation regularly diminishes the benefits of the thermal mass and natural ventilation in traditional building structures. The combined impacts of a changing climate coupled with unsuitable energy efficiency retrofit interventions can undermine the integrity of a building's envelope, whilst failing to deliver a comfortable, healthy environment for occupants. This highlights the risk of ill-informed energy retrofits leading to unintended consequences, otherwise known as maladaptation.
3. **Overheating risks:** Overheating is an increasing concern and will continue to be so in the future, and the combined effect of internal insulation and increased outdoor temperatures may exacerbate overheating risks, potentially increasing the energy demand for cooling. Any decisions to retrofit must consider known climate projections, building performance, and occupant behaviour, as occupant behaviours can either enhance or aggravate the situation further.
4. **Moisture risks:** Moisture risks are more likely to occur due to climate change, i.e., changed precipitation patterns, impacting building envelope moisture dynamics. This will also impact indoor environmental quality and occupant health.
5. **Solar risks:** Solar degradation is more likely to occur due to climate change, i.e., changed temperatures and solar radiation, with the potential to affect the performance of building fabric

(both solid and cavity wall construction) especially south-facing facades. This will also impact indoor environmental quality and occupant health (see overheating risks).

6. **Inadequate ventilation:** Reduced ventilation (should indoor air not be regularly exchanged / extracted) not only results in the build-up of moisture that can lead to damp and mould growth, but it also leads to a build-up of indoor contaminants or pollutants, which both contribute to poorer indoor environmental quality and subsequently reduced health and wellbeing.
7. **Summary:** Improving our understanding of the relationship between energy use, indoor health and comfort, the thermal mass and moisture dynamic of the building envelope, will allow better informed decisions, as they will provide a better sense of future risks to energy efficiency, occupant health and comfort, and dwelling management.

Desk study – Welsh building regulations, related national reference standards, and assessment tools findings

1. Compulsory and voluntary building regulations, standards and assessment tools clearly have a role to play in tackling the complexities of climate change.
2. An analysis of the climate change evidence base in pertinent specifications and guidelines (see Chapter 5) revealed that little reference is currently made to climate change, and there is a shortage of advice and tools to tackle the impact of future climatic conditions on the built environment.
3. When reference is made to climate change, there is no evidence of the potential impact climate change will have on buildings in the future, and a lack of consistent messaging on the interconnectedness of climate change, building fabric and occupant health.
4. In conclusion, current building regulations, standards and assessment tools fail to meet the needs of the industry.

Desk study - UK climate adaptation case studies

1. There is a paucity of UK case studies featuring climate change adaptation decision-making (see Chapter 6).
2. The key driver for many of the projects that assert climate change impacts focus on mitigation rather than adaptation, principally delivered through energy efficiency measures, both building fabric improvements and the application of renewable energy technologies.
3. Whilst interventions to prevent overheating are the most common climate change adaptation, there are a few examples where the potential for high winds, storms and flooding have been addressed.

4. No published case study makes the relationships between energy efficiency, occupant health and comfort, and dwelling management explicit. Accordingly, they fall short of holistic decision-making.
5. Although the city-region plans purport to a holistic policy approach to the design, build and planning process, there is currently no published evidence of this.

Climate vulnerability modelling

Climate vulnerability modelling, undertaken in collaboration with Professor Paul Chinowsky, Matt Huddleston and Jake Helman of the University of Colorado and Resilient Analytics, reveals that the owners and occupiers of Welsh dwellings will experience significant challenges (Chapter 7).

Modelling rationale:

1. The modelling aimed to determine vulnerabilities to building fabric and indoor environmental quality, specifically thermal comfort and moisture as a consequence of climate change.
2. The UKCP18 local (2.2km) projections were used, under an emissions scenario of RCP 8.5.
3. Three time periods were modelled, named 'baseline' (1981-2000), '2030' (2021 – 2040), and '2070' (2061-2080).
4. 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.
5. The relationship between outdoor temperature and indoor temperature was based on a previous study that monitored 193 free-running dwellings, without heating or cooling (Beizaee *et al.,* 2013).
6. 11 separate building classes were identified, which aimed to represent the 40+ dwelling categories found across Wales according to age, construction and dwelling type.
7. 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.

Summertime overheating risk:

- Modelling results reveal increased incidences of summertime overheating in a majority of dwellings across Wales, as identified by the number of hours exceeding the CIBSE TM59 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 results show that cooling strategies to reduce indoor air temperature will increasingly be required.

Summertime moisture risk:

- There is an optimal range of between 30-60% relative humidity for human health and comfort. Anything beyond 60% is deemed too moist.
- Results demonstrate the potential for poorer indoor environmental quality 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.
- 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.

Building fabric vulnerabilities:

- Building fabric vulnerabilities were calculated using service life data.
- Adjusted service lives, and associated costs were determined as a measurable and quantifiable output, by applying discrete climate variables to individual building materials and components.
- Changes in service life and resultant increases in baseline costs, which are predicted to be between 1-7%, are material dependent.
- It is important to recognise that not every building material or component will be impacted by every climate variable. Building orientation will also make a difference.
- In addition to projected incremental climate impacts, extreme events, including concentrated downpours, and associated events such as flooding, must be recognised in repair and maintenance planning.

Adaptation priorities:

- Adaptation priorities for both indoor environmental quality and building fabric were scrutinised (see Chapter 8).
- Adaptations are characterised as behavioural adjustments, internal fit-out alterations and building fabric modifications. However, as identified in the literature, these should not be tackled in isolation. Future risks to energy efficiency, occupant health and comfort, dwelling protection and management will be informed by our understanding of climate vulnerabilities and alleviated by

informed decision-making across the piece. For example, when considering improvements in energy efficiency to reduce winter heating costs, it is important to ensure adaptations won't have a negative impact on overheating in the summer. Similarly, when considering adaptations to increase ventilation, it is important to ensure that they won't have a negative impact on any improved thermal performance.

Conclusions:

- The desk study has provided an overview of the resilience of buildings in Wales, and more widely the UK, to the challenges associated with a changing climate.
- The climate vulnerability modelling has identified climate vulnerabilities specific to the Welsh housing stock, namely:
    1. Increased incidences of **summertime overheating** in a majority of Welsh dwellings;
    2. Poorer indoor environmental quality principally due to an **increase in relative humidity**; and
    3. **Building fabric vulnerabilities** from solar, wind, rain etc.
- The stakeholder engagement has demonstrated the interest in and the need for more research and government guidance on the practicalities of risk-based adaptation (see Chapter 11).

Recommendations:

Recommendations are made to the UK and Welsh Governments, building regulations and standards authorities, and the wider housing sector (Chapter 11) as follows:

1. A holistic policy approach to climate change decision making is urgently needed. We cannot continue to attempt mitigation and adaptation in isolation. Systems thinking (considering the connected wholes rather than separate parts) should be at the heart of UK and Welsh climate change policy design and delivery; as should foresight (futures thinking). This will help ensure that necessary risk-based adaptation decisions have *equal footing* with carbon reduction targets.
2. Welsh building regulations and related national reference standards should address the lack of consistent messaging on the interconnectedness of climate change, building fabric and occupant health.
3. Welsh building regulations and related national reference standards should address the shortage of advice and the tools needed by the design and construction industry, to tackle the impact of future climatic conditions on the built environment.
4. Welsh building regulations and related national reference standards must embed climate change risk-based building fabric vulnerabilities, such as extreme wind and rain and subsequent flooding, in their guidance.

5. Welsh building regulations and related national reference standards must legislate for overheating, among other aspects of building safety, to help reduce the risk in existing homes undergoing retrofit, in addition to new build.
6. Welsh building regulations and related national reference standards must ensure that ventilation guidelines reflect projected climate change, to help reduce the risk of inadequate air circulation in existing homes, especially those undergoing retrofit.
7. Investment in skills and training on climate mitigation and adaptation, to avoid maladaptation, is urgently needed.
8. Social housing decarbonisation strategies should be merged with climate adaptation action plans. For example, adaptation measures implemented at the same time as energy efficiency measures, could significantly reduce the risk of overheating, mould and damp.
9. Government-backed schemes for private-sector dwellings also need to do the same.
10. Climate change mitigation and adaptation advice must be made accessible to everyone. If we democratise skills, knowledge and understanding of climate vulnerabilities, we give building occupants and owners agency to improve their circumstances.
11. Influencing occupant behaviours has been identified as a key catalyst for boosting constructive risk-based decision making. A Welsh government led campaign or strategy that guarantees the dissemination of knowledge and understanding of climate adaptation behaviours, will ultimately improve and enhance occupants' experience of their dwelling.

Future dissemination:

1. Stakeholder engagement activities
2. Publication of bi-lingual summary document.
3. Publication of online guides to:
    a. Considering summertime overheating in newer build properties
    b. Considering summertime overheating in highly insulated homes
    c. Considering summertime relative humidity in older properties
    d. Climate change adaptation - maintenance and repair priorities for older properties.
4. An interactive map to highlight the potential impacts of climate change on dwellings located across Wales.

Table of Contents

[1] Introduction

Under the Climate Change Act 2008, Welsh Government is required to address the challenges of Climate Change including threats to health, economy, infrastructure, and natural environment. One important aspect of this is the 'health' of our buildings. However recent reports suggest that UK buildings, and in particular its aging housing stock, are "not fit for the future" (Committee on Climate Change, 2019, p.9). Greenhouse gas emission reductions for buildings have stalled, and 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 buildings (schools, hospitals, municipal buildings, public and private housing) across the UK must be improved now to address the challenges of Climate Change (specifically higher temperatures and fluctuating precipitation patterns); this is particularly pertinent in Wales, which has a high proportion of e.g., ageing housing stock. Climate adaptation will improve health, wellbeing, and comfort. This is particularly pertinent when considering housing, which is the most common building type and forms large parts of the built environment. Housing has been and will need to be subject to significant developments to meet climate targets, for both new build and importantly for this study, retrofit. Meeting climate targets (e.g., through insulation) whilst maintaining healthy environments (e.g., appropriate ventilation) is a major challenge.

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 May 2019, Wales became the first national Parliament to declare a climate emergency. As a government with devolved powers, WG have a responsibility to ensure policy is resilient to future change. This requirement is set out in the well-being goal of "A Resilient Wales", within the *Wellbeing of Future Generations (Wales) Act 2015* (Welsh Government, 2015).

In November 2019, Welsh Government published a 5-year climate change adaptation plan "*Prosperity for All: A Climate Conscious Wales (2020 - 2025)",* which sets out commitments to respond to current and future impacts of climate change (Welsh Government, 2019a). The plan aims to address the areas of greatest risk to Wales and complements the steps being taken to decarbonise the economy of Wales, as set out in *Prosperity for All: A Low Carbon Wales* (Welsh Government, 2019b). The plan also responds to the more urgent risks detailed in the UK Climate Change Risk Assessment (CCRA2), i.e., the existence of evidence gaps, the need to prioritise areas of research to fully understand the risks and the development of policy to manage the impacts of those risks (Committee on Climate Change, 2017).

The Welsh Government has devolved competencies in policy areas relating to building standards and conditions, health, and air pollution. Specific to this research, in their CCRA2 (2017) report, the Committee on Climate Change identified two overlapping priority areas of research that fall into these areas of devolved competence, and are of particular interest to Welsh Government, namely:

1. CCRA2 Risk Ref. PB7 - Risks to building fabric from moisture, wind and driving rain under future climate driven changes in weather patterns; and
2. CCRA2 Risk Ref. PB10 - Risks to health from changes in air quality, including indoor air quality.

The third Climate Change Risk Assessment (CCRA3) from the Committee on Climate Change was published during this research project. In this most recent climate risks report, the Committee on Climate Change identified risks to human health, wellbeing, and productivity from increased exposure to heat in homes (and other buildings) to be one of the highest priorities for further adaptation in the next two years. Indeed, they highlight the lack of inclusion of measures to prevent overheating in Building Regulations and other housing policy as a major policy gap across all the UK nations (Committee on Climate Change, 2021).

The areas of research aim to determine the measures and applied practices required to ensure that existing and future housing in Wales is:

a. Capable of being resilient to the pressures of Climate Change;
b. Able to benefit the health and well-being of future generations, including if Climate Change is likely to exacerbate heath impacts caused by increased temperature and/or indoor air pollution; and
c. Cost-effective to build and maintain.

In the UK, as experienced in other countries, holistic and sustainable decision-making in the retrofit of existing buildings to meet the challenges of Climate Change, is inconsistent at best and absent at worst. Inconsistencies and knowledge gaps exist for environmental performance guidance, specifically balancing carbon reduction with contemporary expectations of occupant comfort.

Additionally, there are issues surrounding the conservation and preservation in buildings of cultural value, in particular listed buildings, and dwellings in conservation areas. This situation becomes even more problematic when climate resilience, the ability to adapt a building to changes in climate associated with global warming, is absent from stakeholder guidance.

The research project outlined in this report was designed to look at the resilience and vulnerabilities of the housing stock in the UK, and in Wales specifically, to the risks associated with Climate Change. The project aimed to identify a range of potential impacts on the structure and fabric of dwellings, potential health impacts on occupants, and identify practical interventions for adaptation[1]. The research constituted a desk study, climate vulnerability modelling and stakeholder engagement:

Desk Study: The desk study aimed to establish research and evidence currently available, to inform Climate Change risks to buildings (current and future). This was achieved by examining current mandatory and voluntary building regulations and standards pertaining to Wales, and collating existing research, evidence and datasets to determine how they can be brought together to assist with the mapping of risks/vulnerabilities to advance decision-making capability relating to building practices and adaptation plans.

Climate vulnerability modelling: The climate vulnerability modelling was undertaken for a range of Welsh building typologies. Quantifiable and measurable climate vulnerabilities were identified through the climate impact analysis for the agreed sample of residential dwellings in Wales. Adaptation/refurbishment strategies and proposals for specific implementation measures were developed, based on the results of the climate vulnerability modelling.

Stakeholder engagement: Stakeholder responses to the vulnerabilities identified through engagement activities including workshops and presentations.

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[2] Climate change projections

Climate change

In recent years, the severity and potential impact of climate change has been rigorously assessed by scientists, the results of which are now widely published in academic literature (e.g., see IPCC 2014; EEA, 2017; 2019) and regularly reported in the mainstream media.

The Intergovernmental Panel on Climate Change (IPCC) is the UN's body for assessing the science related to climate change. According to IPCC's Fifth Assessment report published in 2014, the increase of global surface temperature by the end of the 21st century is expected to exceed 2.6–4.8˚C compared to 1986–2005, in the most pessimistic scenario[2].

Together with this temperature increase, extreme climate events are expected to occur more frequently. For instance, the length, frequency, and intensity of heatwaves might increase in large parts of Europe, Asia, and Australia. It is also likely that "extreme precipitation events will become more intense and frequent in many regions" (IPCC, 2014). Indeed, heavy precipitation events are likely to become more frequent in most parts of Europe. The projected changes are strongest in Scandinavia and northern Europe during the winter months (EEA, 2019).

UK Climate Projections (UKCP)

The UK Climate Projections (UKCP) provides the most up-to-date assessment of how the UK climate may change in the future. UKCP is a climate analysis tool that forms part of the Met Office Hadley Centre Climate Programme, supported by the Department of Business, Energy, and Industrial Strategy (BEIS) and the Department for Environment, Food and Rural Affairs (Defra).

The UK Climate Projections launched in 2018 (UKCP18) build upon UKCP09 (and UKCP02), to provide the most up-to-date assessment of how the climate of the UK may change over the 21st Century. UKCP18 delivers a major upgrade to the range of UK climate projection tools, designed to help decision-makers assess their risk exposure to climate. UKCP18 provides updated observations and climate change projections to the year 2100 in the UK (and globally). See Table 1 for a summary of UKCP18 projections.

[2] The IPCC is currently in its Sixth Assessment cycle, during which the IPCC will produce the assessment reports of its three working groups, three special reports, a refinement to the methodology report and the Synthesis report. The Synthesis Report will be the last of the AR6 products, it is anticipated that it will be finalised in 2021 and is due for release in 2022.

UKCP18 updates the probabilistic projections over land and provides a set of high-resolution spatially coherent future climate projections for the globe at 60km scale and for the UK at 12 km scale. The 12km climate model has been further downscaled to 2.2km scale. This level allows the realistic simulation of high impact events such as localised heavy rainfall in summer. The marine projections of sea-level rise and storm surge have also been updated (Met Office, 2019).

Local (2.2km) Climate Projections

In 2019 the Met office released a set of 12 climate projections at a 2.2 km resolution. This was the first time anywhere that national climate scenarios were provided at a resolution equal to operational weather forecast models. This was a major step forward in national climate capability, permitting examination of future changes in e.g., hourly rainfall, and on small spatial scales, such as cities. Consequently, a decision was made to use the local (2.2km) results for this piece of research. This higher level of detail means that it is possible to better represent small scale behaviour in the real atmosphere, for example thunderstorms and heavy showers. It also allows for a better representation of the influence of mountains, coastlines, and urban areas. The data is produced using the high emissions scenario RCP 8.5 (Met Office, 2019).

Representative Concentration Pathway 8.5

RCP 8.5 is the only representative concentration pathway available for the 2.2km scale data (Fung and Gawith, 2018). A Representative Concentration Pathway (RCP) is a Greenhouse Gas concentration (not emissions) trajectory, adopted by the Intergovernmental Panel on Climate Change (IPCC). When compared to the total set of RCPs, 8.5 is the most 'aggressive' scenario in assumed fossil fuel use, and thus corresponds to the pathway with the highest greenhouse gas emissions (Riahi *et al.,* 2011).

In Riahi *et al's* 2011 paper detailing the development of the RCP8.5 scenario, they describe RCP8.5 as depicting a 'high emission business as usual scenario'. In other words, they describe it as being on the higher end of 'business as usual' baseline scenarios, as identified in the literature. However, their description of RCP8.5 as 'business as usual' has ended up as the headline shared by many, without any of the accompanying nuance. RCP8.5 is, because of its assumptions of high population and slow technological progress, on the higher end of the range of possible baseline scenarios (Hausfather and Peters, 2020). Indeed, RCP8.5 combines assumptions of high population and relatively slow income growth, with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and Greenhouse Gas emissions in absence of climate change policies.

Relative to historical and anticipated trends the rendered facts underpinning RCP8.5 are described by some authors as showing faster economic growth, overestimates in carbon intensity, overaggressive coal use, and overpricing renewables relative to fossil fuels (e.g., *see* Burgess *et al.,* 2021). It should be noted that climate change sceptics consider RCP 8.5 to be profoundly inaccurate and dangerously misleading, views frequently acknowledged by grey literature sources.

However, despite some recent progress on bending the emissions curve, RCP8.5 continues to serve as a useful tool for quantifying physical climate risk, especially over near to mid-term policy relevant time horizons. Not only are the emissions consistent with RCP8.5 in close agreement with historical total cumulative CO_2 emissions (within 1%), but RCP8.5 is also the best match to mid-century, under current and stated policies; with still highly plausible levels of CO_2 emissions in 2100 (Schwalm *et al*., 2020).

RCP 8.5 is widely endorsed by the UK Met Office and the Intergovernmental Panel on Climate Change (IPCC) as an appropriate tool for considering risk and identifying future vulnerabilities.

UKCP data sets used in the design and construction industry

Within the UK design and construction industry, energy calculations and modelling of building can be undertaken using the Chartered Institute of Building Services Engineers (CIBSE) weather data files, which are the industry standard weather data for the UK in the form of Test Reference Years (TRYs) and Design Summer Years (DSYs). TRY is composed of 12 separate months of data each chosen to be the most average month from the collected data. The TRY is used for energy analysis and for compliance with the UK Building Regulations Part L (conservation of fuel and power). DSY is a single continuous year rather than a composite one made up from average months. The DSY is used for overheating analysis.

CIBSE guides, BREAAM, and the Home Quality Mark ONE Technical Manual, all recommend this approach. indeed, TRY weather data is used for Part L Building Regulations compliance, with DSY weather data used to assess overheating and thermal comfort. However, whilst both weather data sets provide a detailed representation of the climate today, they do not accurately predict how the weather may change in the near and distant future due to climate change, whereas future weather data can be used to evaluate the performance of the building over time.

CIBSE has developed a set of future weather files, based on the UKCP09, in collaboration with UK Climate Impacts Programme (UKCIP), Arup and Exeter University**.** These future hourly weather files, based on the existing Design Summer Years and Test Reference Years *incorporating the UKCIP09 climate change scenarios*, and are available for 14 sites, for three time periods:

1. 2020s (2011-2040);
2. 2050s (2041-2070); and
3. 2080s (2071- 2100).

10th, 50th, 90th percentiles are provided for emission scenarios:

1. 2020s: High;
2. 2050s: Medium and High; and
3. 2080s: Low, Medium and High.

CIBSE has recently been awarded an Innovate UK funding grant for a 30-month project with the University of Exeter to produce new files based on the most recent UK climate projections.[3]

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Table 1: Summary of the key findings from the initial analysis of UKCP18
(Adapted from the Met Office, 2019)

- ❖ 2008-2017 has been on average 0.3°C warmer than the 1981-2010 average; and 0.8 °C warmer than 1961-1990. *All of the top ten warmest years have occurred since 1990.*
- ❖ There has been an increase in annual average rainfall over the UK. The most recent decade (2008–2017) has been on average 11% wetter than 1961–1990 and 4% wetter than 1981-2010. However, natural variations are also seen in the longer observational record. *Observations made in the future will be dependent on both long-term climate trends and natural variability.*

Projected future changes over land areas:

- ❖ The UKCP18 projected climate change trends are like those identified by UKCP09, i.e., *warmer, wetter winters and hotter, drier summers*. However, natural variations mean that some cold winters, some dry winters, some cool summers, and some wet summers will still occur, and users may need to factor this into decision-making.
- ❖ In UKCP18, the probabilistic projections provide local low, central, and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of average warming between the 10% and 90% probability levels. *By 2070, in the high emission scenario, this range amounts to 0.7°C to 4.2°C in winter, and 0.9°C to 5.4°C, in summer. For precipitation, corresponding ranges of UK average changes are -1% to +35% for winter, and -47% to +2% for summer, where positive values indicate more precipitation and negative values indicate reduced precipitation.*
- ❖ Hot summers are expected to become more common. In the recent past (1981-2000) the probability of seeing a summer as hot as 2018 was low (<10%). The probability has already increased due to climate change and is now estimated to be between 10-20%. With future warming, hot summers by mid-century could become even more common (with probabilities of the order of 50% depending on the emissions scenario followed).

Additionally, UKCP18 simulates sub-seasonal and sub-monthly extremes of climate and their changes, such as daily extreme temperature and rainfall. There is also the potential for future changes in the time spent experiencing different types of weather regimes. These can be examined using the new global and regional projections.

Future changes at the coast and in the sea:

- ❖ UK coastal flood risk is expected to increase over the 21st century and beyond under all emission scenarios considered. This means that we can expect to see both an increase in the frequency and magnitude of extreme water levels around the UK coastline. This increased future flood risk will be dominated by the effects of time-mean sea level rise, rather than changes in atmospheric storminess associated with extreme coastal sea level events. There may also be changes in tidal characteristics.
- ❖ 21st century projections of time-mean sea level change around the UK vary substantially by emissions change scenario and geographic location. The very likely ranges for Cardiff at 2100, calculated using three Representative Concentration Pathways (RCPs) are: RCP 2.6 (0.27 – 0.69m); RCP 4.5 (0.35-0.81m); and RCP 8.5 (0.51-1.13m) relative to the 1981-2000 average.

The risk of coastal flood events will rise with the projections of increase in time-mean sea level.

- ❖ 21st century projections of average wave height suggest changes of the order 10-20% and a general tendency towards lower wave heights. Changes in extreme waves are also of order 10-20%, but there is little agreement in the sign of change among the model projections. High resolution wave simulations suggest that the changes in wave climate over the 21st Century on exposed coasts will be dominated by the large-scale response to climate change. However, more sheltered coastal regions are likely to remain dominated by local weather variability.
- ❖ Exploratory, time-mean sea level projections to 2300 suggest that *UK sea levels will continue to rise over the coming centuries under all emission scenarios considered*.

[3] Climate change policy

European climate change policy

Until very recently, European policy has shaped the UK and consequently Wales's approach to climate change mitigation and adaptation. EU-wide, the climate-energy policy framework has been developed to mitigate climate change since 1990 (EU, 1990). In 2009 the EU renewed its commitment to the goal of keeping global warming below 2°C above pre-industrial levels. Heads of State and Government also formally adopted the objective to reduce emissions by 80–95% by 2050 in comparison to 1990 levels. By 2018, the EU set out a vision for a climate-neutral EU by 2050. This was endorsed by the European Council in 2019, and its long-term strategy submitted to the UN framework convention on climate change (UNFCCC) in 2020. This objective is at the heart of the European Green Deal (2020a) and in line with the EU's commitment to global climate action under the Paris Agreement (EU, 2015).

Climate change mitigation

Climate mitigation necessitates taking action to reduce the emissions of greenhouse gases. Its aim is to reduce future climate change by slowing the rate of increase in (or even reducing) greenhouse gas concentrations in the atmosphere. It is defined by the IPCC as:

> "Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic, and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks" (Verbruggen, 2007, pp. 818).

Mitigation will not stop climate change or climate change impacts from happening. Greenhouse gases already released into the atmosphere will remain for many years and some climate impacts, such as the relatively slow absorption of heat by the oceans (from the atmosphere), means that global sea level rise is a slow process. Indeed, increased climate change impacts must be expected in the future because of the delayed impact from greenhouse gases already released into the atmosphere and the continued release of greenhouse gases into the atmosphere now and in the future.

Energy efficiency

Climate change mitigation in the building and construction industry has concentrated on improving energy efficiency to reduce carbon emissions, with a particular focus on the energy used to heat and cool buildings. Several directives have been issued to improve the energy performance of both new and existing buildings. In the Energy Performance of Buildings directive (EPBD) 2002/91/EU (EU, 2002), the four key considerations were:

- ❖ A common methodology for calculating the integrated energy performance of buildings;
- ❖ Minimum standards on the energy performance of new buildings and existing buildings that are subject to major renovation;
- ❖ Systems for the energy certification of new and existing buildings and, for public buildings, prominent display of this certification and other relevant information. Certificates must be less than five years old; and
- ❖ Regular inspection of boilers and central air-conditioning systems in buildings and in addition an assessment of heating installations in which the boilers are more than 15 years old.

In the "Energy Performance of Buildings" directive recast 2010/31/EU (2010), the standards to calculate energy performance and the compulsory energy certification, were formulated. To fulfil the energy requirements, the directive also introduced the nearly zero-energy building concept. The intention was for Member States to ensure that by the end of 2020, all new buildings were nearly zero-energy buildings. Directive 2012/27 (EU, 2010) established a common framework to ensure the achievement of the 20% headline target on energy efficiency. To fulfil the target, Member States were expected to establish a long-term strategy for mobilizing investment renovation and expressed that public bodies' buildings should play an exemplary role. More specifically, 3% of the total floor area of heated and/or cooled public buildings must be renovated annually to meet the minimum energy performance requirements. Recast 2018/844 (EU, 2018a) requires the Member States to plan long-term renovation strategies and update every three years as part of the National Energy Efficiency Action Plan[4].

However, despite increasing concerns about climate change and recognition of the need for mitigation e.g., through the introduction of nearly zero-energy building, greenhouse gas emissions continue to increase, and governments face major challenges in agreeing on the necessary emissions reductions and on effective means of making such reductions. This makes adaptation, the other major response to climate, very important.

[4] All directives state that buildings officially protected because of their special architectural or historical merit and buildings for worship and religious activities are exempt from energy performance requirements.

Climate change adaptation

Climate change adaptation involves adjusting to meet current or expected climate change impacts, and is defined by the IPCC as:

> "Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, for example, anticipatory and reactive, private and public, and autonomous and planned." (Verbruggen, 2007, pp. 809).

The ability to adapt to a climate threat depends upon an organisation or an individual's adaptive capacity (their resources or assets e.g., human, natural, social, and physical), available for adaptive responses, and the extent of the adaptation required to reduce or eliminate the adverse consequences of that threat. The IPCC states that:

- Adaptation is necessary to address impacts of climate change because of inevitable warming due to past emissions;
- Adaptation cannot cope with anticipated climate change impacts in the future unless there is significant mitigation (a target of mitigation to prevent surface temperature rising more than 2 °C above pre-industrial levels is often taken to be a practical target, although this is not without risks and controversy); and
- Both adaptation and mitigation are needed and can be effective in a portfolio of measures to reduce the risks and threats associated with climate change (IPCC, 2007, pp. 19-20).

According to the EU, climate change adaptation, as it relates to infrastructure and buildings means:

> "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" (2020b).

Compared with climate mitigation policies, climate adaptation policies fall behind significantly. The first time the EU set out a framework to reduce vulnerability to the impact of climate change was in their "Adapting to Climate Change" White Paper of 2010. It addressed the objectives and actions to increase the resilience of several sectors, including physical infrastructure. A key deliverable was the web-based European Climate Adaptation Platform[5] (Climate-ADAPT), established in 2012.

The EU adaptation strategy, which aims to make Europe more climate-resilient, by taking a coherent approach and enhancing preparedness and capacity of all governance levels to respond to the impacts of climate change, was launched in 2013 (EU, 2013a). Since 2013 it has become clearer that international climate action, as enshrined in the 2015 Paris Agreement (UE, 2015), must acknowledge and tackle ongoing and projected impacts at 1.5ºC or 2ºC global warming levels. EU policy seeks to create synergies between adaptation, sustainable development, and disaster risk reduction to avoid future damage and provide long-term economic and social welfare in Europe and in partner countries (EU, 2018b). By creating a basis for better informed decision-making on adaptation and making key economic and policy sectors more resilient to the effects of climate change, this strategy encourages and supports Member States' action on climate adaptation. In the building sector, the EU adaptation strategy includes a Staff Working Document (EU, 2013b), which provides guidance to adapt the infrastructure. It addresses the common challenges brought by climate change and the instruments on the EU level that might need to be revised. One of the most important instruments used to regulate infrastructure sectors are building standards. Since 2014, the European Standardisation Organisations have fostered the integration of climate change adaptation in the standardisation of the construction/building sector (EU, 2014). In February 2021, the EU launched a new strategy on Adaptation to Climate Change, setting out the pathway to prepare for the unavoidable impacts of climate change. In the strategy they pledge to support the integration of climate resilience considerations into the criteria applicable to construction and renovation of buildings and critical infrastructure. They acknowledge that they need to do more to prepare Europe's building stock to withstand the impacts of climate change. Extreme weather and long-lasting climatic changes can damage buildings and their mitigation potential e.g., solar panels or thermal insulation after hailstorms. However, buildings can also contribute to large-scale adaptation, for example through local water retention that reduces the urban heat island effect with green roofs and walls. The Renovation Wave and the Circular Economy Action Plan identify climate resilience as a key principle. The Commission will explore options to better predict climate-induced stress on buildings and to integrate climate resilience considerations into the construction and renovation of buildings through Green Public Procurement criteria for public buildings, the Digital Building Logbook, and as part of the process to revise the Energy Performance of Buildings Directive and the Construction Products Regulation (EU, 2021).

[5] Climate-ADAPT (2020b) is a partnership between the European Commission and the European Environment Agency.

In Europe, according to a study of building energy renovations activities and the uptake of nearly-zero-energy buildings in the EU, the average total rate of energy renovations that achieved more than a 3% primary energy saving in residential buildings was only 5.2% during 2012–2016 (EU, 2019). Amongst the renovated building stock, the share of buildings renovated to nearly zero energy building standard was 17.5% in 2016 (EU, 2019).

UK Climate Change policy

In May 2019, the UK Government and the devolved administrations committed to the Net Zero target as recommended by the UK's Committee on Climate Change[6]. The Committee on Climate Change recognise that reaching net-zero greenhouse gas emissions requires unprecedented changes across the economy but suggest that the foundations are in place. They do advise that major infrastructure decisions need to both be made soon and quickly implemented (Committee on Climate Change, 2020).

However, efforts to reduce greenhouse gas emissions must be accompanied by adaptation measures to improve resilience to the impacts of climate change. Despite this, the Committee on Climate Change (2020) found a substantial gap between current plans and current requirements for adaptation, and an even greater shortfall in action. The world is currently experiencing the impacts of a global temperature rise of just 1°C above pre-industrial levels. The Paris Agreement targeted a global temperature rise threshold of well below 2°C, ideally 1.5°C, but current global projections suggest we only have a 50% chance of meeting 3°C. In these circumstances, although the UK is committed to working for global action to parallel its adoption of the net-zero statutory target, it could be considered prudent to plan adaptation strategies for a scenario of 4°C, but there is little evidence of adaptation planning for even 2°C. Indeed, planning for a minimum of 2°C, with consideration of more extreme scenarios should be a government requirement for all departmental and public sector plans and policies that are likely to be affected by climate change. Adaptation planning takes time, especially for infrastructure, buildings, and the natural environment, which means actions need to start now to avoid 'lock-in' to high levels of risk in 2050 and beyond (Committee on Climate Change, 2020).

[6] The Committee on Climate Change (CCC) is an independent, statutory body established under the Climate Change Act 2008. CCC advises the UK and devolved governments on emissions targets and provides Parliament with reports on progress made by the UK in reducing greenhouse gas emissions and preparing for and adapting to the impacts of climate change.

Climate Change policy in Wales

In Wales, the UK Climate Change Act (2008) requires Welsh Ministers to produce reports on the Welsh Government's objectives, actions, and future priorities regarding the impacts of climate change. The Environment (Wales) Act (Welsh Government, 2016c) provides a framework to manage natural resources, while the Well-being of Future Generations (Wales) Act (Welsh Government, 2015) aims to improve the social, economic, environmental, and cultural well-being of Wales. Both Acts include measures that are important to climate change adaptation.

In 2019 the Welsh Government declared a climate emergency to co-ordinate action both nationally and locally to help combat the threats of climate change. The planning system in Wales plays a key role in tackling the climate emergency through the decarbonisation of the energy system and the sustainable management of natural resources.

Most recently, "Future Wales: The National Plan (2040)" was published in February 2021 as the national development framework for Wales. The proposed plan reflects on the UK 2018 climate projections (UKCP18) for Wales, which indicate that climate change will have an impact on marine, road and rail infrastructure, buildings and those who populate them. Future Wales together with Planning Policy Wales will ensure the planning system focuses on delivering a decarbonised and resilient Wales (Welsh Government, 2021a). The Welsh Government is targeting its housing and planning interventions towards achieving this aim within the broader context of increasing supply and responding to different needs, including an ageing society and climate change.

The 11th edition of Wales's planning policy was also published in February 2021. It acknowledges that the planning system has a vital role to play in climate change resilience, decarbonising society and developing a circular economy for the benefit of both the built and natural environments. It clearly states that the planning system should support new development that has very high energy performance, supports decarbonisation, tackles the causes of the climate emergency, and adapts to the current and future effects of climate change through the incorporation of effective mitigation and adaptation measures; and that development proposals should mitigate the causes of climate change, by minimising carbon and other greenhouse gas emissions associated with the development's location, design, construction, use and eventual demolition; and include features that provide effective adaptation to, and resilience against, the current and predicted future effects of climate change (Welsh Government, 2021b).

Most recently, to coincide with COP26 in Glasgow, Welsh Government launched its Net Zero Wales emissions reduction plan, following on from Prosperity for all: A Low Carbon Wales covering the first carbon budget (2016-20). Net Zero Wales is presented as the first all-Wales Plan to tackle the climate emergency, and the first which has net zero as its guiding ambition (Welsh Government, 2021c). There is no indication how this plan will be delivered alongside climate adaptation policy.

For an overview of Welsh and wider UK Climate adaptation policy, assessment, and regulations relevant to buildings see Table 2.

Additional energy efficiency drivers in Wales

It is recognised, although not the focus of this research, that cold homes and fuel poverty have been identified as public health issues requiring policy interventions in Wales. Much has been published on the health impacts of cold homes and fuel poverty and there are strong arguments to support current energy efficiency improvements for low income, fuel-poor households, for both improved indoor temperatures and reduced fuel consumption (e.g., *see* Friends of the Earth, 2011; Public Health England, 2014).

Innovative housing and Optimised Retrofit Programmes

Welsh Government launched the 'Innovative housing programme' in 2017 as a demonstrator scheme that sought to stimulate the design and delivery of new high quality and affordable homes. These homes aimed to significantly reduce or eliminate fuel bills and help inform the Welsh Government about the type of homes it supports in the future. The Optimised Retrofit Programme (ORP) is part of the Innovative Housing Programme and is funding the installation of energy efficiency measures in up to 1000 existing homes owned by registered social landlords and councils (Welsh Government, 2020d).

Building stock climate adaptation in Wales

Buildings designed according to existing standards may become increasingly costly to operate and maintain in the future. The projected rise in both average and extreme temperatures in the future will likely make buildings more uncomfortable to live and work in, and as seen elsewhere in the world, potentially dangerous for occupants' health, as a consequence of higher internal temperatures, especially in poorly ventilated indoor environments. According to Hamdy *et al*. (2003), climatic change is likely to result in activity reduction, in a need to retrofit mechanical ventilation or cooling systems, as well as in depreciation of property values. Climatic variability may also affect the performance of building technical services because of anticipated power outages and inconsistent quality, prolonged cold and rainy seasons, winter storms, flooding and intense heat wave (Hamdy *et al*., 2003).

Improved building design and refurbishment are therefore important measures to help adapt to, for example, higher temperatures under climate change (Vardoulakis et al., 2015). Indeed, the UK is expected to experience a substantial reduction in heating needs but an increase in cooling needs going forward (Li *et al.,* 2012). Certainly, any increase in active cooling demand will significantly increase related CO_2 emissions by 2030 (Day *et al.,* 2009).

It has been estimated that around 70% of current building stock will still exist in 2050, and four out of five homes that will be occupied by 2050 have already been built. These householders will generally face the greatest challenges in both decarbonising and adapting to the changing climate.

Unlike new builds, the incentive to, and responsibility for, retrofitting existing homes sits firmly with individual householders or landlords. Decision making will be influenced by a range of factors, including cost, recognised behaviour and the inconvenience associated with retrofitting. Committee on Climate Change suggest that a householder's willingness to act depends on several issues, including:

- Awareness of need;
- Availability of information on appropriate measures, their costs and benefits;
- Availability of funds to make the adaptations;
- Locally skilled tradespeople willing to undertake work; and
- Availability of (emerging) technologies (Committee on Climate Change, 2019).

Advice given by e.g., the Committee on Climate Change on adaptation does include relatively simple 'low regret' actions such as improved water saving, ventilation and shading. These can be retrofitted to existing buildings but are a lot easier to address and can be more effective in new build scenarios[7] (Committee on Climate Change, 2020).

[7] CCC advice includes, for example: "*Ensuring adequate ventilation and the orientation of windows to reduce the risk of overheating in homes should be done at the new build stage to avoid the need for costly retrofit later"* and "*Siting new buildings and infrastructure in low flood risk areas where possible, will have a long-term benefit, but decisions on siting now need to consider future risk given the long lifetimes of these assets"*

Table 2: Overview of Welsh and wider UK Climate adaptation policy, assessment and regulations relating to buildings
(*Adapted from Climate ADAPT, 2020*)

ITEM	STATUS	RELEVANT LINKS
National Adaptation Strategy	Adopted	❖ UK: Climate Change Act 2008 ❖ Wales: Well-being of Future Generations (Wales) Act 2015 ❖ Wales: Environment (Wales) Act 2016
National Adaptation Plan	Adopted	❖ England (and UK reserved matters[8]): Climate change: second National Adaptation Programme (2018 to 2023) ❖ Wales: Prosperity for All: A Climate Conscious Wales. Climate Change Adaptation Plan for Wales: Monitoring and Evaluation Framework ❖ Wales: Historic Environment & Climate Change Sector Adaptation Plan
Impacts, vulnerability, and adaptation assessments	Completed	❖ UK Second Climate Change Risk Assessment (CCRA) 2017 ❖ UK Climate Projections 2018 (UKCP18) ❖ Wales: Climate change: its impacts for Wales
Relevant research packages	Underway or completed	❖ UK Climate Resilience Programme (UKRI and Met office ❖ EA and NRW: Flood and Coastal Erosion Risk Management Research and Development Programme ❖ Flooding and coastal erosion risk management network ❖ UKCIP - UK Climate Impacts Programme ❖ Ireland Wales Programme Priority 2 - Adaptation of the Irish Sea and Coastal Communities - to Climate Change ❖ Tackling fuel poverty
Meteorological observations	Established	❖ UK National Meteorological Service (the Met Office) ❖ State of the UK Climate report
Climate projections and services		❖ UK Climate projections ❖ Met Office Hadley Centre for Climate Science and Services ❖ IPCC approved General Circulation Models (GCM)
Monitoring indicators, methodologies	Established/ under development	❖ England and Reserved matters: 2017 Report to Parliament: Progress in preparing for climate change Report by: Adaptation Sub-Committee of the Committee on Climate Change (CCC) ❖ Wales: Prosperity for All: A Climate Conscious Wales. Climate Change Adaptation Plan for Wales: Monitoring and Evaluation Framework
Monitoring mechanism regulation	Last reporting on Adaptation (Art. 15) submitted	❖ 2019 submission
National communication to the UNFCCC	Last National Communication Submitted	❖ 2020 National Inventory Report (NIR)

The importance of avoiding climate change maladaptation

Maladaptation is when adaptation to climate change has unintended or unexpected consequences. The notion is that maladaptation is an unexpected and unwanted outcome of an adaptation strategy that was originally implemented with good intentions (Schipper, 2020). With growing experience of building retrofit programmes to promote energy efficiency, it has become clear that some poorly

[8] Reserved matters are the areas of public policy where the UK Parliament has retained the exclusive power (jurisdiction) to make laws (legislate) in Scotland, Wales, and Northern Ireland.

designed adaptation strategies have resulted in unintended and unexpected consequences, and they have been the drivers for maladaptation concerns within the sector.

Widespread improvements in energy efficiency in residential (as well as commercial and public) buildings have considerable potential for reducing energy demand towards achieving Wales's Net Zero target. However, care is needed to ensure that suitable construction materials, ventilation and air management are in place to avoid unintended consequences such as overheating, moisture build up and the accumulation of air pollution indoors. Dwelling energy efficiency measures need to be carefully considered so that potential negative impacts can be appropriately mitigated. With increasing energy efficiency measures to reduce greenhouse gas emissions, such as increased insultation, draughtproofing and e.g., triple glazing, there may be an increased risk of indoor overheating in summer, which could lead to increased seasonal demand for electricity (DEFRA, n.d.).

Increased energy efficiency may also lead to reductions in air exchange rates and ventilation, resulting in an increase in moisture build up, causing damp and mould. It can also reduce overall indoor air quality as air pollutants are in effect trapped and therefore accumulate.

Highly energy efficient buildings materials can themselves also be a source of indoor pollution (Royal Society, 2021). This is particularly relevant for Particulate Matter (PM), Volatile Organic Compounds (VOCs) and the by-products of indoor chemical reactions. Indeed, exposure to VOCs (and their by-products) from construction, but also from other professional and consumer products, must also be considered, and standalone measures may be needed to control these. Poor indoor air quality is by no means an inevitable consequence of energy efficiency measures, but it is a factor that must be considered at an early phase of strategy development, including establishing clear indoor air quality objectives alongside those for energy efficiency. According to the UK Air Quality Expert Group (AQEG), the development of national indoor air quality objectives that could sit alongside those for future energy efficiency standards would be highly beneficial and ensure that effective management of the built environment was delivered in a joined-up way (AQEG, 2020). Indeed, building regulations and standards are a key lever for driving up design and build specifications for new homes and should play an important role in setting standards for retrofitting or refurbishing existing homes. However, climate adaptation requires a much wider set of guidance and policies, as well as a range of actions from landlords and homeowners. Ultimately, there is a scarcity of advice on adapting existing buildings for future climates, and in particular adapting older (pre-1919) buildings, and little evidence of adaptation benefits, those that do not compromise either building performance or occupant comfort.[9]

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[4] Literature review

Background

In this review of existing and emerging research on the impacts of climate change on buildings, an emphasis has been placed on traditional building fabric impacts in line with the initial scope of the research, including the impacts of energy efficiency measures and the propensity for unintended consequences, i.e., maladaptation. Indeed, the initial focus of this research was on buildings, specifically dwellings, that have been in existence for more than 50 years, which equates to more than half of all Welsh housing stock, with a particular interest in the performance of buildings of traditional construction, built before 1919, which equates to 26% of the total dwelling stock[10] (BRE, 2020).

Climate change is an increasing challenge for the conservation of our built heritage. It could lead to accelerated degradation or loss of cultural heritage (Gandini *et al.,* 2017), due to continuous degradation or destructive climatic events. Weather and climate-related natural hazards, such as river and coastal floods, landslides, wildfires, etc., could cause catastrophic loss of traditional and historic buildings.

Buildings exposed to weather and climate-related natural hazards attract much attention because of the immediacy of the losses. Nevertheless, cumulative degradation risks are also perceived to be increasing due to climate change and can be accelerated as a consequence of maladaptation.

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[10] Historic buildings are defined in line with European standards (EU, 2017), whereby a historic building does not necessarily have to be formally "listed" or protected; but is a building worth preserving, be it for cultural, social, economic, or environmental reasons. For the purposes of this research, historic or traditional buildings are identified as having been built before 1919 dwellings. In London, pre-1919 dwellings make up 40% of the existing housing stock, whilst in Wales more than 26% of all dwellings were built before 1919.

For instance, the temperature increase in winters could lead to a higher prevalence of insect pests and fungal attack, warping of timber elements, staining, and discoloration of masonry, as identified by Historic Environment Scotland (Curtis and Snow, 2016). Consequently, risk assessments and adaptation plans are necessary to ensure all buildings' resilience to new climate conditions, but particularly older building stock that may have undergone greater adaptations over the years.

Since 2000, several European and UK-funded projects have studied the impact of climate change on historic buildings. NOAH'S ARK (2010) defined the meteorological parameters that are critical to the built heritage and developed a vulnerability atlas and a guideline to support practitioner decision making, to prepare structures, and their material components, for future climate risks. The NANOMATCH project (2011-2014) aimed to produce nanostructured materials for historic materials under the climate change context, whilst the PARNASSUS project, led by UCL (2010-2013) focused on the impact on historic buildings of future flooding and wind-driven rain, whilst validating adaptation measures (see Aktas *et al.,* 2017; D'Ayala and Aktas, 2016; Aktas *et al.,* 2015; Parkin *et al.,* 2015; Stephenson and D'Ayala, 2014; Erkal *et al.,* 2013; Erkal, A. and D'Ayala, 2014; Smith *et al.,* 2015; Erkal *et al.,* 2012). In addition, researchers from the ADAPT NORTHERN HERITAGE project (2017-2020) have been working on the identification of possible adaptation activities for heritage sites in Iceland, Ireland, Norway, Russia, Sweden, and Scotland. The project, led by Historic Environment Scotland, aims to develop an online tool to assess the risks for and vulnerabilities of historic places and provide guidance for the planning of strategic adaption measures in Europe's arctic areas and northern periphery. Meantime, the CLIMATE FOR CULTURE project (2020) aims to enhance climate risk predictions using high-resolution climate models and whole building simulation for specific climate zones. According to their website they have five UK case studies, all sizeable National Trust properties: Blickling Hall House, Aylsham, Cragside House, Morpeth, Ham House, Richmond-Upon-Thames, Knole House, Seavenoaks, and Lanhydrock House, Bodmin.

These projects demonstrate the importance that is being placed on investigating and understanding the potential impact of climate change on historic buildings of traditional construction. The studies investigated the consequences of higher temperatures, shifting precipitation patterns, higher flooding risks, and rising sea levels, which will influence heritage conservation, energy performance, and future retrofit decisions. Overall, these particular studies have considered historic buildings in their original state, that is, before any major retrofit or other energy improvement interventions.

The implications of changing precipitation patterns on masonry degradation

Climate change will undoubtedly have some impact of existing building fabric performance. Changes in climate factors are expected to accelerate the erosion of detailing and construction or undermine binder and coating on traditional buildings (Curtis and Hunnisett Snow, 2016; Cavalagli *et al*., 2019).

Solid masonry walls are characterised by higher surface water absorption coefficients and are more sensitive to exterior climate factors such as rain, wind, and solar radiation. For example, solar radiation can reduce moisture accumulation considerably (see Budaiwi and Abdou, 1999; Arumagi *et al*., 2015).

The cyclical expansion and contraction of masonry and mortars are subject to the weathering cycle, which may alter because of climate change. Simulating the onsite conditions of masonry structures subjected to rising damp and salts attack, due to daily and seasonal microclimates changes, has proven that building fabric will be weakened in the long run (e.g., Franzoni *et al.,* 2014). Che Sobry Abdullah's (1989) doctoral thesis proved that cyclical wetting-drying results in greater expansion in bricks than continuous soaking. This cyclical action has also been proven to cause changes in pore structure (pore size distribution) in natural stone (Hall and Hall, 1996; Yavuz, 2012) including the swelling of clays in sandstone (Hayles and Bluck, 1995; Jimenez-Gonzalez *et al.,* 2008).

Differential expansion and shrinkage in different materials forming the building envelope can also be induced by temperature oscillation and temperature gradients across buildings (Camuffo, 2019). Previous research has determined that daily temperature variations of circa 14°C, or more, could induce cracking (Facconi *et al.*, 2015). These daily temperature gradients are particularly harmful as they can induce strain accumulations in materials, which can lead to microcracking, which in turn can change the permeability of the outer surface and make them more susceptible to the adverse effects of wind-driven rain, as well as other sources of moisture (D'Ayala and Aktas, 2016). Consequently, weakening building materials and strain values beyond reversible limits can create damage via creep and fatigue in many construction materials including natural stone, concrete and brick (Brooks, 2015; Hall and Hall, 1996; Yavuz, 2012;).

Shear behaviour depends on moisture content, porosity, strength of mortar, and conditioning type. Franzoni *et al.*'s research on bricks and mortar demonstrated that the presence of salt crystals within the pores results in higher failure loads. Resultant tensile stresses, during the drying stage, can cause cracking of thin elements, whilst shear forces can lead to the buckling of wetted surfaces, more generally, eventually resulting in scaling and/or contour scaling. Deterioration will be further accelerated by pre-existing flaws that can be inherent to the stone (e.g., bedding planes) or because of other weather mechanisms, such as salt crystallisation. This can lead to the detachment of sizeable stone layers, and consequently is readily observed on building façades. The more porous the stone, the more susceptible it will be to deterioration. Similarly flaking, crumbling and spilling deterioration, due to swelling of clays, are observed in the facade of the stone buildings constructed using tuff (Yavuz, 2012), whilst Limestone areas are predominantly affected by chemical weathering when rainwater, which contains a weak carbonic acid, reacts with the limestone, causing it to dissolve.

Moisture moves under different mechanisms in each of its phases. The primary transport processes are vapour diffusion (and surface diffusion within some porous materials), vapour convection (air movement), liquid water capillarity (i.e., wicking) through porous materials and liquid gravity flow (including hydrostatic pressure) through cracks, openings, and macropores (Straube, 2020). Moisture transport processes rarely act alone to move water or 'damp' within and through buildings. Every mode of moisture transport that can cause moisture problems can also help dry building materials and surfaces. Therefore, attempting to block transport mechanisms is not always the best approach for managing moisture (Straube, 2002).

Among all climate factors, wind-driven rain (WDR) impacts are likely to be pervasive. WDR can cause both surface erosion and weaken building fabric. Studies on climate change and the effect increased extreme rainfall events may have on building façades, has renewed the scientific interest in determining the risk of accelerated surface erosion. Erkal *et al.* (2012) summarise the evidence of WDR erosion on historic façades and explored materials' response to three different diameters of raindrops. It was seen that the behaviour of drops changes depending on the drop characteristics and masonry material. As the drop size gets bigger, water drops tend to do more splashing and run-off after striking the surface. The rougher the surface, the more splashing occurred. Their research revealed greater erosion of unfired clay bricks because of their low bond strength, whilst solid hand-cut historic clay bricks were wetted more, due to their high permeability. It should be noted that is not only the type of brick and the wall thickness that determine the moisture properties of the wall, but also the type of mortar between the bricks.

Abuku *et al.* (2009) compared the mould growth risk with and without WDR in a moderately cold and humid climate, on the inner side of an historic solid brick wall. The results demonstrated that the impact of WDR loads on the moisture contents in the walls is much larger near the edges of the walls than at the centre. The results therefore show that WDR loads can have a significant impact on mould growth especially at the edges of the walls, where fungal spores are more likely to germinate. Finally, for the case analysed, the WDR load was found to result in a significant increase in indoor relative humidity and consequently lead to higher energy consumption for heating the building. Johansson *et al.'s* (2014b) concluded that WDR was the dominant factor determining moisture movement in walls exposed to normal rain loads from Gothenburg, Sweden and Bergen, Norway; they were exploring historic wall construction and changing hydrothermal performance as a consequence of interior wall insulation.

D'Ayala and Aktas undertook comprehensive environmental monitoring of two traditional buildings in Tewkesbury, Gloucestershire to provide thorough insight on their performances under environmental loading to make comparisons regarding their performance. They monitored temperature and relative humidity in two walls and concluded that bricks and mortar can have different moisture absorption and desorption characteristics, even within the same building. They observed that current (and consequently future) environmental conditions pose a threat to building envelopes (either due to biological activity or to microcracking associated to temperature and moisture fluctuations), causing the onset of deterioration, unless routine maintenance is provided. They propose the monitoring of in-wall and surface values to produce accurate temperature and relative humidity profiles across the wall. WDR gauges developed as part of this study have also been shown to be useful and are easy to replicate for the aim of monitoring vertical rain flux in similar studies. They conclude that meteorological station data cannot be used as a robust proxy when the emphasis is on determining the conditions to which the envelopes of specific buildings are exposed. In this work, D'Ayala and Aktas (2016) not only verified the adverse impact of WDR but also infer that more frequent rain could be even more dangerous for the solid wall building envelope. Table 3 provides a summary of suggested adaptation measures to reduce the potential impact of WDR and flooding on building fabric, and occupant comfort and safety.

Nik *et al.* (2015) investigated the prospective impacts of climate change and WDR on buildings, through simulating the hygrothermal performance of rain screen on common vertical wall constructions, for the climatic conditions of Gothenburg in Sweden. Simulation results show that higher amounts of moisture will accumulate in walls in the future. Besides WDR, moisture that diffuses across the wall as vapor was proven to be another main source of moisture accumulation. The research highlights the impact that climate uncertainties have on predicting the hygrothermal performance of building façades, as greater variability results. It is important to remember that in WDR calculations, the microclimate around a building plays an important role, since the actual wind profile, which affects WDR, is influenced by surrounding buildings.

Table 3: **Adaptation measures for rain, mould, damp and flooding in the built environment**
(*Adapted from* Vardoulakis et al., 2015)

Aim	**Adaptation measure**	**Impact on built environment**
Adaptation of existing building stock against penetrating/driving rain	Repair/reinstate/replace damp proof course (DPC)	Avoid water entering the building Reduce rain penetration
	Repair/reinstate/replace mortar and render	
	Repair/reinstate/replace drainage/rainwater systems	
Adaptation of existing building stock against flooding *(see Cadw, 2019)*	Identify and block all potential entry points (doors, airbricks, sinks and toilets, and gaps in external walls around pipes and cables)	Avoid water entering the building (resistance measures for short duration floods).
		Cannot avoid rise of groundwater which can occur through the floor
	Prevent water entering through the walls	Avoid structural damage to steel components and permanent damage to certain insulation types.
		Avoid mould growth within the walls (resistance measures for longer duration floods)
	Fit rising hinges so doors can be removed	In deep floods, it helps prevent structural damage by allowing water to enter the building, avoiding the imbalance between internal and external water levels
	Use water-resistant paint for the lower portions of internal walls	Reduce mould growth
	Raise electrical points above flood level with wiring drops from above	Prevent electrical blackout
	Relocate meters and the boiler above flood level	Prevent damage on meters and boilers
	Replace carpets with vinyl and ceramic tiles and rugs	Reduce time for drying out

In the case of wooden structures, their durability depends on the moisture and temperature conditions as well as the exposure time. The decay of the wooden beams is usually caused by damaged downpipes, leaking roofs, and WDR (Kehl, 2013). With more extreme rain events in the future, the risk of water runoff along masonry due to unsuitable drainage systems will increase, while at the same time, inadequate retrofit solutions, could further increase the relative humidity in timber construction. Vapor and airtight sealing of joist pockets can improve the microclimate of wooden beam ends by improving hygrothermal performance. However, relative humidity can still approach critical values for the onset of mould growth. So, whilst reducing mould growth, this approach does not completely eradicate it (Kopecky *et al.,* 2019).

Moisture related risks of the envelope are found in buildings with large rates of moisture production or lack of ventilation. Lourenco *et al.* (2006) looked at buildings in the historic centre of the city of Braganca, located in the North-East of Portugal, surveying: building typology and materials, damage in the building envelope, indoor survey of damage, and measurements in indoor air temperature and relative humidity. They discovered that water-related problems were the single most important defect, combined with inadequate sun exposure, ventilation and heating, and excessive indoor moisture production. Extremely low temperatures, high humidity, and presence of mould, therefore, compromise the indoor quality of life of the inhabitants (Haldi, 2015).

Future changes in indoor climate could change the moisture states in solid walls. Several studies have been undertaken using physical models to help evaluate the impact of heat and moisture on the stress and strain of building fabric, and consequently inform improvements in the indoor climate of historic buildings, particularly in structures that are heated intermittently (e.g., Wessberg *et al.,* 2019; Portal *et al.,* 2014; Ganguly *et al.,* 2020), and could be a useful method for investigating the impact of climate change on historic building envelopes. For example, Wessberg *et al'*s 2019 work, which aimed to develop a model with easy to apply parameter identification procedures, based on in-situ measurements, that would allow building interiors to be heated to a predefined temperature while keeping the ranges and change rates of relative humidity in a safe region, both for the comfort of occupants and to preserve the building's fabric.

The implications of changing precipitation patterns on mould growth

Wetted or damp building materials are usually contaminated by fungi[11], and especially by moulds. Consequently, mould growth is one of the most common ways that moisture-induced deterioration manifests itself in both traditional and new-build structures alike. Many researchers have studied the relationship between diffusion, the transport of moisture across the building envelope, and indoor temperature and humidity, with a particular focus on mould growth. Mould growth negatively affects the durability of the building envelope as well as the environmental quality of the internal climate. Different mould risk management approaches have been developed in buildings with both active (thermal ventilation and control), e.g., Hagentoft, *et al.,* 2010; and through passive building design approaches. With passive controls, it is desirable to keep indoor relative humidity at 60%, but certainly below 80%, the threshold of mould gemmation, in buildings not designed with permanent active controls (e.g., see Su, 2006).

Climate change will inevitably impose new challenges for mould prevention. Mould growth affects indoor environmental quality and can lead to health complications when certain moulds are inhaled systematically. The critical moisture level varies across different building materials and there are different methods used to identify the minimum relative humidity value, which encourages mould germination in different building materials. Johansson *et al.* (2014a) undertook a comparison of six methods used to estimate the mould resistance of building materials, insulation materials (and their facings), panel products (containing materials of organic origin), synthetic polymeric materials, plastics and a variety of materials commonly used in the construction of military infrastructure. The authors present a universal critical moisture level test for determining critical moisture level for mould growth, that is the lowest relative humidity at which mould can grow. They assert that if the expected temperature and RH in a building part is known, either by measurements or by using heat-and-moisture simulation software, knowledge of the critical moisture level of a material may be used as a tool for choosing materials for construction (and consequently retrofit/refurbishment) to minimise the risk of mould growth (Johansson *et al.*, 2014a).

In addition to material type (and consequently material surface characteristics) the cleanliness of material surfaces are important considerations. Viitanen *et al.* (2010) compared stone with timber and found that surface type and dirtiness of material has an influence on mould growth. In wood materials the finish of the surface was a critical factor, e.g., more mould growth was detected on

[11] A fungus is any member of the group of *eukaryotic organisms* that comprises microorganisms such as yeasts and mushrooms; whilst mould is the superficial, often woolly, growth produced on moist or decaying organic matter or living organisms by a fungus.

planed pine sapwood than in edge-glued spruce board. Grant *et al.* (1989) found that surfaces which are soiled or covered with a susceptible paint or paper do not need to become as damp for mould to develop.

There are still significant uncertainties and many unknowns in relation to mould growth, in both modelling and real life. However, despite the lack of standard testing methods, there are known approaches to the evaluation of the susceptibility of a construction material to mould growth, proven to be predominantly caused by moisture, and it is also known that some mould spores are toxic, which is why eradicating damp is such an important issue in delivering occupant health and wellbeing (Sustainable Traditional Building Alliance, 2012). Although ISO 13788:2012 (hygrothermal performance of building components and building elements – internal surface temperature to avoid critical humidity and interstitial condensation-calculation methods) proposes calculation methods for critical surface humidity values, in order to assess risks posed by excessive moisture, these do not take into account a number of factors that are quite influential on moisture migration within the building envelope, such as hygroscopic moisture capacity of materials, capillary suction and moisture transfer ((D'Ayala and Aktas, 2016).

Grant *et al.* (1989) and Pasanen *et al.* (1992) both report that fungi species appear on recurrently moist building materials in a succession based on the moisture requirements of different fungal species, and that those species that eventually develop because of prologued dampness tend to be highly toxigenic and difficult to detect. These studies looked at several interior surfaces including wallpaper, wood, gypsum board, fibre board, and painted surfaces.

Based on previous empirical research it is known that fungal growth can begin after only a short period of 'favourable' conditions and that spores can survive for a long time after contaminated materials dry and growth ceases (Pasanen *et al.,* 1992). Pasanen *et al.,* 1992; Johansson *et al.,* 2014a; and Isaksson *et al.,* 2010, all report that it is possible to predict onset of mould growth with reasonable reliability. Fungal activity in and on building materials may occur from circa 75% relative humidity. Likelihood of fungal activity significantly increases with a relative humidity of 80% and over (see e.g., Grant *et al.,* 1989; Pasanen *et al.,* 1992). Indeed, BS 5250 (2016) states that relative humidity values higher than 80% for a sufficiently long time (i.e., a few hours) can result in an onset of mould growth; and importantly, once the germination starts taking place, the process can continue under lower relative humidity values.

A study by the BRE (Grant *et al.,* 1989), which measured living room and bathroom wall surfaces in a dwelling over a six-week period during the coldest winter months, found that more than 80% relative humidity only occurred on average between one-third and two-fifths of the time. Mould fungi present either as ungerminated spores or as mycelium would therefore be subject to fluctuating conditions of temperature and humidity, which would be likely to adversely affect their ability to colonise and survive on susceptible substrates.

The temperature values reportedly needed for an onset of mould formation can be quite low for very high relative humidity values (i.e., over 90%), however for relatively moderate humidity levels the reported optimum temperature value for most fungal species varies between 20˚C and 30˚C (e.g., see Grant *et al.,* 1989; Hukka and Viitanen, 1999; and Sedibauer, 2001).

A significant body of work has been undertaken to address the impact attic conditions may have on mould growth. In the last 20 years, mould growth has been observed more frequently than before in ventilated attics. It is predicted that temperature and humidity levels will increase in cold attics in future climate scenarios, and the risk of mould growth increases with these changes. For example, Nik *et al*. (2012) investigated hygrothermal performance of ventilated attics in respect to possible climate change in Sweden. Hygrothermal simulations for four attic constructions were investigated. Simulations were done for the period of 1961–2100, using weather data from the Rossby Centre Regional Climate Model (RCA3). Effects of three different emissions scenarios are considered. Hygrothermal conditions in the attic are assessed using a mould growth model. Based on the results the highest risk of mould growth was found on the north roof of the attic in Gothenburg, Sweden. Results point to increment of the moisture problems in attics in future. Different emissions scenarios do not influence the risk of mould growth inside the attic due to compensating changes in different variables. Assessing the future performance of the four attics shows that the safe solution is to ventilate the attic mechanically, though this solution inevitably requires extra use of electrical energy for running the fan. Insulating attic roofs can decrease the condensation on roofs, but this was not found to significantly decrease the risk of mould growth on the wooden roof underlay (Nik *et al.,* 2012).

Similarly, Jensen *et al.* (2020) conducted a large-scale experiment to investigate the hygrothermal performance (measuring indoor and outdoor relative humidity and temperature) of 18 north-facing attic spaces, with varying ventilation principles and varying infiltration scenarios, over a three-year period. Different measures to tackle the problem of unfavourable moisture conditions in cold attic spaces, under the eaves, were combined and studied. These included varying the underlay, ventilation strategy, infiltration rate and externally insulated underlay as parameters. The results showed that following recommended passive ventilation strategies made the hygrothermal performance in attics with diffusion-open roofing underlay worse. In addition, increasing vapour diffusion tightness of the roofing underlay made the hygrothermal performance of the cold attic spaces under the eaves worse, except for attics with passive ventilation but without infiltration. The hygrothermal performance of the attics with diffusion-tight roofing underlay was poor when combining infiltration and the assessed ventilation strategy. The performance of the same attic without infiltration showed that some degree of ventilation was needed. External roof insulation did not significantly improve the hygrothermal performance of the attic. There was a good correlation between predicted and observed mould growth, suggesting that post-processing hygrothermal measurements with a mould growth give a good predication of real performance. It appears that retrofitting an attic with insulation can decrease the condensation risk but cannot reduce the risk of mould growth.

Clearly, the risk of mould growth increases considerably when the relative humidity of a construction material exceeds 80%. Buildings susceptible to damp both now and under future climate predictions require special consideration, as the succession of fungi they attract can be highly toxigenic and difficult to detect but may lead to significant issues of poor indoor environmental quality and subsequently poor health, if not suitably accounted for and resolved.

Energy performance of buildings

It is well recognised that average energy consumption of traditional buildings is noticeably higher than that of modern buildings. Therefore, to limit climate change and guarantee energy security, increasing attention has been paid to the energy retrofit of older buildings in recent years (IPCC, 2014). According to the European standard EN 16883:2017 (Conservation of cultural heritage: Guidelines for improving the energy performance of historic buildings), 'retrofit' is defined as the modification of the existing configuration, aimed at improving the building's conditions to an acceptable level while minimising energy consumption (EU, 2017).

Savings in energy consumption and carbon emissions are dominant criterion when assessing the effectiveness of an energy retrofit (Martinez-Molina *et al.,* 2016). There is, however, an argument that due to their historical, cultural, and aesthetic significance, historic building preservation should be as important as meeting any energy efficiency and/or emissions targets (Merlino, 2014).

Climate change will inevitably result in a change in the heating and cooling requirements of a building, to achieve a comfortable indoor environment. Therefore, energy consumption will vary with climate change. There is still a substantial lack of understanding when it comes to what this means for traditional building stock. Indeed, there is a paucity of literature on historic buildings' energy performance in the climate change context (Hao *et al.*, 2020). In general terms, due to the increasing global temperature, heating load is decreasing in winter, while in summer, buildings are facing the dilemma of increasing cooling load or more uncomfortable conditions (Weyr *et al.,* 2019). However, the impact on the total energy use will vary according to different climate zones, and in the UK, there is still a focus on reducing energy consumption associated with heating rather than cooling. Nevertheless, potential changes in energy use highlight the need for complimentary adaptation and mitigation strategies. Since existing climate zones may change in the future, and with them, anticipated heating and cooling degree days[12].

Although a drastic reduction in carbon emissions would slow climate change, some changes in the climate are already certain, and therefore the impact of future climate scenarios should be considered when retrofitting an older building. Combined with a changing climate, inappropriate choices of retrofit solutions might result in unexpected consequences, and potentially reduce that building's overall performance. Therefore, it is necessary to ensure retrofit approaches align carbon reduction (mitigation) with climate change adaptation, to avoid maladaptation.

One of the barriers to climate change mitigation in the built heritage sector is the compatibility of energy saving retrofit solutions with historic building fabric (Sesana *et al.,* 2019). There are challenges with preserving the authenticity of historic buildings, maintaining their traditional passive behaviours and choosing adaptive solutions compatible with the characteristics of traditional materials, to avoid an acceleration of decay processes[13]. It is thus important to understand what the enablers, or the barriers, are to reduce the carbon footprint of historic buildings to meet climate change mitigation targets. Certainly, using renewable energy to mitigate greenhouse-gas emissions is an increasingly viable solution for buildings that cannot readily be retrofitted for energy efficiency. For example, in

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[12] Degree days assume that when the outside temperature is 18°C (65°F), we do not need heating or cooling to be comfortable. Degree days are the difference between the daily temperature mean, (high temperature plus low temperature divided by two) and 18°C (65°F). If the temperature mean is above 18°C (65°F), we subtract 18 (or 65) from the mean and the result is Cooling Degree Days. If the temperature mean is below 18°C (65°F), we subtract the mean from 18 (65) and the result is Heating Degree Days.

[13] Thermal mass, which refers to construction mass that can store heat, is a passive climate regulation strategy commonly found in historic buildings. Older buildings usually have a building envelope constructed of high heat capacity materials such as bricks, natural stone, and tiles (Balaras, 1996). A large body of literature has verified the thermal inertia effect of thermal mass and associated internal thermal comfort for building occupants (e.g., Verbeke and Audenaert, 2017; Johra and Heiselberg, 2017 and Buhagiar and Jones, 2011).

the medieval historic centre of Siena (Tuscany, Italy), where the most effective environmental policy for energy transition towards decarbonization is not building envelope adaptation, but the installation of photovoltaic panels on roofs (outside the medieval district), which could enable the carbon neutrality of the historic centre in about 30 years (Marchi *et al.,* 2018).

A literature review by Martínez-Molina *et al.,* '*Energy efficiency and thermal comfort in historic buildings: A review',* outlines energy retrofit impacts of different building types, with examples from across the world, in order to calculate the energy reduction potential for residential buildings, which they believe to be between 20% and 68% (Martínez-Molina *et al.,* 2016). Another review explains the importance and potential of user-driven energy efficiency in historic buildings, highlighting the importance of occupant behaviours and engaging with occupants to develop climate mitigation strategies (Berg *et al.,* 2017).

Meanwhile, other studies highlight the importance, but current limitations, of using building performance simulation and energy modelling in assessing the impacts of building retrofit (Webb, 2017). Webb's work on '*Energy retrofits in historic and traditional buildings: a review of problems and methods'* highlights the need for the development and selection of appropriate software, and the increased gathering of measured data (e.g., material properties, indoor climate conditions) to reduce the performance gap (discrepancy between simulated and actual building performance).

Historic buildings of traditional construction are arguably the most difficult to refurbish for energy efficiency because frequently the external envelope of the building cannot be modified. Indeed, many older buildings have both a cultural and heritage value and may be *'listed'* for their exterior appearance. Consequently, retrofit efforts to improve the overall energy efficiency of such buildings has focussed on the addition of internal wall insulation to drive energy costs down. This is a topic which has been investigated continuously during the past few years**.**

Understanding moisture dynamics and building retrofit

A building's envelope is the interface between the indoor and outdoor environment. Besides thermal conductivity, the two main interactive processes that are controlled by this interface, and that therefore influence the indoor climate, are thermal inertia and air exchange. Retrofit interventions can significantly change a building's performance, from the building envelope's moisture dynamics to its indoor climate (e.g., see Sesana *et al.,* 2019; Martínez-Molina *et al.,* 2016). Furthermore, how retrofitted building envelopes will respond to future climate change remains unclear. Certainly, few studies have investigated traditional buildings in both retrofit and future climate scenarios (see Cavalagli et al., 2019; and Nik *et al.,* 2012, 2015).

As outlined previously, hygrothermal impacts (the movement of heat and moisture through buildings) including repeated wetting, drying, freezing, and thawing of building fabric, can cause problems such as damp, condensation, mould growth, and loss of thermal performance and may even result in premature failure. The hygrothermal performance of historic building materials should be assessed before any energy efficiency retrofit action is implemented to ensure the compatibility of the measures proposed. Wood, for example, generally used in older residential buildings (although timber-framed newbuild is on the rise), is highly susceptible to mould growth. With suitable relative humidity and temperature, the decay process will start with mould growth and follow with fungal attack. Moreover, if the high moisture content continues through winter, frost damage is likely to occur. Masonry with a low surface temperature is more vulnerable to moisture risks due to the increase of relative humidity. These low temperatures are especially found in places such as thermal bridges, corners, or cold attics. A study by Ge and Baba (2015) who conducted research on the dynamic effect of thermal bridges on the energy performance of residential buildings (through simulations), found that for colder climates, the presence of thermal bridges can increase the annual heating loads by 18%.

Before a retrofit intervention, historic buildings are often sufficiently ventilated by uncontrolled air infiltration through old windows and doors. Any energy retrofit is likely to increase the airtightness of the envelope, which could reduce the building's capacity to remove any excess of moisture. When combined with inappropriate window operation by the occupant, risks of moisture damages could increase (Haldi, 2015). It has been suggested that in addition to modelling and/or predicting the occurrence of moisture-induced damage to building environments, it is pertinent to undertake probabilistic modelling based on 'measured' occupant behaviour, to determine whether *passive* ventilation is sufficient and/or whether *active* mechanical ventilation or humidity regulation is needed. Probabilistic models for predicting occupant behaviour could be further developed to integrate stochastic predictions of occupancy and activities, which have an important impact on humidity production. Haldi (2015) poses a behavioural model that could be directly integrated into more detailed modelling software, including the complete coupling of heat, air, and moisture processes. Residential environments and those with intermittent heating and occupation require special consideration.

Internal wall insulation and moisture dynamics

Interior insulation systems are either vapour tight or vapour open. A vapour tight system is often referred to as a 'traditional' or 'conventional' system (Vereecken *et al.,* 2015), and includes a vapour barrier to avoid interstitial condensation. However, as these systems are also known to prevent walls from drying out towards the interior climate, vapour open solutions are preferred. Indeed, most solid walls were built to be 'vapour-open'. This means that moisture can pass through the wall. If 'vapour-closed' insulation materials are used (such as foil-faced insulation foam) there is the risk that moisture will be trapped inside the wall, which could lead to damp, mould, and ultimately damage to the building. If the existing wall is vapour-open then vapour-open insulation materials, plasters and paints should really be used. Suitable insulation materials may include wood fibre, mineral boards, and cork. These should always be plastered with a lime-based finish and painted with vapour-open paints (Centre for Sustainable Energy, 2021).

The inappropriate use of internal wall insulation has been proven to detrimentally change the moisture dynamics of solid walls, and these adverse effects are especially significant in the application of vapor-tight insulation systems. In some cases, internal insulation creates extra vapor diffusion resistance, which impedes the inward drying of the wall (Johansson, 2014b). Additionally, the temperature gradient across the original wall can be reduced with the addition of insulation, which will also impact building performance.

Outlined below are the results of several studies that have considered the impact of wall insulation on traditional, solid wall, buildings. For instance, Odgaard *et al.* (2018) monitored the hygrothermal performance of a listed multi-storey dormitory with solid masonry walls in Copenhagen (with and without 100mm of diffusion-open interior insulation) for more than two years. Continuous monitoring revealed that seasonally low surface temperatures and high differences between room air and surface temperatures were recorded on the un-insulated wall; whilst an increased surface temperature and a smaller difference between indoor and surface temperatures, were reported on the insulated wall. The relative humidity of the un-insulated masonry wall was in the range 50% on the inside to 60% on the outside; whilst the insulated wall showed uniformly distributed values around 80%. In other words, the relative humidity of the insulated wall was 20–30% higher than that of the untreated wall. The overall outcome of the results shows that when applying interior insulation, subject to expected normal indoor climate, the magnitude of relative humidity throughout the wall increases and temperature decreases, and there will be only small differences between inside and outside. The changed hygrothermal conditions were evaluated visually for frost and mould, supplemented by on-site inspections for mould and mathematical predictions of risk of mould and decay of wood. Neither of the evaluated damage criteria showed damage after application of interior insulation. The authors note that the façade of the building studied has a rendered and painted façade and is not exposed to wind-driven rain. The temperature conditions in the courtyard were such that the wall did not experience temperatures below freezing point. They suggest that if the inside and outside boundary conditions were worse, then the risk of moisture induced damage, such as mould, decay of wood, and frost could increase (Odgaard *et al.,* 2018).

Similarly, Kehl *et al.'s* (2013) simulations, where they analysed several interior insulation projects, with wooden beam ends, demonstrated that moisture load from outside by wind-driven rain had influenced the behaviour of moisture content of the wooden beam ends, and in masonry walls, which increased when coupled with interior insulation. They assert that the moisture content of wooden beam ends in masonry walls depends mainly on exposure to wind-driven rain.

Biseniece *et al.* (2017) studied the thermal behaviour of retrofitted historic buildings in the cold climate of Riga, Latvia, comparing two types of insulation material (aerogel and vacuum insulation panels). The renovation also included insulation of the floor and roof, change in windows, new ventilation, and the installation of an air heat pump. Results showed that the calcium silicate masonry part of the internally insulated wall was exposed to freeze-thaw damage. In cold climates, frost damage will prevail where the moisture content of brick is higher than the capillary saturation. Certainly, Zhou *et al.* (2017), who simulated both uninsulated and internally retrofitted brick walls in two Swiss climatic conditions, using the number of actual ice growth and melt cycles as an indicator for freeze–thaw cycles, found an increase in freeze–thaw cycles and ice content within the external brick wall following the retrofit of internal insultation[14].

In old brick masonry buildings, unprotected brick walls may be susceptible to freeze-thaw damage. The addition of internal insulation can change the thermal and moisture balance in the wall assembly and, in some cases, initiate or exacerbate moisture problems such as freeze-thaw damage in masonry units (Mensinga *et al.,* 2010). Researchers used detailed computer modelling to compare the moisture contents of brick masonry, in a proposed building retrofit, both before and after insulating. If the moisture contents predicted in service before and after retrofit are both below the critical degree of

[14] Frost damage is a mechanical weathering process caused by the water freeze–thaw cycle. Due to the change in conditions that retrofit interventions place on existing structures (e.g., lowering the temperature of building fabric on the outer surface, due to the application of internal insulation), frost damage is more likely to occur.

saturation of the brick, the design can be considered safe. Authors suggest applying frost dilatometry, to characterise dimensional changes of a material as a function of temperature, alongside hygrothermal modelling to ensure the retrofit approach adopted doesn't result in, or further exacerbate, freeze-thaw damage. Certainly, the modelling of e.g., wind-driven rain loads, and the measurement of the material response will enable a more confident assessment of the impact of different climates, insulation strategies, rain control approaches, building orientations, water-repellent coatings, vapor-permeable or capillary active insulations, and many other common questions that arise during interior insulation retrofit (Mensinga *et al.,* 2010).

The frequencies and intensity of precipitation in winter will increase in many regions of Europe, including Wales, which implies an enhanced risk of frost damage. With moisture accumulation in traditional building's envelopes, the durability of materials and thermal efficiency of the building may be endangered. To prevent this, some historic retrofit projects have adopted capillary-active insulation systems designed to transport the moisture content. Capillary active insulation is a specific kind of vapour open insulation system, aimed at absorbing liquid water that has accumulated on the interface of the former interior surface and the insulation (either caused by driving rain or by interstitial condensation), transporting it inwards (Vereecken and Roles, 2015).

For example, Toman *et al.* (2009) undertook an assessment of the hygrothermal performance of a capillary active insulation system applied to a 19th century brick-built house and determined that over the four-year period of testing, the thermal performance was good and there was no water condensation inside the building envelope, and no ventilation problems in the winter. The results lead the researchers to recommend this as an economical and environmentally friendly approach to retrofitting older buildings.

Marincioni and Altamirano-Medina (2014) looked at the effect of orientation on the hygrothermal behaviour of a capillary active internal wall insulation system installed in a 16th century building in Maidenhead, west of London. Temperature and relative humidity at the interface between the existing wall and the insulation were monitored for a period of two years. It was observed that the walls have a different hygrothermal performance. The south-facing wall presented a faster reduction in relative humidity compared to the north-facing wall. Discrepancy in the performance was found to be associated to wall orientation, especially when it came to the impact of solar radiation. The hygrothermal performance of a capillary active internal wall insulation system was found to allow dry-out of moisture within the building envelope enhanced by changes of temperature in the external wall due to longer and constant periods of solar radiation.

Zhao *et al.* (2017) studied four capillary-active mineral insulation systems (autoclaved aerated concrete, calcium silicate, mineral foam, and perlite) and compared them with a vapor-tight and non-capillary-active polyurethane insulation system. The hygrothermal properties of the capillary-active systems were measured and analysed, and results showed that they had different moisture storage and transport characteristics, which influenced the hygrothermal behaviour of the case study, a renovated historic masonry wall. The thermal performance of the four mineral insulation systems was comparable, but a thicker layer of the calcium silicate system was needed to achieve the same thermal performance as the others, as the material has a lower thermal resistance. Meanwhile, the four materials show quite different moisture properties. Calcium silicate exhibits high moisture storage capacity/retention and water wicking ability, while autoclaved aerated concrete showed a low moisture storage capacity and water absorption rate. Perlite absorbed moisture quickly, but once moistened, took time to dry out. The four capillary-active mineral insulation systems exhibited a good moisture buffering capacity, when compared with a vapor-tight and non-capillary-active polyurethane insulation system, which had a moderate moisture buffering performance. With the installation of the interior insulation system the solid masonry wall became colder and wetter during the cold season. As freezing water penetrated the construction, the risk of the frost damage at the external portion increased. Compared to the vapor-tight and non-capillary-active polyurethane insulation system, the mineral insulation systems have a higher inward drying potential and thus can reduce the moisture mass in the underlying masonry wall. The risk of spore germination at the inner surface of the external wall corner insulated by calcium silicate was also higher compared to the other systems. The autoclaved aerated concrete system enabled the wall to keep in a relatively dry condition. And the mineral foam insulation system can achieve a higher temperature and a lower relative humidity at the inner surface of the wall. Under moderate rain protection, four mineral insulation systems perform well at the normal indoor moisture load for the massive wall investigated in this study. However, under high indoor moisture load condition the relative humidity behind the insulation system becomes quite high in cases where the calcium silicate and perlite insulation systems are applied, resulting in the possibility of mould growth. With the polyurethane insulation system, there was a high risk of the mould growth and interstitial condensation occurring behind the insulation system.

Jensen *et al.* (2020) investigated the hygrothermal performance and risk of mould growth in solid brick masonry walls fitted with three diffusion-open capillary-active interior insulation systems. The focus of the study was on the conditions in the interface between the masonry and the interior insulation, and in the embedded wooden elements. The effect of exterior hydrophobisation (water repellence) was also investigated. In Denmark, like Wales, south-west is the prevailing wind direction and thus the most critical in assessing the potential impact of wind-driven rain. A combination of wind-driven rain with high solar irradiation on a south-facing wall may lead to moisture transport towards the indoor environment. A north-facing wall receives less wind-driven rain, but at the same time less solar irradiation. Consequently, eight of the twelve test walls faced south-west and four faced north-east. The test containers were installed so wind-driven rain would not be obstructed by nearby buildings, and so shadows onto to the wall surfaces were minimal. Relative humidity and temperature were measured at several locations in the test walls over a period of four years. The findings show that exposed walls with interior insulation and high indoor relative humidity performed poorly in terms of the risk of mould growth. The researchers observed that high indoor relative humidity in the winter caused high relative humidity behind the interior insulation, with the level dependent on the diffusion tightness of the insulation material. Combined with exterior hydrophobisation against driving rain, the semi diffusion-tight insulation system performed better than the highly diffusion-open systems. Good performance was observed for the semi diffusion-tight polyurethane foam insulation with calcium silicate channels combined with exterior hydrophobisation. The effect of hydrophobisation varied with the orientation. Mould observations found no growth in the interface in most walls, probably because the high alkalinity of the adhesive mortars and scarce nutrition prevented growth. Growth was however found in some walls having low alkalinity and possibly available nutrition. Little correlation was found between on-site and modelled mould growth. The authors suggest that mould-growth models may overestimate risk and that risk of mould growth in the critical locations may be reduced considerably by application of an insulation system using high pH (>12) adhesive mortar, even if the relative humidity is high. The more diffusion-tight systems seem to better maintain the high pH (Jensen *et al.,* 2020).

The results of some investigations therefore still show scepticism about capillary-active insulation systems. Vereecken and Roels (2014) compared the hygric performance of different internal insulation systems in the laboratory: vapor-open, non-capillary active system, capillary-active systems, and vapor-tight systems. Their results demonstrated that, in the steady-state winter conditions, moisture captured by capillary-active systems was higher, than by the traditional vapor-tight system. X-ray projection analysis showed that moisture accumulated between the glue mortar and the insulation panels. The increase of stored moisture inside walls with a capillary active system was found to be higher than for walls with a traditional vapour tight system (Vereecken and Roels, 2014).

Therefore, it should be checked if the advantages of using capillary systems offset the potential disadvantages. Indeed, to date, no real methodology is available to select the interior insulation system and thickness resulting in the best balance between energy savings and hygrothermal risks. Vereecken *et al.* (2015) present their decision tool based on a Monte Carlo analysis. In the study, both vapour-tight interior insulation systems and a capillary-active insulation system were considered. The researchers determined that, overall, vapour-tight systems tend to be preferable for structures that are resistant to frost damage. For buildings sensitive to frost damage or where wooden beam ends were present, however, capillary-active systems were recommended. They found a capillary active system to be more sensitive to small modifications of the wall structure (e.g., interior finishing coat, wall thickness), while hardly any differences could be observed for the wall with a vapour tight system. In addition, they established that wind-driven rain could impede beneficial hygrothermal behaviour in a capillary-active interior insulation system by inducing a lower thermal resistance or increased indoor relative humidity (Vereecken *et al.,* 2015).

Klõšeiko *et al.* (2013) also determined high levels of humidity in capillary-active systems (applying calcium silicate, aerated concrete, and polyurethane board with capillary-active channels). They measured the hygrothermal behaviour of insulation materials during both drying and wetting seasons. The temperature and relative humidity condition inside the wall between the added insulation and brick wall favoured mould growth. The results show that timing of the renovation works should be considered to avoid the hygrothermal risks inside the retrofitted wall assemblies. The results show that additional moisture during installation can cause high relative humidity levels in a wall for a long time, which can lead to interstitial condensation.

Koci *et al.* (2015) examined the energy efficiency and hygrothermal performance of retrofitted historical building envelopes under Prague's climate conditions. Again, to retain the original appearance of building's facade, retrofitting was carried out using different types of interior thermal insulation systems. Sandstone and solid brick were chosen as representative historical building materials and the envelopes were retrofitted from the interior side with calcium silicate, *Multipor* (mineral insultation boards) and hydrophilic mineral wool. The simulations were performed under dynamic climatic conditions. The authors determined that capillary active or hydrophilic insulation materials can be an appropriate choice for interior thermal insulation in historical buildings, as results from their study showed significantly improved energy efficiency of the building envelopes, while retaining the original appearance of the façade. Among the investigated thermal insulation materials, the best results were obtained when hydrophilic mineral wool was applied. In this case, the energy transfer through the sandstone building envelope was reduced by 87.17% and for the solid brick building envelope it was 71.29%. However, the other analysed thermal insulation materials, namely calcium silicate and *Multipor* (mineral insulation boards), evidenced very good hygrothermal and energy performance as well. Importantly their research showed no accumulation of moisture in the building envelope. Therefore, they concluded that common problems reported when using interior thermal insulation with a water vapor barrier, were eliminated. However, they suggest that it may be necessary to provide some additional solution to protect the external facade against rain and subsequent liquid water penetration.

Multiple approaches to energy efficiency retrofit

In Cirami *et al.'s* (2017) thermal and economic analysis of renovation strategies for a historic building in the Mediterranean, the authors analysed the effectiveness of different energy efficiency retrofit measures, including three types of internal wall insultation (aerogel boards, calcium silicate board or thermal plaster, which could also be applied to the external envelope if permitted), roof insulation or glazing replacement. Aerogel has very low thermal conductivity, which makes it promising for historic buildings, where it is important to minimize the impact in terms of lost useful floor surface. Calcium silicate boards are quite popular for retrofitting historic buildings; indeed, their thermal conductivity is slightly higher than other insulating materials, but they also perform as a capillary active material that facilitates drying possible liquid water accumulated in the walls (also see Walker and Pavia, 2015 for a study on the thermal performance of a selection of insultation materials suitable for historic buildings). Finally, the selected thermal plaster was based on natural hydraulic lime and contained lightweight aggregates, hence its relatively low density (650 kg/m^3). It also showed a high attitude of water vapor diffusion, with a water vapor resistance factor (μ value) of around five. The energy retrofit of the roof meant the installation of polyurethane boards (80 mm) below the tiles. On the other hand, in the windows, it was preferable to keep wooden frames that showed a sufficiently good performance and a certain aesthetic value; hence, only the glazed component was replaced with double-glazing filled with air (4-8-6 mm). Cirami *et al.'s* (2017) simulations found the room temperature of retrofitted buildings, regardless of intervention, to be higher than an un-retrofitted room, on the hottest days. However, they stress that the benefits of effective ventilation, and night cooling, could still counterbalance the adverse effects of retrofitted insulation, even in southern Italy. They conclude by stating that the initial investment costs for energy renovation actions in historic buildings are still a significant obstacle (based on the cost and effectiveness of non-invasive interventions) and current standards and codes show the lack of a specific protocol that provides balanced solutions to significantly improve the energy efficiency of historic buildings.

Meantime, Hartwig Künzel's research directly compared internal with external wall insulation. Results showed that external wall insulation can dry out a wall, with the drying rate dependant on the vapour permeability of the insulation system applied. However, he found rising water content of the wall when internal wall insulation was applied, due to decreasing masonry temperature. This effect was almost independent of the vapour permeability of the insulating material. While external wall insulation also improved the thermal resistance of the masonry, internal wall insulation had the opposite effect and increased the wall's susceptibility to frost damage risk. Kunzel (1998) concludes that when applying internal wall insulation to exposed walls, façade rain protection measures should also be implemented.

In some instances, it has indeed been possible to apply external wall insulation to an older building. Retrofitting insultation to an exterior wall will change the hygrothermal performance of that wall. If it is not properly done, this could lead to surface damage at best and building failure at worst. When adding insulation to the exterior of a building, the existing structure can be kept in a warm and dry condition, which is beneficial from a moisture point of view. However, the exterior wall surface can become colder and more susceptible to moisture damage, and as a result, organic growth. For example, external thermal insultation composite systems (ETICS), common in both new and renovated buildings in Europe, may have serious problems of biological growth causing deterioration and degradation of the exterior cladding. Barreira and de Freitas (2013) studied the influence of orientation on surface humidification, by external condensation and wind-driven rain on ETICS-covered façades of a University of Porto campus building (on the west coast of Portugal), whose walls face north, south, east, and west. They found that façade orientation has a significant impact on surface condensation, with the west façade at greatest risk from condensation, followed by the east, north and south. Wind-driven rain measurements show that, on annual bases, the south façade was more exposed to rain (74 l/m2), followed by the west façade (29 l/m2), east façade (19 l/m2) and north façade (7 l/m2). It is proposed that understanding the influence of orientation on surface condensation, WDR and drying process is needed to understand whether certain orientation(s) are more prone to surface humidification and, which of the 3 parameters, surface condensation, WDR and drying process, are more likely to lead to biological growth on ETIC (Barreira and de Freitas, 2013).

Similarly, it was found that external insulation applied to traditional masonry walls (with no cultural heritage value) lead to an increase in indoor temperature of up to a 3˚C, as evidenced in a Mediterranean climate, and consequently, may cause overheating (Stazi *et al.,* 2013). The researchers looked at the dynamic performance of three building envelopes characterised by different traditional wall constructions adopted in temperate climates. In each case the optimal retrofit solution from the point of view of comfort and energy savings is identified. The researchers chose three buildings with distinct wall constructions: capacity (high thermal mass); stratification (different layers and a cavity); and resistance (the use of an insulation layer). Dynamic parametric analyses were carried out to verify the impact of different retrofit solutions on each of the buildings studied. The results show that the behaviour of the three envelopes differs greatly because they interact in different ways according to the outdoor temperature. This has significant implications when considering occupant comfort as the use of considerable thicknesses of thermal insulation, when coupled with high thermal mass, lead to overheating, while it is an improvement in the stratified envelopes. The authors propose that the problem of summer discomfort could be resolved by adopting mixed insulation strategies, such as a ventilated external insulation layer, which would allow the existing building envelope to maintain its dynamic behaviour.

As previously identified, older buildings are arguably the most difficult to refurbish for energy efficiency, as frequently the external envelop of buildings of cultural, historic, and architectural merit cannot be modified. Better performing technologies do not necessarily fit in with the aesthetics or mechanics of older, traditional buildings. In other words, what might be considered the best available technologies, cannot essentially be adopted, to optimise the building energy performance in older buildings. Following on from Kunzel's comparison of internal and external wall insulation, there are several studies that have compared multiple approaches to energy efficiency retrofit.

With culturally significant historic buildings there is a preference for non-invasive, but conceivably, lower performing approaches. To analyse the effectiveness of perceived lower performing technologies, Milone *et al.* (2015) investigated the energy performance of two different refurbishment configurations of the building envelope of a typical historic dwelling in Italy, a *Best Available Technology* scenario, in which interventions consisted of a thermal barrier coating and aluminium-framed secondary glazing; and an *Allowed Best Technology* scenario, in which interventions assumed an alveolar (lime-based) coating and timber-framed secondary glazing with timber rolling shutters, allowable interventions according to cultural heritage preservation requisites and rules. A cost-based comparison between these two configurations was made. Results of this comparative analysis showed that both approaches would reduce the yearly energy demand, with less energy consumption for heating and refrigerating purposes, in relation to the baseline situation. The study showed therefore that energy retrofit of historic buildings could be carried out using modern technologies aimed at improving the building envelope's performance, without altering the architectural and artistic merit of such buildings. Both technological solutions were also compared in terms of economic performances. Considering the results of the energy and economic comparisons, the *Allowed Best Technology* do require a higher up-front investment cost than the *Best Available Technology* ones, whose adoption, in turn, results in a lower yearly energy saving.

Also in Italy, Ciulla *et al.* (2016) analysed the energy performance of typical residential buildings in four climate zones and calculated the impact of commonly used (building envelope) retrofit solutions, on (improved) energy performance. Eight different retrofit scenarios or combinations of scenarios were considered:

1. Internal coating system;
2. Internal/external thermal plaster application;
3. Roof insulation;
4. Internal coating system + roof insulation;
5. Internal/external thermal plaster application + roof insulation;
6. Window substitution;
7. Internal coating system + roof insulation + window substitution; and
8. Thermal plaster + roof insulation + window substitution.

For each action or combination of actions, economic feasibility analyses were also undertaken. Issues included high costs for owners, poor energy benefits and high payback times. Investment payback times and the yearly economic savings were calculated. Results showed that historic building refurbishment must be evaluated on a case-by-case basis, taking into consideration the climate zone, surface/heated gross volumes ratio, and payback times. Indeed, it was found that the same energy action can be more advantageous in some climate zone that others, whilst having the same economic cost. In general, payback time was found to increase from colder to warmer zones.

Lime-based insulating renders may be an option for some historic buildings, particularly those with façades that were finished with mortar layers, primarily employed to protect the building envelope from weathering, but now considered to be of great importance as a decorative feature of traditional buildings. Govaerts *et al.* (2017) investigated the hygrothermal performance of 49 different insulating lime-perlite render configurations on brick masonry, to establish whether this approach could reduce energy consumption whilst improving/contributing to a comfortable indoor climate. Their research highlights how important it is to examine the functionality of the original render before replacing, as existing renders may serve as a good barrier against moisture ingress, providing a satisfactory or even better insulation capacity in winter than substitute renders. When selecting an insulating render, it must be kept in mind that the insulation layers have a strong buffering effect towards water absorption, which may modify the hygrothermal behaviour of the masonry. To prevent freezing temperatures in the structure, simulations have shown that a minimum thickness of three centimetres of insulation render is needed when using a similar lime-perlite configuration. The insulation layers and top renders are not very susceptible to frost damage. The thicker the insulation coating, the less heat losses and the faster the exterior finishes will dry. Bond strength experiments and moisture transfer analysis point out that a base layer is of no use on rigid, porous substrates. If no exterior insulation is applied, an insulating render layer at the interior side will increase the damage risk to the building envelope. A divided insulation will always send more moisture into the building façade and will be less efficient than when the total layer thickness is applied on the exterior side. Finally, similar top layers have proven their resistance against water migration in the event of short showers, but under prolonged exposure they are of little use since their limited vapour permeability reduces the overall drying capacity (Govaerts *et al.,* 2017).

Non-solid masonry wall retrofit

There is a lack of research on the hygrothermal risks (movement of heat and moisture through buildings) of applying internal wall insulation to constructions that are not solid masonry walls. A focus on the impact of internal insultation on solid masonry walls is to be expected, as this is the most common construction type for historic buildings in the UK and Europe. However, as newer built structures (e.g., modernist architecture) are increasingly being recognised as significant and thus worthy of preservation, interior insulation is being applied in other types of constructions as well. There is a clear lack of understanding of the risks involved in applying insulation in these types of constructions, including the impact that a changing climate may have on indoor environmental conditions.

Other construction typologies that have been studied include the *Airey-houses* of the post-war era (Havinga and Schellen, 2019). These prefabricated concrete structures are formed from closely spaced one-storey height columns of steel tube reinforced concrete columns to which thin concrete cladding panels are fastened with copper wire. The properties are considered unattractive by some, but in some settings have gained considerable recognition for their contribution to dwelling design development. They are extremely difficult to heat due to the poor thermal properties of the concrete slabs. In some instances, these particular houses have been retrofitted with external insulation e.g., include housing owned by Powys County Council; but research has also been undertaken to establish the impact of applying interior insulation by removing the non-bearing part of the structure (the inner wall of the Airey system consists of non-load-bearing pumice concrete blocks), replacing it with interior insulation (Havinga and Schellen, 2019). Research on this approach will be of value, especially to building owners who are looking for affordable approaches to futureproofing their homes. Havinga and Schellen (2019) emphasise the hygrothermal risks associated with applying internal insulation to non-solid walls, and the importance of accounting for convection in hygrothermal assessments, including a recognition that imperfections in the vapour barrier will increase moisture transport significantly.

Work to date in the UK has focused on the retrofit of historic solid masonry construction, with little research into historic timber-framed buildings. However, Whitman *et al.,* 2020 have studied the potential retrofit of infill panels for historic timber-framed buildings (of which they estimate there are 1023 buildings in Wales), with the aim of establishing the risk of interstitial condensation and increased moisture content within replacement infill panels for timber-framed buildings, as well as the risk posed to surrounding historic fabric. Measured results, from panels mounted between two climate-controlled chambers were compared with those obtained through hygrothermal simulation. This allowed the assessment of three potential replacement infill panel details (wattle and daub; expanded cork insulation; and wood fibre) and the evaluation of the use of numerical modelling for the assessment of this type of construction. The results show that for steady-state conditions the simulations successfully anticipated interstitial condensation where it occurred, however, increases in moisture content towards the external face of all three panels were not predicted by the hygrothermal simulation. Overall, the cork infill detail performed the best, with the greatest thermal performance (average U-value of 0.48 W/m2K), and no interstitial condensation being identified. It should however be noted that these results are for forced steady-state conditions that are unlikely to exist in real life or for more realistic conditions over only a two-week period. Further research is required and is being funded by Historic England. This will allow longer term monitoring of test panels exposed to real external climatic conditions. It is expected that initial results will be published in due course.

Retrofit and maladaptation

It's well reported that applying internal insulation to traditional buildings may result in interstitial condensation, surface condensation, mould growth and decay (Havinga and Schellen, 2019). However internal wall insulation is commonly used in traditional buildings located in conservation areas, listed buildings, and buildings with decorative façades, to facilitate thermal upgrades. Solid masonry walls with high surface water absorption coefficients have a higher dependence on external climate conditions e.g., rain, solar radiation, which are likely to affect the performance of internal wall insulation. King (2016) undertook an analysis of approaches to improving the thermal performance of older homes in the UK with solid wall construction. This BRE report identifies 29 major unintended consequences that can be introduced during the application of solid wall insulation, either externally or internally. These include overheating and increased relative humidity, as well as the increased risk of dust mites, bed bugs, clothes moths, and other insects within the home, and both the short- and long-term reduction of indoor air quality due to increased levels of volatile organic compounds (VOCs) and reduced ventilation. The report states that unintended consequences can and are introduced at all stages of the solid wall insulation process from specification, surveying, installation and in use. Many if not all the unintended consequences can be designed out of the process if considered early enough and if the buildings are considered using a *whole house approach*, rather than singular elemental improvements, which tends to be the case currently. This *whole house approach* must include an assessment of the environmental factors, including weather and radon levels, to which the dwelling in question is exposed and devise solutions appropriate for these environmental factors (King, 2016).

Climate change impacts

Various studies have demonstrated that constant indoor temperatures achieved before, have been found to wildly fluctuate after, retrofit. This, combined with projected outdoor temperature increases due to climate change, means that overheating risk might increase significantly in retrofitted buildings in the future.

Adding insulation, as demonstrated in many of the studies outlined above, may introduce a higher risk to moisture accumulation and consequences such as mould growth and material decay. To investigate resilience to future moisture loads, three interior insulation assemblies (conforming to two U-value guidelines) were simulated in *DELPHIN* under reference, near-future (2040), and far-future climate (2080) scenarios. Calcium silicate, phenolic foam, and wood fibre assemblies were simulated. The reference year climate file was compiled from observed data and future files developed using the UK Climate Projections 2018 (UKCP18). Assemblies were evaluated for moisture accumulation, mould growth risk, and freeze-thaw risk. Results show low-to-medium risks in 2040 and high risks in 2080, assemblies of higher absorptivity and thinner insulation comparatively performing best. The calcium silicate assembly fared best for moisture performance; however, all assemblies will be subject to high moisture risk levels in the far future and responsible retrofits must take this and alternative design solutions into account (Lu *et al*., 2021).

In a retrofitted Victorian house in Birmingham, Huws and Jankovic found that overheating hours could be effectively limited to 3% of building occupied hours, under current climatic conditions, with appropriate window shading and ventilation. In comparison, in the future, this was limited only to 10% of the hours in 2050 and 22% in 2080. Without natural ventilation or solar protection, thermal mass cannot remedy reduced occupant comfort issues exacerbated by climate change. Additionally, the implementation of new solar protection features on historic façades is, in most cases, not conducive to the conservation of cultural heritage (Huws and Jankovic, 2013).

In Lee and Steemers' 2017 London-based study they completed an energy retrofit simulation case study of a typical terraced dwelling, under different climate scenarios. The simulation setup included four construction types, in this instance considering cavity not solid walls:

1. Unfilled cavity masonry/as built;
2. Insulated cavity masonry /refurbished;
3. Timber frame/uninsulated; and
4. Insulated timber frame/refurbished).

Two occupancy patterns, four window operation and two blind operation schedules under 21 sets of current and future climate scenarios. The operative temperatures for the summer season (May–September) of each scenario were then extracted and assessed for overheating. Their simulation results show that timber-frame construction performs worse than cavity masonry; but in future climates all four different construction typologies exhibited overheating. They note that significant improvements could be achieved via blind and window operations, but neither lowering the blinds nor four hours of evening ventilation (night purging) alone or combined would be enough to eliminate overheating altogether. That, they determine, can only be achieved with constant natural ventilation, which may not be practical or realistic due to security, noise, and privacy concerns. Indeed, they conclude that without natural ventilation or solar protection, the overheating exacerbating effect of insulation trump the potential ameliorative capacity of thermal mass (Lee and Steemers, 2017).

Pretelli and Fabbri (2016) introduced several concepts to describe the indoor microclimate of traditional buildings at different stages, which emphasises the changes in indoor climate due to both occupation and retrofit interventions. They acknowledge and define indoor environmental quality in older properties as *Historic Indoor Microclimates*, a product of the interaction between temperature and relative humidity, as well as other conditions such as air speed, radiation etc. They further subdivide *Historic Indoor Microclimates* into *Original Indoor Microclimate*, the original microclimate that existed when the building was first occupied; *Subsequent Indoor Microclimate*, the state that existed with variations to the building and its occupation; and *Actual Indoor Microclimates*, the contemporary microclimate, determined by the state of the building (and its use) in present times. They made these distinctions to inform approaches to building deterioration and occupant comfort, and better understand appropriate retrofit/refurbishment solutions. As part of this process, there must be an acknowledgement of changes in occupant expectations of comfort as well as decarbonisation approaches to controlling heating (and cooling).

What is clear from the literature, is that with the increase in the adoption of retrofit solutions to traditional residential buildings, occupants' thermal comfort needs to be carefully evaluated. Internal insulation is a standard solution in the energy retrofit of historic buildings (Milone *et al*., 2015; Ciulla *et al*., 2016 and Koci *et al,* 2015) and there is growing evidence that this has a damaging impact on the indoor environment to the detriment of both the building and its occupants.

There is still a need for further research to quantify the effect of climate change and to identify alternative retrofit solutions that prevent overheating and achieve thermal comfort both in the present and future scenarios. Research must address the impacts of climate change and retrofit on the passive climate regulation system of a dwelling, to optimise indoor comfort for future occupants. Despite this, current efforts to conserve older housing whilst meeting energy reduction targets, will most likely result in the continued widespread installation of internal wall insulation across Wales and the UK.

The relationship between indoor and outdoor temperature

Building envelopes are both directly impacted by external weather conditions, and internal heating and cooling loads. The purpose of the envelope is to protect against unwanted external exposure, such as wind, rain, excess sun, dust, noise, etc. yet to allow beneficial communication between the interior and exterior spaces via e.g., windows for fresh air and ventilation, natural daylight, and satisfying views. Several approaches can be used to both protect and enhance building envelope performance.

Indoor climatic conditions are the result of a complex interaction of numerous factors, including building geometry and envelope, heating, ventilation, air conditioning, occupation rates, occupant behaviours and external climate. Despite the complexity of indoor climate, there is a direct correlation between internal and external conditions that has been largely investigated and verified. For example, Coley and Kershaw (2010) explored changes in internal temperatures within the UK built environment as a response to climate change. Over 400 different combinations of future weather, architecture, ventilation strategy, ventilation type (natural, mechanical and buoyancy driven stack ventilation), thermal mass, glazing, *U*-value and building use (house, school, apartment, or office) were studied. The study, which was based on building simulations, included the dynamic representations of occupancy densities, solar gains, air densities, airflow, and heating systems. Despite the complexities of modelling heat flow, they ascertained a direct relationship between changes in internal and external temperature (fitting to a linear regression), with different constants of proportionality (steepness) depending on the building types. The authors describe this as a 'surprising' result, as it had been assumed, that, given the complexity of the heat flows within large structures, no simple relationship would exist, and this outcome had not been found in previous work (Coley and Kershaw, 2010).

Similarly, Tink *et al.* (2018) in their study of the overheating risk from retrofitted internal wall insultation in solid wall dwelling[15], found a linear relationship between outdoor running mean temperature and indoor daily mean temperature. Experiments were conducted in a pair of thermally matched, solid walled houses, located in the UK. One of the pair was retrofitted with internal wall insulation, while the other remained uninsulated; both houses were monitored for four weeks during the summer of 2015. Operative temperatures in the living room and main bedroom were observed to be higher in the internally insulated house in comparison to the uninsulated house. The houses were again monitored for a further three weeks with a simple overheating mitigation strategy applied consisting of night ventilation and shading using internal blinds. The data were normalised for variations in external weather conditions using a linear regression model, with the exponentially weighted outdoor running mean air temperature as the predictor variable of indoor operative temperature. The results showed that the mitigation strategy was effective at reducing the internal temperature in the internally insulated house to a level similar to that observed in the uninsulated house (Tink *et al*., 2018).

[15] Upgrading the thermal insultation of UK houses to improve wintertime energy efficiency raises concerns about potential summertime overheating risk.

In Nguyen *et al.*'s study of the relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity[16] in 16 homes in Greater Boston, Massachusetts, they found that indoor absolute humidity has a strong correlation with outdoor absolute humidity, whilst indoor and outdoor temperatures only correlated well at warmer outdoor temperatures. Results were similar for outdoor apparent temperature. The relationships were linear for relative humidity and apparent humidity. The correlation for relative humidity was modest. They concluded that whilst outdoor relative humidity can be considered a poor indicator of indoor relative humidity, indoor absolute humidity has a strong correlation with outdoor absolute humidity all year round (Nguyen *et al.*, 2014).

Indoor thermal comfort

Comfort is defined as the feeling of complete physical and mental well-being inside the building envelope (Nicol *et al.,* 2012). The most widely accepted definition of thermal comfort is that of a person's subjective judgement or evaluation that expresses satisfaction with one's immediate thermal environment (ASHRAE, 2013).

Indoor thermal comfort is highly influenced by six fundamental parameters (see Auliciems and Szokolay, 2007; Fanger , 1970; and Szokolay, 2014), namely:

- Four environmental variables:
    1. air temperature;
    2. mean radiant temperature;
    3. humidity; and
    4. air.
- Movements combined with two personal factors:
    5. Activity level; and
    6. Clothing of individuals.

Indeed, Humphrey (1974), found different comfort temperatures for different sorts of clothing.

[16] Apparent temperature is the temperature equivalent perceived by humans, caused by the combined effects of air temperature, relative humidity, and wind speed. The key difference between absolute and relative humidity is that absolute humidity is a fraction, while relative humidity is a percentage. Furthermore, absolute humidity is a measure of water vapour in the air regardless of temperature, while relative humidity is a measure of water vapour measured relative to the temperature of the air.

Thermal comfort differs between the genders; and specifically, females feel the cold more readily than males (e.g., Karjalainen, 2012). However, research has not only confirmed a difference in how men and women experience comfort, but that age will play a role with the elderly and young most vulnerable. Elderly people are undoubtedly more susceptible to thermal conditions, be they extremes of heat or coolth, which can ultimately lead to mortality (and happens more quickly in the case of extreme heat); whilst studies performed by Singh *et al.* (2019), Lee *et al.* (2012), Teli *et al.* (2014), and Hwang *et al.* (2009) reveal that children are more vulnerable to high temperatures, and consequently children favour cooler thermal conditions.

Although spring and autumn are not commonly considered to be times in the year with overheating risks, it should be noted that according to the adaptive response method (EN 15251, 2007), occupants are much more likely to be sensitive to higher temperatures during colder periods. The above indicates that overheating issues can also occur during these periods.

Adaptive comfort

Adaptive comfort is based on the principle that if there is a change in the thermal environment that produces discomfort, people react in ways that tends to restore them to personal comfort (Humphreys and Nicol, 1998). It is believed that people are not the passive receiver of thermal stimuli but rather are an active component of a dynamic system of people, their social and physical environments. Behavioural adjustment are adaptive actions that a person makes consciously or unconsciously to attain thermal comfort, by changing his or her body's heat balance. Behavioural adjustment can be classified as:

1. Personal adjustments e.g., modifying activity and posture, removing items of clothing, moving to different locations;
2. Technological adjustments e.g., modifying the environment or surroundings by opening/closing windows or shades, controlling fans, or turning on/off air conditioning systems; and
3. Cultural adjustments e.g., taking a nap in the heat of the day, schedule adjustments, adapting the dress code (Brager and de Dear, 1998).

Future climate risks have been investigated in multiple European locations, employing an adaptive comfort approach for naturally ventilated buildings (Brotas and Nicol, 2015), whilst Jenkins *et al.* (2014) developed a probabilistic tool for assessing future climate overheating risk for domestic buildings in the UK, aimed at providing guidance for designing buildings, or retrofitting existing buildings, so that they could provide adequate thermal comfort for a future climate, where occupants are actively engaged in controlling their own environments.

Indeed, based on previous research, it is widely recognised that people who have a level of control over their immediate situation, are more tolerant of their environmental conditions. Certainly, people are more forgiving of discomfort if they have some control over alleviating it (e.g., see Leaman and Bordass, 1999; Kwon *et al.,* 2019). Remarkably, many modern buildings take away that personal control. To regulate or reduce energy consumption, they are designed to take control from occupants and place that control in the hands of an automated system, one that regulates indoor environment conditions, and denies occupant intervention.

Thermal comfort during the winter

It is important to acknowledge that cold homes due to fuel poverty have been identified as a public health issue requiring policy interventions e.g., *see* Poortinga *et al.* (2018) and Camprubi *et al.* (2016). Camprubi *et al.* (2016) found that despite the expected benefits of energy efficient interventions, certain social groups (e.g., low-income, renters, elderly), those who suffer most from fuel poverty, experience more barriers to accessing/enabling building retrofit. To avoid exacerbating these inequalities and their impact on health equity, energy efficiency policies should pay careful attention to issues of affordability, lack of incentives and residents' needs and preferences. Camprubi *et al.* (2016) highlight the need for coordinated policy and education and suggest the introduction of health-related eligibility criteria for accessing fuel-poverty grants in privately owned homes, with priority given to those suffering from chronic conditions that may be exacerbated by living in cold housing. Poortinga *et al.* (2018) also argue the benefits of energy efficiency improvements for low income, fuel-poor households, for both improved indoor temperatures and reduced fuel consumption. They studied a range of interventions, external wall insulation, new windows and doors, new boilers, or heating system, with control properties for comparison, from across five locations in Wales and overall found the introduction of external wall insulation to be the most effective. However, all interventions raised indoor air temperature, and although the increase was mostly relatively small (1-1.5°C), it was found to be enough to reduce the potential for exposure to substandard temperatures and bring most indoor temperatures within the 'healthy' comfort zone of 18-24°C.

Thermal comfort during the summer

The projected rise in both average and extreme temperatures in the future will make buildings more uncomfortable to live in and potentially dangerous for occupant health as a consequence of the higher internal temperatures in poorly ventilated environments (Hamdy *et al*., 2003). To date, in Wales, strategies for keeping dwellings cool has not been considered a priority. However, as temperatures continue to rise, the number of cooling degree days will increase[17], and consequently the need for cooling strategies will increase too. D'Ippoliti *et al.* (2010) 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. Climate change predictions for Europe show an increase in the frequency and the intensity of heat waves, and as consequence heat-related mortality will become a relevant threat even in areas usually not exposed to extreme hot temperatures. 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 (D'Ippoliti *et al.,* 2010). Mavrogianni *et al.* (2010) undertook a pilot monitoring study of 36 London dwellings during the summer of 2009. Their results show that at night, 42% of the bedrooms failed the CIBSE overheating criteria, a large proportion of which were in purpose-built flats. In addition, it is likely 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. Subsequently Beizaee *et al.* (2013), undertook one of the first national scale studies of summertime temperatures in English dwellings, during one of the coolest English summers of the last decade. They found a large proportion of living rooms and bedrooms had more than 5% of their occupied hours above the CIBSE recommended temperature thresholds of 25°C and 24 °C respectively. Moreover, a significant number of bedrooms exceeded more than 1% of occupied hours above the 26°C threshold. The incident of warm bedrooms is even more striking when considering only the post 1990 dwellings and flats; where 80% and 74% of the bedrooms respectively, exceeded the 5% (24 °C) threshold, with 55% and 32% respectively also exceeding 1% (26 °). From their sample of 193 dwellings, they found that the oldest of the dwellings (pre-1919), solid wall houses and detached homes were significantly cooler than more modern homes, homes with cavity wall construction and homes of other built-form types.

Peacock *et al.* (2010) Investigated the potential of overheating in UK dwellings due to existing climate change. They used dynamic simulation with defined domestic building variants to investigate internal

[17] When the temperature mean is above 18°C (65°F), subtract 18 (or 65) from the mean, and the result is the number of Cooling Degree Days.

temperatures of UK dwellings. Factors such as a warming climate and varying internal heat gains were estimated to examine whether UK domestic buildings were prone to overheating in the future, and therefore could require mechanical air conditioning. The study suggests that the ability, or inability, of the occupant to adapt to bedroom temperature is paramount in the understanding of the conditions for overheating. While this is difficult to quantify (and a range of comfort temperatures are proposed), the effect of changing the building construction and geographical location can result in significantly different thermal conditions. As might be expected, the problem appears most noticeable for buildings in the south of the UK and with lightweight constructions. Even with a window-opening schedule applied to such a scenario (night purging), the average internal temperature is simulated as being over 28C for almost 12% of the year. A different metric, defined as *cooling nights*, suggests that there might be a cooling problem in bedroom areas for approximately a third of the year. In the North of the UK, and for solid wall dwellings, this problem diminishes significantly. The authors suggest that, If the behavioural response of UK householders to a warming climate is akin to that of relationships found in the USA, then they forecast that 18% of homes in the South of England will have installed domestic air conditioning systems by 2030. This would suggest that 'surviving' climate change will pass through a tipping-point in the next two decades creating a domestic cooling season. Whilst the deployment of domestic air conditioning may not represent a step change in domestic energy consumption, the extension of controlled climates to the domestic sector may prompt behaviour that is more likely to accentuate rather than ameliorate energy consuming behaviour (Peacock *et al.,* 2010).

Ventilation and cooling strategies

Commonly people will only open windows, and therefore create air movement, to either cool indoor temperatures or enhance the air quality of their indoor environment. Certainly, traditionally window (and door) opening has been the only mechanism for managing household cooling. Although this has changed in recent years, window opening as a form of natural or passive ventilation still dominates. However, as determined by Andersen *et al.* (2013), who studied passive ventilation in 15 residential buildings in Denmark, window opening will become less effective in the future due to warmer summers, and consequently additional measures must be considered.

Passive (natural) cooling effects combining thermal mass and natural ventilation, especially night ventilation (night purging through windows), can still, in some instances, remove excess heat to maintain a comfortable temperature during summer. However, this passive cooling technique relies heavily on a building's thermal mass and is therefore more successful in buildings of traditional construction with solid stone walls. Additionally, success depends on the outdoor temperature daily swing (e.g., *see* Shaviv *et al.,* 2001), solar radiation, and, ultimately, user behaviour, as it has to be appropriately managed. In urban areas where the heat island effect dominates, but where issues around climate and safety are more prevalent, security and overnight aperture opening need to be a consideration.

Table 4 outlines perceived passive or natural ventilation strategies than can be adopted to reduce overheating. Passive strategies will not be able to fully eliminate the increasing risk of overheating in the future. In this context, active cooling may become necessary to maintain thermal comfort and even to safeguard life. This is in line with other research studies (e.g., Dodoo and Gustavsson, 2016; Tettey *et al.,* 2017; Ascione *et al.,* 2015; Pisello, 2015; Gourlis and Kovacic, 2017), indicating the advantages of a series of control cooling strategies that progress from airing and solar shading through to the need for mechanical cooling with stand-alone room air conditioners.

Table 4: Adaptation measures to reduce building overheating
(*adapted from* Vardoulakis *et al.,* 2015)

Aim	Adaptation measure	Impact on built environment
Minimise outside solar gains	Management of the external microclimate e.g., planting trees	Reduce external temperatures and improves shading
	Construct cool paving using additives to reflect solar radiation	Reduce external temperatures
	Create green roofs	Reduce the roof temperature by absorbing heat into their thermal mass and due to evaporation of moisture, as long as they do not dry out
		Roof structure may need to be modified to improve stability and water tightness
		Plants need to be carefully selected to avoid risks related to aeroallergens (pollen)
Minimise internal solar gains	Paint external walls a light colour to increase their reflectivity	Particularly effective for dwellings with solid external walls and larger external wall areas (e.g., end-terraced house).
		Painted walls need to be kept clean.
	Install external shutters	Improves solar shading (but potentially problematic in terms of cleaning and maintenance)
		Increases security
		More effective than internal blinds or curtains, as solar radiation, already passed through the windows before being absorbed by the blinds or curtains, is transmitted to the room as heat
	Install external awnings for south and west facing windows	Benefits rooms that tend to be heavily occupied during the daytime (e.g., kitchens, living rooms)
	Install double glazing and glazing with low-e coatings	Reduces heat gain in summer as well as heat loss in winter
	Install low e-triple glazing or specialist low SHGC (or g-value) glazing	Control solar energy by reducing visible transmittance, which would affect daylight levels all year round

Manage internal heat	Increase thermal mass on floors and/or walls in combination with adequate night cooling (purge ventilation, combined with fans):	Effective but the location of thermal mass (floors and/or walls) is a highly sensitive issue: If misplaced or misused, thermal mass has the potential to increase hours of overheating and/or increase space heating energy.
	External wall insulation	Keep homes cool in the summer and increase winter heating efficiency
		Reduce heat loss through the building fabric at night; but must ventilate at night
	Internal wall insulation	Reduce heat loss in summer (may not be possible for certain building typologies)
	Internal roof insulation	Very effective for top floor flats, less effective for houses with pitched roofs containing loft insulation
	Loft insulation	Little effect on overheating reduction
	Replace carpets with wooden floors or tiles to expose the cooling effect of the ground	Increase heat loss in summer, but colder homes in winter, particularly with tiles
	Reduce lighting and other electrical gains	Control internal heat
		Reduce energy consumption
Manage ventilation	Increase natural ventilation at night	Increase heat loss in summer and provide a cooling benefit during the daytime (check security issues)
	Install ceiling fans in each room	Better circulation of air and reduced indoor temperatures
	Open windows during peak daytime hours (with daytime occupancy)	Not always effective, e.g., good for end-terraced houses; not for top floor flats
		Safety/security issues as well as noise need to be considered.
		Open windows in the early morning if temperatures are low, and shut them if the outdoor temperature rises above indoor temperature during daytime
	Open windows at a lower set point	
	Air conditioning	Provide cooling comfort but increase CO_2 emissions
		Increase outdoor temperatures in built up areas

Active (mechanical) cooling using domestic air conditioning units or heat pumps tend to be expensive to run, both environmentally and financially; and consequently, provide a short-term solution; whilst ceiling or free-standing fans are less effective. However, fans may not always be enough to cool the occupant as they only provide a cooling sensation, the movement of air increases the comfort limit by 3 °C for an air speed of 0.9 m/s (E.N. CEN, 2007), rather than reducing the air temperature. The feeling of thermal comfort is therefore ensured at higher temperatures. In addition, during the winter fans can work in the opposite direction and transfer /circulate warm (energy generated) hotter air that has risen towards the ceiling.

Shading systems can be integrated in the building envelope for sun protection and can be used by occupants to control solar gains. Indeed, appropriate sun protection for glazed surfaces is essential to ensure both thermal comfort during summer months, as well as daylight control throughout the year. Moreover, shading systems can enhance thermal and sound insulation. According to the literature, appropriate sun protection for south-facing openings can be achieved by horizontal shutters or blinds, with recommendations for vertical blinds, awnings, or similar, for east and west orientated openings (Heracleous, 2021). There are many approaches to shading (exterior, interior, inter-pane or integrated), some of which may be permanent fixtures (e.g. horizontal overhangs, fixed blinds, lighting shelves), whilst others are removeable, including reclining shading systems that can be completely removed from the opening (e.g. outer opening leaves, awnings, Venetian blinds), and adjustable shading systems that cover part of an opening and can be adjusted, for example, blinds or canopies that can rotate, slide, etc. The benefits of what can be a simple intervention should not be underestimated. For example, Baborska-Naroznya and Grudzinska (2016) looked at overheating in a high-rise retrofit apartment block in Leeds and established that overheating might have been avoided if shading measures such as blinds had been introduced to prevent excessive solar heat gains. Shading along with window opening are the first defence against internal heat gains.

Vegetation is an excellent yet frequently unrealistic solution to the reduction of temperatures surrounding buildings. Plants have a relatively high rate of solar absorption; however, they do not overheat, as they use solar radiation as an energy source to convert carbon dioxide into sugar. Therefore, the surface temperature of vegetation is much lower than that of building materials (Irmak *et al.,* 2017; EPA, 2020). Consequently, appropriate vegetation can be used for both sun protection during the cooling period and to exploit solar gains during the heating period. Vegetation can block, filter, and divert air flow, thus impacting the natural ventilation of adjacent buildings. For example, evergreen trees, planted facing the direction of prevailing winds, can be used as barriers to airflow, deflecting some of the unwanted cold winds. During the summer, vegetation ensures a reduction in the temperature of the winds passing through the foliage (due to evaporation and perspiration), improving the indoor comfort conditions through natural ventilation. Vegetation adjacent to a building, can result in significant solar radiation reduction, by decreasing surface soil temperatures during the day. Deciduous vegetation can protect a building façade from solar radiation during the summer months whilst allowing the building to exploit solar gains during the winter. On the south side of the building, the planting of deciduous trees contributes to the shading of the openings in the lower floors. However, the use of an artificial sun protection system is dictated by the large angles of solar altitude that characterize the south orientation during the summer months. On the east and west sides of the building, planting deciduous trees can greatly contribute to shading, given the low angles that characterize the sun in the morning and afternoon, making vegetation a measure of sun protection in the east and west facades. The shading achieved depends to a large extent on the geometric characteristics of the trees (height, diameter, and crown shape), the distance from the facades of the building and the distances between the trees (Heracleous, 2021). It is recognised that this is more of a strategy for urban design and strategic planning than the individual household.

The use of the water to achieve cooling by evaporation, cool paving, and the use of appropriate coating materials to reduce surface temperatures, including light-reflecting paints, are a number of other cooling strategies referenced in the literature and summarised in Table 4.

An effective ventilation strategy coupled with insultation measures[18], could be the difference between occupant comfort and discomfort. Barbosa *et al.* developed a vulnerability framework and methodology for the assessment of thermal comfort in 1960s dwellings in Lisbon, Portugal. The methodology also considered the possibility of variants both in occupancy and the physical characteristics of dwellings. An important finding of this study was that, while thermal comfort vulnerability can be found and quantified in relative terms, both optimal ventilation (which also considers night ventilation in bedrooms but disregards potential constraints such as safety or privacy) and insulation measures appear to lead to a decrease in internal temperatures. Indeed, by improving the ventilation plan, the researchers found that discomfort hours would be cut from 53% to 7% in 2080 in a living room. Consequently, it is possible to reduce vulnerability significantly, although not totally, in the occurrence of extreme events. The authors recommend increasing insulation as an option, not only for potential energy-saving reasons, but also for the adaptive capacity it may provide. Therefore, they propose that it is important to consider the benefit of insulation for the cooling season, in addition to the impact of such retrofit options for winter thermal performance (Barbosa *et al.* 2015). Interestingly, overheating in UK passive-house standard social housing was explored by Sameni *et al.* (2015) where 72% of all monitored flats failed their designed criteria due to overheating; and the future performance of this stock researched by McLeod *et al.* (2013), who determined that by optimizing a small number of design inputs, including glazing ratios and external shading devices, can play a significant role in mitigating future overheating risks.

Indeed, although some individual passive strategies reduce heating and cooling degree hours significantly, combined strategies may prove to be more effective solutions. For example, Gupta and Gregg (2013) report that adaptation measures implemented at the same time as energy efficiency measures, can significantly reduce the risk of overheating. Minimising the effect of direct or indirect

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[18] Enhancing the thermal properties of building envelopes through additional insulation has been well documented. Adding insulation aims to improve overall thermal comfort by reducing heat losses to the external environment during the winter, whilst theoretically, they also minimise external heat gains during the cooler, warmer summer months.

solar radiation into the home (fabric changes) and limiting or controlling heat within the building (e.g., reduced internal gains or managing heat with thermal mass and ventilation) tend to be most effective. External shading is effective for reducing overheating in homes. This shading can take many forms, but for optimal seasonal effectiveness (i.e., not reducing winter solar gain) it is suggested that shading elements be user operated. This could potentially require a new level of occupant interaction with the home. External insulation is the most effective insulation for reducing overheating risk. Internal insulation, on the other hand, is least effective in reducing overheating and is projected in most cases to lead to more overheating. A fabric-based future-proofing approach comprising both mitigation and adaptation measures (i.e., wall, roof, and floor insulation, shading with shutters and high albedo surfaces) is recommended for the large-scale refurbishment of existing housing.

Gupta and Gregg (2013) assessed the overheating risk and evaluated the possibility of preventing overheating using adaptation packages through dynamic thermal simulation in six suburban house archetypes in three cities in the UK, namely Bristol, Oxford, and Stockport. Results showed that although the UK is perceived to remain a heating-dominated climate, adaptive measures to reduce the risk of future overheating at a house level need to be introduced as a matter of some urgency. High-risk property characteristics are revealed through the dynamic thermal simulation (Table 5).

Table 5: High-risk property characteristics (*After* Gupta and Gregg, 2013)

Characteristic	**Overheating risk**
Built Form	❖ Flats are at highest risk ❖ mid-terrace homes, second highest
Fabric Characteristics	❖ Internally insulated homes ❖ Homes with dark-coloured facades ❖ Home with large, exposed areas of glazing
Orientation and Exposure	❖ Homes with east or west orientation ❖ Homes on streets with less tree cover are especially problematic for daytime occupied dwellings. ❖ South-facing rooms can also experience overheating but are easier to shade from the high angle summer sun
Occupancy and Behaviour	❖ An occupant who stays at home all day will experience more overheating than an occupant who is not. ❖ With certain adaptations that depend on user control, e.g., opening windows for ventilation and adjusting shading elements. ❖ The immobile and highly vulnerable will likely have more difficulty avoiding overheated conditions.
Limited Ventilation	❖ Where noise and security issues may discourage the use of window opening for cooling.

Elsewhere, Escandon *et al.* (2019), investigating the impact of climate change on thermal comfort in social housing stock in southern Spain, found that discomfort hours will increase by 35% by 2050. They conclude that future climate projections (particularly those relating to thermal behaviour) should be used to inform energy retrofitting decision-making. Meanwhile, Heracleous *et al* (2021) have demonstrated the impact of climate change on the energy performance (of educational buildings in Cyprus) and associated thermal comfort. The results of this study, which included dynamic simulation software modelling with future climate scenarios, demonstrate the need to plan timely retrofitting actions to mitigate the predicted effect of climate change on building performance and occupant health. Indeed, the impact of climate change is expected to further aggravate the overheating risk and thus the discomfort of building occupants if no action is taken; and many studies (Yang and Lam, 2012; Moazami *et al.,* 2019; Pilli-Sihvola *et al.,* 2010; Cartalis *et al.,* 2001; Mirasgedis *et al.,* 2007; Aguiar *et al.,* 2002; Asimakopoulos *et al.,* 2012; Wang *et al.,* 2010; Hosseini *et al.,* 2018) 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 cooling degree days.

Managing the indoor environment of historic buildings

The impact of climate change on the indoor environment of historic buildings across Europe has been extensively studied, to ensure the integrity of building interiors and objects contained within (e.g., The Netherlands and Belgium (Huijbregts *et al.,* 2012), Southern England (Lankester and Brimblecombe, 2012), Croatia (Rajcic *et al.,* 2018). Consistently, these studies demonstrate that across Europe there will be an increase in indoor temperature. However, studies show that the change in indoor relative humidity differs depending on the location, where previous studies have shown it rising in the Netherlands, Belgium, and Croatia, but with little change in Southern England. These variations impact on predicted damage. Rajcic *et al.* (2018) modelled climate change impacts on a wooden chapel in Croatia. Future indoor climate data was assessed for possible risks of biological, mechanical, and chemical damage to painted wooden panels. An increase of mechanical damage as well as biological damage from insects was reported. Huijbregts e*t al.* (2012) in their study of two historic museum buildings in The Netherlands and Belgium, found that expected climate change considerably increases both indoor temperature and relative humidity. However, of these two factors, the rising relative humidity is believed to potentially have the highest impact on indoor environmental quality, as it is expected to result in increased mould growth (but not mechanical degradation). The UK-based study undertaken by Lankester and Brimblecombe (2012) predicts future indoor temperature and humidity, and damage arising from changes to climate in historic rooms in Southern England with little climate control, using simple building simulations coupled with high resolution climate predictions. The calculations suggest an increase in indoor temperature over the next century that is slightly less than that outdoors. Annual relative humidity shows little change, but the seasonal cycles suggest drier summers and slightly damper winters indoors. Damage from mould growth and pests is likely to increase in the future, while humidity driven dimensional change to materials (e.g., wood) should decrease somewhat. The authors reflect that future temperature is predicted with a fair degree of reliability, as is specific humidity, but relative humidity which, combines both these parameters, is less reliably predicted so errors need more attention in future research.

Table 6: Passive measures that reduce temperatures in overheated conditions in buildings
(Adapted from Gupta and Gregg, 2013)

PASSIVE MEASURES	HOT, ARID CLIMATES	HOT, HUMID CLIMATES	UK CLIMATE	*IES-TESTED UK DWELLING
PERSONAL/BEHAVIOURAL				
Remove clothing	Behavioural measures known to be effective in reducing the risk of heat related stress or worse (NHS, 2012).			
Increase hydration				
Use water to assist the skin with thermo-regulation				
Seek a cool refuge outside of the dwelling				
PHYSICAL /BUILT ENVIRONMENT				
Daytime cross-ventilation (window opening)	At times the air can be so hot that daytime ventilation is not beneficial	Not effective	Effective	Assumption built-in to modelling
Night ventilation (window opening)	Effective	Effective (dehumidification required at times)	Effective	Assumption built-in to modelling
Reduced internal gains (using heat-generating appliance early morning/late evening or moving activities outdoors where possible)	Not effective	Not effective	Effective	Effective
Shading Trees or deciduous vegetation	Effective	Effective	Effective	
External shading devices, e.g. louvers, fixed horizontal and vertical, porches, and awnings	Effective	Effective	Effective	Effective
Internal shading devices, e.g. curtains and blinds			Effective	
External wall insulation			Effective	Effective
Loft insulation			Effective	Effective
Decreased floor insulation (limited to the perimeter)		Effective		
Solar selective low-e glazing			Effective	
High albedo surfaces	Greater impact in hot, arid climates	Effective	Effective	Effective
Thermal mass	Effective	Effectiveness dependent on ability to night-ventilate		
Passive ground cooling		Effective		
Passive downdraught evaporative cooling – (e**ncouraging the convection of air downwards)**	**Effective**			
Enclosed courtyard	Effective	Effective		

*Note IES – Integrated Environmental Solutions - provide software aimed at improving the environmental performance of buildings.

These studies, with their focus on cultural heritage and museum collections, have concentrated on the impact climate change could have on the indoor environment (materiality, artifacts, and objects) rather than on indoor environmental quality for building occupants. The increase in indoor temperature could cause both a rise in the degradation of materials, but importantly for this study, a decline in thermal comfort and indoor air quality. *It should be noted that studies on future thermal comfort are still very limited in traditional buildings even though the passive cooling effect of thick walls and ventilation could fail to compensate for a future temperature rise.*

Indoor Environmental Quality

Proper and adequate 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 (see Table 7).

Table 7: **Adaptation measures to improve indoor environmental quality**
(*Adapted from* Vardoulakis *et al.,* 2015)

Aim	Adaptation measure	Impact on indoor air quality
Manage ventilation	Keep rooms well ventilated, especially high-moisture spaces such as bathrooms and kitchens	Prevent the build-up of relative humidity, which can cause damp and mould.
	Optimum location of ventilation inlets (away from outdoor pollution sources)	Minimise the ingress of outdoor air pollutants into the indoor environment.
	Increased airtightness in combination with mechanical ventilation (Mechanical Ventilation with Heat Recovery systems (MVHR))	Prevent ingress of outdoor air pollutants
		Remove indoor air pollutants generated from indoor sources (as long as MVHR systems are properly installed, operated and maintained)
	Air filtering in mechanical ventilation systems	Partial removal of allergens, particles and ozone
Remove sources of indoor contaminants	Appliances, flues, and chimneys correctly installed and serviced by registered engineers	A reduction of indoor concentrations of combustion products (CO and NO_2)
	Keep rooms well ventilated while using an appliance and do not block chimneys, flues, or air vents	
	Fit an audible CO alarm that meets European Standards (EN 50291)	
	Use furnishing, DIY, construction, and consumer products with low VOC emissions.	Reduce VOC emissions from building materials and consumer products

Sources of air pollution

Over the past 30 years, researchers have attempted to understand the interaction between the different contributors to poor indoor air quality, but very little is understood of the inter-relationship between indoor air quality, energy use and energy efficiency of buildings, indoor pollutants, and outdoor air quality (Kwot, 2016; Sarka and Gabriel, 2013; Tham, 2016; Spiru and Simona, 2017). However, it is understood that inadequate ventilation is a primary cause of indoor air pollution and is why pollutants rise in homes during the winter (Yang *et al.,* 2017).

There are numerous sources of indoor air pollution, and these have been summarised in Table 8. The concentrations of some indoor pollutants increase significantly overnight, while outdoor pollutants concentrations have reduced, so night-time ventilation is recommended, i.e., during periods when outdoor air is less polluted. Indoor air quality varies seasonally and spatially and consequently is influenced by the seasons, outdoor environment, heating, and ventilation systems type, and building characteristics. It is important to recognise that although ventilation is very important, in some cases it may not provide the desired effects, such as in areas with high outdoor pollution, and cannot prevent the introduction of pollutants into buildings such as volatile organic compounds (VOC's) present in everyday products.

In recent years attention has focused on outdoor air pollution in urban area, and consequently people tend to believe that they are safer indoors, assuming that the air they breathe is cleaner (Xinying *et al.*, 2015; Otto *et al.,* 2017).

Certainly, outdoor air pollution remains an important determinant of residential indoor air pollution (Meier *et al.,* 2015). For example, it has been observed that the type of windows and the frequency of their opening will affect the degree of infiltration of outdoor pollutants into the indoor environment. (Spiru and Simona, 2017). However, in urban and industrial areas, a lack of air exchange or extraction and high levels of humidity can increase the concentration of pollutants inside. Other sources include gases from cooking and heating, chemicals from candles and household cleaning products, mould and mildew and a host of toxins from building materials (Xueyan *et al.,* 2015). How we heat our buildings also has an impact on indoor air quality especially when high volatile content solid fuels are burnt; and this pollution is exacerbated by poor ventilation. Indeed, the Environmental Protection Agency states that the air inside homes and other buildings is more polluted than outdoor air, and can cause major health problems (EPA, 2021).

Table 8: Overview of the sources of outdoor and indoor air pollutants and their impacts on housing occupants
(Adapted from Vardoulakis *et al.,* 2015; with data from:
ATSDR, 2019, AQEG, 2020; DEFRA, n.d.; McGrath et al., 2021; Welsh Government, 2020c)

Sources	Outdoor sources	Indoor sources	Impacts	Additional notes
Combustion products (NO_2 and CO)	Local traffic Other combustion sources	Open fires Tobacco smoking Fossil fuel Biomass fuelled cooking Biomass fuelled heating appliances	❖ Concentrations of NO_2 may lead to respiratory symptoms/lung function (e.g., wheeze) ❖ NO_2 health effects are more common in females than males (which could be attributed to women spending more time indoors) ❖ CO can cause accidental poisoning in occupants, with varying health effects from headache and dizziness, nausea and sickness to coma and death. ❖ high peaks of CO (> 100 mg/m^3) can occur with malfunctioning or inappropriately used flued and un-flued domestic appliances (boilers, heaters, fires, stoves, and ovens), which burn carbon containing fuels (coal, coke, gas, kerosene, and wood)	❖ Indoor levels of nitrogen dioxide (NO_2) and CO are influenced by indoor sources, ventilation conditions, occupancy (with larger households generally having higher pollutant levels) and location (with highest values in towns and lower levels in suburban and rural areas) ❖ Children with asthma or infants who are at risk of developing asthma are more sensitive to the respiratory effects of indoor NO_2 exposure. ❖ Increasing airtightness of dwellings may increase concentrations of CO to levels that could cause poisoning or lead to chronic exposure with subclinical adverse health effects.
Particulate matter (PM)	Road transport Industry Construction Resuspended dust particles (biological origin) Domestic solid fuel burning Natural sources (e.g., sea salt, dusts, and biogenic emissions) Secondary PM precursor emissions Imported transboundary emissions (primary and secondary PM) and international shipping	Wood burning Cooking /cleaning activities Tobacco smoke Secondary particles (indoor air chemistry	❖ PM generated from indoor combustion processes has been associated with increased respiratory illness (wheezing, cough, including asthma) and Chronic obstructive pulmonary disease (COPD) ❖ Indoor air chemistry products, especially those of ozonolysis of terpenes (limonene and a-pinene) emitted from cleaning products, include fine and ultrafine particles (UFPs), which may cause irritation of the eyes and upper airways at high ozone and terpene indoor concentrations ❖ Exposure to passive smoke has been associated with higher risk of coronary artery diseases, lung cancer, respiratory diseases, and stroke ❖ the effect of simultaneous exposure to dust (i.e., total suspended particles) and ozone at relatively high concentrations is larger than the effect of these two pollutants individually in indoor environments ❖ There are some specific components of indoor mineral dust particles (e.g., boron, metals, and soil minerals) that are classified as human carcinogenic or toxic to reproduction	❖ Exposure to indoor damp will increase both the risk and severity of wheezing illness, exacerbated by Indoor pollutants. ❖ Increasing airtightness of dwellings may increase concentrations of CO to levels that could cause poisoning or lead to chronic exposure with subclinical adverse health effects. ❖ There is also some limited evidence that the effect of simultaneous exposure to dust (i.e., total suspended particles) and ozone at relatively high concentrations is larger than the effect of these two pollutants individually in indoor environments
Volatile organic compounds (VOCs) Formaldehyde Benzene Other aromatic		Building materials Furniture Carpets Paints Consumer products (including cleaning products, air fresheners, etc.)	❖ Irritation to the eyes or nose, headaches, dizziness, nausea, and allergic reactions ❖ Some VOCs are carcinogenic, e.g., formaldehyde and benzene ❖ There is evidence suggesting a link between VOCs emitted from consumer products and an increased risk of certain symptoms, such as wheezing, vomiting, diarrhoea and headache among infants and their mothers	❖ Exposure to indoor damp will increase both the risk and severity of wheezing illness, exacerbated by Indoor pollutants. ❖ Increased airtightness in the absence of adequate mechanical ventilation may increase indoor VOC levels ❖ Higher indoor temperatures will lead to greater volatile emissions of VOCs, from household products and materials leading to higher indoor concentrations, although enhanced natural ventilation (e.g., opening of windows) may

hydrocarbons		Tobacco smoke and other combustion sources	❖ Frequent use of domestic consumer products in the prenatal period has been associated with persistent wheezing in young children	balance higher indoor volatile emissions during summer
Persistent organic pollutants		Polychlorinated biphenyls (PCBs) e.g., used as electrical insulator or coolant Polybrominated diphenyl ethers (PBDEs) e.g., flame retardants Perfluorooctane sulfonate (PFOS) e.g., stain resistance	❖ Cancer ❖ Immunosuppression ❖ Metabolic disorders ❖ Neurobehavioural disorders ❖ Endocrine disorders ❖ Reproductive disorders	❖ Higher indoor temperatures will lead to greater volatile emissions of POPs from household products and materials leading to higher indoor concentrations, although enhanced natural ventilation (e.g. opening of windows) may balance higher indoor volatile emissions during summer ❖ Increased use of thermal wall insulation in houses may increase indoor contamination with flame retardants, such as hexabromocyclodecane (HBCD) used in insulation materials. ❖ Exposure to indoor damp will increase both the risk and severity of wheezing illness, exacerbated by Indoor pollutants.
Radon	Radon is a naturally occurring radioactive gas, emitted from rocks and soils, which can enter buildings and reach high indoor concentrations	Most radon enters buildings with soil gas that is drawn in by the slightly lower air pressure indoors (caused mainly by heating and ventilation)	❖ Lung cancer (greater incidence with smokers) ❖ Respiratory illnesses such as asthma, bronchitis, and pneumonia	❖ Poorly ventilated retrofits can double radon retrofit risk ❖ Ventilation is the most effective mechanism of radon removal from indoor air as low ventilation rates can cause a build-up of radon gas in properties ❖ Exposure to indoor damp will increase both the risk and severity of wheezing illness, exacerbated by Indoor pollutants.
Ozone	High outdoor ozone levels have been observed during heatwaves in the UK Ozone is higher near the top of urban canyons compared with street-level concentrations	Printers Photocopiers Electronic appliance	❖ Reduced lung function ❖ Exacerbation of chronic respiratory illness	❖ Buildings offer protection from ozone, due to a combination of envelope filtration, deposition on internal surfaces and reaction with gas-phase indoor compounds ❖ Increased indoor concentrations of ozone could result in higher levels of formaldehyde and UFPs through chemical reactions (although ozone is removed rapidly in the indoor environment by deposition on surfaces and by gas-phase reactions) ❖ Warmer summer temperatures may result in occupants opening more often their windows in naturally ventilated houses during periods of high outdoor ozone levels ❖ The overall impact of potentially higher ambient concentrations, the increased airtightness in new built houses, and any changes in ozone-initiated chemical reactions on indoor ozone levels is uncertain and needs further investigation ❖ There is also some limited evidence that the effect of simultaneous exposure to dust (i.e., total suspended particles) and ozone at relatively high concentrations is larger than the effect of these two pollutants individually in indoor environments

Indoor air quality and energy efficiency

Indoor air quality has gained increasing scientific attention due to the awareness that in developed societies, people spend on average more than 90% of their time indoors (Katsoyiannis and Bogdal, 2012). A lifestyle involving the continuous consumption of new products and repeated renovation of building interiors, has increased occupant exposure to indoor-derived pollutants. The large number of indoor sources of air pollutants and their close proximity to exposed inhabitants makes the study of indoor air quality even more imperative. Smith (1988) underlined the importance of understanding indoor pollution sources and introduced the "Rule of 1000", which suggests that the release of a gram of a compound into indoor air has the same exposure effect as the release of a kilogram of the same compound into ambient air. Indoor and ambient air are characterised by different pollution patterns, but it is well documented that ambient air pollution influences the indoor air quality and vice versa (Katsoyiannis and Bogdal, 2012).

Researchers have identified that the recent focus on energy-efficiency in housing has resulted in retrofit solutions, such as increased insulation, that do not always allow outside air to infiltrate (Moreau-Guigon *et al.,* 2016). As a consequence, indoor pesticides, cleansers, paints and varnishes and air fresheners, distribute toxins throughout the home that are in effect trapped. Although some indoor air pollutants have been present for years, they were largely lower in concentration, due to dilution with outside air infiltration into the house, and therefore the problem wasn't as prominent or pressing as it is now. Although reducing energy demand for heating and cooling is essential for improving the energy efficiency of a building, modern technology frequently re-circulates the air instead of refreshing it, which leads to reduced air quality (Spiru and Simona, 2017). Consequently, whilst poor indoor ventilation can reduce the infiltration of pollutants from the outside, it can also increase the concentrations of indoor pollutant (Spiru and Simona, 2017), so reducing the sources of indoor pollutants becomes even more important, as we advocate air-tight dwellings. It has therefore proven more difficult to balance building energy use and occupant health in existing buildings, which makes it more difficult to address future building resiliency.

Indoor air quality and mechanical ventilation

There is a strong correlation between the NO_2 concentration in the outdoor and indoor air in most buildings located in heavily populated areas; and this relationship is accentuated by the use of mechanical ventilation (Spiru and Simona, 2017). During the night, NO_2 concentrations in buildings remains higher than on the outside, so it is recommended to increase air exchange between the outdoors and indoors during night periods to reduce indoor air pollutants. Research by Martins and

Carrilho da Graca (2018), shows that mechanically ventilated buildings can reduce indoor PM2.5 concentrations (resulting from traffic and domestic combustion such cooking and heating) more effectively than natural ventilation, the latter being most effective at night, when outdoor pollutants are at their lowest.

Several studies, principally in school and office buildings, have shown that ventilation type and the air exchange rate significantly affect indoor air quality (e.g. Irga and Torpy, 2016; Salonen *et al.,* 2019; Samet and Spengler, 2003), and that inadequate ventilation accelerates the accumulation of pollutants, from both outdoor and indoor sources (Pegas *et al*., 2011). However, if outdoor NO_2 concentrations are relatively close to those found indoors, ventilation rates will likely cause negligible changes in indoor NO_2 concentrations (Kornartit e*t al.,* 2010).

Wichmann *et al.* (2010) studied $PM_{2.5}$, soot and NO_2 indoor-outdoor relationships at homes, pre-schools and schools in Stockholm and found that the ventilation type and the air exchange rate influence infiltration factors of NO_2. The main source of indoor NO_2 at schools and pre-schools was outdoor levels. Between 64-71% of outdoor NO_2 infiltrated indoors, despite the fact that all the schools and pre-schools had mechanical ventilation. The ventilation systems used at the participating buildings therefore appear to be ineffective in removing incoming NO_2 from outdoor air. In Ireland, Challoner and Gill (2014) found that lower indoor NO_2 concentrations were present in naturally ventilated buildings compared to buildings with centralised mechanical ventilation systems. These observations were attributed to the deposition of NO_2 on internal surfaces (the building fabric) as well as the age of buildings (buildings with the greatest reduction for NO_2 were older naturally ventilated offices). Indoor/outdoor ratios of NO_2 (and to a lesser extent $PM_{2.5}$) increased significantly overnight as outdoor concentrations reduced to a much greater extent than indoors. As previously intimated (Martins and Carrilho da Graca, 2018) this underlines the benefits of increased air exchange between the outdoors and indoors during the night to dissipate air pollutants (Challoner and Gill, 2014). Whist a Korean study that tested the effect of mechanical ventilation on indoor NO_2 concentrations, found a higher mean NO_2 level in classrooms when mechanical ventilation was off (50.7 $\mu g/m^3$) than when mechanical ventilation was on (45.3 $\mu g/m^3$) (Moon *et al.,* 2015). They concluded that the operation of ventilation systems could decrease the levels of indoor pollutants (in this case, in classrooms) and that adequate ventilation by means of a mechanical ventilation system could play a key role in improving indoor air quality.

The lack of attention to indoor environmental quality may be due to the intangibility of health and the problems associated with measuring quantifiable benefits. Additionally, a shortage of guidelines or regulatory levels for pollutants is affecting the ability to deliver robust indoor environmental quality criteria. Barriers to standardised indoor environmental quality guidelines for the UK include issues regarding responsibility of monitoring, legal implications of exceeding pollution guidelines, and questions over the types of building to be included (Table 9). In addition, changes in the Building Regulations towards more stringent demands on airtightness, including requirements for pressure testing of new homes, will put pressure on architects and construction professionals to focus more on detailing. Sources of air pollution will have a greater impact on indoor environmental quality and occupants may experience more adverse health effects, as dwellings become more airtight. Furthermore, trade-offs between indoor environmental quality and building energy conservation such as ventilation rates and specification of materials may be more heavily weighted to energy conservation goals (McGill *et al.,* 2016).

Table 9: Summary of barriers and solutions
(*adapted from* McGill *et al.,* 2016).

Barriers	**Solutions**
Intangibility of health and problems associated with measuring quantifiable benefits	Further research needed on indoor air pollutants and associated health and well-being impacts
Complexity of indoor emission behaviour-variability of indoor environmental quality and problems with assessment methods	Need for a standardised comprehensive protocol for the measurement of indoor environmental quality in residential environments
Lack of universally accepted indoor environmental quality guidelines	Development of universal guidelines for major indoor air pollutants
Increase in demands for airtightness and energy-efficient ventilation strategies	Development of effective indoor environmental quality criteria in existing building energy standards and legislations. indoor environmental quality certification of building materials and products
Emphasis of design goals as opposed to performance goals	Need for more post-occupancy evaluations, particularly for indoor environmental quality, comfort, and occupant health. Evaluation system where certificates and standards only achieved after 1–2-year monitoring period
Lack of knowledge integration, architect's lack knowledge on indoor environmental quality	Need for trans-disciplinary research. Translation of existing knowledge to practical design guidelines aimed at architectural and sustainable consultant professionals, further training needs
Ratings Tools criteria are often considered in isolation, which may result in a lack of focus	Minimum standards needed for indoor environmental quality and a greater awareness of interconnectivity between sustainability concepts
Cost of physical indoor environmental quality measurements	Development of economical indoor environmental quality measurement strategy for implementation in conjunction with domestic energy codes

McGill *et al.* (2016) observed the following:

- Sustainability assessment methods neglect the importance of providing information on indoor environmental quality to occupants through the building user guide.
- The importance of post-occupancy evaluations, particularly the physical measurement of indoor environmental quality, has been overlooked.
- Existing knowledge on indoor environmental quality (conducted by indoor science specialists) needs to be translated into practical, accessible language for design guidelines aimed at educating architectural and sustainable consultant professionals.
- Further research, investigating the effectiveness of sustainability assessment methods, including emission certifications, on reducing occupant exposure to indoor air pollution, is required.
- An economical indoor environmental quality measurement strategy is needed to ensure indoor environmental quality criteria are sufficiently represented in future domestic sustainability and energy codes.

In addition, it is suggested that information should be provided to homeowners on volatile organic compound (VOC) emissions from everyday products, such as air-fresheners, fragrances, cleaning products, and glues. Consideration should also be given to the maintenance of building materials and products, including whether or not VOC-emitting products are required for their upkeep, i.e., cleaning and maintenance purposes.

A detailed break-down of Wales's average outdoor PM2.5 concentration, as a population weighted mean concentration (PWMC) can be found in the Clean Air Plan for Wales, which also provides detailed information on sources of emissions in Wales (Welsh Government, 2020c). Meanwhile, Defra have published a useful summary of typical air pollutants, their source and associated health impacts (Defra, n.d.).

Indoor air quality and health evidence

The quality of indoor air is dependent on a multi-faceted relationship between building design, maintenance, operation, environmental conditions, and climate (McGill *et al.,* 2016). Indoor air pollution can cause health problems and premature deaths due to pneumonia, stroke, ischemic heart disease, chronic obstructive pulmonary disease and from lung cancer. The symptoms which may be a sign of indoor air pollution include unusual odours, stale or stuffy air, lack of air movement, dirty or faulty central heating or air conditioning, excessive humidity, moulds, health reaction after remodelling or feeling healthier outside the home (Carmichael *et al.*, 2020).

With rising awareness of the impact of increasing greenhouse gas emissions and the significant contribution of building energy use to UK greenhouse gas emissions, Mulville and Stravoravdis (2016) have even suggested that this focus on protecting the planet has been at the expense of the comfort and health of building occupants. They argue that although the current drive to reduce heat loss is not without obvious merit, as levels of insulation increase and infiltration decreases, there is increasing risk of summertime overheating linked to climate change, particularly in urban areas. They argue that current standards used for predicting overheating risk in the UK, may not be fit for purpose, as they do not consider potential climate change and make unrealistic assumptions in terms of occupant adaptations. Mulville and Stravoravdis (2016) suggest that instead of a single temperature or hours of exceedance metric to predict overheating, a risk-based scale may be more appropriate. This risk-based assessment, embedded in regulations and standards, could take account of the duration of the high temperatures experienced and the predicted impact of climate change; taking account not only of increased temperatures but also of the reduced ability of thermal mass and ventilation to minimise overheating[19]. Such an approach would present a clear role for standards and regulations in defining anticipated scenarios in relation to overheating risk linked to climate change with the aim of ensuring resilience in both the predicted 'normal' future climate and during 'extreme' events.

Reis *et al.* (2015) amongst others, advocate a model that considers the co-benefits of an intervention, e.g., energy efficiency AND wellbeing. However, it is not necessarily easy to translate the model to the real-world. There are a number of factors that must be considered:

- The strength of evidence varies for different risk factors (e.g., refer to Public Health England, 2017; Ige *et al.,* 2018);
- Assigning health risks to various factors is a complex issue; and
- Regulatory regimes remain siloed, with different parts of the built environment ruled by their own sets of standards and regulations, reflecting different disciplines, professions, practices, and policies (Siri *et al*., 2016).

The upstream project's evidence review (2018), took a different approach. In a report aimed to promote the need for the greater consideration of health factors in urban development decision making, the authors also report a lack of robust health evidence related to overheating in buildings.

[19] The increase in energy performance targets required by the UK climate change act (2008) and the EU energy performance of buildings directive, which is implemented in the new residential buildings through building regulations (e.g. Part L) are considered to have brought a positive impact on occupant health in new build dwellings.

However, as an incentive, they also provide a cost estimate of the financial impact of poor health as a consequence of the built environment (Upstream, 2018), see Table 10.

Meanwhile, Ige *et al.* (2018) undertook a systematic review of the relationship between buildings and health and found very limited evidence highlighting a link between health and overheating in buildings. Indeed, no UK policy indicates indoor temperature levels for homes in summer that could be detrimental to health. Consequently, Ige *et al.* find it difficult to conclude whether the health risks associated with living in an overheated house will be significant and could be considered as an emerging concern for UK housing stock. There are examples of UK research on the causes of overheating in homes and possible implications of future temperature increases due to climate change. If health and wellbeing is to drive policy change, more research on propensity for and the health impacts of overheating as a consequence of climate change, is required.

Building policy and health evidence

More recently, Carmichael *et al.* undertook a review of public health evidence in 2020, to determine whether or not indoor air quality is informing current building policy. They investigated whether or not in this case, English policy on building construction, was informed by public health evidence. They identified relevant policy documents and literature, to explore the evolution of drivers influencing building policy and regulations and the extent to which public health evidence competes with other priorities. They mapped the link between the following:

- A health impact (e.g., asthma, obesity, injury, cancer, heart disease)
- A building design feature (e.g., ventilation, thermal properties); and
- A policy/regulation/standard/directive.

The only governance tools to specifically reference health evidence were Building Regulations F1: Means of Ventilation[20], which refers to the impact of mould growth and pollutants on occupant health and referenced evidence including from the department of health and WHO; and Guide A: Environmental Design (CIBSE, 2019), with broad health references including WHO, DEFRA, NHS, and the Department of Housing. Some did reference the HSE regulations and HMSO acts and regulations.

In doing so, Carmichael *et al.* (2020) identified a stark lack of influence of health evidence in current building regulations and standards. They observe that a lack of integrated thinking in regulating new building quality has led to an uneven system favouring climate change mitigation over securing broader health outcomes. They argue that the health impact of sub-standard housing is not sufficiently recognised. They reflect on the fact that whilst there is a focus on reducing energy consumption in new homes (this can be extended to the retrofit of existing homes), where consequently energy consumption is reduced[21], thermal comfort is improved, but problems with damp, mould, overheating, and adequate ventilation are exacerbated, due to increased insulation and air-tightness levels.

Building regulations have made progress towards addressing UK climate change mitigation and fuel poverty targets[22]. However, even within new build, more emphasis should be placed on designing and building for new climate circumstances i.e., climate adaptation[23]. Also relevant to existing buildings and their refurbishment, building regulation policy needs to continue to regulate for improved building fabrics and technologies to save energy whilst addressing the unintended consequences (see Table 10) of more insulated and air-tight buildings; consequences that are likely to be exacerbated by climate change. Currently no approved tool focuses on healthy design. Additionally, whilst building regulations have made clear the need to mitigate climate change, research has emphasised that the predicted temperature rises in temperate and cooler countries such as Wales and the UK as a whole, also requires adaptation (Mulville and Stravoravdis, 2016). What is more, as previously surmised, overheating in residential buildings in recognised in the UK-context. Examples have been cited by, for example, Baborska-Naroznya and Grudzinska, 2016; D'Ippoliti *et al*., 2010; and Mavrogianni *et al.,* 2010.

As the current UK Building Regulations and retrofitting programmes are primarily concerned with heat retention and CO_2 reduction, it is essential that the implementation of government decarbonisation programmes, and future revisions to Building Regulations tackle the risks of, and potential for adapting to, climate change-driven overheating to ensure a comfortable environment for occupants now and in the future. In the Southeast of England for example, implications of increased mechanical cooling on future energy use and grid strain should be investigated further by both the building and the energy sectors. Policy priority is for the energy efficient design of buildings, without sufficient consideration of health impacts. This has led to unintended health consequences and is inadequate for building a housing stock resilient to future climate change. To address this, Carmichael *et al.* (2020) suggest that the planning authority should be able to regulate specific hazards (cold, heat, damp, and mould), placing more pressure on those responsible for buildings to make holistic decisions when it comes to addressing energy efficiency and climate change measures.

[21] Energy efficiency measures also aim to tackle fuel poverty.
[22] Building regulations apply to new and retrofitted buildings, whilst building standards are not applied retrospectively to existing stock.
[23] Developers are disinclined to building to higher standards for health than set out in the UK Building regulations. There is therefore a strong argument of the need to legislate for health and wellbeing.

Two key areas must be targeted, the performance gap (between designed and built performance) and that driven by occupant behaviours, whereby occupants do not understand how to effectively use e.g., more energy efficient homes. Carmichael et al. (2020) suggest mandating user guides for all homes, which could be extended to homes that have been retrofitted. However, crucially, they propose a systems-based approach, one that considers all the factors and actors that influence building policy. Public health, environmental quality, climate resilience and greenhouse gas reduction must be tackled collectively, rather than as separate issues. This is essential if we are to avoid the unintended health consequences of focussing on one driver, such as energy efficiency and improve the overall health and wellbeing impact of homes. Building occupants can learn how to support both energy savings and indoor air quality, but this requires informed and reliable end-user behaviour (Michael and Phocas, 2012; Phocas *et al.,* 2011).

Table 10: A summary of the linkages between building performance hazards and consequent undesirable health outcomes

(Adapted from Carmichael et al., 2020)

HAZARD	POSSIBLE HEALTH EFFECT	LINK/CAUSE	DESIGN FEATURE/ DEFECT	ESTIMATED FINANCIAL IMPACT
Damp and mould	• Asthma • Depression, anxiety, social isolation • Allergy: rhinitis, conjunctivitis, eczema, cough and wheeze • Fungal infection • Suppressed immune system	• Reduced ventilation • Increased humidity (especially 70% and above) • Warmer indoor temperatures in winter	• Lack of damp-proof course • External fabric allowing rain penetration • Lack of frost protection • Poor bath and sink design • Poorly installed drainage • Poorly installed rainwater goods • Poorly ventilated roof and under floor spaces • Inadequate means of ventilation • Poor extraction of moisture laden air	The health impact potential of damp and mould on respiratory illnesses, eczema and headaches could be valued at £325,000 per 1000 people per year (Upstream, 2018).
Excess heat Mortality increases in temperatures over 25°C	• Thermal stress • Cardiovascular conditions, e.g., stroke	• Poor ventilations • Smaller dwellings • Larger areas of south facing glazing • Faulty or sub-standard heating controls	• Shuttering or blinds • Natural ventilation or air conditioning • Controllable heating systems	the health impact potential of excess heat on mortality could be valued at £470,000 per 1000 people per year (Upstream, 2018).
Excess cold Small risk <19°C, Serious health risk <16°C, Great risk <10°C (especially for the elderly)	• Cardiovascular conditions: stroke, heart disease, hypertension • Respiratory disease • Suppressed immune system	• Changes in outdoor temperature • Low energy efficiency ratings (poor insulation) • Absence of central heating/poor inefficient heating systems	• Thermal insulation • Appropriate/properly installed or maintained occupant controllable heating system • Appropriate/properly installed or maintained occupant controllable low-level background ventilation • Means for rapid ventilation at times of high moisture	The health impact potential of cold on mortality, sickness absence and hospital admissions could be valued at £240,000 per 1000 people per year (Upstream, 2018)

		• Excessive damp which reduces thermal insulation	production in kitchens/bathrooms • Properly sited/sized permanent openings (e.g., air brick/open-able windows) • Properly fitting butt-jointed floor boarding/doors/windows.	

Occupant behaviour and overheating

Occupant behaviour can have a significant impact on overheating[24]. Coley *et al*. (2012) undertook a comparison of hard adaptations i.e., structural building adaptation, against soft adaptation i.e., behavioural change, and their results reveal that both can lead to similar reductions in temperatures and hours of overheating. For behavioural approaches to reducing the risk of overheating identified in the literature, see Table 4.

Comfort conditions, that is the set of conditions that individuals require in order to experience personal comfort, such as temperature, humidity, indoor environmental quality and sunlight will vary from one occupant to another. Building occupants will naturally respond to changes in their comfort conditions, changing their behaviours, to achieve and sustain personal comfort. Researchers have used occupant 'profiles' to attempt to classify occupants based on demographics related to age, gender, family size, vulnerability etc. in order to predict their personal comfort conditions to support design decision making. However, occupants are not homogenous groups of people. Occupants may not always react on the basis of logic but may also be driven by their emotions, which will influence their behaviour. As a result, it is difficult to predict how occupants will respond, and yet an understanding of occupant behaviour is vital for the accurate prediction of building performance, e.g., the operational energy use in buildings.

Occupant behaviour and energy efficiency

Energy consumption in buildings is driven by the 'needs' of occupants. Occupants are the ones who consume the energy, often wasting said energy through their behaviours (Masoso and Grobler, 2010). There are several UK-based studies that have tackled occupant behaviour and energy efficiency. Hayles *et al.* (2013), Hayles and Dean (2015), Trotta (2018), Boomsma *et al.* (2019) and Bardley *et al.* (2019) considered behaviour impacts and interventions aimed at energy saving behaviours. Goulden *et al.* (2018) and Sweetnam *et al.* (2019) considered the role of the end user in determining the future of demand-side response to energy efficiency including district heating networks. Hope *et al.* (2019)

[24] As insufficient research is yet to be carried out in the UK, we can look to central and southern Europe for best practice in ameliorating overheating, weighing up the application of passive and active cooling alternatives.

have looked at energy demand and occupant engagement in low-carbon home energy, and the behaviours of people with constraints on their energy use. Behaviours as a driver of fuel (warmth & energy deprivation) have been explored by Kearns *et al.* (2019) and as associated with students (Morris and Genovese, 2018).

Occupants have a direct effect on the heating, cooling, and ventilation of buildings. Indeed, occupant behaviour is considered to be one of the important reasons for the performance gap and has the biggest impact on in-use energy consumption (see Figure 1), since its complexity makes it difficult to analyse and predict (Harputlugil and de Wilde, 2020).

The European Environment Agency's 2013 report suggested that measures targeting occupant behaviour could help to save up to 20% of in-use energy demand. Despite this, there has been a continued focus on improving technology for greater energy efficiency, at the expense of targeting occupant behaviour and the promotion of environmental stewardship to avoid waste. This is an example of why occupant behaviour and consequently occupant engagement is one of the most important considerations when making recommendations for any building adaptation, including both energy conservation and efficiency decisions (to mitigate greenhouse gas emissions) and in the wider climate change adaptation of buildings (to prevent poor indoor environmental quality including overheating, damp and the concentration of pollutants). Behaviour change enabling support should be given to occupants on moving to a new home or when retrofitting an existing property. Hayles *et al.* (2013) provide one example of this, using their Awareness Behaviour Intervention Action (ABIA) framework to support social housing tenants to transition towards more environmentally responsible behaviours (*see also* Hayles and Dean, 2015).

Energy use of buildings shows a strong correlation with the activities of the building occupants. A lack of understanding of building occupant behaviour makes it difficult to reduce building energy use. As greenhouse gas reduction through energy efficiency has been identified as essential to delivering climate change amelioration in the built environment, understanding occupant behaviour must be the key to unlocking further energy savings.

Harputlugil and de Wilde (2020) examined the literature around the interaction between occupants and building for energy efficiency, in doing so they tried to identify problems and knowledge gaps in the field. They determined that:

- research on building occupant behaviour relies strongly on quantitative methods;

- ❖ occupant behaviour studies prioritise heating over cooling of buildings (as most studies have been conducted in the Global North);
- ❖ energy demand and thermal comfort are the main research topics associated with occupant behaviour, followed by retrofit and renovation;
- ❖ most research focuses on technical aspects rather than socio-economic issues;
- ❖ current research is mostly limited to studies of single buildings and typically lacks data-gathering standards, which makes it hard to conduct cross cultural data comparisons; and
- ❖ Most research concentrates on individual topics, such as window, door and blind adjustments, effects of Heating Ventilating Air Condition (HVAC) systems etc. and does not provide a wider, holistic view that can be linked to social and economic factors.

Habits and attitudes differ across cultures, regions, climate, geography and local topography. Research therefore should pay more attention to lifestyles in order to understand profiles and patterns of occupants. Without understanding occupant lifestyles and thus their behaviours, it is difficult to predict the success of proposed recommendations of interventions that could be implemented to reduce climate vulnerability in buildings in Wales and the UK.

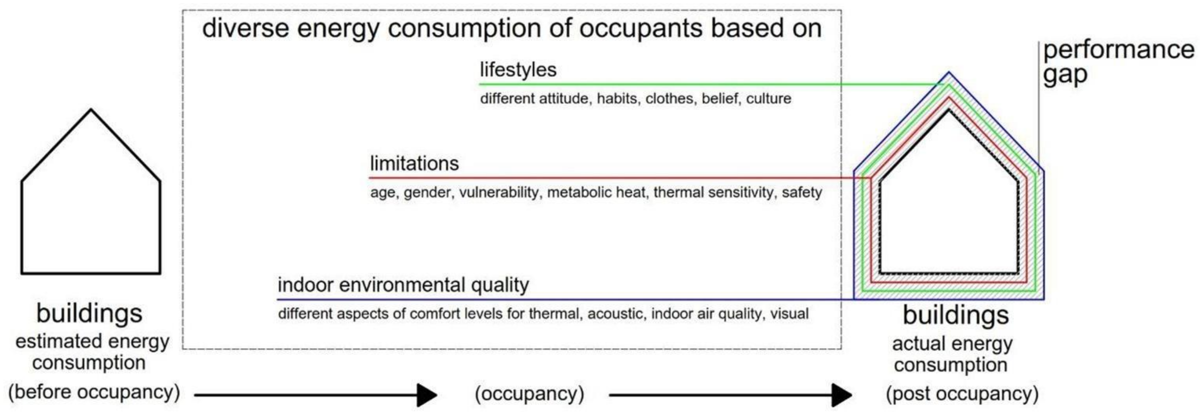

Figure 1: Effects of Occupant Behaviour on the building energy performance gap
(*After* Harputlugil and de Wilde, 2020)

Occupant behaviour, moisture and damp

The impact of human behaviour on the occurrence of moisture induced damage to buildings is frequently encountered in practice, but there has been relatively little research. This type of problem has been gaining greater importance as a consequence of the increase in the application of insulation but also the more general thermal refurbishment of existing building stock. But are the occupants able to maintain an appropriate indoor air humidity based on the mere operation of windows? Which are the behaviour patterns that influence this result?

For example, in the case of older buildings in colder climates, which prior to retrofit, are sufficiently ventilated by air infiltration through old windows, subsequently encounter too high indoor air humidity due to increased airtightness after replacing windows (Haldi, 2015). If such buildings are not equipped with mechanical ventilation systems, the evacuation of excess humidity mostly relies on occupant window opening behaviour. This may result in mould growth on poorly insulated surface or at thermal bridges (Sedlbauer, 2002), as well as further risks within the construction in the case of interior insulation. In this instance, Haldi (2015) highlights the importance of including the frequency of window opening by building occupants, when predicting the risk of moisture induced damage to building envelope and the propensity for this to result in mould growth, in properties not fitted with active ventilation systems.

A relationship between energy saving behaviours, frequently driven by fuel poverty, and incidences of increased moisture, resulting in damp and mould, has also been identified. A study among English social housing residents suggest that the presence of condensation, damp and mould was associated with more frequent heating-related energy saving behaviours, but not other energy saving behaviours (Boomsma *et al.,* 2019).

Summary

Climate change is projected to increase temperature and change rain patterns in Wales and, more widely, across the UK. This weather pattern, coupled with current approaches to energy retrofit, may not only change the energy use of dwellings, but also the indoor climate, air quality and associated pollution levels, as well as the moisture dynamic of buildings. As outlined in the literature summarised above, when high moisture conditions persist within the indoor environment, condensation, mould growth, wood decay, and frost damage may all occur; and the first three, in particular, have the ability to negatively impact the health of building occupants.

Despite this, in order for climate change mitigation and carbon reduction targets to be met, the emphasis continues to be on delivering approaches to building retrofit that aim for greater operational energy efficiency (Dixit, 2017). Certainly, the energy efficiency gains from retrofitting housing in general, has accelerated the implementation of both external and internal insulation in older, traditional housing stock, as they tend to be the most energy inefficient of the wider housing stock.

However, as demonstrated in many of the case study examples outlined above, the addition of internal wall insulation may subsequently diminish the benefits of thermal mass and natural ventilation found in older buildings, particularly during the summer months. Considering, therefore, that retrofit interventions could reduce the drying capacity of walls and modify the temperature gradient, the combined effect of a changing climate coupled with energy efficiency retrofit interventions could undermine the long-term integrity of the building envelope (Hao *et al.,* 2018). Where approaches to energy efficiency have proven to have failed, it is hoped that further solutions will be developed. Any decisions should bear in mind known climate projections, building performance, and occupant behaviour.

It is therefore anticipated that projected reductions in energy demand, as a direct consequence of climate change, could be built into decision making, with both mitigation and adaptation strategies considered side by side. For example, overheating is an increasing concern and will continue to be so in the future. To that end, the combined effect of internal insulation and increased outdoor temperature may increase energy demand for cooling. Furthermore, moisture risks are more likely to occur due to climate change, e.g., changed precipitation pattern, and impact building envelope moisture dynamics, and subsequently, this too will impact indoor environmental quality and occupant health.

Through these studies, it is evident that the role of thermal mass and natural ventilation in future climate scenarios, and the relationship between the moisture state of an older building, rain pattern changes, and retrofit solutions (both mitigation and adaptation), should be further evaluated. Ultimately, improving our understanding of the relationship between energy use, indoor environmental conditions, and the moisture dynamic of the building envelope, will allow better informed decisions as they will provide a better sense of future risks to energy efficiency, occupants' health and wellbeing including thermal comfort, and dwelling management.

What is needed is a multi-criteria approach to decision making for mitigation and adaptation; applying systems thinking, using an integrated framework, to tackle the myriad of issues that climate change presents.

Please see full Bibliography at the end of this document, for literature review reference details.

[5] Climate evidence applied to mandatory and voluntary building regulations, standards and assessment tools

This section summaries a piece of work that was undertaken to scrutinise mandatory and voluntary technical standards and assessment tools for climate change evidence. In doing so, health evidence and fabric risk evidence, were also recorded. In 2020, Carmichael *et al.* undertook a similar approach to establish whether an appropriate public health evidence base was being used to inform current building policies.[25]

This qualitative review of current policy identifies where and how climate change (and the related issues of health and building fabric risks) have been evidenced. Policy documents were reviewed using key word searches for (a) climate change, energy efficiency, carbon; (b) wind, rain, flooding, fabric; and (c) health, occupant comfort, pollution, air quality, damp, mould. Policy documents with positive matches to the keyword search were further interrogated to identify any specific reference to the evidence base, with in-policy references crosschecked with the evidence base identified from e.g., UK Government, WHO, academic literature, etc.

The results of the current exercise (see Appendix A for complete analysis) indicate that climate change and the need to plan for future climate scenarios, are yet to be effectively and consistently integrated or delivered through building policy and regulation:

- Overall, there is little reference made to climate change in Welsh Building Regulations and related national reference Standards, and when it is, there is no evidence of the potential impact climate change will have on buildings in the future. This is changing, as evidenced in language used the BSI 5250 2020 consultation draft.
- Currently revisions to Part L and F (consultation drafts) are not based on any climate modelling.
- A summary of the potential impact of climate change on the built environment is provided in CIBSE Guide A.
- Climate adaptation decision-making is currently reliant on energy calculations and building modelling using CIBSE's weather files.
- CIBSE weather data files, considered to be the industry standard weather data for the UK, in the form of Test Reference Years (TRYs[26]) and Design Summer Years (DSYs[27]) are also recommended by BREAAM, and the Home Quality Mark ONE Technical Manual.

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[25] The key challenge they identified was the lack of a systems approach and integrated policy environment to consider all the factors and actors influencing the building policy process.

[26] TRY is composed of 12 separate months of data each chosen to be the most average month from the collected data. The TRY is used for energy analysis and for compliance with the UK Building Regs. Part L.

[27] DSY is a single continuous year rather than a composite one made up from average months. The DSY is used for overheating analysis.

- ❖ CIBSE weather files currently use UKCP09 data. This has not been updated to include UKCP18 data[28].
- ❖ CIBSE is seeking the endorsement of a newer set of weather files for compliance in Part L2A, where practitioners still need to use the 2008 TRYs. CIBSE have tried to encourage the Ministry of Housing, Communities and Local Government (MHCLG) to update their document and propose the use of the latest TRYs, but without success so far. The new overheating standard is requesting the use of the latest DSYs (2020s, UKCP09 based)[29].
- ❖ There is a lack of information of how to use climate change predictions (weather files) and the impact these predictions will have on building performance, to *inform design decision*s.

BREEAM and Home Quality Mark ONE Technical Manuals do encourage consideration and implementation of measures to mitigate the impact of more extreme weather conditions arising from climate change over the lifespan of the building. Despite this, there is no consistent messaging to encourage and/or enable the industry to build-in resilience. Ultimately, no consistent recognition of the need to acknowledge the interconnectedness of e.g., climate change, building fabric and health, and the systems approach required in order to tackle climate change, particularly in the refurbishment of existing dwellings. E.g., the development of national indoor air quality objectives that could sit alongside those for future energy efficiency standards would be highly beneficial and ensure that effective management of the built environment was delivered in a joined-up way (AQEG, 2020).

One of the shared concerns when preparing for and adapting to a changing climate is that of the unintended consequences of focussing on one driver, for example energy efficiency (to reduce carbon emissions), over another, e.g., the health and wellbeing of building occupants. Carmichael *et al.* (2020) propose a more holistic policy approach to housing design and construction, with an integrated framework, based on the UN Sustainable Development Goals (SDGs), highlighting a broader set of key drivers including health. BRE's home quality mark, which builds on best practice in the housing sector, drawing together a range of quality and performance standards and combining this with the latest scientific research, goes some way to address this proposition. This scheme does not however, currently meet the needs of those involved in building retrofits, where climate amelioration is a necessity (not just to reduce carbon emissions but to protect building fabric and occupant health and wellbeing); and where maladaptation is more likely to occur.

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[28] CIBSE has been awarded an Innovate UK funding grant for a 30-month project with the University of Exeter to produce new files based on the most recent UK climate projections.

[29] The most up-to-date guidance and use of the latest weather files for residential developments is recommended by the London Plan.

The current exercise has highlighted the need for consistent messaging on and the enforcement of climate change adaptation, particularly when it comes to existing dwellings. Developers are disinclined to build to higher standards than those set out by the UK Building Regulations. Building Regulations and British Standards must therefore lead the way with consistent messaging and by legislating for climate adaptation. For example, Part L and Part F of Building Regulations could be better coordinated to reflect interdependencies. An approach which supports the holistic consideration of energy efficiency, overheating and ventilation strategies is likely to support the best outcomes for occupants. Combining energy efficiency and ventilation requirements could drive this. Part F of the Building Regulations should be reviewed alongside Part L, with a view to tightening standards and coordinating requirements to fully reflect interdependencies. Where updates affect Part B and vice versa, Government should review the standards in their totality. (CCC, 2019)[30].

Since this analysis was completed, the Committee on Climate Change have produced their third Climate Change Risk Assessment (CCRA3, 2021 a and b). In doing so they challenge the regulatory authorities. With respect to cultural heritage, CCRA3 factsheets suggest that there may be benefits to putting a greater emphasis on *embedding risk assessments accounting for climate change hazards, such as extreme wind and rain and subsequent flooding, into building regulations and standards over the next five years* (Committee on Climate Change, 2021a). For housing they *recommend improved building regulations and building design that consider overheating among other aspects of building safety would help to reduce the risk in new and existing homes undergoing retrofit* (Committee on Climate Change, 2021b). They also identify the need for a systems approach, stating that decarbonisation strategies for housing would benefit from being combined actions to avoid overheating.

In summary, this exercise has exposed the lack of influence climate change evidence has on current building policy and regulation; and a shortage of advice and tools to tackle the impact of future climatic conditions on the built environment. The complexities of tackling climate change demand a holistic policy approach to the design, build and planning process.[31]

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[30] Building regulations are a key lever for driving up standards in new homes and play an important role in setting standards for new work to existing homes. However, the retrofit challenge requires a much broader package of policies and actions from developers and homeowners. Given the scale of the challenge, retrofit should be supported by HM Treasury and the Devolved Governments as a national infrastructure priority (CCC, 2019).

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[31] **References:**

1. Carmichael, L., Prestwood, E., Marsh, R. Ige, J., Williams, B., Pilkington, P., Eaton, E. and Michalec, A. (2020). Healthy buildings for a healthy city: Is the public health evidence base informing current building policies? Science of the total environment 719 (2020) 137146.

[6] Climate Change adaptation: Case studies from the UK

Currently there are very few UK-based case studies where climate change decision-making has been integral to the retrofit of existing dwellings, and none which holistically address climate change adaptation decision making.

Table 11 provides an overview of UK-based case studies (2012-current), identifying the drivers, mitigation and/or adaptation, and whether or not the adaptation was to improve the performance of the building envelope or the health and wellbeing of the building occupants.

The projects have been ordered according to the scale of the scheme, from individual dwellings, through community housing, to large-scale city region plans for housing.

As highlighted in the table, the key driver for many of these projects is climate change mitigation rather than adaptation, through energy efficiency measures, both building fabric improvements and/or the application of renewable energy technologies.

Whilst interventions to prevent overheating are the most common climate change adaptation, there are examples where the potential for high winds, storms and flooding have been a significant consideration.

It should be noted that both the London Plan and Glasgow City region plans have wide remits, however there are currently no tangible outputs from these strategic plans, with no published case studies demonstrating how these strategies are working at a dwelling/scheme level.

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2. CIBSE (2014). TM48: Use of Climate Change Data in Building Simulation. Available online at: CIBSE - Building Services Knowledge
3. CCC (2019). UK housing: Fit for the future? The committee on Climate Change. Available online at: UK housing: Fit for the future? - Climate Change Committee (theccc.org.uk)
4. CCC (2021a). CCRA3 cultural heritage briefing. Available online at: CCRA3-Briefing-Cultural-Heritage.pdf (ukclimaterisk.org)
5. CCC (2021b). CCRA3 housing briefing. Available online at: CCRA3-Briefing-Housing.pdf (ukclimaterisk.org)
6. AQEG (2020). Impacts of Net Zero pathways on future air quality in the UK, This is a report from the Air Quality Expert Group (AQEG) to the Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of Agriculture, Environment and Rural Affairs in Northern Ireland.

Table 11: Climate Change adaptation: Case studies from the UK

#	Project name	Location	End Date	Drivers	Climate Adaptation				Climate Mitigation		Additional information	Website [hyperlinks]
					Internal		External		Decarbonisation/ energy efficiency			
					Over-heating	Indoor air/environmental quality	Drainage/ Flooding/ moisture	Planting/ shading	Energy systems/renewables	Thermal mass /fabric improvements		
Individual dwellings												
1	HES	Scotland	2018	Refurbishment case studies focused on energy efficiency. Some examples outlined below:					✓	✓	Energy efficiency measures to improve thermal comfort without compromising the character and functionality of traditional buildings.	Historic Environment Scotland #24
2	HES	Shetland	2016	Repair and adaptation of a 18th Century Laird's dwelling		✓			✓	✓	HES's Climate change adaptation and hot-mixed mortars research programme	Historic Environment Scotland #25
3	HES	Edinburgh	2020	To improve thermal performance of a former dwelling		✓			✓	✓	Materials that preserved the character and appearance of the listed building and minimise disruption to the original fabric.	Historic Environment Scotland #37
4	HES	Granton on Spey	2018	To retrofit insulation measures to improve energy efficiency and reduced mould growth		✓				✓	Building suffered from mould growth due to poorly specified energy efficiency measures.	Historic Environment Scotland #27
Community housing schemes												
5	The EastHeat project	Lothians and Falkirk, Scotland	2016	To increase residents' comfort and tackle fuel poverty by providing low-cost heating and hot water					✓		Local energy systems including micro renewables and heat storage [continued heating for tenants during power cuts] There is expected to be an increase in extreme high winds and storms due to climate change.	EastHeat project
6	Octavia Housing	West London	2012	Climate risk of pluvial flooding and highly vulnerable basement flats and predicted temperature profiles and heat wave thresholds.	✓		✓					Octavia Housing
7	Cliftonville	Margate, England	2020	Retrofit of Victorian and Edwardian buildings of exceptional architectural merit, typically very large, four to five storeys terraced (coastal) properties to help facilitate the regeneration of the area.	✓		✓				Baseline thermal modelling exercises against predicted weather data for 2080 under the high and medium emission scenarios, at 50 and 90 per cent confidence intervals	Cliftonville
8	PortZED	Brighton & Hove, England	2013	Regeneration	✓				✓	✓	Energy plus modelling for overheating to determine when the installation of active cooling will be required.	PortZED
9	Nottingham City Homes	Nottingham	2019	Energy retrofit					✓	✓	Retrofitted to the *Energiesprong* standard	Nottingham City Homes
10	Life and climate proofing social housing landscapes	Hammersmith and Fulham	2016	Green infrastructure solutions to flooding and overheating risks	✓		✓	✓			Raised awareness of potential benefits of sustainable drainage systems [SuDS], rain gardens and other green infrastructure initiatives.	Hammersmith and Fulham
Examples of large-scale schemes/city region plans for housing												
11	Better Homes Yorkshire	Leeds city region	On-going	Energy efficiency					✓	✓	Aims to help residents (owners, tenants, and landlords) in ten local authority areas to take advantage of Government funding options to make energy efficiency improvements to their homes.	Better Homes Yorkshire
12	London Plan	London	2016-present	Includes tackling climate change by moving towards a zero-carbon city by 2050	✓	✓	✓	✓	✓	✓	A zero-carbon target for major residential developments has been in place for London. Plan also includes requirements for planners to ensure buildings are designed to adapt to a changing climate, through making efficient use of water, and reducing impacts from natural hazards like flooding and heatwaves.	London plan 2021
13	Climate Ready Clyde	Glasgow city region	2012-present	place-based adaptation initiative	✓		✓	✓		✓	Regional climate change risk assessment considered risks to the housing stock in the region.	Climate Ready Clyde

[7] Climate Vulnerability Modelling and Associated Outputs

The Climate vulnerability modelling was undertaken in collaboration with Professor Paul Chinowsky, Matt Huddleston and Jake Helman of the University of Colorado and Resilient Analytics.

Climate data sets

The climate data used in this analysis is the UK Climate 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 include 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 while the 2021-2040 and 2061-2080 time periods were used to represent projected results for 2030 and 2070, respectively. Results were generated for six locations throughout Wales. The locations were chosen for their geographic spread throughout the country as well as their elevation and coastal proximity.

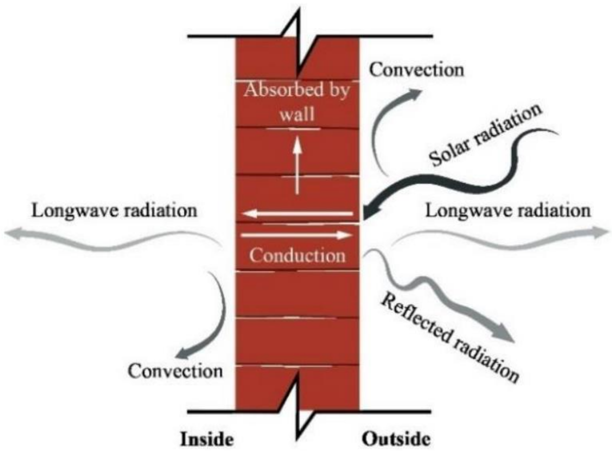

Figure 2: Diagram of heat transfer through a wall section. Such heat transfer is part of what drives the change in a building's indoor environment in response to a change in the outdoor environment (Jannat *et al.,* 2020).

Indoor Environment Calculation

A building's indoor environment, measured here by its indoor temperature and humidity, influences the health and comfort of occupants as well as the longevity of the interior building fabric and objects within the building. Indoor temperature and humidity are influenced by factors such as occupant behaviour, mechanical system operation, and building fabric characteristics such as air tightness, insulation, and exterior wall area. An example of how outdoor heat transfer through a wall can impact the indoor environment is demonstrated in Figure 2 above. From a climate change perspective, the building fabric is especially critical to evaluate since it provides the barrier between occupants and the outdoor environment. As the outdoor environment changes so too will the indoor environment if there are no mechanical cooling systems to provide cooling or dehumidification. One of the aims of this study was to quantify the change in indoor temperature and humidity because of changes in outdoor temperature and humidity for a range of building types and characteristics.

For the purposes of this study, the relationship between outdoor temperature and indoor temperature is based on a monitoring study of 193 free-running dwellings (without heating or cooling) located throughout England (*after* Beizaee *et al.,* 2013; CIBSE, 2015). 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 average hourly outdoor temperature was also reported across all dwellings and for two of England's Government Office Regions (Table 12).

Table 12: Monitored temperatures from English dwellings used in formulation of indoor-outdoor temperature relationship

Monitored Temperature						
Location	**Monitoring Period**	**Room Type[1]**	**Average Outdoor**	**Average Indoor**	**Average Maximum Indoor[2]**	**Source**
England	Jul 22nd - Aug 31st	LR & BR Avg	15.3	21.7	25.6	Beizaee *et al.* (2013)
London	Jul 22nd - Aug 31st	LR & BR Avg	17.6	22.2	26.4	
Southeast	Jul 22nd - Aug 31st	LR & BR Avg	15.6	21.9	26.0	

1) *LR = Living Room, BR = Bedroom*
2) *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.*

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.

Temperatures were monitored and reported in dwelling living rooms and bedrooms separately, with average and maximum temperatures in living rooms reported from 8:00 – 22:00 and bedrooms from 23:00 – 7:00. To allow analysis of a full 24-hour 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 (Tamerius *et al.,* 2013). Conversely, in the case of 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 (Nguyen and Dockery, 2015). Figure 3 is a psychrometric chart which demonstrates the relationship between temperature, relative humidity, and specific humidity. 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 separate monitoring studies were used as the basis for the relationship between average daily indoor and average daily outdoor specific humidity (*see* Tamerius *et al.,* 2013; Nguyen *et al.,* 2014; Nguyen and Dockery, 2015). The three studies include monitored specific humidity data from six global locations sourced from a variety of building types (although mostly from dwellings) of different age, type, 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.

Since only average daily specific humidity is available in the UKCP18 climate data, a daily specific humidity fluctuation range needed to be calculated to find the maximum and minimum daily indoor values. The indoor specific humidity was assumed to fluctuate daily according to the range that is coincident with the monthly 5% dry bulb design day temperature (temperature exceeded for only 5% of hours for that month), and its mean coincident wet bulb temperature, as published by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 2013).

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.

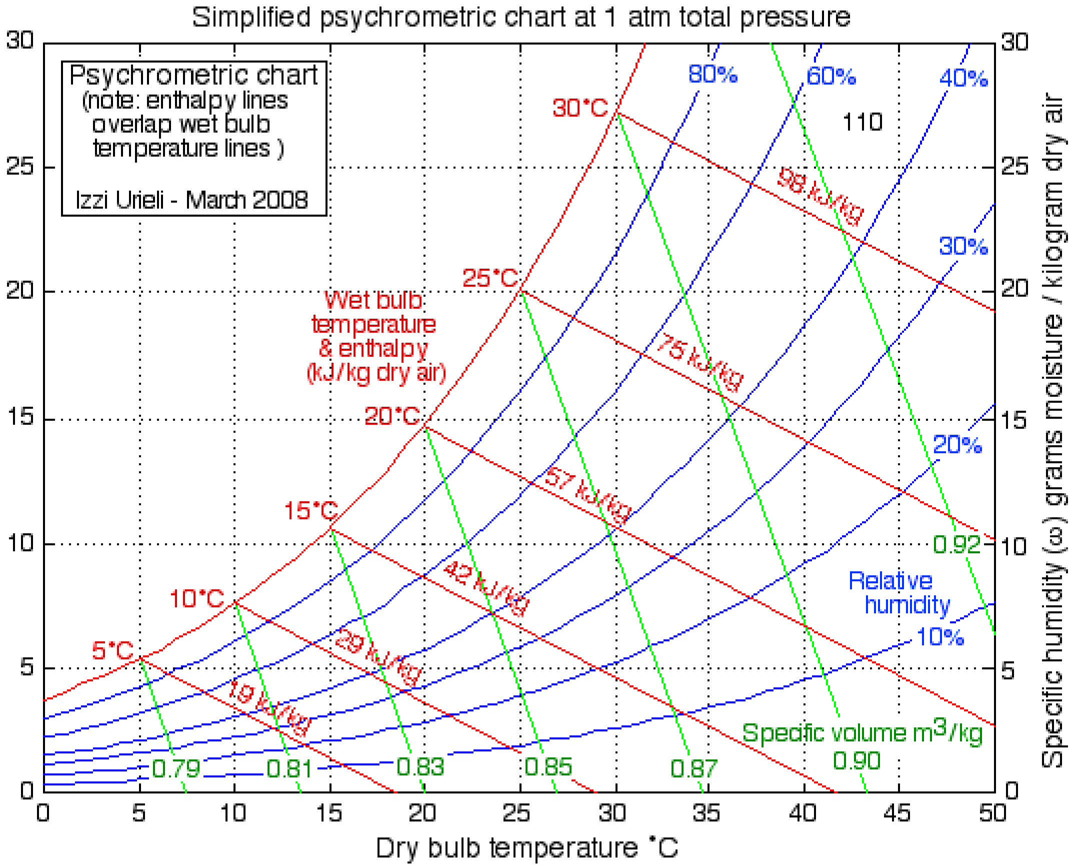

Figure 3: Psychrometric chart which demonstrates the relationship between temperature, relative humidity, and specific humidity. (Urieli, 2021)

There is potential for a more tailored set of results by monitoring indoor temperature and humidity in the specific dwellings for which adaptation strategies are to be employed. This would allow for results, and therefore adaptation recommendations, specific to a given dwelling or dwellings rather than basing recommendations on data from a sample of global homes.

Building Typologies

Results for internal overheating risk and indoor air quality are reported for eleven dwelling classes. 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. The results of the analysis can be found in Appendix B. Differentiation is made between pre- adapted and retrofitted or refurbished dwellings. When considering the characteristics of pre-adapted dwellings, there is an acknowledgement that interventions (e.g., central heating, window replacement, etc.) have been made to most dwellings (>90%) and are therefore included in the pre-adapted scenario. The retrofitted/refurbished dwellings categories include measures that go beyond the status quo, but are standard approaches, within the social housing sector.

In completing the exercise, several assumptions and statements needed to be made. These were as follows:

1. All ages of property are represented across all three regions of Wales (North, Wales, Mid and Southwest Wales, Southeast Wales).
2. Property tenure (owned, rented, social) is divided across dwellings of all ages.
3. Urban refers to all properties found in cities, towns, and their urban fringe. Rural includes dwellings located in villages, hamlets, and other isolated dwellings.
4. Dwellings of all ages are found in both urban and rural settings. *A differentiation has been made between urban and rural dwellings pre-1919 as rural dwellings during these periods are predominantly detached properties.*
5. Dwelling orientation varies across all housing stock.
6. More than one quarter (26%) of dwellings in Wales are what is described as 'pre-1919' housing stock (BRE, 2020).
7. 23% of dwellings were built between 1965-1980 (BRE, 2020).
8. 16% of dwellings were built between 1945-1964 (BRE, 2020).
9. There is twice as much terraced housing (and purpose-built flats) found in Southeast Wales compared with North and Mid and Southwest Wales (Welsh Government, 2020).
10. Gas central heating is prevalent. Between 85-90% for all dwellings considered in this study, bar pre-1919, where it can be found in 75% of homes. Oil central heating is most likely to be found in pre 1919 properties in rural locations (Welsh Government, 2018b and 2020).
11. All dwellings post 1919 are considered as having double glazing as a matter of course. Results from the Welsh Housing Condition Survey (Welsh Government, 2018b and 2020) verify that between 91-100% of all post 1919 properties have at least 80% of their windows double glazed.
12. All dwellings have some level of loft insulation**.** Between 95-100% of all dwellings surveyed in WHCS have loft insulation (Welsh Government, 2018b and 2020). *In the 1970's the recommendations were to have 25mm and then more recently it was increased to 100mm, and by 2013 it had increased again. The full thickness of insulation in the United Kingdom (from August 2013) should be a minimum of 270mm.*
13. The glazing ratio (i.e., the window-to-wall ratio) is assumed to be between 15-35%.

14. Separate entries are suggested to differentiate between the following approaches to wall insulation (although it wasn't possible to model all of these)
    - EWI = External wall insulation;
    - IWI= Internal wall insulation; and
    - CWI = Cavity wall insulation.

The eleven building classes outlined in Table 13 seek to represent the most common Welsh dwelling types, as identified and summarised in Appendix B.

The temperature adjustments listed in Table 13 are applied to the indoor temperature calculation discussed in the previous section, which is based on data from all 193 free-running dwellings in the English monitoring study by Beizaee *et al.,* 2013. The same monitoring study also reported separate dwelling temperature data for five different dwelling types, six different dwelling age bands, and four different external wall types. This data formed the basis for nine of the eleven Welsh dwelling categories used in the current study.

Internal wall insulation (IWI) and double-glazing temperature adjustments are based on a study by Mavrogianni *et al.* that used *Energy Plus* thermal simulations to model temperature conditions within London dwellings (Mavrogianni *et al.,* 2012). In the study, 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 (Welsh Government 2018b, 2020) 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.* 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 indoor environmental 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 a relative humidity for each building class.

Modelling parameters

Four climate vulnerabilities are modelled in this study. Two of them, 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. The other two deal with the impact of moisture and sunlight on exterior building fabric.

Table 13: 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	IWI	0.4	0.6
Window	Double Glazing[1]	-0.4 (-1.4)	-0.6 (-2.4)

Beizaee et al. (2013) study did not specify dwelling glazing properties. When applying glazing temperature adjustments, it is assumed that buildings in the study were single glazed. According to Welsh housing survey this is only applicable to pre-1919 buildings. Temperatures indicated are in the format "adjustment of double glazing from single glazing (adjustment of double glazing and pre-1919 from the average)"

Temperatures inside of free running dwellings are heavily influenced by the outside air temperature. Therefore, rising outside temperatures associated with climate change leads 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 by more than 3% of occupied hours for dwellings without sufficient opportunities for natural ventilation (insufficient window area or unfavourable conditions for open windows)(CIBSE, 2017).

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. 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 utilized 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 portion of the study covers 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 (CIBSE, 2013). 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 (Arundel *et al.,* 1986; World Health Organisation, 2009; Lankester, 2013). A relative humidity range of 40%-60% was found by Arundel *et al.* (1986) 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.

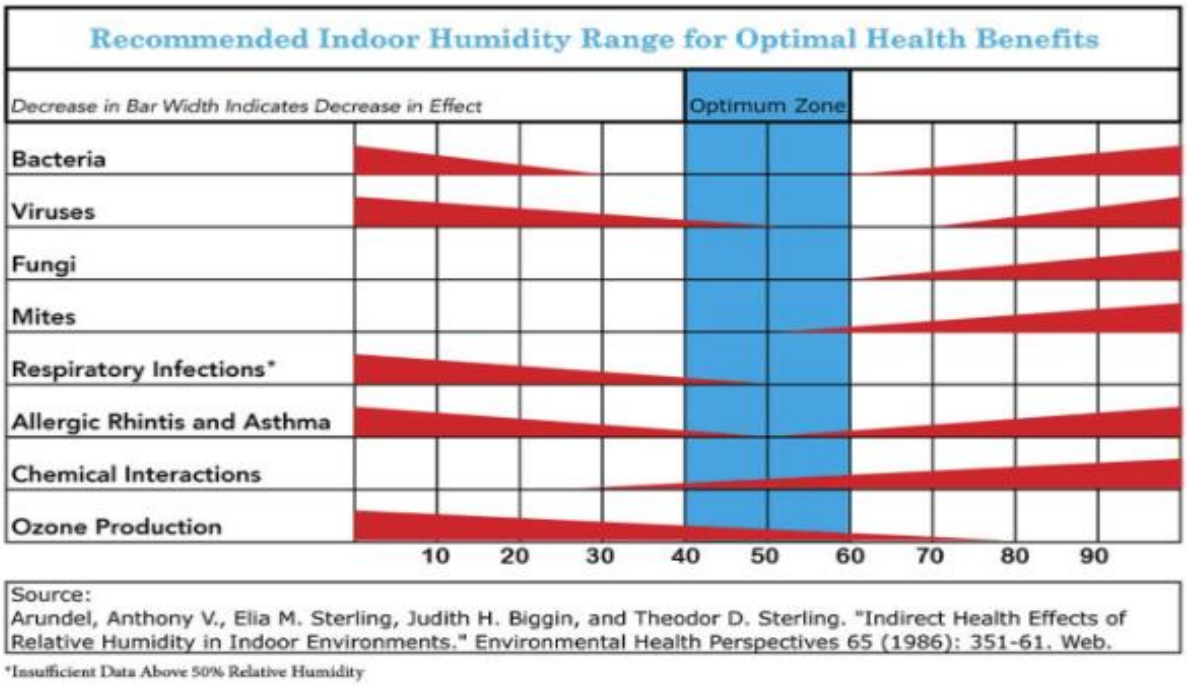

Figure 4: Impact of humidity on various metrics (*After* Arundel *et al.*, 1986)

The final two impact areas focused on the climate impact on the durability of exterior building fabric components. Specifically, the analysis aimed to quantify the impact that projected changes in solar exposure and damp (in the form of precipitation and relative humidity) will have on degradation rates of the six different building fabric components shown in Table 14.

One of the primary promoters of the degradation of external claddings is exposure to damp (Silva *et al.*, 2012; Menzies, 2013; Galbusera *et al.,* 2014; Jardim *et al.,* 2019; Serralheiro *et al.,* 2017; Silva *et al.,* 2016). In this study, exposure to damp because of relative humidity and precipitation is analysed.

Solar exposure is another important factor in the durability of many organic materials used in dwelling construction. Photodegradation is initiated by UV photons in sunlight and generally involves chemical reactions with atmospheric oxygen and/or water vapor, leading to brittleness. Elevated temperatures, such as those caused by solar absorption in dark materials, also lead to acceleration of harmful chemical reactions (Berdahl *et al.,* 2008).

Table *14*: Building fabric components included in the building fabric analysis along with the climate variables that impact each component's longevity

Building Fabric Component #	Materials or Component	Impact from Climate Variables			Service Life
		Solar	Relative Humidity	Damp	
1	Roof Tiles (clay/slate/concrete)	x	x	x	30
2	Walls (brick/stone)		x	x	70
3	Render & Mortar (lime/cement)	x	x	x	50
4	Masonry Paint	x	x	x	20
5	Sealant	x		x	20
6	Window & Door Frames	x		x	20

Per the ISO 15686 Factor Method procedure (BSI, 2011), adjusted service life factors were calculated based on exposure to each climate variable (quantified as the change from baseline) for each building fabric component. Factors were then applied to baseline service life values as published in the British Standard 7543 (BSI, 2015) to find the adjusted service life under projected climate conditions.

Three separate adjusted service lives were calculated, one for each climate variable, which were then used to calculate the percent change in maintenance and/or replacement costs for each building component. Adjusted service life values from a combination of climate factors could not be calculated since degradation data was only available for each individual climate variable for each building component.

Noteworthy is that not all building components were affected by all three climate variables. Additionally, there are many climate variables that were not analysed that would likely have impacts on the durability of these building components. Similarly, there may be other building fabric components that were not analysed here, but that would be critical in a durability analysis of any given dwelling.

Climate Vulnerability Assessment Results

The six locations chosen for this analysis were selected for diversity of climate: locations from every corner of the country, from coastal to inland, and from sea level to higher elevation are represented. Locations are mapped in Figure 5 below.

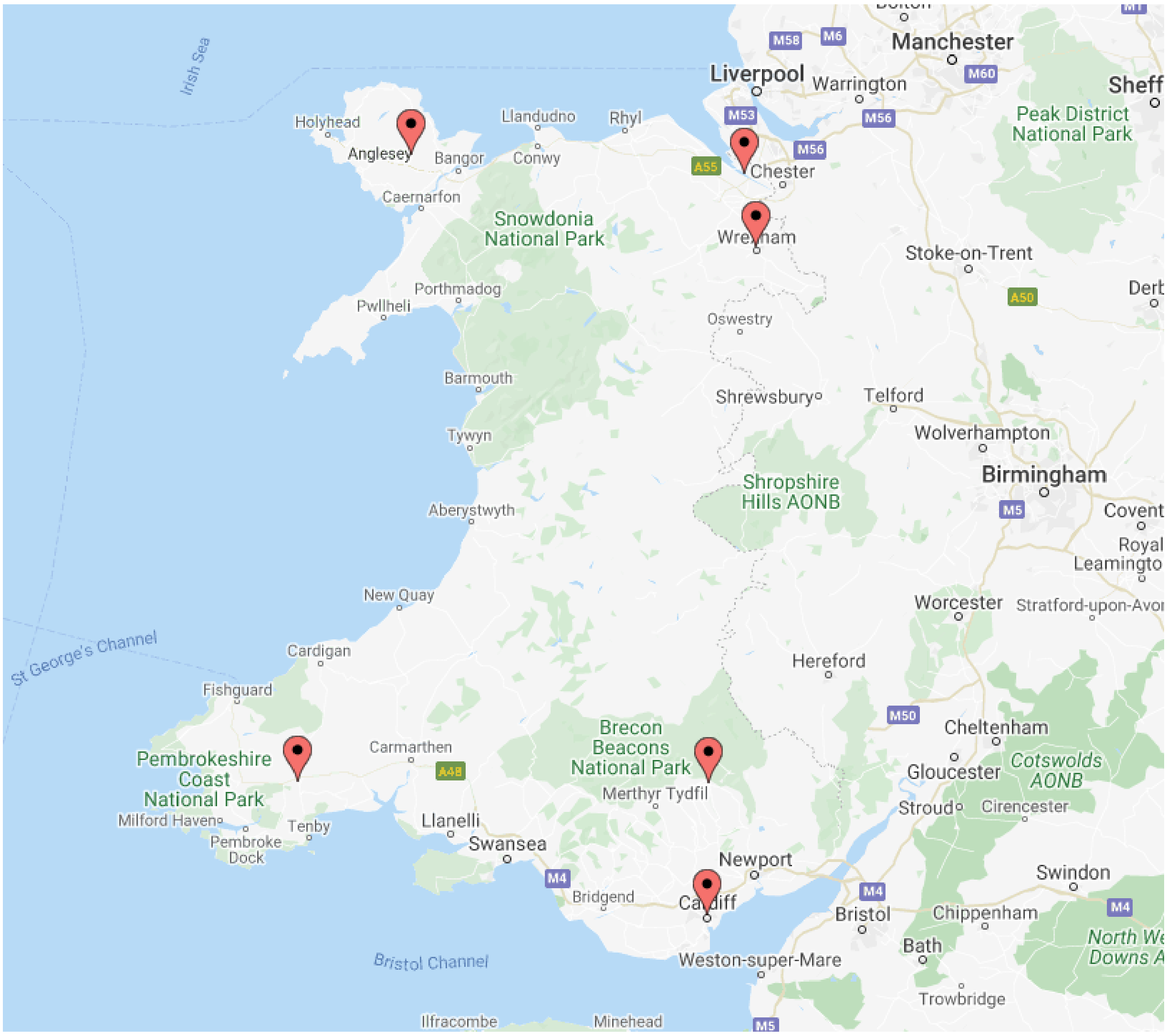

Figure 5: Cardiff, Narberth, Wrexham, Llangefni, Brynmawr, and Shotton are the six locations analysed

Indoor Environmental Vulnerabilities

Across all six locations, daily average and maximum temperatures are projected to increase from baseline (1981-2000) to the future projected periods of 2030 (2021-2040) and 2070 (2061-2080). Projected temperature trends are evident in Figure 6 below, 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. Please refer to Appendix C for temperature trends in the other locations. 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.

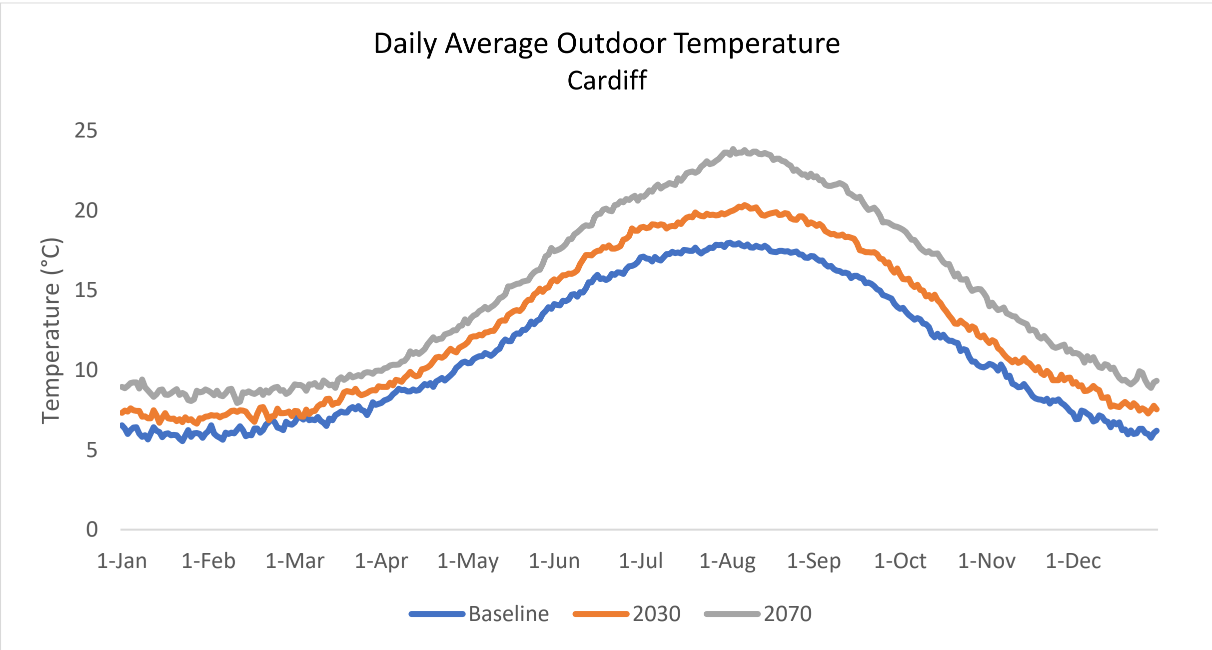

Figure 6: Annual profile of daily average outdoor temperature in Cardiff for baseline, 2030 and 2070

Daily average indoor and outdoor temperatures for the analysis period are shown in Figure 7 below. The increase in outdoor temperatures illustrated in the annual profile in Figure 6 can be seen, with temperatures in all locations steadily increasing from baseline to 2030 and 2070. Changes in outdoor temperature are further illustrated in Figure 8, 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.

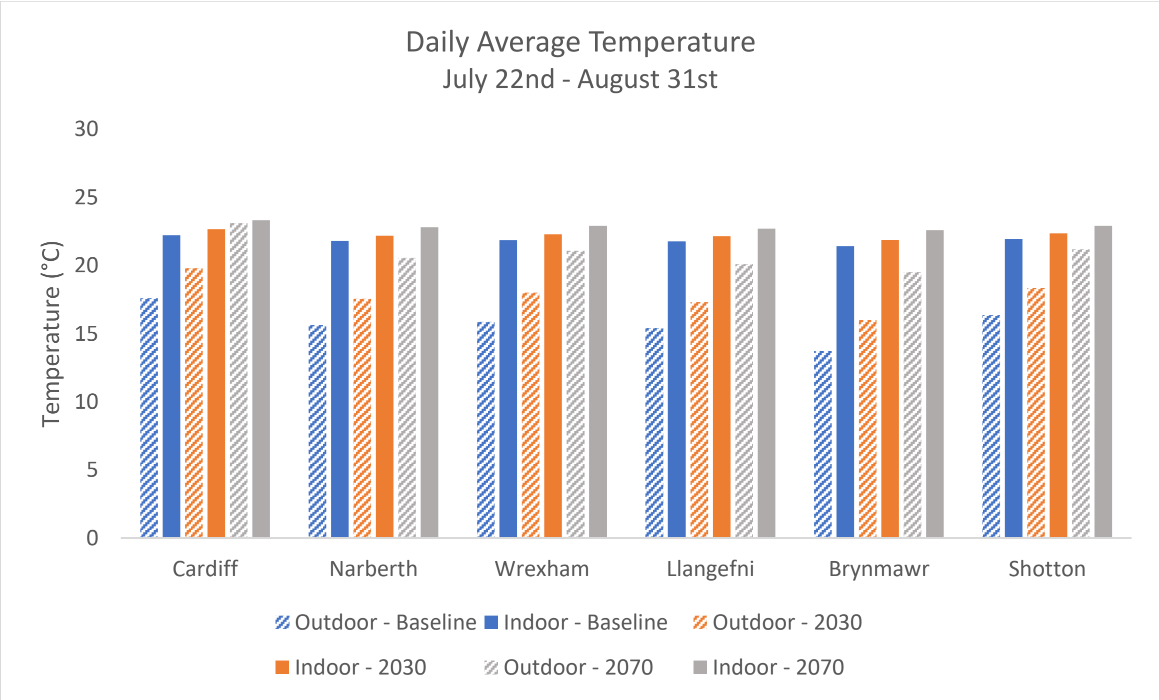

Figure 7: Indoor and outdoor daily average temperature averaged over the study period for six locations throughout Wales for baseline, 2030 and 2070

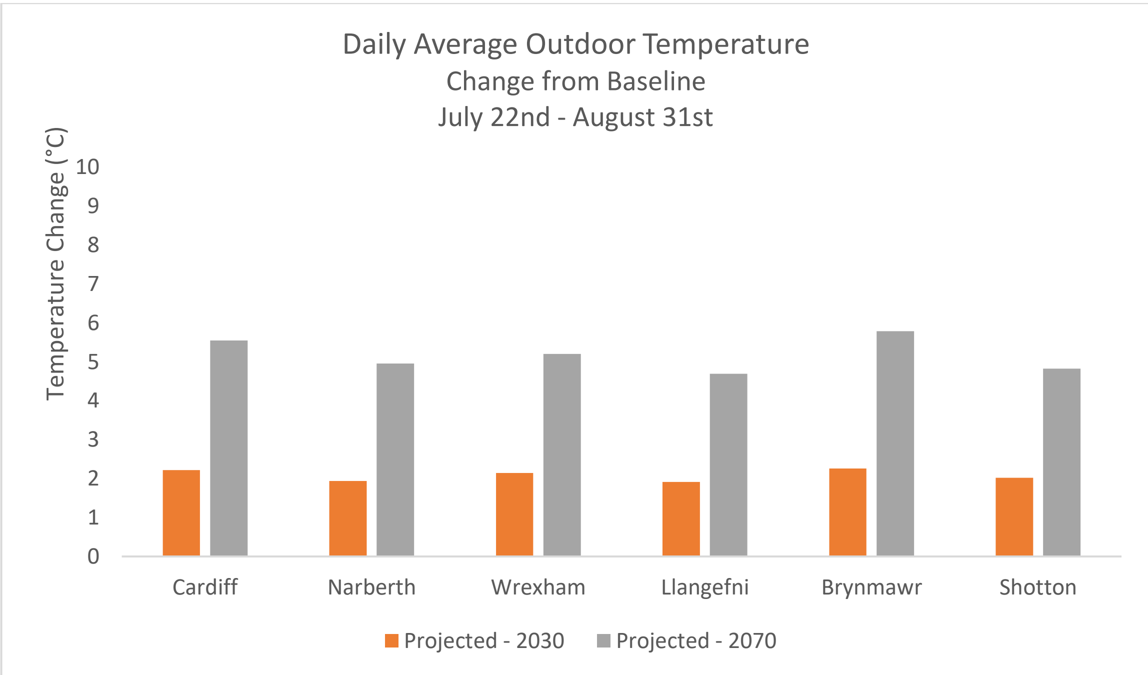

Figure 8 Change in outdoor average daily temperature averaged over the study period for six locations throughout Wales for 2030 and 2070

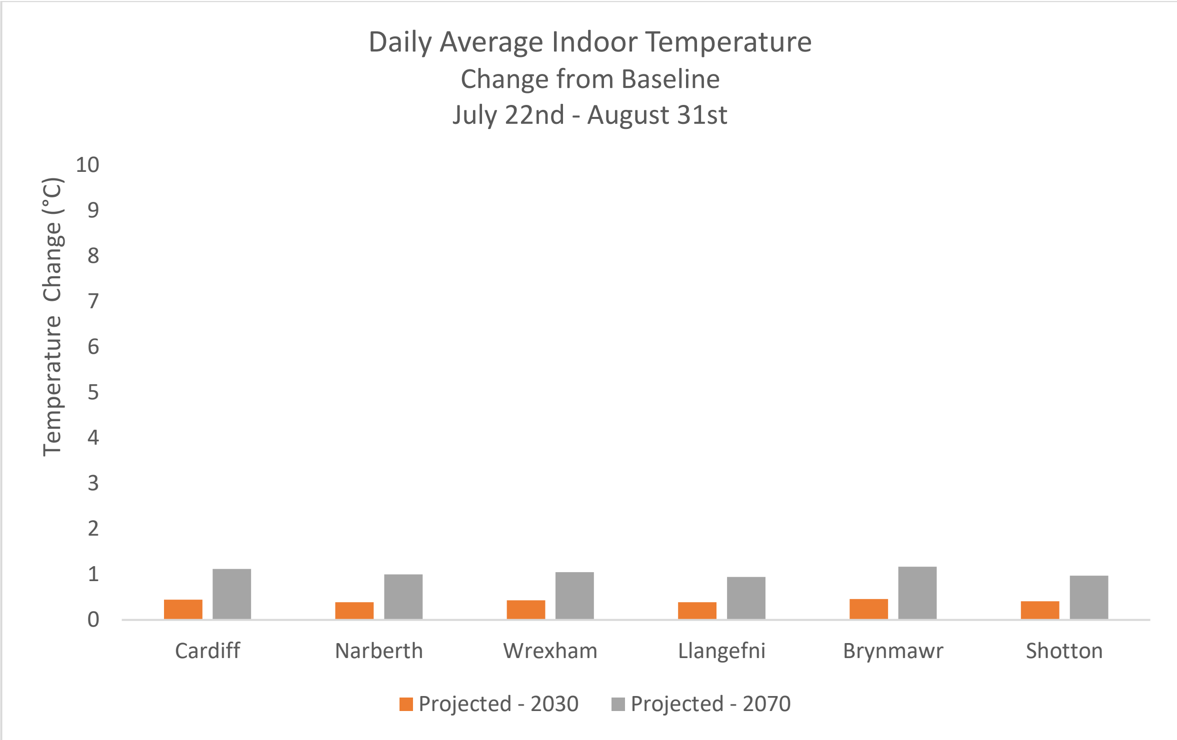

Figure 9 Change in indoor average daily temperature averaged over the study period for six locations throughout Wales for 2030 and 2070

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 Figure 9. As Figure 10 shows, the average daily indoor temperature is greater than the average daily 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 and dwellings built after 1990, which demonstrate higher interior temperatures than average. Variation by dwelling type will be discussed in a later section.

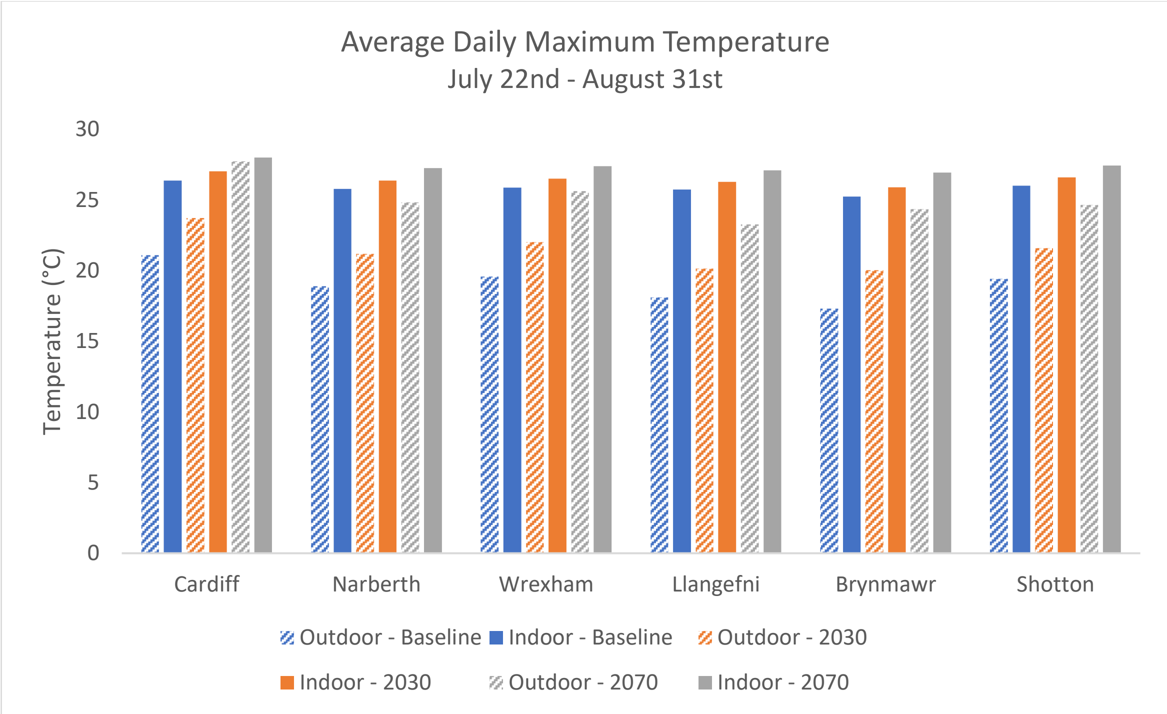

Figure 10: Indoor and outdoor daily maximum temperature averaged over the study period for six locations throughout Wales for baseline, 2030 and 2070

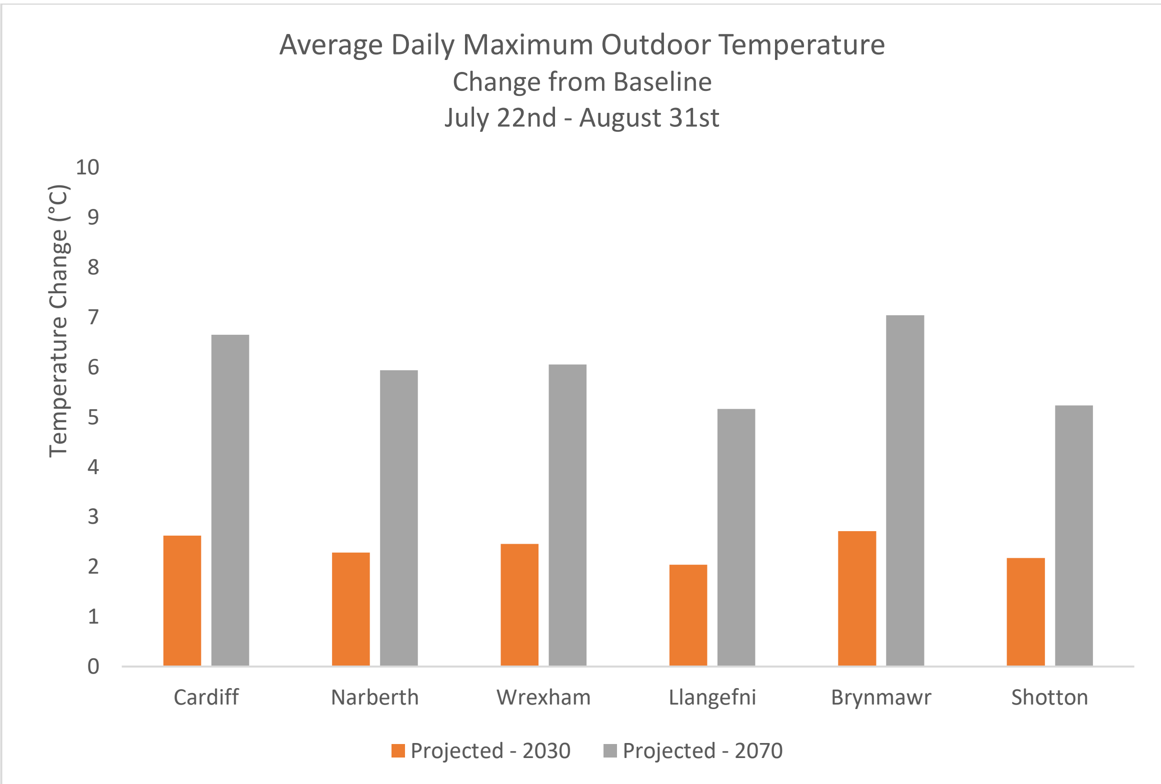

Figure 11: Change in outdoor maximum daily temperature averaged over the study period for six locations throughout Wales for 2030 and 2070

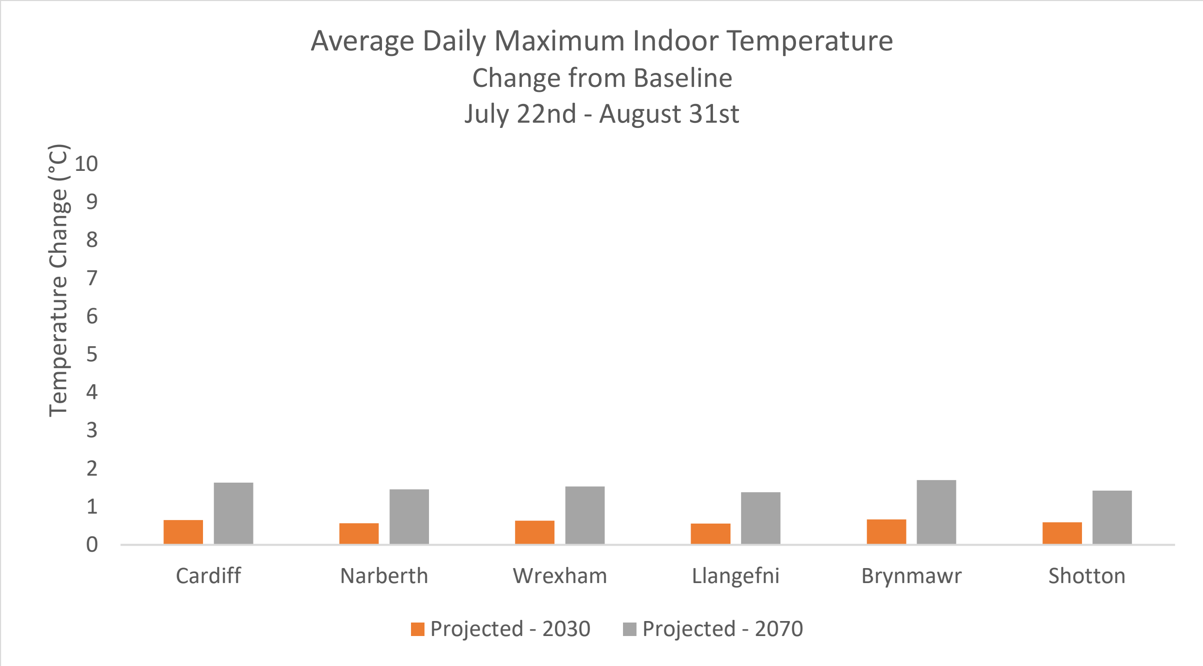

Figure 1: Change in indoor maximum daily temperature averaged over the study period for six locations throughout Wales for 2030 and 2070

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 (Figures 11 and 12). 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 Figure 12. Figure 10 illustrates the higher daily maximum temperatures experienced indoors when compared to outdoors.

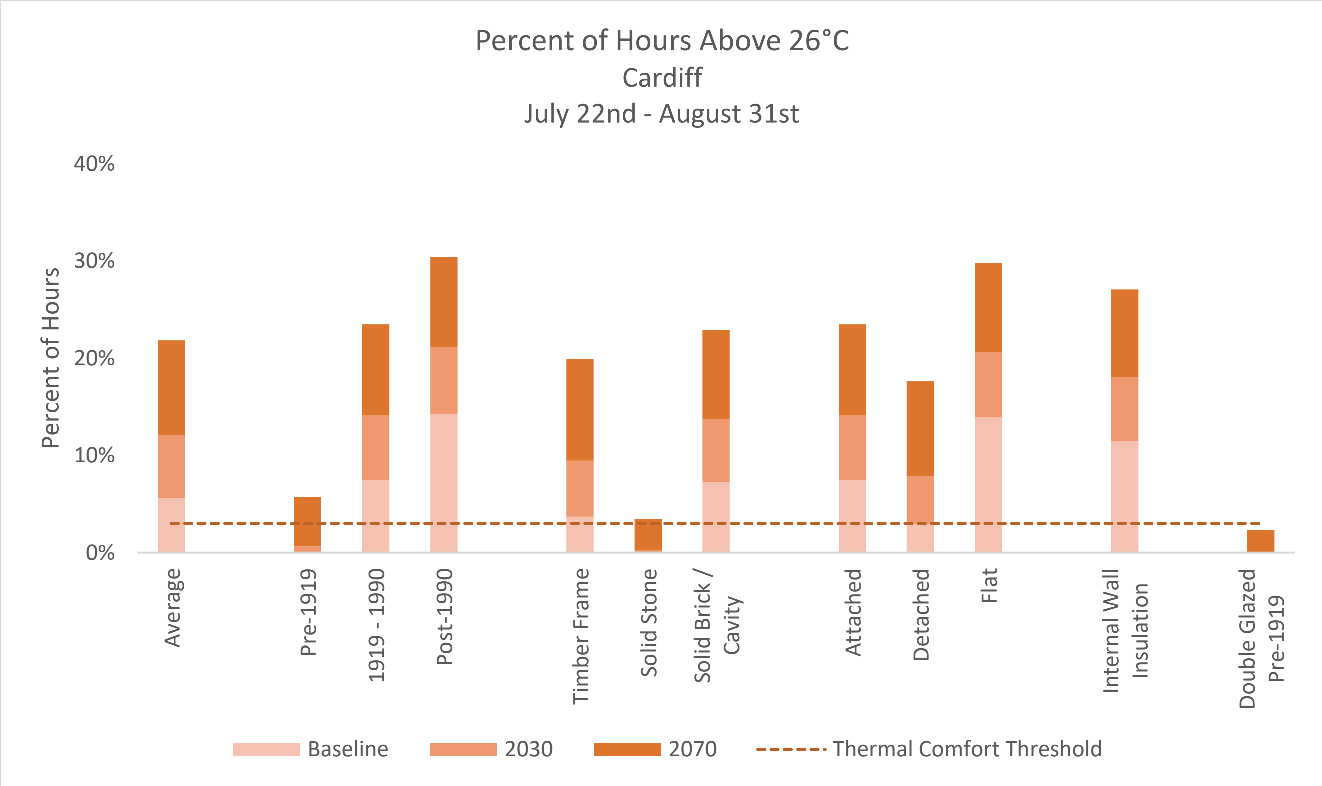

Figure 13: Percent of hours in the study period over 26°C threshold for thermal comfort. Values shown for the average building and eleven building classes. 3% of occupied hours threshold shown for reference.

Hours above the overheating threshold of 26°C were then tallied as shown in Figure 13. 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 Figures 9 to 11. Similarly, the percent of hours that exceed the thermal comfort threshold may decrease from what is shown in Figure 13.

Differences in thermal comfort and overheating by building class are immediately apparent, with higher fabric heat loss likely correlating to lower overall temperatures. Older homes generally exhibited lower temperatures, especially those built before 1919. This is likely due to the greater amount, and increased effectiveness, of insulation used in the construction of newer homes. A similar observation can be made that homes with solid stone walls, which correlate with pre-1919 homes, and which demonstrate markedly cooler temperatures than do homes with timber frame, solid brick, and cavity walls. This is also likely due to 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 flats on the top level of the building typically demonstrate a greater tendency to exceed overheating thresholds than did flats on lower levels (Beizaee *et al.,* 2013). Along these same lines, 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 (Mavrogianni *et al.,* 2012).

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. While the Northwest and Southwest locations of Llangefni and Narberth have the highest baseline daily average relative humidity, at 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).

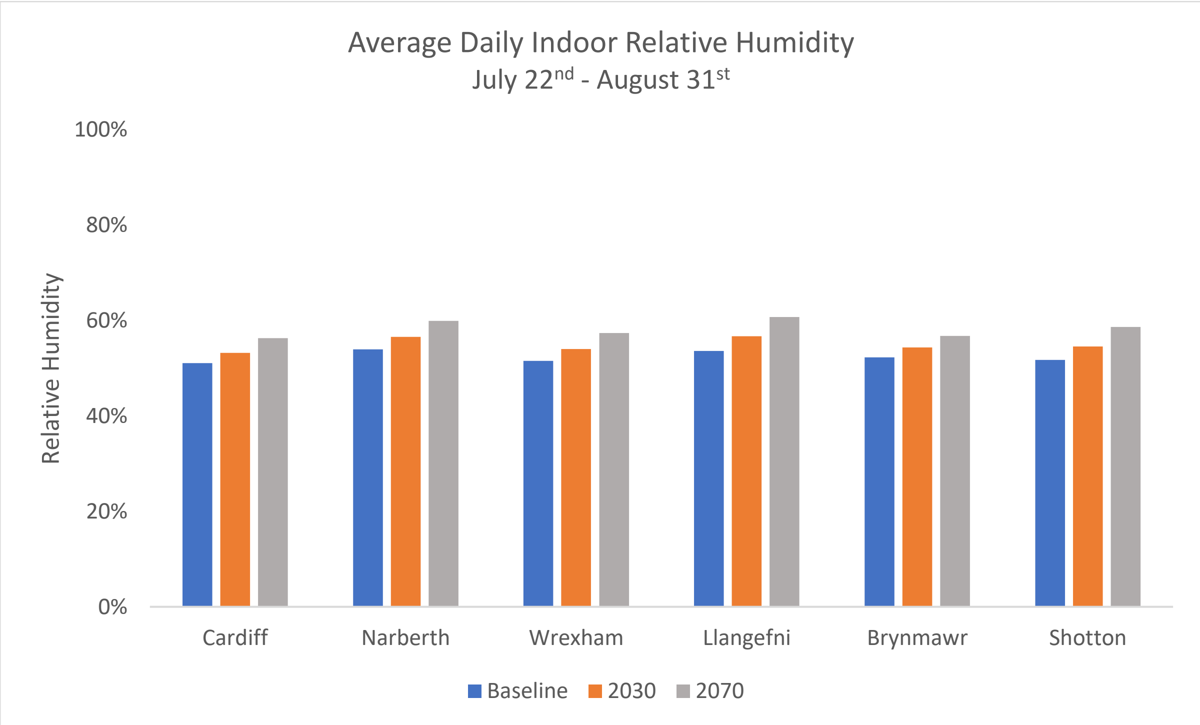

Figure 14: Indoor daily average relative humidity averaged over the study period for six locations throughout Wales for baseline, 2030 and 2070

Daily maximum relative humidity values are also projected to increase across all six study locations, although by a larger margin. 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.

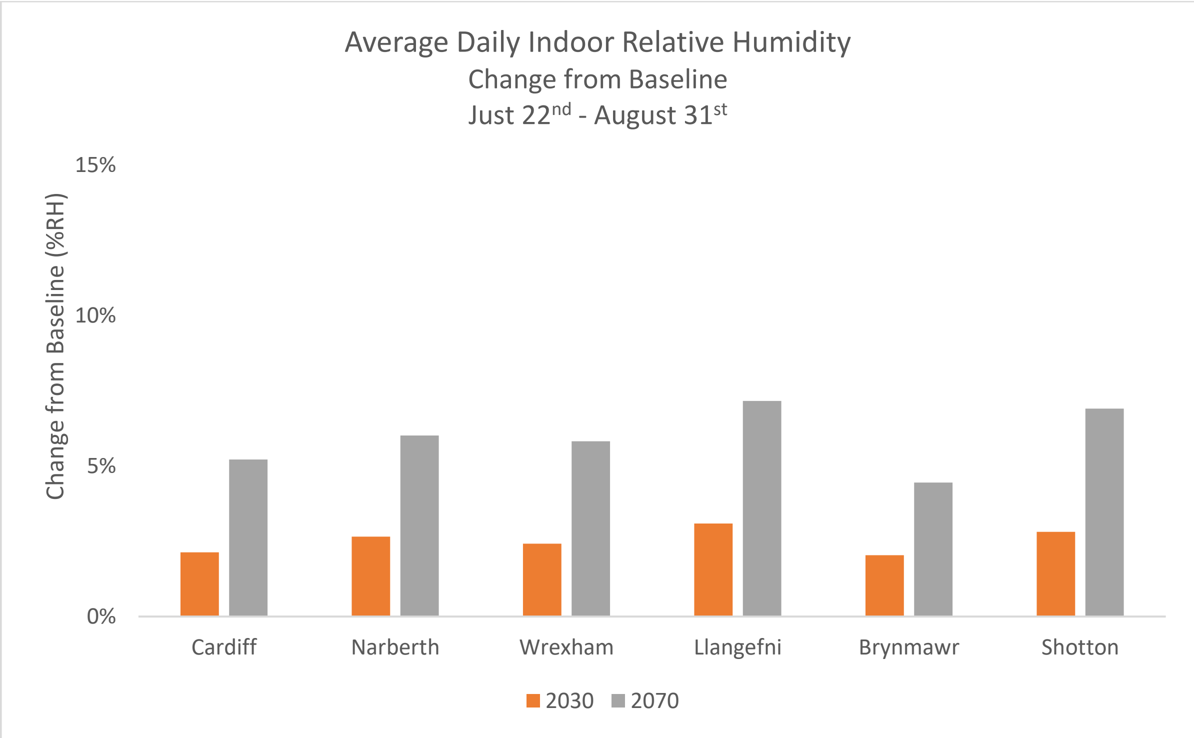

Figure 15: Change in indoor average daily relative humidity averaged over the study period for six locations throughout Wales for 2030 and 2070

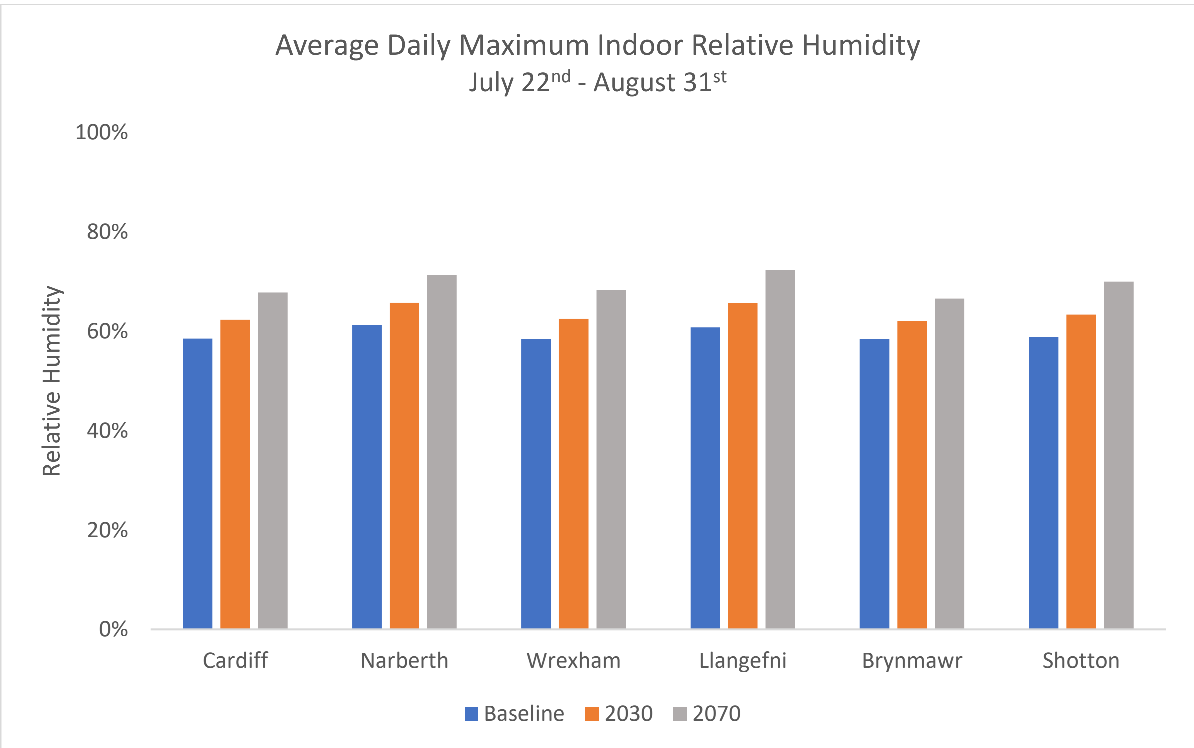

Figure 16: Indoor daily maximum relative humidity averaged over the study period for six locations throughout Wales for baseline, 2030 and 2070

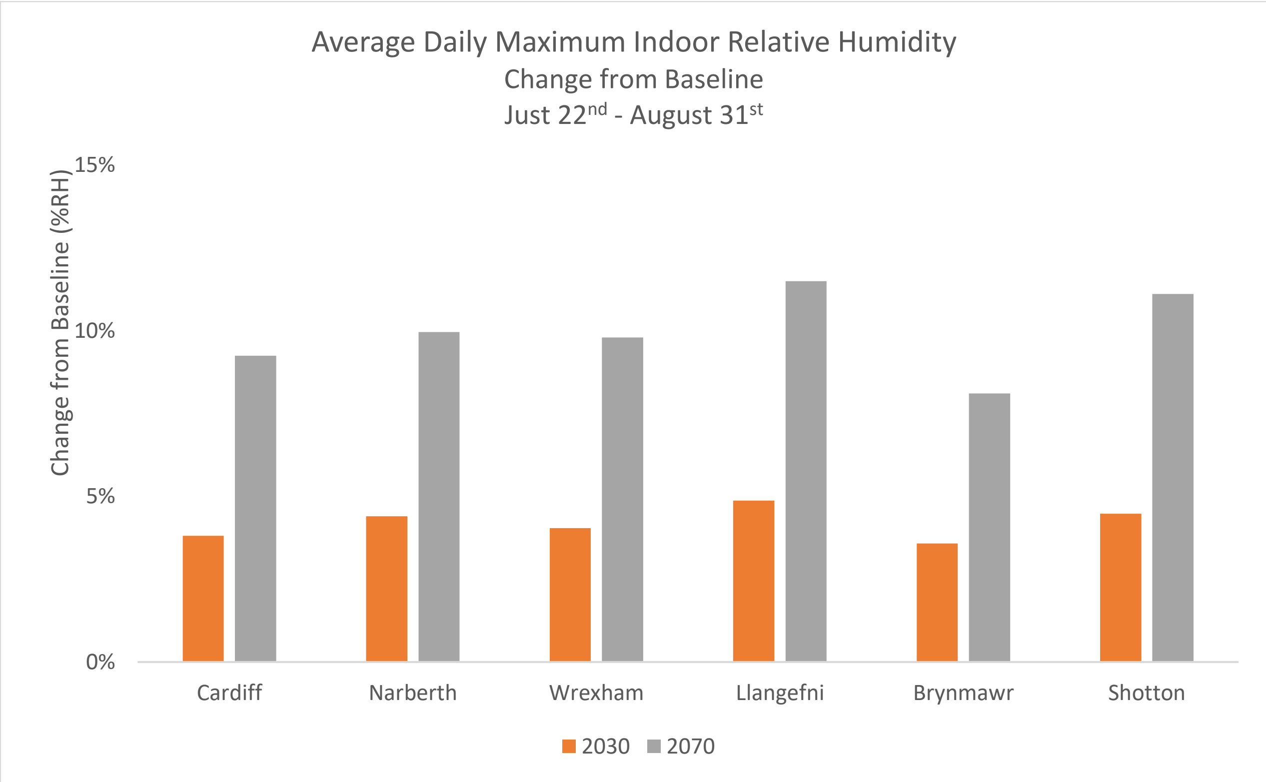

Figure 17: Change in indoor maximum daily relative humidity averaged over the study period for six locations throughout Wales for 2030 and 2070

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 shown in Figure 18. Please refer to Appendix C for results for the other five locations). The same cannot be said for daily maximum indoor relative humidity, which breaches the 60% threshold for eleven out of twelve building classes by 2030 and for all building classes by 2070.

By age, newer homes built after 1990 are predicted to have the lowest relative humidity. Timber frame homes and flats also perform best 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. This is partially because all building classes have the same specific humidity (since there are no building class adjustments for specific humidity) that is 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.

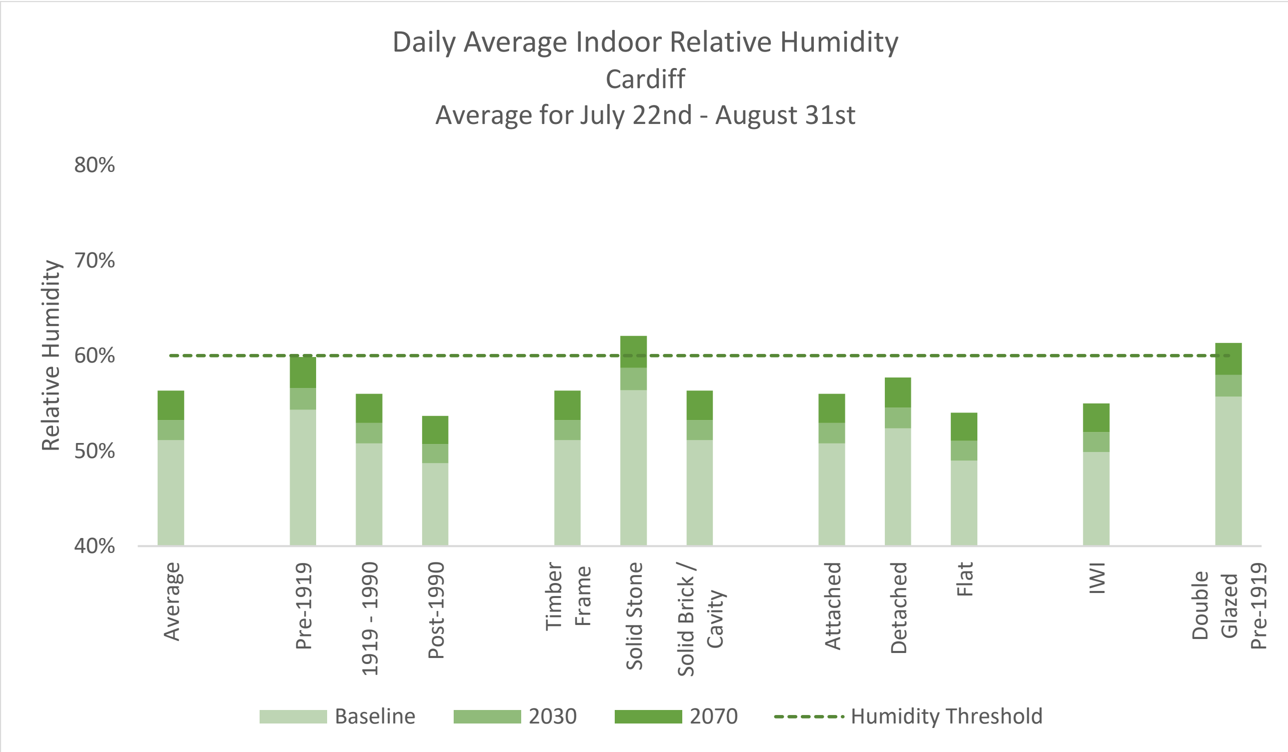

Figure 18: Indoor daily average relative humidity averaged over the study period in Cardiff
60% relative humidity threshold shown for reference

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. As identified in the literature review, predicting mould growth is an imperfect science 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 in Figures 18 or 19, 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.

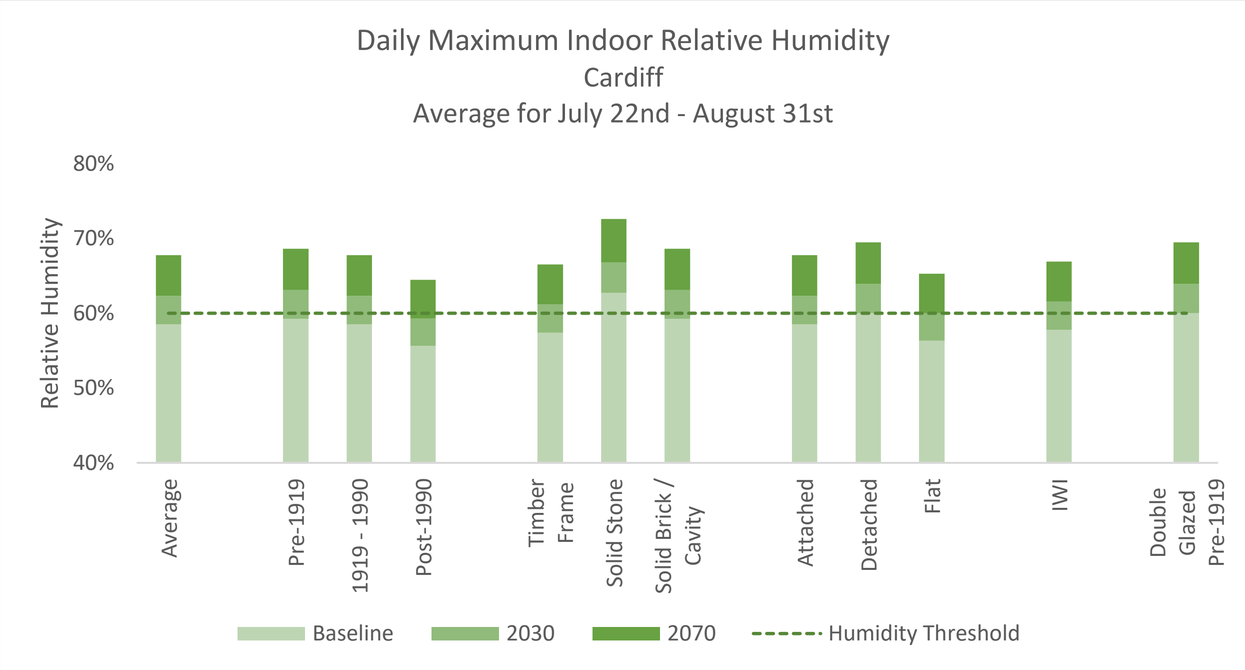

Figure 19: Indoor daily maximum relative humidity averaged over the study period in Cardiff 60% relative humidity threshold shown for reference

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 (Figure 18) and maximum (Figure 19) daily relative humidity exceeds the indoor air quality threshold of 60%. Figure 20 and Figure 21 give an indication of the duration over the study period that 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% other indoor environmental quality threshold until 2070, Figures 20 and 21, illustrate 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 the baseline period, and for 73% of days by 2070. This may indicate a risk for mould growth but also for acute indoor environmental quality related problems that do not depend on extended durations of favourable conditions.

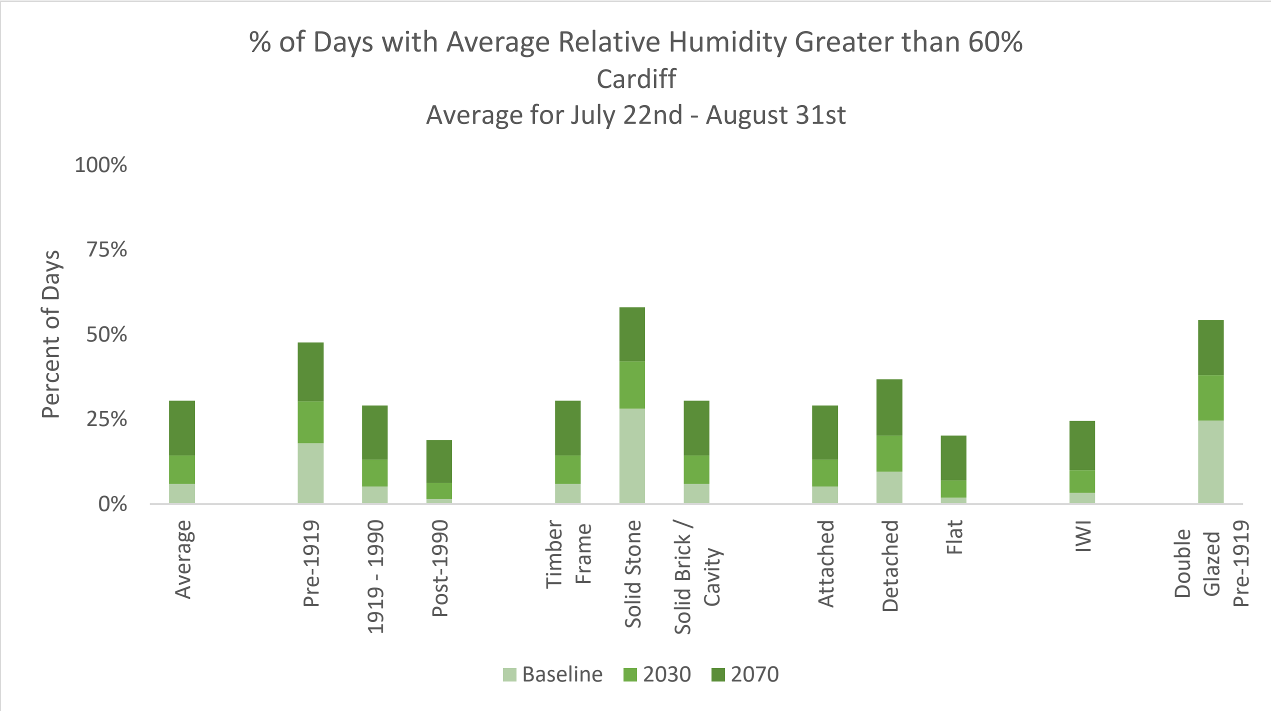

Figure 20: Percent of days in the study period with indoor daily average relative humidity above the 60% relative humidity threshold in Cardiff

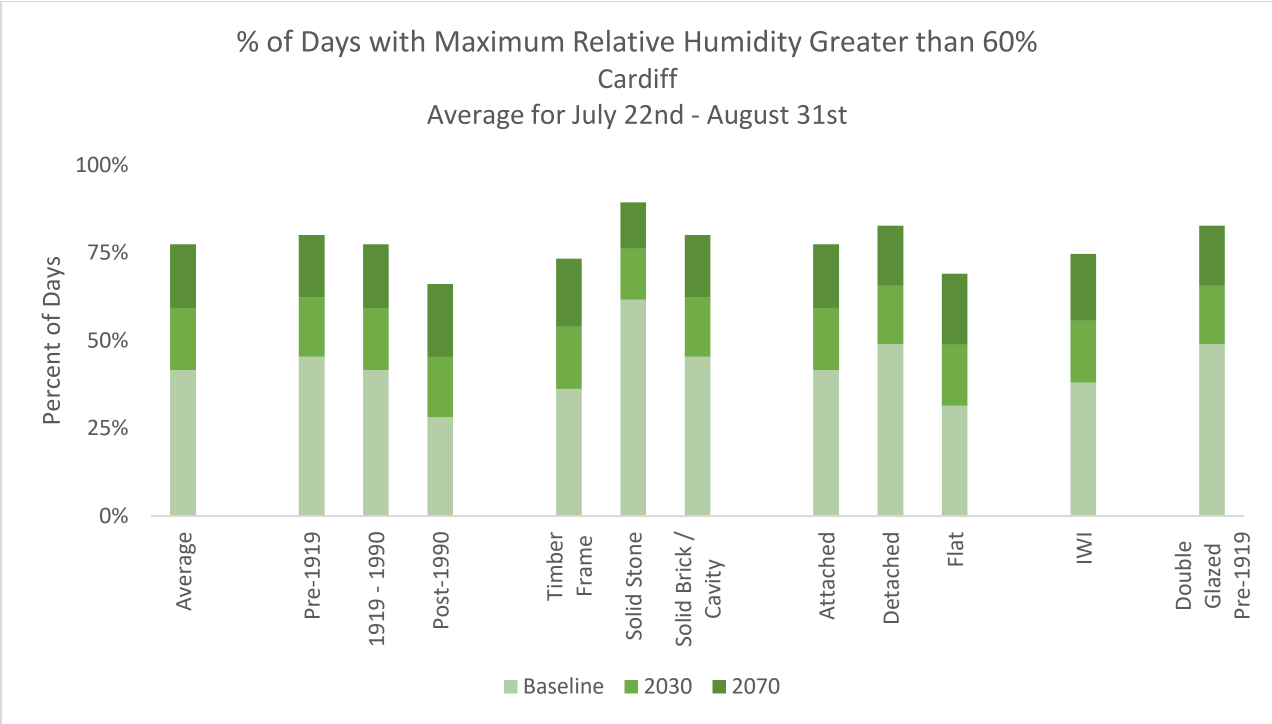

Figure 21: Percent of days in the study period with indoor daily maximum relative humidity above the 60% relative humidity threshold in Cardiff

Building Fabric Vulnerabilities

Whereas the indoor relative humidity is the result of psychrometric calculations involving temperature and specific humidity, the outdoor relative humidity values used in the building fabric portion of this study come from the UKCP18 climate data. The solar flux and precipitation data also come directly from the UKCP18 climate data.

The building fabric analysis is broken into three separate evaluations of vulnerability from solar exposure, from relative humidity and from precipitation. The analysis periods for the building fabric vulnerability metrics each include data for January 1st – December 31st.

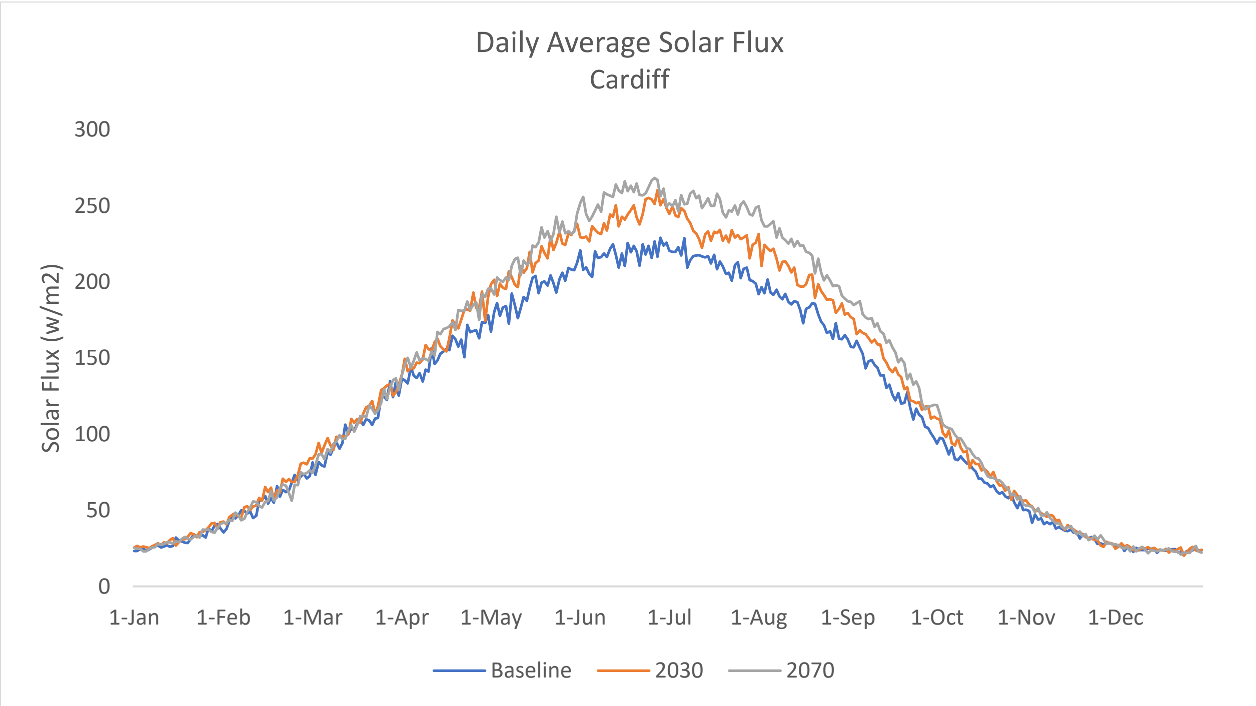

Figure 22: Annual profile of daily average solar flux in Cardiff for baseline, 2030 and 2070

All six locations experience the highest daily average solar flux in the warm months as demonstrated for Cardiff in Figure 22, and for the other locations in Appendix C. Looking forward to 2030 and 2070, the daily solar flux is projected to increase in all locations, with the largest changes from baseline expected in the warmer months from May to September. The daily solar flux, averaged over the whole year, is also projected to increase in all locations as shown in Figure 23.

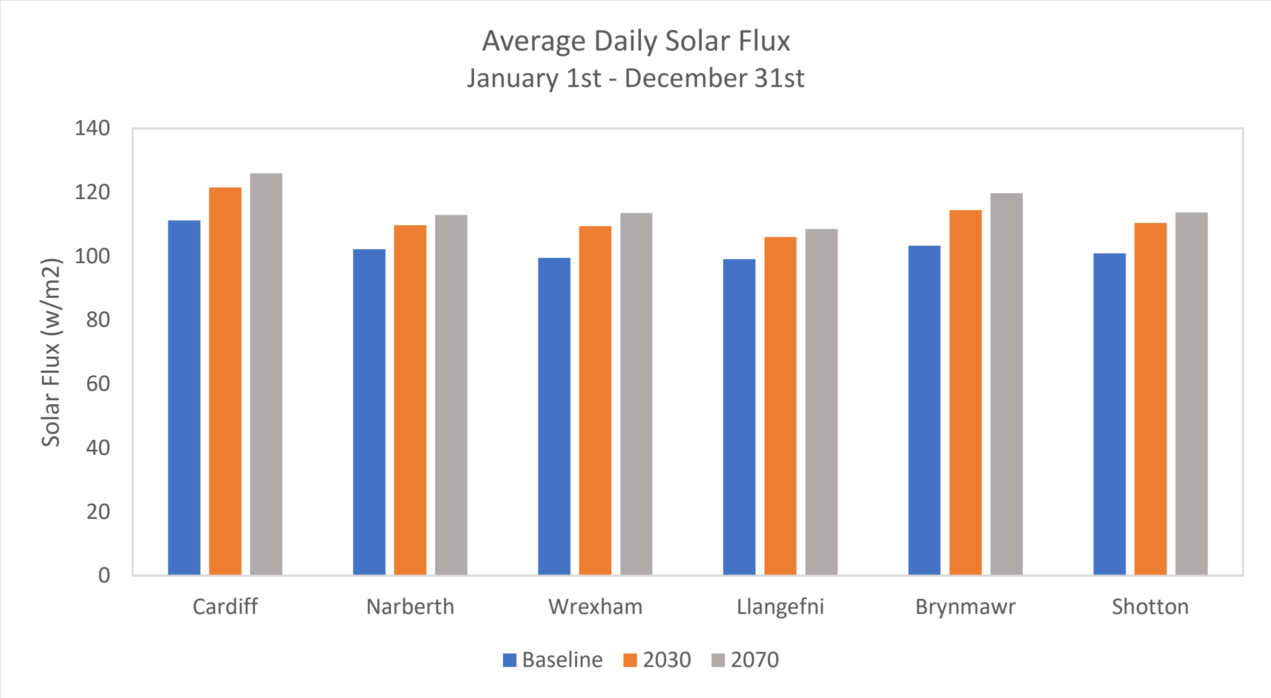

Figure 23: Daily average solar flux averaged over the study period for six locations throughout Wales for baseline, 2030 and 2070

Brynmawr is projected to see the greatest increase in average daily solar flux, with an 11% increase from baseline by 2030 and a 16% increase by 2070. Even Llangefni, the location with the least pronounced increase is still projected to experience a 7% increase from baseline by 2030 and a 10% increase from baseline by 2070.

Across all six locations the daily average relative humidity is highest in the winter months and lowest in the summer months. This is demonstrated for Cardiff in Figure 25, and for the other locations in Appendix C. As can be seen for Cardiff, and which holds true for all locations, is that the largest relative humidity changes from baseline to 2030 and 2070 are seen in the warmer months from May to September. During this period the relative humidity is projected to decrease from baseline.

While the biggest change is in the summertime relative humidity, the daily relative humidity, is also projected to decrease when averaged over the whole year, as shown in Figures 26 and 27.

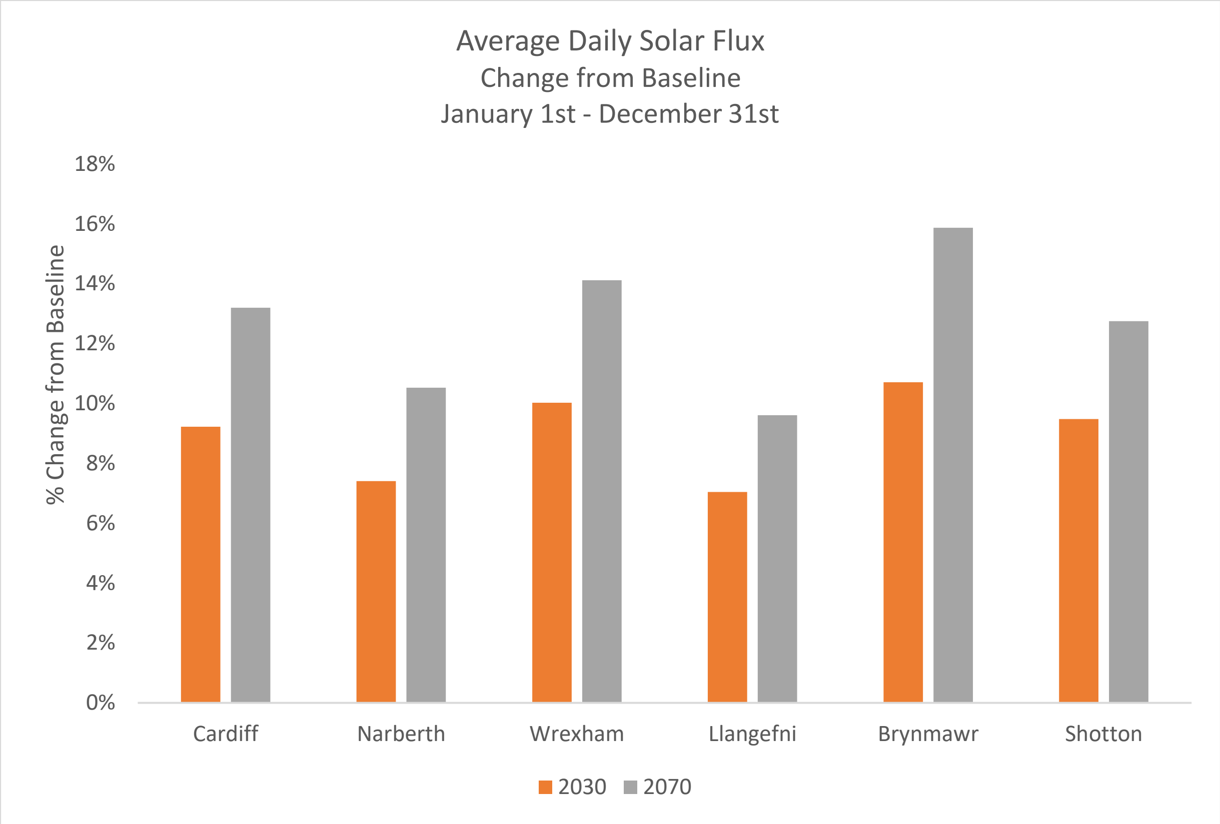

Figure 24: Change in average daily solar flux averaged over the study period for six locations throughout Wales for 2030 and 2070

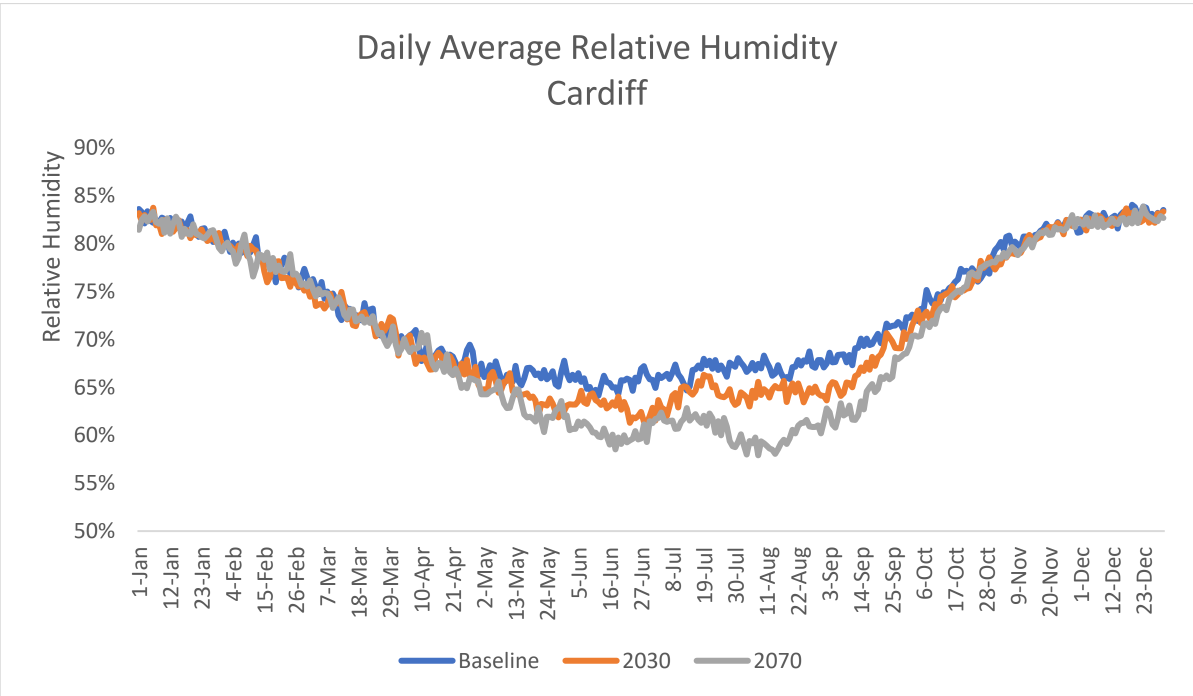

Figure 25: Annual profile of daily average outdoor relative humidity in Cardiff for baseline, 2030 and 2070

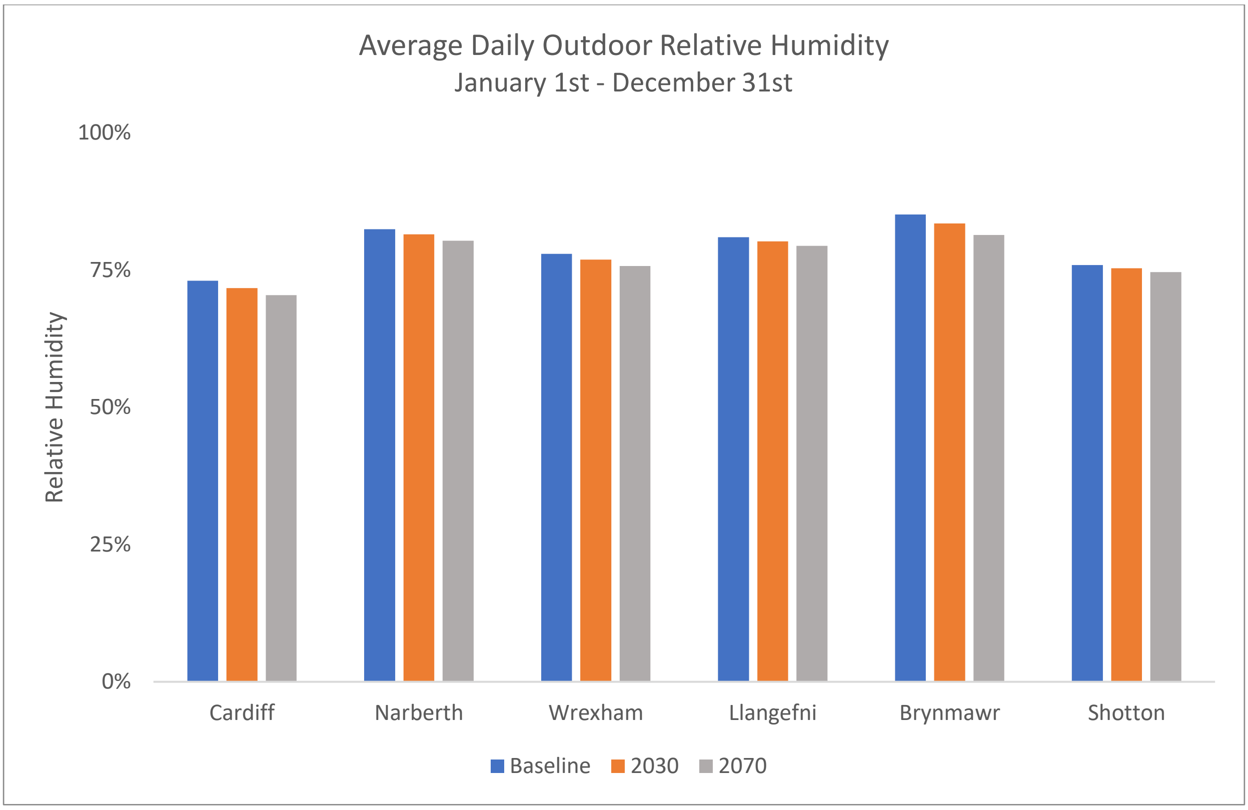

Figure 26: Daily average outdoor relative humidity averaged over the study period for six locations throughout Wales for baseline, 2030 and 2070

The biggest decrease in average daily outdoor relative humidity is projected in the high elevation location of Brynmawr, with a 1.6% decrease by 2030 and a 3.7% decrease by 2070.

Precipitation trends exhibit a more varied set of projections by location and time period. In general, the wettest times of year across all locations are the colder months as seen in Figure 28 for Cardiff. Looking forward to 2030 and 2070 the colder months are projected to see an increase in precipitation, while the warmer months are projected to see a decrease in precipitation.

However, on an annual scale, the trends are not as unanimous across locations as they are for the other climate variables. Cardiff, Narberth, Llangefni and Brynmawr are projected to experience an increase in annual precipitation by 2030 and then another increase by 2070. Conversely, in 2030 Wrexham is projected to see 0.7% more annual precipitation than baseline, but 1.7% less annual precipitation than baseline come 2070. Furthermore, Shotton' s annual precipitation is projected to stay close to baseline levels for both projections, with a 0.6% increase from baseline by 2030 followed by a drop to 0.2% above baseline by 2070.

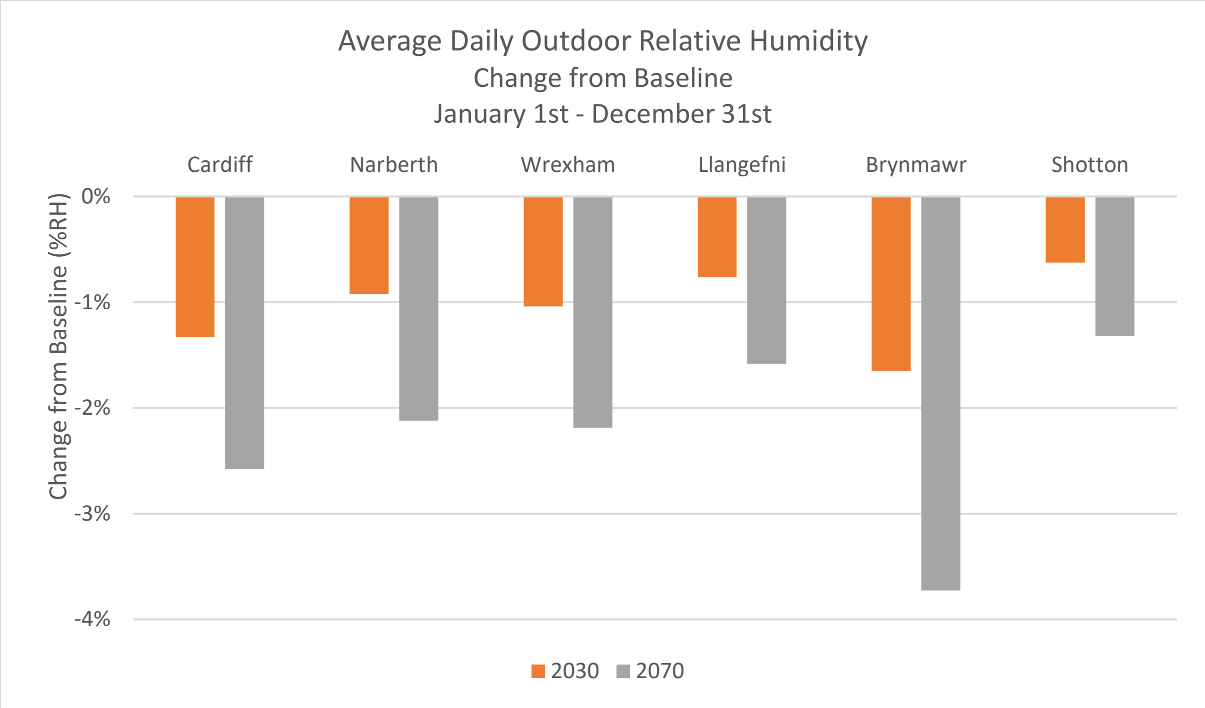

Figure 2: Change in average daily outdoor relative humidity averaged over the study period for six locations throughout Wales for 2030 and 2070

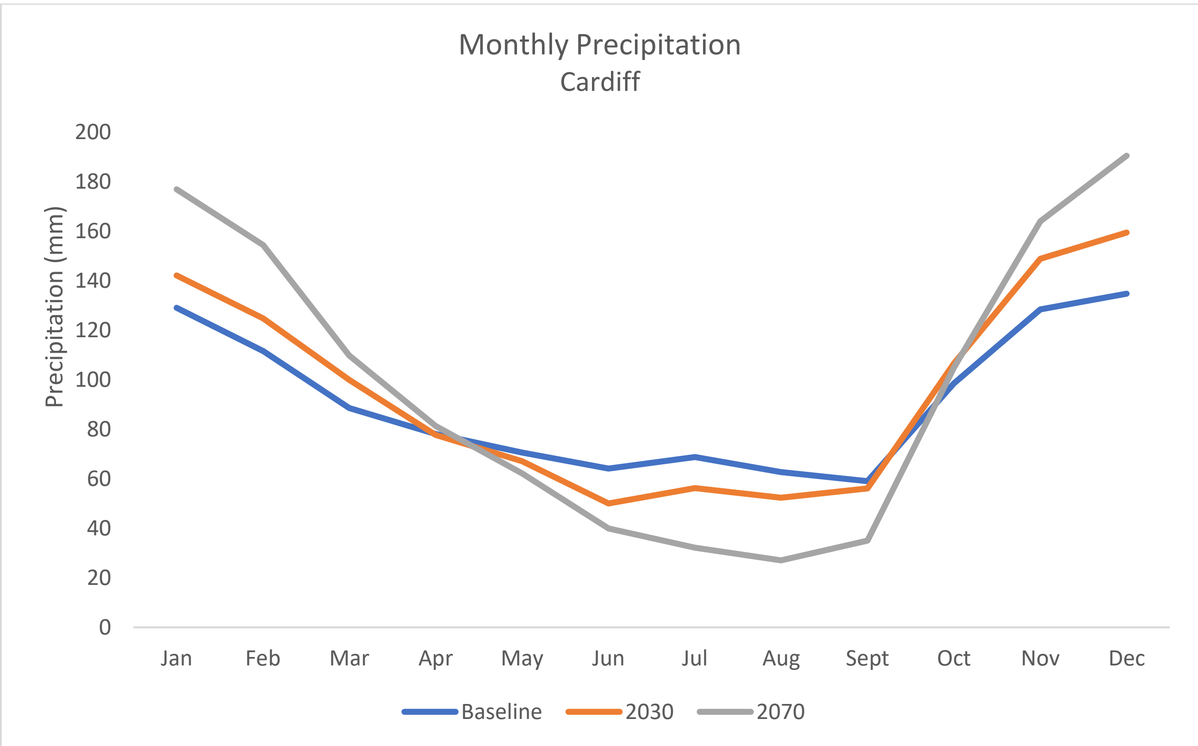

Figure 3: Annual profile of average monthly precipitation in Cardiff for baseline, 2030 and 2070

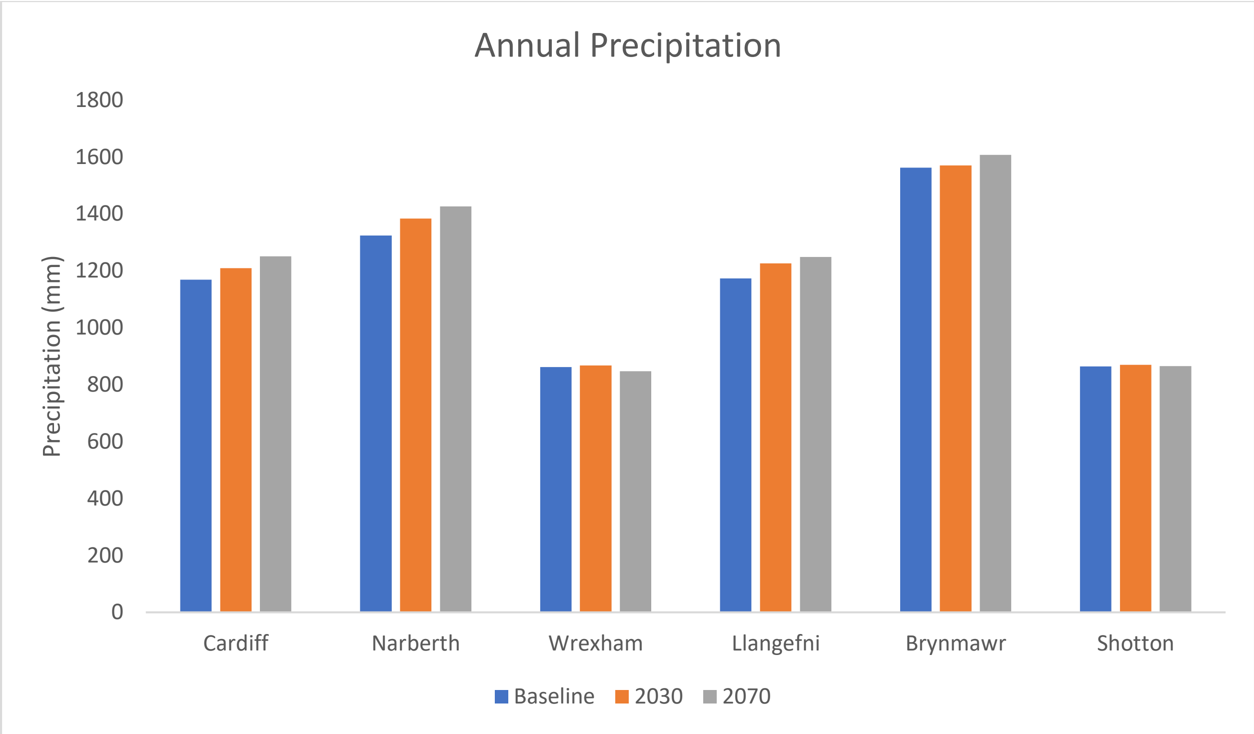

Figure 29: Average annual precipitation for six locations throughout Wales for baseline, 2030 and 2070

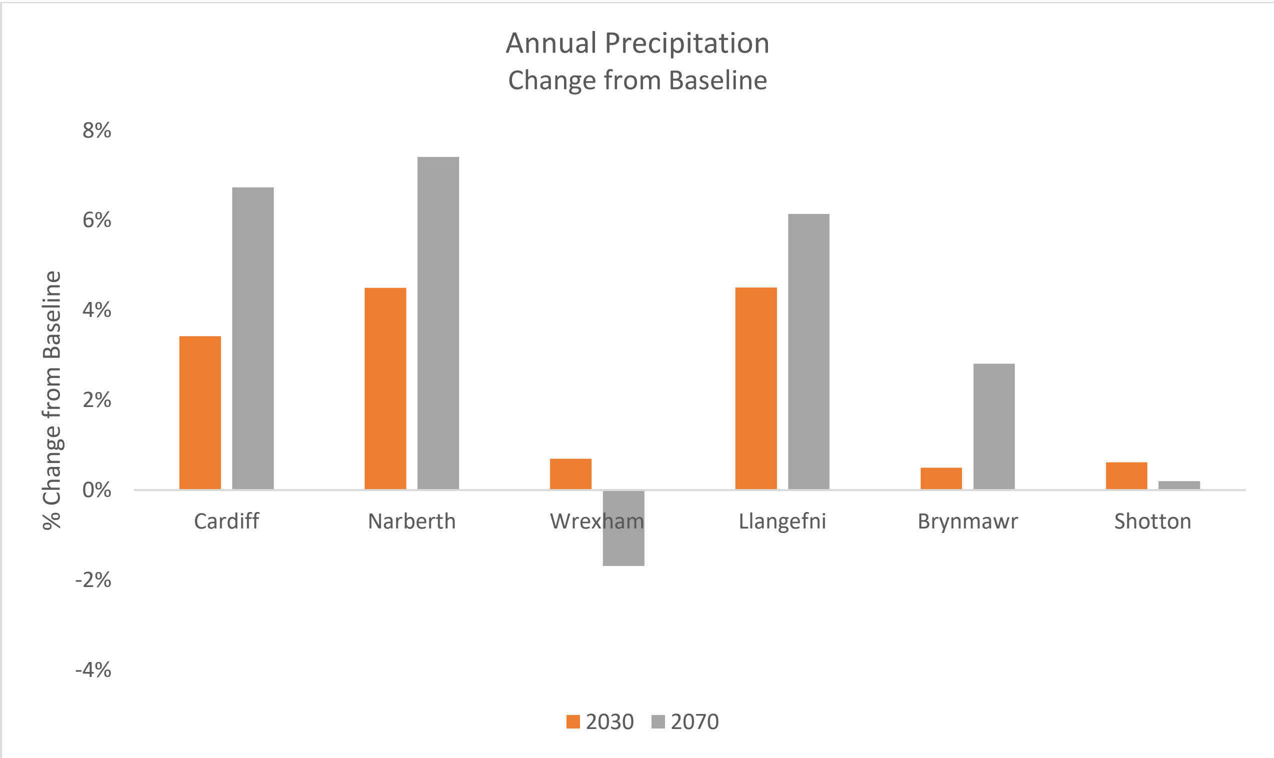

Figure 30: Change in average annual precipitation for six locations throughout Wales for 2030 and 2070

Overall, Narberth is projected to experience the greatest increase in annual precipitation, with a 4.5% increase from baseline by 2030 and a 7.4% increase from baseline by 2070. This, while Wrexham is expected to see a 0.7% increase from baseline by 2030, followed by a decrease to 1.7% below baseline by 2070.

Table ***12*** presents the forecast level of deterioration and adjusted service lives for five building fabric components. No data was available for degradation of the sixth building fabric component, sealants, from the three climate variables. The forecast level of deterioration for each climate variable is deemed "High" if the resulting adjusted service life for a given climate variable is projected to be lower than baseline, and "Low" if it is projected to be higher than baseline. The level of deterioration for each climate variable is rolled into a single forecast level of deterioration, as shown in column five of **Table *12***, which is deemed "Mild" if only one of the three climate variables shows "High" deterioration, "Moderate" if two show "High", and "Severe" if all three show "High".

The adjusted service life values are calculated using the solar flux, relative humidity and precipitation climate projections presented above. Percentage change from baseline costs represent the costs associated with the change in the number of replacements that are projected to be necessary in comparison to the baseline service life of the given building component. Blank spaces correspond to building components that were not found to be impacted by the corresponding climate variable.

Table *12*: Results for building fabric degradation analysis for Cardiff showing deterioration classification, adjusted service life, and change in cost for 2030 and 2070

Building Fabric Degradation Results for: Cardiff													
Material / Component	Solar Flux	Relative Humidity	Precipitation	Forecast Level of Deterioration	Baseline Service Life	Adjusted Service Life Change from Baseline (Years)				Change from Baseline Cost			
						Solar Flux	Relative Humidity	Precipitation	Total	Solar Flux	Relative Humidity	Precipitation	Total
2030													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.9	1.1	-0.3	-1.1	6.7%	-3.6%	1.1%	4.2%
Walls (brick/stone)		Low	High	Moderate	70		2.6	-0.7	1.8		-3.6%	1.1%	-2.5%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-3.1	1.8	-0.5	-1.8	6.7%	-3.6%	1.1%	4.2%
Masonry Paint	High	Low	High	Moderate	20	-1.3	0.7	-0.2	-0.7	6.7%	-3.6%	1.1%	4.2%
Window & Door Frames	High		High	Severe	20	-1.3		-0.2	-1.5	6.7%		1.1%	7.7%
2070													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.9	1.3	-0.6	-1.2	6.7%	-4.3%	2.1%	4.5%
Walls (brick/stone)		Low	High	Moderate	70		3.1	-1.5	1.7		-4.3%	2.1%	-2.1%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-3.1	2.2	-1.0	-1.9	6.7%	-4.3%	2.1%	4.5%
Masonry Paint	High	Low	High	Moderate	20	-1.3	0.9	-0.4	-0.8	6.7%	-4.3%	2.1%	4.5%
Window & Door Frames	High		High	Severe	20	-1.3		-0.4	-1.7	6.7%		2.1%	8.8%

In Cardiff, solar flux and precipitation are projected increase from baseline to 2030, and then again from 2030 to 2070. This leads to adjusted service lives for these two climate variables in 2030 and

2070 that are lower than the baseline, and replacement costs that are higher than baseline. Conversely, relative humidity in Cardiff is projected to decrease, which leads to increases in adjusted service life and a decrease in replacement costs. Similar tables for the other five locations can be found in Appendix C.

The totalled values across all applicable climate variables for a given building fabric component, shown in columns 10 and 14 of
Table ***12***, give an indication of how that component may fare under the combined stresses of the climate variables. For example, by 2030 the roof tile service life is projected to decrease by 1.9 years as a result of increased solar flux degradation, increase 1.1 years as a result of decreased relative humidity, and decrease 0.3 years as a result of increased precipitation. These service life changes equate to a 6.7%, -3.6% and 1.1% change in in replacement costs, respectively. Totalling across the adjusted service life values for the climate variables applicable to roof tiles gives an estimated decrease in adjusted service life of 1.1 years, indicating an overall trend towards a decreased service life when all climate variables are considered. It is important to note that degradation data is only available as it pertains to single climate variables, and not for the impact of multiple climate variables simultaneously. For this reason, totalling the change in service life and cost across each climate variable simply gives an indication of impact trends, while more work is needed to accurately assess the impact from the combination of climate variables.

Window and door frames are most vulnerable since both climate variables that impact their degradation rate show trends of increasing into 2030 and 2070. This results in a 1.5-year loss in service life and 7.7% increase in replacement costs in 2030, increasing to 1.7 years and 8.8% in 2070.

Climate vulnerability modelling limitations

This study aims to inform a deeper understanding of the vulnerability of the Welsh housing stock to a changing climate. 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 covered in the sections above, while those that have not been previously covered are discussed in this section.

Indoor temperature calculated as a function of outdoor temperature 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 these pre-defined dwelling characteristics. Tailored temperature calculations cannot be performed for a dwelling's specific combination of construction materials, wall types, etc. Additionally, the monitoring study only reported three outdoor average temperature values: one for all 193 dwellings across 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-hour 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 (cooking, exercise, etc.) was not included in the monitored data and so is not included in this analysis. Rather, indoor specific humidity fluctuation was assumed to mimic the outdoor specific humidity fluctuation.

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 ASHRAE monthly 5% dry bulb design day as detailed previously.

A sub-assumption of using the ASHRAE specific humidity fluctuation values is that the specific humidity fluctuates on all days the same amount that it does on the 5% monthly design day and that this fluctuation will remain constant in the future time periods. Using a different design day range, such as the 50% monthly design day or the wet bulb (rather than dry bulb) design day, would likely result in a different specific humidity range.

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.

Data availability is also a limiting factor in the building fabric analysis. A building's exterior fabric is made up of many different materials, each uniquely impacted by a variety of climate variables. A group of six building fabric components were chosen in this study because of their prevalence in Welsh dwelling construction. However, even for this limited selection of building fabric components there is an absence of data on definitive climatic thresholds and the associated impact on durability if the threshold is breached. The published durability factors were defined for qualitative thresholds such as "moderate" or "severe" or, in the case of solar exposure, by compass orientation. As such, an adjusted service life factor of 0.9 was assigned each day for a given climate variable if it was projected to increase from the baseline average and a 1.0 if it was projected to decrease from the baseline average.

Also absent is data on the combined effect of multiple climate variables on any of the building fabric components. For example, a single adjusted service life could not be calculated for a component from the combination of high solar exposure, high precipitation exposure, and low relative humidity exposure. Instead, separate adjusted service lives were presented for each of the three climate variables for each building fabric component. Additionally, while there are likely additional climate variables that impact the durability of these building components, only three were analysed because of data and project scope limitations.[32]

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[8] Applying the Climate Vulnerability Modelling

Vulnerabilities

The climate modelling has identified vulnerabilities that will need to be considered by those with both a personal and professional interest in the impacts of climate change on their dwellings or those that they manage. These are the potential for:

- Increased incidences of **summertime overheating** in a majority of Welsh dwellings;
- Poorer indoor environmental quality principally due to an **increase in relative humidity**; and
- **Building fabric vulnerabilities** from solar, wind, rain etc.

Overheating

When considering overheating, 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. As a direct consequence, cooling strategies to reduce indoor air temperature will increasingly be required. Cooling strategies identified in the literature are summarised in Table 4.

Increased Relative Humidity

When reflecting on the potential for poorer indoor environmental quality (as modelled for the summer month) due to an increase relative humidity, it is important to remember that all dwellings 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. Therefore, ventilation strategies to improve the extraction of moisture-laden air [and indoor-generated

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pollutants] 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 (see Table 7).

Building fabric vulnerabilities

Building fabric vulnerabilities have been established for solar flux, relative humidity, and precipitation, measured using an adjusted service life. This is to assist with repair, maintenance, and refurbishment planning. It is important to remember that not every building material/component is impacted by every climate variable. Other climate variables may have detrimental impacts, including extreme events such as high winds, concentrated downpours, and associated events such as flooding. Climate change adaptations for rain, mould, damp, and flooding were identified by Vardoulakis *et al.* (2015), see Table 3; however currently there are no holistic adaptation examples published in the literature.

Building orientation will impact on adjusted service life, frequency of repair and maintenance, and thus change from baseline cost.

The building fabric vulnerability results can be applied, alongside with our knowledge and understanding of building fabric performance [and deterioration mechanisms], to better inform frequency of repair and maintenance to mitigate further damage. For example, Table 15 demonstrates how knowledge of climate vulnerabilities [including severe events and associated safety measure requirements] can be considered alongside expected deterioration mechanisms and associated costs, repair, and maintenance routines, to plan building maintenance and repair, including any adaptations that might be required, for a pre-1919 terraced sandstone dwelling in Cardiff.[33]

[33] **References**

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Table 15: Applying building fabric Vulnerability results to inform repair, maintenance and adaptation works
Example: Pre-1919 dwelling in Cardiff

Location	Dwelling Age	Main materials/component	Solar Flux	Precipitation	Relative Humidity	Temperature	Forecast level of deterioration	Service life	Adjusted service life	Frequency of repair and maintenance	Change from baseline costs	Deterioration mechanisms	Severe event safety measures
Cardiff	1830-1910 urban	Solid stone or brick	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline	Moderate	50-70	-3	See render /repointing	~0	❖ Masonry deterioration is associated with excessive moisture content. ❖ Water ingress, wet-dry cycles, freeze-thaw cycles, rain splatter at base of walls. ❖ Discoloration (staining) micro-cracking, biological/organic growth. ❖ Relative humidity < 75% can escalate crystallisation–hydration cycles, so drier, hotter summers could be a potential threat, especially for carbonate and sandstone *but no estimate is yet available related to their correlation* [Basu *et al.*, 2020].	❖ WDR and heavier downpours will require more regular maintenance of stone/brickwork ❖ Address micro-cracking to reduce moisture ingress ❖ Increased impact likely on northerly elevations.
		Painted render	High	High	Low	Higher than baseline	Moderate	50	-5	Increased painting and repair frequency	1-7%	❖ Water ingress, wet-dry cycles, freeze-thaw cycles, rain splatter at base of walls. ❖ Discoloration (staining), cracking, biological/organic growth. Loss of strength may also occur. ❖ A reflective/pale coating can prevent walls exposed to sunlight reaching a critically high temperature [BSI, 2008]	❖ Address cracking to reduce moisture ingress. ❖ Increased impact likely on northerly elevations.
		Painted/treated timber (window frames and door)	High	High	Lower than baseline	Higher than baseline	Severe	5-10 for painting	-4 max	Increased painting/varnishing especially southern elevations	1-7%	❖ Solar radiation and moisture lead to erosion or stains and blistering of varnish/paint, that allow timber saturation ❖ With high Solar flux, increased blistering will occur on painted timber on south facing elevations increased frequency of repair. ❖ If level of moisture is raised >20%, rot can damage frames [BSI, 2015]	Frequency of repaint/retreating will increase on southern elevations.
		uPVC replacement window frames and doors	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline	Severe	20+	-4	Replacement most likely on southern elevations.	1-7%	Moisture, atmospheric gases, and solar radiation acts on edge seal.	Frequency of brittle failure of uPVC may increase on southern elevations.
		Lime/cement mortar repointing	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline		50		Increased		Mortar should be sacrificial; a level of deterioration is expected over its lifetime	❖ Repointing the mortar more regularly will reduce moisture ingress in stone/brickwork ❖ Increased impact likely on northerly elevations.
		Roof - Slate tiles	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline	Moderate	30		Regularly check fixings etc.	2-7%	Rare delamination of poor-quality slates [usually fixings/supporting timbers that deteriorate before the slate tiles themselves]	High winds/WDR, more regular safety checks required including chimney stack [check orientation of prevailing winds]
		Decorative ceramics	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline	Moderate	5 -10	-2 max	See render /repointing	2-7%	Moisture in backing or adhesives	WDR and heavier downpours will require more regular maintenance of ceramic tiles
		Guttering uPVC	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline	Moderate - severe	20-30	-5max	Increase regularity of clearing and fixings checks	~5%	❖ Plastic rainwater drainage pipes can be subject to UV degradation and physical impacts during maintenance access. ❖ Moisture ingress through cracks and gutter over-spill will occur more frequently	WDR and heavier downpours will require more regular maintenance of gutters, joints, and drainage
		Drains	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline	Moderate - severe	50	-10max	Increase regularity of clearing channel and storm drains	~5%	Pooling and rain splatter at base of walls	Heavier downpours will require more regular maintenance of grates and drainage
		Sealants	Higher than baseline	Higher than baseline	Lower than baseline	Higher than baseline	Severe	5 - 20	3-5	Increase regularity of frames and seals detailing checks	10%	Moisture, atmospheric gases, and solar radiation. A polyurethane sealant will degrade in sunlight, whilst a silicone sealant will be virtually unaffected. Hardening, chalking, crazing, cracking, and reverting all suggest the sealant needs replacing.	Frequency of replacement of polyurethane sealant will increase on southern elevations

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[9] Climate Adaptation Workshops

A cross-section of experienced and specialist practitioners, with a professional interest in the impacts of climate change on dwellings, were invited to attend a virtual seminar on 11th August 2021, to hear and discuss the results of the climate modelling, including the principal climate vulnerabilities identified through the modelling. This two-hour event involved a one-hour presentation of the climate vulnerability modelling methodology and results, and a one-hour facilitated discussion of the results and their potential impact on the housing and more widely buildings sector.

Following this seminar, participants were encouraged to sign up for a dwelling adaptation workshop. These virtual workshops aimed to provide an opportunity for the co-exploration of approaches to climate adaptation, including the co-creation of adaptation prioritisation indices.

Three, two-hour workshops, were scheduled for the mornings of 21st and 28th of September and 13th October. The October workshop had to be cancelled due to illness.

The two September workshops took place online with twelve participants in each. The small group setting was designed to encourage participation from everyone invited to attend, in order to elicit their ideas, experience and knowledge. Through facilitated discussions using Miro, an online visual collaboration platform (virtual whiteboard), strategies for climate adaptation implementation, with a specific focus on retrofitting existing Welsh (and more widely UK) dwellings, was debated.

The discussion was divided into three distinct sections, namely:

1. Indoor temperatures and preventing overheating risks;
2. Indoor environmental quality and preventing moisture build up (and poor indoor air quality, in general); and
3. Building fabric vulnerabilities, including service life impacts, repair, and maintenance programmes.

Perceived barriers, including cost, materials selection (opportunities to reintroduce breathable materials and/or more sustainable solutions) and current knowledge and skills gaps, were all debated as part of the process.

Participants discussed the range of adaptations outlined in Tables 3, 4 and 7. In addition, they generated several adaptation ideas that had not been identified in the literature. The results of the adaptations discussed has been summarised and presented as decision trees in Figures 31-33. Building fabric adaptations focussed on pre 1919 dwellings, as it is perceived there are more issues with repair, maintenance, and maladaptation in older dwellings designed with traditional building techniques, including solid wall construction and breathable materials.

Originally, it was intended that these sessions be used to develop prioritisation indices for adaptation. However, the results of the climate vulnerability modelling demonstrated that climate vulnerabilities adaptation priorities may be very different depending on a dwelling's location (including orientation), age and construction typology, and influence by previous interventions including e.g., energy efficiency measures such as external, internal and cavity wall insulation. It may be necessary to prioritise flood risk adaptation over heating risk adaptation, for example. However, it is also recognised that there are some behavioural adaptations that could be promoted across the board, including approaches to passive cooling and ventilation, as well as increasing the frequency of repair and maintenance plans, investing in prevention rather than treatment.

Figure 31: Cooling strategies for a more comfortable indoor environment

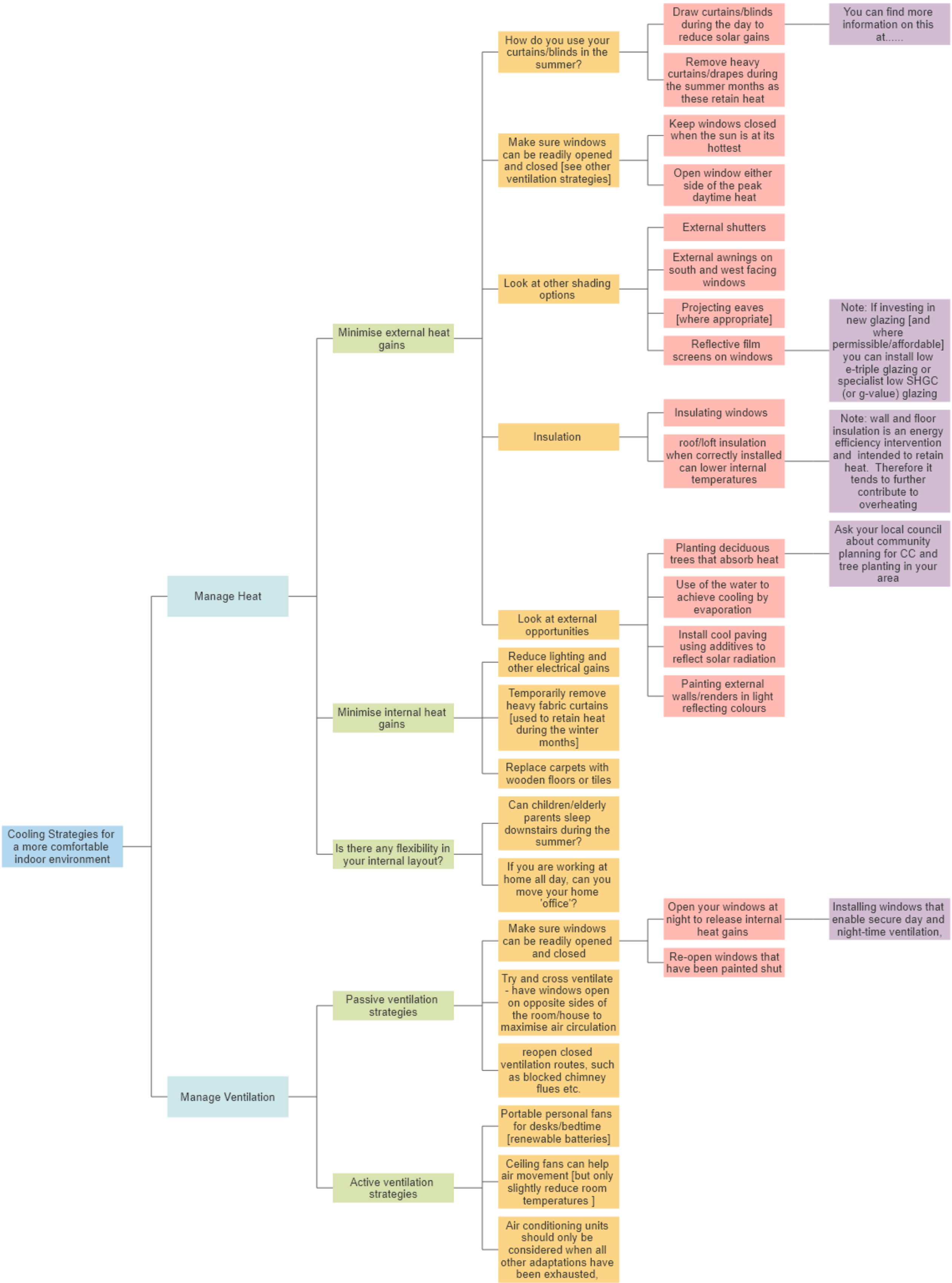


Figure 32: Drying strategies for a more comfortable indoor environment

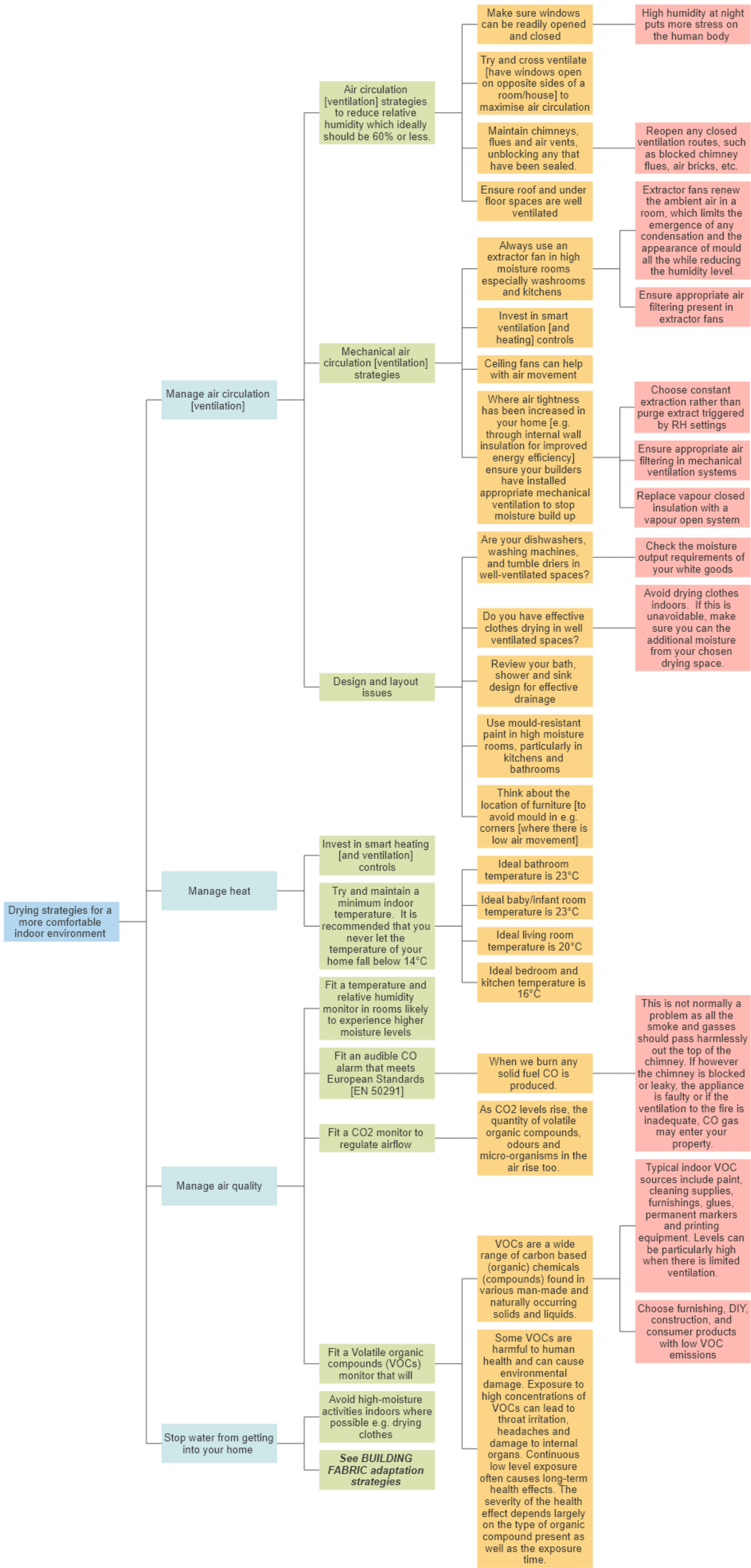
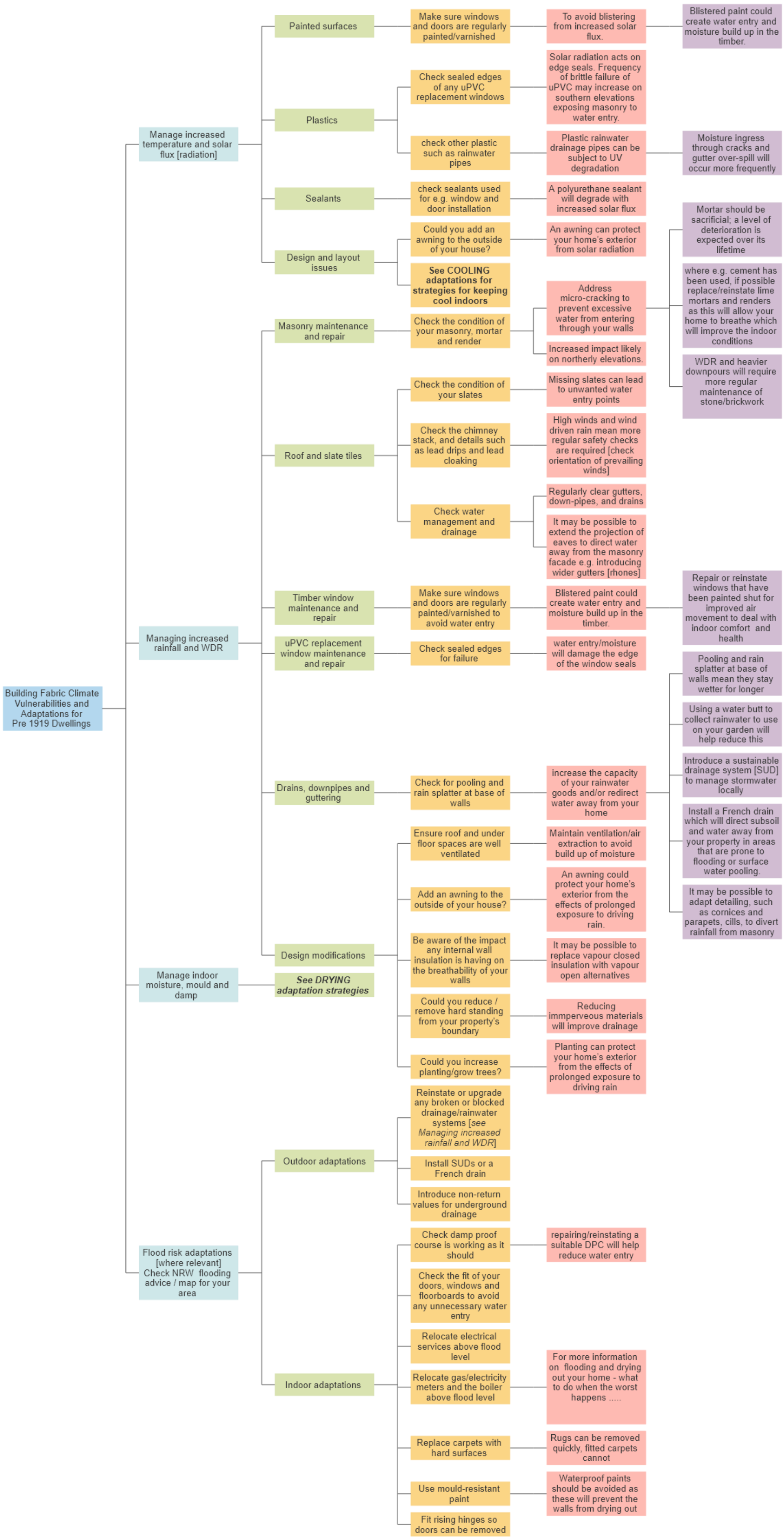


Figure 33: Building fabric vulnerabilities and adaptations in Pre-1919 dwellings



[10] Discussion

Introduction

Climate change is and will undoubtedly continue to impact how we live in and manage the physical condition of our homes both now and in the future. In general terms, due to increasing temperatures, heating loads in Wales will decrease in winter, while in summer, we will experience more uncomfortable conditions across the board, although the climate vulnerability modelling has revealed that residents of pre-1919 and solid stone dwellings will be less affected by overheating, assuming their properties have not been 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.

Building fabric performance

Climate change will indeed have an impact of existing building fabric performance, as identified in the climate vulnerability modelling. Solid masonry walls are characterised by higher surface water absorption coefficients and are more sensitive to exterior climate factors such as rain, wind, and solar radiation. Changes in climate factors are expected to quicken the erosion of detailing and construction or undermine binder and coating on traditional buildings (Curtis and Hunnisett Snow, 2016; Cavalagli *et al*., 2019). This may be further impacted by maladaptation. It's well documented that applying internal insulation to traditional buildings may result in interstitial condensation, surface condensation, mould growth and decay (Havinga and Schellen, 2019). Certainly, there are challenges with preserving the authenticity of historic, traditional buildings, maintaining their traditional passive behaviours and choosing adaptive solutions compatible with the characteristics of traditional materials, to avoid any unintentional consequences.

In the UK, there is still a focus on reducing energy consumption associated with heating rather than cooling, driven by UK and Welsh government decarbonisation policies and programmes[34]. Although the current drive to reduce heat loss is not without obvious merit, as levels of insulation increase and air infiltration decreases, there is increasing risk of summertime overheating linked to climate change, particularly in urban areas (Mulville and Stravoravdis, 2016). Researchers have identified that the recent focus on energy-efficiency in housing has resulted in retrofit solutions, such as increased

[34] One solution to decarbonisation not at the expense of the building fabric (and the health of its occupants) is that of renewable energy, which is considered to be an increasingly viable solution to mitigate greenhouse-gas emissions for buildings that cannot readily be retrofitted for energy efficiency (Marchi *et al.,* 2018). However, there is limited research available on availability, affordability, reliability, and indeed sustainability at this time.

insulation, that do not always allow outside air to infiltrate (Moreau-Guigon *et al.,* 2016). Indeed, Carmichael *et al.* (2020) recognised that whilst wintertime thermal comfort is improved through energy efficiency measures, problems with damp, mould, overheating and inadequate ventilation, which are frequently exacerbated due to increased insulation and air-tightness levels, will become more prevalent.

Indeed, the inappropriate use of internal wall insulation has been proven to detrimentally change the moisture dynamics of solid walls, in some cases, initiating or exacerbating moisture problems (Mensinga *et al.,* 2010); and these adverse effects are especially significant in the application of vapor-tight insulation systems. If wall insulation is to be applied, based on research covered during the literature review, capillary-active systems have been found to have the best results with a solid wall. However, to date, there is no fail-safe methodology to ensure the selection of insulation system results in the best balance between energy savings and hygrothermal risks (Vereecken *et al.*, 2015).

Previous research outcomes purport it necessary to assess the hygrothermal performance of pre-1919, solid wall housing, before any energy efficiency retrofit action is implemented, to ensure the compatibility of the measures proposed. Any energy retrofit is likely to reduce ventilations (e.g., through a reduction in air infiltration), and increase the airtightness of the envelope, which could reduce the building's capacity to eliminate any excess of moisture through its *breathable* building envelope. For example, Odgaard *et al.* (2018) found that the relative humidity of an insulated wall was 20–30% higher than that of the untreated wall. Walls exposed to wind-driven rain, with interior wall insulation and high indoor relative humidity, perform poorly when it comes to mould growth risks (Jensen *et al.,* 2020).

Wall orientation will also make a difference. This aspect could not be built into the climate vulnerability modelling; however, it has been recognised as being impactful. We know from previous research that south-facing walls dry out quicker than north-facing walls, as they present a faster reduction in relative humidity compared to the north-facing walls, due to solar flux (Marincioni and Altamirano-Medina, 2014). Additionally, Barreira and de Freitas (2013) found that façade orientation has a significant impact on surface condensation of walls with external thermal insulation, with the west façade at greatest risk from condensation, followed by the east, north and south, as a consequence of the prevailing wind-driven rain. Indeed, Vereecken *et al.* (2015) established that wind-driven rain could impede beneficial hygrothermal behaviour in a capillary-active interior insulation system by inducing a lower thermal resistance or increased indoor relative humidity.

Clearly, the risk of mould growth increases considerably when the relative humidity of a construction material exceeds 80%. Buildings susceptible to damp both now and under future climate projections will require special consideration, as the succession of fungi they attract can be highly toxigenic and difficult to detect but may lead to significant issues of poor indoor environmental quality and subsequently poor health, if not suitably accounted for and resolved.

Ultimately, avoiding unintended consequences or maladaptation is in everyone's interests. King's (2016) analysis of approaches to improving the thermal performance of older homes in the UK with solid wall construction, identified 29 major defects introduced during the application of solid wall insulation, either externally or internally. These included overheating and increased relative humidity, as well as the increased risk of dust mites, bed bugs, clothes moths, and other insects within the home, and both the short- and long-term reduction of indoor air quality due to increased levels of volatile organic compounds (VOCs) and reduced ventilation.

Occupant health and wellbeing

Overheating in residential buildings in recognised in the UK-context and its relevance 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 examples cited, Baborska-Naroznya and Grudzinska, 2016; D'Ippoliti *et al*., 2010; and Mavrogianni *et al.,* 2010. Yang and Lam, 2012; Moazami *et al.,* 2019; Pilli-Sihvola *et al.,* 2010; Cartalis *et al.,* 2001; Mirasgedis *et al.,* 2007; Aguiar *et al.,* 2002; Asimakopoulos *et al.,* 2012; Wang *et al.,* 2010; Hosseini *et al.,* 2018) 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 cooling degree days experienced. If the behavioural response of UK householders to a warming climate is akin to that of relationships found in the USA, then it is forecasted that domestic air conditioning systems will be adopted by occupants. Whilst domestic air conditioning may not represent a step change in domestic energy consumption, and may be powered by e.g., renewable electricity, the extension of controlled climates to the domestic sector may prompt behaviour that is more likely to accentuate rather than ameliorate energy consuming behaviour (Peacock *et al.,* 2010).

Occupant behaviour can also have a significant impact on overheating, and a number of adaptation strategies have been proposed in order to support building occupants. Indeed, it has been proposed that structural building adaptation, and behavioural change, can both lead to similar reductions in temperatures and hours of overheating (Coley *et al*. (2012). 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 the management of indoor overheating, as well as humidity fluctuations (and the use of ventilation strategies); including a number of behaviour adaptations that can improve indoor environmental quality. It is well recognised that inadequate ventilation accelerates the accumulation of contaminants and is a primary cause of indoor air pollution and is why pollutants rise in homes during the winter (Pegas *et al*., 2011; Yang *et al.,* 2017). 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 can be key to reducing moisture build up and awareness of high-moisture generation activities, particularly in kitchens and bathrooms, can support air exchange practices. However, the climate modelling research outcomes suggest that mechanical ventilation will increasingly be required to alleviate moisture build up, especially where indoor relative humidity levels regularly exceed 60%.

The lack of attention given to indoor environmental quality 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.

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. 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.

Welsh building regulations and related national reference standards

The analysis of current regulations, standards and guidelines, exposed the lack of influence climate change evidence has on current building policy and regulation; and a shortage of advice and tools to tackle the impact of future climatic conditions on the built environment. In the Committee on Climate Change’s third risk assessment (CCRA3), they have challenged regulators to embed risk assessment accounting for climate change hazards, such as extreme wind and rain and subsequent flooding, into building regulations and standards over the next five years; and specifically for housing, they have endorsed improved building regulations and building design that consider overheating, among other aspects of building safety, to help reduce the risk in new and existing homes undergoing retrofit. They also identified the need for a systems approach, acknowledging that housing decarbonisation strategies would benefit from being combined with actions to avoid overheating.

Comprehensive climate adaptation decision making is needed now. In 2013, Gregg stated that adaptation measures implemented at the same time as energy efficiency measures, could significantly reduce the risk of overheating. Whilst Carmichael *et al.* (2020) called for a more holistic policy approach to housing design and construction, with an integrated framework. Certainly, it is necessary to ensure retrofit approaches align carbon reduction (mitigation) with climate change adaptation, to avoid maladaptation. 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

[11] Conclusions and recommendations

Introduction

Climate change is threatening the stability of our built, as well as our natural, environment. It is and will continue to impact our expectations of building performance and occupant health and wellbeing; and climate impacts will especially be felt at a domestic level. Managing overheating and incidence of damp will be more commonplace for many of us, whilst the need to repair and rebuild due to more severe storm events such as wind-driven rain and flooding due to changing precipitation patterns, will become more prevalent.

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. However, the climate vulnerability modelling results reveal that comparable motivation is now required to meet the needs of climate adaptation, with particular emphasis on reducing building fabric risks and improving the indoor environmental quality of our 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.

Evidence Gaps and associated recommendations

This research aimed to address a number of evidence gaps as identified by Welsh government.

Regulations, standards and guidelines

The analysis of current regulations, standards and guidelines, exposed the lack of influence climate change evidence has on current building policy and regulation; and a shortage of advice and tools to tackle the impact of future climatic conditions on the built environment. Currently climate adaptation decision-making is tackled through energy calculations and building modelling using CIBSE's weather files. These still use UKCP09 data. CIBSE has been awarded an Innovate UK funding grant for a 30-month project with the University of Exeter to produce new files based on the most recent UK climate projections (UKCP18). The Committee on Climate Change have challenged regulators to embed risk assessment accounting for climate change hazards, such as extreme wind and rain and subsequent flooding, into building regulations and standards over the next five years. This will be a significant undertaking, but it is crucial. Additionally, and specifically for housing, the Committee on Climate Change advocate improved building regulations and building design that consider overheating, among other aspects of building safety, to help reduce the risk in existing homes undergoing retrofit in addition to new build.

CCRA2 evidence gaps for Wales

The research aimed to inform two further knowledge gaps identified by Welsh government, as evidenced in the Committee on Climate Change's 2nd risk assessment (2017): CCRA2 Risk Ref. PB7 - Risks to building fabric from moisture, wind and driving rain under future climate driven changes in weather patterns; and CCRA2 Risk Ref. PB10 - Risks to health from changes in air quality, including indoor air quality.

Risks to building fabric

When considering risks to building fabric from moisture, wind and driving rain under future climate driven changes in weather patterns, the research has specifically highlighted vulnerabilities associated with solid masonry walls, which are characterised by higher surface water absorption coefficients and are more sensitive to exterior climate factors such as rain and wind. It is anticipated that changes in climate factors will accelerate the erosion of detailing and construction, with the potential to undermine the integrity of e.g., binders and coatings. The climate vulnerability modelling suggests that there will be a modest reduction in the service life of building materials (and an associated increase in repair and maintenance costs) due to increases in and changing patterns of precipitation and subsequent moisture ingress. Dwellings retrofitted with inappropriate wall insulation systems are predicted to experience further issues with increased mould and damp where moisture-wicking pathways have been modified.

Hygrothermal impacts, including repeated wetting, drying, freezing, and thawing of building fabric, can cause problems such as damp, condensation, mould growth, loss of thermal performance, and may even result in premature material failure. Consequently, any energy efficiency retrofit action should consider the known hygrothermal performance of the building in question, to ensure the compatibility of the measures proposed. This is particularly pertinent to the historic building sector, where a balanced approach to climate change mitigation and adaptation is required to provide the appropriate temperature and relative humidity equilibrium for sustained building performance.

Risks to health

Risks to health from changes in air quality, including indoor air quality, have been analysed through the literature review, policy document review and climate vulnerability modelling. As outlined above, it has been determined that changes to building fabric performance will impact indoor environmental quality, with concerns raised over the inappropriate use of internal wall insulation that has been proven to detrimentally change the moisture dynamics of solid walls, in some cases, initiating or exacerbating moisture problems. It is understood that whilst wintertime thermal comfort is improved through energy efficiency measures, increased insulation and air-tightness levels can frequently lead to problems with damp, mould, overheating and inadequate ventilation, and this needs to be addressed. In addition, a lack of air exchange or extraction and high levels of humidity can increase the concentration of other indoor pollutants. These include contaminants from cooking and heating, chemicals from candles and household cleaning products, and a host of toxins from building materials and home furnishings, as well as mould and fungi. The climate vulnerability modelling identified a future propensity for elevated indoor relative humidity, with values above the optimal range for human health and comfort of between 30-60% relative humidity. This is a useful indicator for assessing the overall future 'health' of the indoor environment and infers that indoor environmental quality in general is likely to decrease. Indoor air quality can be improved through appropriate levels of air filtration, including mechanical air extraction in high-moisture rooms. Suitable ventilation will meliorate indoor air quality by both reducing relative humidity and diluting the concentration of pollutants that are present indoors.

Green recovery for Wales

During the height of the COVID-19 crisis, the Committee on Climate Change proposed what they considered to be a post-pandemic resilient and *green* recovery for Wales. It is contended that the evidence collated and reported in this current research project can start to inform the following areas identified by the Committee on Climate Change:

1. Investments in low-carbon and *climate-resilient* infrastructure;
2. Supporting reskilling, retraining and research for a net-zero, *well-adapted* economy; and
3. Upgrades to homes ensuring they are *fit for the future*.

Improving our understanding of the relationship between energy use, indoor health and comfort, the thermal mass and moisture dynamic of the building envelope, will allow better informed decisions, as they will provide a better sense of future risks to energy efficiency, occupant health and comfort, and dwelling management.

Recommendations

12. A holistic policy approach to climate change decision making is urgently needed. We cannot continue to attempt mitigation and adaptation in isolation. Systems thinking (considering the connected wholes rather than separate parts) should be at the heart of UK and Welsh climate change policy design and delivery; as should foresight (futures thinking). This will help ensure that necessary risk-based adaptation decisions have *equal footing* with carbon reduction targets.
13. Welsh building regulations and related national reference standards should address the lack of consistent messaging on the interconnectedness of climate change, building fabric and occupant health.
14. Welsh building regulations and related national reference standards should address the shortage of advice and the tools needed by the design and construction industry, to tackle the impact of future climatic conditions on the built environment.
15. Welsh building regulations and related national reference standards must embed climate change risk-based building fabric vulnerabilities, such as extreme wind and rain and subsequent flooding, in their guidance[35].
16. Welsh building regulations and related national reference standards must legislate for overheating, among other aspects of building safety, to help reduce the risk in existing homes undergoing retrofit, in addition to new build.
17. Welsh building regulations and related national reference standards must ensure that ventilation guidelines reflect projected climate change, to help reduce the risk of inadequate air circulation in existing homes, especially those undergoing retrofit[36].
18. Investment in skills and training on climate mitigation and adaptation, to avoid maladaptation, is urgently needed.
19. Social housing decarbonisation strategies should be merged with climate adaptation action plans. For example, adaptation measures implemented at the same time as energy efficiency measures, could significantly reduce the risk of overheating, mould and damp.
20. Government-backed schemes for private-sector dwellings also need to do the same.
21. Climate change mitigation and adaptation advice must be made accessible to everyone. If we democratise skills, knowledge and understanding of climate vulnerabilities, we give building occupants and owners agency to improve their circumstances.

[35] This is particularly pertinent to solid masonry walls, which are characterised by higher surface water absorption coefficients and are more sensitive to exterior climate factors such as rain and wind.
[36] Suitable ventilation will meliorate indoor air quality by both reducing relative humidity and diluting the concentration of pollutants that are present indoors.

22. Influencing occupant behaviours has been identified as a key catalyst for boosting constructive risk-based decision making. A Welsh government led campaign or strategy that guarantees the dissemination of knowledge and understanding of climate adaptation behaviours, will ultimately improve and enhance occupants' experience of their dwelling.

[12] Dissemination and future research

The fellowship activities undertaken during Phase 1 aimed to provided Welsh Government with a broad understanding of the resilience of buildings in Wales to the challenges associated with climate change, Wales-specific climate vulnerabilities and stressors, and provided practical recommendations for risk-based adaptation. This aimed to deliver environmental evidence to help inform urgent climate risks detailed in the UK Climate Change Risk Assessment (CCRA2), published in 2017, which identified two overlapping priority areas of research of particular interest to Welsh Government, namely:

3. Risks to building fabric from moisture, wind and driving rain under future climate driven changes in weather patterns; and
4. Risks to health from changes in air quality, including indoor air quality.

During Phase 1 of the climate embedded researcher's tenure, CCRA 3 was published (2021). Again, this identified that further investigation environmental evidence is needed to understand risks to building fabric. Indeed, CCRA3 concludes that progress in adaptation policy and implementation is not keeping up with the rate of increase in climate risk. There is still much to be done to fully understand climate risks. The aim of Phase 2 of the research is to disseminate these research findings more widely within Welsh Government, but also to devolved government and other UK-wide agencies, including those organisations responsible for building standards and regulatory frameworks.

[1] Stakeholder engagement events

Work Package 1 will constitute a series of stakeholder engagement activities, to include policy groups from across Welsh Government, as well as UK government and the devolved nations, be scheduled in order to disseminate current findings and shape future engagement and research activities.

A number of stakeholder groups have been identified; these are:

1. The Department for Business, Energy and Industrial Strategy (BEIS)
2. Retrofit industry representative group (IAA, CIGA, SWIGA, INCA, etc.)
3. Building regulations and standards; British standards institute
4. Heritage bodies (NT, NTS, NES, HE, Cadw)
5. Sustainable traditional buildings alliance (STBA)
6. Public Heath Wales (PHW)
7. Welsh Government Flooding team
8. Welsh Government Planning team

9. Welsh Government Air quality team
10. Welsh Government Housing teams, including WQHS, warm-home, decarb.

[2] Development of two summary documents [English and Welsh Language]

Production of a bi-lingual summary document, including key messages, visuals and graphics.

This work package includes writing a stand-alone document of the salient points raised by the climate vulnerability modelling, the idea is that this document will be designed to include appropriate graphics that will help the reader to readily decipher the research outcomes and what they mean for their circumstances, policy area, etc.

[3] Pilot Mapping Project

It is proposed that Work Package 3 will use the online analytics platform Tableau [Business intelligence and analytics software (tableau.com)](), a platform that makes it easier for people to explore and manage data, to create an interactive map of Wales. The results presented in Phase 1 for 6 locations across Wales, will be expanded and embedded in an interactive map in order to provide representative data for anyone interested in the impacts of climate change on dwellings located across Wales. *Initially the results presented will be for the 6-week period studied in Phase 1, but eventually it is hoped that this map could be extended to look at year-wide impacts.*

[4] Factsheets [English and Welsh Language versions]

Work package 4 will combine research outcomes from Phase 1 with known adaptation pathways, advice and guidance, to produce a series of downloadable PDF guides/factsheets aimed at better understanding the impacts of climate stressors on buildings. These factsheets will highlight known vulnerabilities and propose behavioural and physical interventions that would help people better live with climate change impacts in the summer months. The PDFs will also direct readers to specialist/expert organisations and regulations and standards so that they can find out more. For example, guidance on relative humidity in older buildings will explain the issues, the climate stressors and vulnerabilities, outline approaches to adaptation and direct the reader to advice provided by e.g., Cadw, Historic England, etc. to support them in looking for the signs and acting on them to reduce relatively humidity and thus moisture, damp and mould build-up over time. It is suggested that the following factsheets are produced in the first instance:

1. Considering summertime overheating in newer build properties [including older buildings converted into flats]

2. Considering summertime overheating in highly insulated homes
3. Considering summertime relative humidity in older properties
4. Climate change adaptation - maintenance and repair priorities for older properties.

Future research

There are limitations to using building performance simulation and energy modelling in assessing future building performance and the impacts of retrofitting buildings, as identified in the literature. The climate vulnerability modelling starts to address this by using a previous monitoring study that details the relationship between outdoor temperature and indoor temperatures of a variety of lived-in dwellings.

However, more tailored results could be achieved if whole-year hourly monitoring data existed for a range of Welsh dwellings, with temperature and humidity differences tracked between combinations of building types and occupant characteristics. Not only would this allow climate vulnerability modelling for a full calendar year, rather than a six-week period, but it would also improve the data on each building class. In addition, it could inform the influence of occupant behaviour, building orientation or indeed specific decarbonisation retrofits of climate vulnerabilities. It would also allow for actual daily indoor specific humidity ranges to be calculated. Consequently, a three-year research project proposal is being developed, one that would identify a range of existing Welsh dwellings, a set of agreed geographical locations for monitoring, install appropriate monitoring equipment that would record real-time data for a full calendar year, conduct climate vulnerability modelling, and use the result to provide more detailed feedback on climate vulnerabilities and appropriate adaptations.

It is also possible to apply the current climate vulnerability modelling methodology to non-domestic buildings. It is proposed that future projects could identify buildings of significant cultural interest. The building managers would need to already monitor indoor environmental conditions, else monitoring could be installed, as above, and climate vulnerability modelling undertaken once suitable data has been collected.

In conclusion, this research has provided an understanding of the resilience of buildings in Wales, and more widely the UK, to the challenges associated with a changing climate, identified climate vulnerability specific to Wales, and provided practical recommendations for risk-based adaptation. Despite advancements in our understanding of climate change impacts, more research is needed to inform our understanding of the impacts of climate change on selected building materials, energy efficiency retrofits, overheating and poor indoor environmental quality, all of which may lead to an increased risk of adverse climate related outcomes, increased vulnerability to climate change, or reduced health and wellbeing, of building occupants, both now and in the future.

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Appendix A

Climate Change, Occupant Health, and Building Fabric: Evidence base in mandatory and voluntary Welsh Building Regulations, related National reference Standards and Assessment Tools

Climate Change, Occupant Health and Building Fabric: Evidence base in mandatory and voluntary Building Regulations, Standards and Assessment Tools

Policies and Regulations Mandatory /Voluntary	Reference to Climate Change risk evidence	Reference to health evidence (indoor environmental quality)	Reference to building fabric risks (from rain, mould, and damp)
Housing health and safety rating system (HHSRS): guidance for landlords and property-related professionals (WG, 2006)	❖ **No Climate Change risk evidenced in document**. ❖ No consideration of the impact of climate change on housing health and safety is specifically referenced.	❖ Appendix III references hygrothermal conditions, causes and possible health effects [pp22-23] ❖ Appendix III references excess cold conditions, causes and possible health effects [pp23-24] ❖ Appendix III references excess heat conditions, causes and possible health effects [pp25-27] ❖ Appendix III references non-microbial pollutants, causes and possible health effects [pp27-28] ❖ Appendix III references to combustion pollutants, causes and possible health effects [pp28-30] ❖ Appendix III references to pollutants including lead and radiation, causes and possible health effects [pp29-31] ❖ Appendix III references to VOC pollutants, causes and possible health effects [pp32]	Appendix III references preventative measures to reduce risk to building fabric from damp and mould, excess cold and heat [pp22-26]
National Planning Policy Framework (DCLG 2012/2019)	❖ **No Climate Change risk evidence** referenced in document. ❖ Reference made to the need to mitigate and adapt to climate change. ❖ Section 12: Achieving well-designed places, does not reference Climate Change [pp 38-39]. ❖ Section 14: Meeting the challenge of Climate Change, flooding and coastal change, references the Climate Change Act (2008) and suggests that "plans should take a proactive approach to mitigating and adapting to Climate Change, taking into account the long-term implications for flood risk, coastal change, water supply, biodiversity and landscapes, and the risk of overheating from rising temperatures" [pp44- 48].	❖ **No health risk evidence referenced in document.**	❖ **No building fabric risk evidence referenced in document.**
Planning Policy Wales. Edition 10 (WG, 2018)	❖ **No Climate Change risk evidence referenced in document.** ❖ Embedded within the document are approaches to the planning process aimed at mitigating climate change and climate change resilience. ❖ No mention of climate change in section 4.2. (Housing) ❖ 5.7.3 (Energy) "Climate change is a global challenge, *with impacts felt at the local level presenting a significant risk to people, property*, infrastructure and natural resources. We need to plan for these impacts, reducing the vulnerability of our natural resources and build an environment which can adapt to climate change. The planning system plays a significant role in managing this risk. Development allowed today will be around for decades to come. The most important decision the planning system makes is to ensure the right developments are built in the right places." ❖ 5.8.3 (Reduce Energy Demand and Use of Energy Efficiency) "Sustainable building design principles should be integral to the design of new development. Development proposals should: mitigate the causes of climate change, by minimising carbon and other greenhouse gas emissions associated with the development's location, design, construction, use and eventual demolition; and include features that provide effective adaptation to, and resilience against, the current and predicted future effects of climate change." ❖ Resilience to Climate Change is listed as one of the national sustainable placemaking outcomes.	❖ **No health risk evidence referenced in document.** ❖ Embedded within the document are references to promoting physical health and well-being ❖ Promoting physical and mental health and well-being is listed as one of the national sustainable placemaking outcomes.	❖ **No building fabric risk evidence referenced in document.** ❖ Embedded within the document are references to promoting high quality buildings.
Building Regulations 2010: Conservation of fuel and power in existing dwellings L1A (WG, 2016)	❖ **No Climate Change risk evidence referenced in document.** ❖ Climate Change mitigation issues are addressed through the conservation of fuel and power. ❖ Criteria for compliance includes the requirement to limit CO_2 emissions and not exceed the dwellings' target emissions rate (TER); meet minimum energy efficiency standards to encourage the reduction of demand for space heating (and cooling) and efficient use of fuel; and passive control measures to limit the effect of solar and	❖ **No health risk evidence referenced in document.**	❖ **No building fabric risk evidence referenced in document.**

	other heat gains on indoor temperatures in summer. This is to help avoid the need for mechanical cooling and associated energy consumption [pp 9]. ❖ Promotes use of low and zero carbon technologies that produce renewable non-fossil fuel energy and fossil-fuel technologies that can supply low carbon energy such as combined heat and power and heat pumps [pp10].		
Building Regulations: Conservation of fuel and power in existing dwellings L1A (consultation version)	❖ **No Climate Change risk evidence referenced in document.** ❖ Climate Change mitigation issues are addressed through energy efficiency. ❖ Provides practical guidance on ways of complying with energy efficiency requirements for dwellings of the Building Regulations [pp 2; 8]. ❖ Buildings which meet the standards set out in this Approved Document will meet the definition of nearly zero-energy buildings [pp 13]. ❖ Budlings can meet the standards through the fabric energy efficiency, systems measures, or low/zero carbon technologies integrated in an appropriate mix [pp 20].	❖ **No health risk evidence referenced in document.**	❖ **No building fabric risk evidence referenced in document.**
Building Regulations 2010: Conservation of fuel and power in existing dwellings L1B (WG, 2016)	❖ **No Climate Change risk evidence referenced in document.**	❖ **No health risk evidence referenced in document.**	❖ **No building fabric risk evidence referenced in document.** ❖ Section 1.5 (consideration of technical risk), references the need to consider water ingress, condensation risk and ventilation when incorporating energy efficiency measures in dwellings, *and refers to BRE Report 262 Thermal insulation: avoiding the risks* [pp5].
Building Regulations 2010: Means of Ventilation F (WG, 2010)	❖ **No Climate Change risk evidence referenced in document.** ❖ Energy conservation: ventilation systems in buildings result in energy being used to heat fresh air taken in from outside and, in mechanical ventilation systems, to move air into, out of and/or around the building. Consideration should be given to mitigation of ventilation *energy use,* where applicable, by employing heat recovery devices, efficient types of fan motor and/or energy saving control devices in the ventilation system [pp 23].	❖ A ventilation strategy is required for one or more of the following health-related purposes: (a) provision of outside air for breathing. (b) dilution and removal of airborne pollutants, including odours. (c) control of excess humidity (arising from water vapour in the indoor air). ❖ Ventilation may also provide a means to control thermal comfort, but this is not controlled under the Building Regulations [pp24]. ❖ Purge ventilation to aid the removal of high concentrations of pollutants and water vapour released from occasional activities e.g., painting, decorating, smoke from burnt food or spillage of water [pp25]. ❖ The moisture criteria needed to avoid house dust mite (HDM) are more complex and demanding than those needed to avoid mould. The reduction of mite growth may be feasible in UK dwellings via appropriate ventilation, heating, and moisture control as part of an integrated approach that involves the removal of existing mite allergens. ❖ **Health evidence referenced:** DoE Medical effects of air pollutants (2004); European Concerted Action (ECA) Indoor air and its impact on man (1992), WHO Guidelines for air quality (2000 and 2005) and WHO (2008) Public health significance of urban pests (who.int) ❖ *Several the hyperlinks to evidence/guidance are broken.*	❖ **No building fabric risk evidence referenced in document.** ❖ References air infiltration (uncontrollable air exchange between the inside and outside of a building through a wide range of air leakage paths in the building structure) [pp24]. ❖ In dwellings, humidity-controlled devices are available to regulate the humidity of the indoor air and, hence, minimise the risk of condensation and mould growth. These are best installed as part of an extract ventilator in moisture generating rooms (e.g., kitchen or bathroom) [pp26].
Building Regulations: Means of Ventilation F (Vol. 1 dwellings consultation version, Nov 2020)	❖ **No Climate Change risk evidence referenced in document.** ❖ *The Welsh Government is seeking views on the standards for existing dwellings, mitigating overheating in new dwellings, and amendments to non-domestic buildings.* ❖ Energy efficiency should be considered when specifying ventilation systems. Energy efficiency, including the control of infiltration, is dealt with under Part L of the Building Regulations [pp 11].	❖ **Health risk evidence referenced in document** ❖ Embedded in the document are references to the risk of ingress of external pollutant, and further guidance from the 'Indoor Air Quality Handbook' [pp 29; 30]. ❖ Reduction in (infiltration) ventilation because of retrofit for energy efficiency, m which may reduce IAQ below ads given in App. B. [pp 31]. ❖ Performance criteria for the management of indoor air pollutants are given in Table B.1. based on WHO (2010) guidance [pp 48].	❖ **No building fabric risk evidence referenced in document.** ❖ The guidance given by English Heritage and in BS 7913 Principles of the conservation of historic buildings should be considered in determining appropriate ventilation strategies for building work in historic buildings [pp 10]. ❖ Reference is made to making provision for the fabric of historic buildings to 'breathe' to control moisture and potential long-term decay problems [pp 10]. ❖ Reference made to the fact that the whole dwelling ventilation rate is based on winter weather conditions. During warmer spring and autumn periods, the moisture removal capacity of outdoor air is less, and additional ventilation may be required [pp 51].
Building Regulations C: Site preparation and resistance to contaminants and	❖ **No Climate Change risk evidence referenced in document.** ❖ Flood risk evidence includes Planning Policy Guidance Note PPG 25 Development and flood risk, DTLR, 2001; Preparing for floods: interim guidance for improving the flood resistance of domestic and small business	❖ **No health risk evidence referenced in document.** ❖ Embedded in the document are references to the risk of potential inhalation of contaminants found in soil particles/dust/vapours from the ground [pp 23]. ❖ Guidance to preventing radon exposure (BRE Report BR 211, 1999) [pp 32].	❖ Moisture can rise from the ground to damage floors and the base of walls on any site, although much more severe problems can arise in sites that are liable to flooding. ❖ Driving rain or wind-driven spray from the sea or other water bodies adjacent to the building can

moisture (WG, 2010)	properties, ODPM, 2002; BRE (for Scottish Office) Design guidance on flood damage for dwellings, 1996; CIRIA/Environment Agency Flood products. Using flood protection products – a guide for homeowners, 2003. Available from: www.ciria.org/flooding. ❖ UK zones for exposure to driving rain [pp 48]		penetrate walls or roofs directly, or through cracks or joints between elements, and damage the structure or internal fittings or equipment. ❖ Surface condensation from the water vapour generated within the building can cause moulds to grow which pose a health hazard to occupants. ❖ Interstitial condensation may cause damage to the structure. ❖ Spills and leaks of water, in rooms where sanitary fittings or fixed appliances that use water are installed (e.g., bathrooms and kitchens), may cause damage to floor decking or other parts of the structure [pp14].
BSI Code of Practice for control of condensation in buildings: 5250 (BSI, 2016)	❖ **No Climate Change risk evidence referenced in document.** ❖ Reference made to the external climate as follows: Designers should assess and document the factors likely to affect the formation and persistence of condensation in buildings, including exposure to sunlight, clear night skies, wind and driving rain [pp 7].	❖ **No health risk evidence referenced in document.** ❖ Embedded in the document are references to: ❖ The impact of contaminated air and excess humidity on occupant health. ❖ Air, which is contaminated by combustion products, bacteria, mould, smoke, smells, high levels of CO2, excess water vapour and heat should be removed and replaced by fresh air [pp 6]. ❖ Excess moisture in a building that can lead to condensation and mould growth, which represent risks to the health of building occupants [pp 13]. ❖ Mould closely associated with respiratory allergies, especially asthma [pp 15].	❖ **Building fabric risk evidenced <u>throughout</u> document.** ❖ Risk of external envelope damage because of solar gain, night sky radiation, wind and driving rain [pp 7]. ❖ Excess moisture in a building leading to condensation and mould growth which represent risks to the structural integrity of the building envelope, internal building fabric and finishes [pp 13].
BSI Code of Practice for control of condensation in buildings: 5250 (consultation draft)	❖ **Climate Change risk evidence referenced in document.** ❖ Predicted changes due to climate change over the next century, including milder, more humid winters and larger volumes of driving rain, are also likely to increase the number and severity of moisture problems [pp 4]. ❖ Where there is uncertainty about the moisture performance of a building, capacity can be built into the processes of assessment, construction, and use. Capacity considers not only current but future uncertainties, such as potential building use and occupancy patterns as well as the effects of increased driven rain or wind because of possible climate change [pp 23].	❖ **No health risk evidence referenced in document.** ❖ *There is a growing acknowledgement of the key role of moisture in the health of occupants as well as in the condition of the building fabric* [pp 4]. ❖ The guidance states that air, which is contaminated by combustion products, bacteria, mould, smoke, smells, high levels of CO2, excess water vapour and heat should be removed and replaced by fresh air [pp 12]. ❖ Reference is made to: ❖ Moisture in buildings as a significant cause of most building failures, including some building-related occupant health problems. Some problems could be	❖ **Building fabric risk evidenced <u>throughout</u> document.** ❖ *The understanding of moisture risk in buildings has developed considerably in the past few years. Not only have the mechanisms of moisture movement been explored more fully, but the types of buildings and applications being studied have widened (in particular, to include existing, retrofitted buildings)* [pp 4]. ❖ E.g., for existing historic timber frame buildings, modern methods of upgrading thermal performance which include vapour barriers and materials that are highly resistant to the passage of water vapour may not be appropriate as they can trap moisture and

	❖ Reference made to climate change resulting in greater volumes of rainwater causing pressure on drains and culverts and overflows impacting on adjacent buildings [pp 56]. ❖ Overhangs and rainwater goods should be designed for the level of exposure, with a view to future climate change. Capacity should be built into all details [pp 93]. ❖ Checklist for design principles includes climate and capacity considerations [pp 73-75].	increasing due to increased airtightness and insulation [pp 4]. ❖ Flood water can be absorbed into the fabric of a building, causing damage, and creating a health hazard [pp 42]. ❖ Efficient ventilation contributes greatly to the health not only of the occupant but also of the building [pp 44]. ❖ Mould presents a hazard to health; it is closely associated with respiratory allergies, especially asthma, in sensitive (atopic) individuals. Mould growth within a building can cause significant distress to the occupants, even in the absence of any physical symptoms [pp 43].	increase the risk of decay to the fabric – including the structural timber frame [pp 104]. ❖ Condensation that occurs *within the fabric* of the building envelope is *not visible* and can cause severe damage, leading to loss of thermal performance and, in extreme cases, structural failure [pp 50]. ❖ If the humidity level remains high, it increases the risk of the corrosion of metals and the decay of timber-based products [pp 42].
BSI Code of Practice for the protection of structures against water from the ground: 8102 (BSI, 2009)	❖ **No Climate Change risk evidence referenced in document.** ❖ It is stated that risk assessment should also consider the effects of climate change [pp 7], however no further detail or evidence is provided.	❖ **No health risk evidence referenced in document.** Embedded in the document reference is made of the need to prevent radon, methane and other ground gases and contaminants from entering a structure (*but no mention of health implications of this or more general water ingress and impacts on health).*	❖ **Building fabric risk evidenced throughout document.** ❖ Risk of water/contaminated water ingress into structures from external environmental conditions
Code of Practice for Assessing Exposure of Walls to Wind-Driven Rain: 8104 (BSI, 1992)	❖ **No Climate Change risk evidence referenced in document.** ❖ The code includes calculations of driving rainfall for different orientations, it allows annal average values to be calculated as well as quantities for the worst likely spell in any 3-year period and it allows corrections to be made for ground terrain, topography, local shelter and the constructional characteristics of the building concerned. *It does not consider climate change forecasts.* However, it is possible to identify a common set of adjustments for use throughout the UK for converting once in 3 years spell amounts into once in 1 year or once in 10 years amounts.	❖ **No health risk evidence referenced in document.**	❖ **Building fabric risk evidenced throughout document.** ❖ The quantity of rain falling on a vertical surface depends on both the intensity of the rainfall and the wind speed. ❖ Risk varies according to topography, proximity to the sea, ground roughness, building design, building height etc. ❖ Microclimatic conditions mean that rainfall intensity can vary significantly over a wall's surface.
CIBSE Guide A: Environmental Design (CIBSE, 2019) *	❖ **Climate Change risk evidence referenced in document.** ❖ Section 2.10: Climate Change: *"It is now generally accepted that the weather data that is used for <u>energy calculations</u> in buildings should account for future as well as present day climate"*. ❖ Guide uses UKCP09 (UKCP18 are current projections).	❖ **Health risk evidence referenced in document** ❖ Indoor environmental quality including heat, cold, light, humidity, air quality (pollutants) and ventilation [section 8-7] with appropriate evidence referenced [8-23 to 8-29].	❖ **Building fabric risk evidenced throughout document,** principally: ❖ Section 3: Thermal properties of building structures ❖ Section 7: Moisture transfer and condensation

	❖ Presents projected impact of climate change on temperature; precipitation; sea level; relative humidity; solar radiation; and wind speed. ❖ Table 2.23* summarises the major potential impact of climate change on the built environment [pp 2-45]. ❖ UKCP09 (like UKCP18) can suggest the probability that this threshold will be exceeded. This can be particularly useful if performing a future overheating risk analysis of a building or investigating the likelihood of existing cooling systems becoming under-sized (and, conversely, existing heating systems becoming over-sized). ❖ *Focus of guide is on using climate change evidence to inform energy decision making and not more widely.*		
CIBSE Guide B0: Applications and activities: HVAC strategies for common building types (CIBSE, 2016)	❖ **No Climate Change risk evidence referenced in document.** ❖ Guidance references the need for 'low carbon' and 'nearly zero-energy' buildings and the growing interest in 'whole-life' assessments of carbon emission and resource use [pp 0-2]. ❖ When developing an HVAC strategy, system designers should consider possible changes to a building, its environment, and the uses of the spaces within it. *Such changes may include the impact of climate change (notably extreme events)* [section 0.3.4].	❖ **No health risk evidence referenced in document** ❖ Guidance references the need to create a healthy indoor environment for occupants' wellbeing and to ensure acceptable levels of thermal, visual, and aural comfort for occupants [pp 0-1]. ❖ Guidance acknowledges that mechanical ventilation is often a source of poor indoor air quality in schools [pp 0-10]. ❖ Document references the importance of ventilation in dwellings to remove allergens: arising from dust mites, odours, and pollutants such as volatile organic compounds (VOCs) [section 0.5.9]. ❖ Document references the need for infection control in specialist environments e.g., hospitals [section 0.5.10].	❖ **No building fabric risk evidenced in document** ❖ Document references the importance of ventilation in dwellings to control of condensation: arising from moisture, mainly generated by cooking, washing and clothes drying. The practice of drying clothes indoors can give rise to high humidity in any room. Moisture is often the dominant pollutant. The key to avoiding mould problems is to avoid a situation where the relative humidity exceeds 70% for a prolonged period, and to avoid cold bridges where surface temperatures are likely to fall below 18 °C [section 0.5.9].
CIBSE Guide B1: Heating (CIBSE, 2016)	❖ **Climate Change risk evidence referenced in document.** ❖ Document refers to CIBSE publications TM36: Climate change and internal environment [pp 1-4]; TM48: The use of climate change scenarios for building simulation [pp 1-4; pp 1-10]; and Probabilistic Climate Profiles: the effective use of climate projections in building design (CIBSE, 2014) [pp 1-10]. ❖ *Consideration should be given to making allowances for anticipated climate change over the life of the building or heating system [pp 1-6].*	❖ **No health risk evidence referenced in document** ❖ Guidance references the need for appropriate indoor thermal comfort [pp 1-3]. ❖ Guidance acknowledges that fuel combustion will have detrimental impacts on local air quality (NOx, SOx and particulates) [pp 1-40].	❖ **No building fabric risk evidenced in document** ❖ Document references the need to heat unoccupied buildings (or parts of buildings) to control temperature or humidity to protect the fabric of a building, its contents, processes going on in the building, or the heating system itself, e.g., from frost and condensation [pp 1-6; 1-13].

	❖ To assist the designer in assessing the likely effects of climate change, CIBSE has developed a set of future weather files. These future hourly weather files, based on the existing Design Summer Years and Test Reference Years *incorporate the UKCIP09 climate change scenarios*, and are available for 14 sites, for three time periods: 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100). 10th, 50th, 90th percentiles are provided for emission scenarios: 2020s: High; 2050s: Medium; 2050s: High; 2080s: Low; 2080s: Medium; and 2080s: High [pp 1-10]. ❖ Guidance states that fuel combustion will have detrimental impacts "on greenhouse gas concentrations in the atmosphere, which is widely recognised as a likely cause of climate change" [pp 1-40]. ❖		
CIBSE Guide B2: Ventilation and duckwork (CIBSE, 2016)	❖ **No Climate Change risk evidence referenced in document.** ❖ Guidance references the UK Climate Change Levy (2012) and carbon reduction targets [pp 2-3].	❖ **Health risk evidence referenced in document** ❖ *Refers to evidence that poor indoor air quality impairs the performance of employees in a workspace (Andersson et al., 2006); and link between poor IAQ and poor health in the home (Bornehag et al., 2005) [pp 2-4].* ❖ Reference is made to strategies to mitigate outdoor pollutant sources within buildings including locating air intakes to avoid outdoor sources; filtration; and temporarily reducing ventilation during transient periods of high pollution [pp 2-9]. ❖ Guidance identifies major indoor pollutants; and metabolic carbon dioxide (and associated health risks) as a marker for the adequacy of ventilation [pp 2-9; 2-119]. ❖ To minimise the risk of mould growth or condensation and maintain comfortable conditions, a maximum design figure of 60% RH is suggested for the design of air-conditioning systems [pp 2-10]. ❖ Reference is made to poor filtration performance in mechanically ventilated buildings that can allow dirt and dust to accumulate, providing potential sites for microbiological activity. Spores and bacteria can then be	❖ **No building fabric risk evidenced in document** ❖ Reference is made to a maximum design figure of 60% RH for the design of air-conditioning systems to minimise the risk of mould growth or condensation [pp 2-10]. ❖ Reference is made to the need to avoid interstitial condensation, which can cause rotting of wood-based components, corrosion of metals and reduction in the performance of thermal insulation [pp 2-10]. ❖ It is recommended that (large) ventilation openings should be designed in a way that avoids rain entering the building through ducts, taking account of the effects of driving wind, splashing etc [pp 2-57; 2-120]. ❖

		released into the occupied space, causing potential comfort and health problems [pp 2-25]. ❖ Reference is made to standard air filters with an anti-microbial coating that is reported to kill or inhibit the growth of micro-organisms on the filter material and any trapped dust and debris [pp 2-27]. ❖ Reference is made to ultraviolet germicidal irradiation (UVGI), effective against all types of bacteria and fungi, as well as spores and viruses that are normally found in the air [pp 2-27; 2-119]. ❖ *The guidance highlights the potential health issues arising from microbial material in ductwork. There are currently no environmental health criteria setting safe microbial exposure. Possible harmful health effects on the occupants of buildings from microbial growth within the fabric include allergies, infection and toxicosis. Further information about these is provided in CIBSE TM26: Hygienic maintenance of office ventilation ductwork (2000)* [pp 2-119].	
CIBSE Guide B3: Air conditioning and refrigeration (CIBSE, 2016)	❖ **No Climate Change risk evidence referenced in document.** ❖ Guidance references the UK Climate Change Levy (2012) and carbon reduction targets [pp 3-1]. ❖	❖ **No health risk evidence referenced in document** ❖ Reference is made to keeping humidity above 40%. Humidity of 35% or below may be acceptable, but precautions must be taken to limit the generation of dust and airborne irritants. An upper limit for humidity of 60% will minimise the risk of mould growth or condensation in areas where moisture is being generated. [pp 3-20].	❖ **No building fabric risk evidenced in document** ❖
CIBSE Guide B4: Noise and vibration control of building service systems (CIBSE, 2016)	❖ **No Climate Change risk evidence referenced in document.**	❖ **No health risk evidence referenced in document**	❖ **No building fabric risk evidenced in document**
CIBSE Guide F: Energy Efficiency (CIBSE, 2012 with corrigendum August 2016)	❖ **Climate Change risk evidence referenced in document.** ❖ Document references UK government commitment to *reduce carbon emissions* [1-1] ❖ Reference is made to CIBSE policy statement on Climate Change, but link is broken http://www.cibse.org/policystatements [1-2]	❖ **No health risk evidence referenced in document** ❖ Reference made to the potential for improved occupant health and wellbeing in low-energy buildings, due to associated improvements in levels of daylight, air quality and natural ventilation [e.g., 1-2 and 1-7]. ❖ Guidance includes ventilation and daylighting strategies to improve IEQ and occupant comfort.	❖ **No building fabric risk evidenced in document** ❖ Reference made to identifying building fabric problems when undertaking an energy efficiency retrofit including condensation and frost damage risks [18-17].

	❖ States that improving energy efficiency will help reduce the risk of dangerous climate change. ❖ *Building professionals should also consider the wider sustainability impacts of their decisions including adapting buildings for climate change. These issues are covered in more detail in CIBSE Guide L: Sustainability* [1-3]. ❖ Design has to consider the predicted rise in summertime temperatures due to climate change, known as 'climate change adaptation' and use of scenarios for building simulation [3-4].	❖	
CIBSE Guide L: Sustainability (2020)	❖ **Climate Change risk evidence referenced in document.** ❖ *Mitigate the risks of thermal comfort issues arising due to climate change* ❖ *Consider how extreme weather events may impact on the design and construction of building fabric* ❖ *Consider the impacts of increased flood risk and the impact on buildings and drainage systems* ❖ *Design for an increased risk of droughts and water shortages (in general, to be reviewed depending on project locations)* [2-4 and 19-14]. ❖ **Section 3.3.1: the changing climate** ❖ Chapter 9: Guidance on the reduction of carbon emissions from energy use in buildings ❖ Chapter 12: Guidance on reducing embodied carbon emissions. ❖ Section 18.2 on alternatives to diesel vehicles and generators during construction. ❖ **Chapter 19: Climate change adaptation** ❖ **Table 19.1: Key predicted climate change effects, implications for buildings and example measures [19-6].**	❖ **Health risk evidence referenced in document.** ❖ Reference made to the sustainability objective of air quality and providing healthy and comfortable environments [6-10]. ❖ Section 8.2: Introduces the impacts of buildings on human health and wellbeing. ❖ Section 8.4: air quality. ❖ Section 8.5: Thermal comfort. ❖ Section 8.6: Humidity. ❖ Section 8.7: visual quality, light and lighting. ❖ Section 8.10: Materials selection, FF&E and VOCs.	❖ **No building fabric risk evidenced in document** ❖ Reference made to considering how extreme weather events may impact on the design and construction of building fabric [2-4]. ❖ **Section 19.5:** Impacts of a changing climate and solutions to adapting buildings, including: ❖ Resistance and resilience to extreme conditions, detailing, and the behaviour of materials; this would include the impact of higher wind speeds on buildings and their surroundings, and on technologies and ventilation (particularly in tall buildings).
Energy performance of Buildings directive (European Parliament, 2018)	❖ **Climate Change risk evidence referenced in document.** ❖ Climate Change mitigation issues are addressed through the conservation of fuel and power. ❖ Document references that reduced energy consumption would allow the EU to comply with the Kyoto Protocol to	❖ **No health risk evidence referenced in document** ❖ Reference is made to the need to take account of general indoor climate conditions, to avoid possible negative effects such as inadequate ventilation [pp 153/19].	❖ **No building fabric risk evidenced in document**

	the United Nations Framework Convention on Climate Change (UNFCCC), and to honour both its long term commitment to maintain the global temperature rise below 2 °C, and its commitment to reduce, by 2020, overall greenhouse gas emissions by at least 20 % below 1990 levels, and by 30 % in the event of an international agreement being reached [pp 153/13]. ❖ *Member States shall ensure that: by 31 December 2020, all new buildings are nearly zero energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings* [pp 153/21].		
Energy Efficiency Directive (European Parliament, 2018)	❖ **Climate Change risk evidence referenced in document.** ❖ Document references the moderation of energy demand as one of the five dimensions of the Energy Union Strategy 'A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy' (2015) [pp 328/210]. ❖ *This is in line with the EU's commitments established by the 2015 Paris Agreement, committing to keep the increase of the global average temperature to well below 2 °C above pre-industrial levels and to pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels* [pp 328/210].	❖ **No health risk evidence referenced in document** ❖ Document recognises that energy efficiency has a impact on air quality, energy efficient buildings reduce the demand for heating fuels, including solid heating fuels. ❖ Energy efficiency contributes to improving indoor and outdoor air quality and help achieve the objectives of the Union's air quality policy (EU Directive 2016/2284) [pp 328/211].	❖ **No building fabric risk evidenced in document**
BREEAM International In-Use standard (Residential V.6)	❖ **Climate Change risk evidence referenced in document.** ❖ The document refers to the need to reduce the total operational energy use in buildings and to increase use of renewable energy sources where possible if the worse effects of climate change are to be avoided [pp 71; 267]. ❖ Document links climate change and water efficiency, due to the energy required to extract, process, delivery and dispose of water [pp 150; 228]. ❖ Document considers an asset's exposure to physical risks including climate change [pp 188]. ❖ Calculations on flood risk should contain an allowance for climate change for all sources of flooding, based on a medium or high emissions scenario from a robust climate model [pp 191; 192]. ❖ Document links a reduction of the use of refrigerants with climate change [pp 212; 222-3]. ❖ The resilience section considers climate–related physical risks, local watercourse pollution, excess material damage and physical security and ways of managing these by identifying climate-related transition risks and opportunities, and emergency plans [311; 314].	❖ **Health risk evidence referenced in document** ❖ *Guidance recognises internal environmental conditions in buildings, including visual comfort, indoor air quality, thermal comfort, and acoustic comfort, can have a significant impact on physical and mental health and links it to SDG 3 [33].* ❖ Guidance supports the physical health of building occupants by reducing the risk of health concerns associated with indoor air pollution from external sources [pp 35]. ❖ In air conditioned/mixed mode buildings, intakes >20 m from external pollution sources and >10 m apart from exhausts [pp 54]. ❖ In naturally ventilated buildings, ventilators/ openable windows over 10m from external pollution sources [pp 55]. ❖ In building areas subject to large and/or variable occupancy patterns carbon dioxide or alternative air-quality sensors requirements with warning signals and/or linked to ventilation system [pp 55]. ❖ Radon risk management systems [pp 69]. ❖ Testing and compliance with relevant VOC emission EU Standards for specific building materials [pp 220]. ❖ Guidance references the need for water systems designed in compliance with Health and Safety Executive's 'Legionnaires' disease [pp 264].	❖ **No building fabric risk evidenced in document** ❖ Identifying sources of moisture and potential for condensation are referred to under indoor air quality management [252].
BREEAM UK Domestic Refurbishment and fit out standard	❖ **Climate Change risk evidence referenced in document.** ❖ The document refers to the UK Government's commitment to the Climate Change Act, which specifies an 80% reduction in CO_2 emissions by 2050 measured against a 1990 baseline. ❖ A core aim of all BREEAM schemes is to recognise and encourage a reduction in CO_2 emissions through the improved energy efficiency of the dwelling and its services as a result of the refurbishment [pp 100]. ❖ This is addressed specifically in the energy issue but also in the foundations of the scheme itself [Appendix F, pp 297]. ❖ Document references the need to allow for climate change when calculating surface water run-off [Pollution, pp 192].	❖ **Health risk evidence referenced in document** ❖ Refence made to the need for ventilation in line with Building Regulations, to prevent condensation and mould growth [pp 91]. ❖ Document references requirements to limit VOCs [pp 82]. ❖ Document references the need to reduce the risks to life, health and property resulting from fire and exposure to carbon monoxide [pp 93].	❖ **No building fabric risk evidence in document.** ❖ Reference made to increased risk of moisture build up in Historic buildings, causing fabric damage and problems with condensation and mould (focus here is on health and wellbeing) [pp 93]. ❖ Reference made to the need to construct a building in such a way to prevent flood water entering the building and damaging its fabric [pp 203].
BREEAM UK New Construction Non-Domestic Buildings (Wales) (2018)	❖ **Climate Change risk evidence referenced in document.** ❖ Guidance refers to dynamic thermal simulation software packages that provide the facility for building designs to be assessed under external climatic conditions specific to geographic location. Industry standard weather data for the UK is available in the form of Test Reference Years (TRYs) and Design Summer Years (DSYs) provided by CIBSE [pp 106].	❖ **Health risk evidence referenced in document** ❖ Guidance recognises that poor indoor air quality can have a range of negative impacts on the physical health of building occupants [pp 90]. ❖ Guidance recognises the need to consider indoor air pollution early in the design process so that a mitigation strategy can be put in place [pp 72]. ❖ Specifying appropriate ventilation strategies to mitigate poor air quality [pp 72; 91]	❖ **No building fabric risk evidence in document.** ❖ Reference made to design durability and resilience: climate change can significantly accelerate the deterioration of materials used in a building. It is therefore important to consider the impact of climate change and its associated environmental changes on the vulnerable elements within the built [environment pp 248].

	❖ Adaption to Climate change is listed under the requirements of passive design analysis [pp 153]. ❖ Reducing water consumption as a response to climate change and possible water shortages [pp 212]. ❖ Guidance encourages waste minimisation through optimised design methods, which consider current and future needs, and respond to functional requirements and climate change adaptation [pp 257]. ❖ Encouraging consideration and implementation of measures to mitigate the impact of more extreme weather conditions arising from climate change over the lifespan of the building [pp 258]. ❖ Waste Section 05 'Adaptation to climate change' includes recommendations for a systematic risk assessment to identify the impact of expected extreme weather conditions arising from climate change on the building over its projected life cycle and adaptation strategy based on scenarios and impacts [pp 281-286]. ❖ Pollution Section 03 refers to the need to consider increased rainwater, surface run-off and flooding because of climate change [pp 335; 337; 343].	❖ WHO guidelines for indoor air quality and selected pollutants, 2010 [pp. 93] ❖ Managing harmful emissions from construction products by specifying finishes and products that have been tested in accordance with the appropriate standards. Refence made to EU standard tests that could be used [pp 72; 96].	❖ Waste Section 05 'Adaptation to climate change' includes assessment to avoid increased risks of deterioration and higher maintenance demands because of climate change [pp 282].
Home Quality Mark ONE Technical Manual Wales (BRE, 2018)	❖ **Climate Change risk evidence referenced in document.** ❖ Document refers to the need for wider site sustainability and climate change mitigation [pp 30]. ❖ Design flood level and allowance for climate change in line with best practice [pp 56; 58]. ❖ Met Office predictions - very significant increase in the incidence of flooding over the next century because of climate change [pp 59]. ❖ Run-off calculations to include an allowance for climate change [pp. 62]. ❖ Overheating risk and energy efficiency [pp. 96]. ❖ Credits achieved for using climate change weather data to control high indoor temperatures [pp 97; 98]. ❖ Reference made to UKCP09 [pp. 99]	❖ **Health risk evidence referenced in the document** ❖ WHO's evidence of deaths associated with poor air quality; Guidelines for indoor air quality: selected pollutants; and Damp and mould: health risks, prevention, and remedial actions [pp 122; 252; 254; 255]. ❖ Document also refers to the need to minimise formaldehyde and TVOCs from all sources and specifying paints and varnishes that evidence protection against mould growth with a focus on paints used in wet areas [pp 76; 77]. ❖ References the importance of ventilation and acknowledges that increasing levels of building airtightness means that the ventilation system must be capable of providing effective continuous ventilation to all areas of a home, for all levels of likely occupancy and without nuisance to avoid issues of poor air quality, stuffiness and high pollutant levels including VOCs and mould spores [pp 102]. ❖ The need for drying space to help protect the inside of the property against moisture build-up which result in increased risks to health from mould growth and poor air quality [pp 153].	❖ **No building fabric risk evidenced in document** ❖ Document refers to the need for drying space to help protect the inside of the property against moisture build-up and consequently damage to the fabric of the home and its finishes [pp 153]. ❖ Refers to importance of considering climate change, as it can significantly speeds up deterioration of materials used in a building [pp 148].
Well Building Standard	❖ **No Climate Change risk evidence referenced in document.**	❖ **Health risk evidence referenced throughout the document.** ❖ The standard's focus is solely on the health and wellness of building occupants. ❖ *Each element is considered from the human health perspective (cardiovascular, digestive, endocrine, immune, integumentary, muscular, nervous, reproductive, respiratory skeletal and urinary systems).* ❖ Air quality [pp 27; 53]. ❖ Smoking [pp 28]. ❖ Ventilation [pp 29; 46]. ❖ VOCs [pp 30]. ❖ Air filtration [pp 32]. ❖ Microbes and mould [pp 33; 51]. ❖ Moisture management [pp 40]. ❖ Humidity control [pp 45]. ❖ Biophilic design [140; 154].	❖ **No building fabric risk evidenced in document.**
Welsh Housing Quality Standard (2008)	❖ **No Climate Change risk evidence referenced in document.**	❖ **No Health risk evidence referenced in document** ❖ Document refers to the HHSRS operating guidance (Hazard 1) for threats to health associated with increased prevalence of house dust mites and mould or fungal growths resulting from dampness and/or high humidity [pp 11]. ❖ Damp is an element in the standard assessment checklist [pp 39].	❖ **No building fabric risk evidenced in document.** ❖ Document states that a lack of adequate ventilation and poor thermal performance of external walls and windows, in addition to inadequate background heating levels, are significant contributors to condensation in older dwellings [pp 18].

* **Major impacts of climate change on the built environment**
(CIBSE Guide A: Environmental Design, 2019, Table 2.23)

Climate change	Impact on built environment	Consequential impacts
❖ Rising summer temperatures	❖ Overheating of buildings	❖ Reduced thermal comfort ❖ Loss of staff hours due to high internal building temperatures ❖ Increased temperature mortality (heat)
	❖ Energy demand for cooling	❖ Increase in cooling loads, reduction in chiller coefficient of performance
❖ Rising winter temps	❖ Less demand for heating	❖ Reduction in heating loads ❖ Reduced temperature mortality (cold)
❖ Decrease in summer rainfall	❖ Limitation of water supply	❖ Pressure on water consumption of building services systems
❖ More intense rainfall and rising sea level	❖ Ground movement	❖ Increased structural damage ❖ Increased flooding, leading to property sea level damage and casualties

Appendix B: A summary of dwellings typologies from across Wales

#	House Age	Average floor size *[Rationale from EHS floor space report and WHCS]*	Foundations	Walls	Windows	Roofing	Ground Floor	Heating Systems	Dwelling to be considered in study? *[Rationale from WHCS data]*	Rationale for construction type chosen *[WHCS 2017-18]*	Additional Notes
1A	Pre 1700 urban	87-105m² [mid-end terrace]	No foundations	Timber frame on a dwarf stone wall wattle and daub infill.	Timber windows with small panes	Slate or stone tiles + 25-100mm mineral wool at ceiling level	Solid ground floor	Gas/oil central heating	Mid/end terrace 2/3 storey		Possible basements
1B	Pre 1700 refurbished	87-105m² [mid-end terrace]	No foundations	Replacement infill panels with increased insulation [100mm] e.g., replacement W&D or cork or wood fibre	Secondary glazing	+ 300mm mineral wool at ceiling level	Solid ground floor	Gas/oil central heating	Mid/end terrace 2/3 storey		Possible basements
1C	Pre 1700 rural	184m²	No foundations	Timber frame on a dwarf stone wall wattle and daub infill.	Timber windows with small panes	Slate or stone tiles + 25-100mm mineral wool at ceiling level	Solid ground floor	Gas/oil central heating	detached		Possible basements
1D	Pre 1700 refurbished	184m²	No foundations	Replacement infill panels with increased insulation [100mm] e.g., replacement W&D or cork or wood fibre	Secondary glazing	+ 300mm mineral wool at ceiling level	Solid ground floor	Gas/oil central heating	detached		Possible basements
2A	1700-1830 [Georgian architecture] urban	93-106m² [mid-end terrace]	shallow or no foundations	Solid walls constructed from brick or stone with lime mortar, with stucco rendering later in the period.	Timber sash windows with smaller panes – tall windows on the first two floors and smaller windows on the top storeys.	Roofs are constructed of timber, formed into principal trusses with secondary rafters. Natural slate tiles	Ventilated suspended timber ground floor.	Gas central heating	Mid/end terrace 3/4 storey	>90% of Welsh dwellings of this age are solid masonry	Possible basements
2B	[Refurbished]	93-106m² [mid-end terrace]		As above	UPVC double glazed replacement windows?	+ 300mm mineral wool at ceiling level	Ventilated suspended timber ground floor.	Gas central heating	Mid/end terrace 3/4 storey	>90% of Welsh dwellings of this age are solid masonry	Possible basements
2C	1700-1830 [Georgian architecture] rural	184m²	shallow or no foundations	Solid walls, exposed stonework, sometimes with additional lime render and/or a limewash	Timber sash windows	Roofs are constructed of timber, formed into principal trusses with secondary rafters. Natural slate tiles+ 25-100mm mineral wool at ceiling level	solid ground floor [flagstones or tiles on earth]	Gas/Oil central heating/electric storage heating/other	Detached two storeys	>90% of Welsh dwellings of this age are solid masonry	Possible basements
2D	[Refurbished]	184m²	shallow or no foundations	As above	UPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	solid ground floor [flagstones or tiles on earth]	Gas/Oil central heating/electric storage heating/other	Detached two storeys	>90% of Welsh dwellings of this age are solid masonry	Possible basements
3A	1830-1910 [Victorian and Edwardian legacy] urban	93-106m² [mid-end terrace]	Shallow stepped brick footings.	Solid walls constructed from brick or stone, at least one brick thick, with lime mortar,	Timber sash windows.	Traditional cut roof with overhanging eaves, natural slate tiles and cast-iron guttering. +25-100mm mineral	Ventilated suspended timber ground floor.	Gas central heating	Mid/end terrace 2/3 storey	>90% of Welsh dwellings of this age are solid masonry	Possible basements

				typically Flemish bond.		wool at ceiling level					
3B	1830-1910 urban [refurbished]	93-106m^2 [mid-end terrace]	Shallow stepped brick footings.	Solid stone walls, as above, no additional insulation	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Ventilated suspended timber ground floor.	Gas central heating	Mid/end terrace 2/3 storey	>90% of Welsh dwellings of this age are solid masonry	Possible basements
3C	1830-1910 [refurbished]	93-106m^2 [mid-end terrace]	Shallow stepped brick footings.	Brick terraced properties as above + 60-100mm EWI	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Ventilated suspended timber ground floor.	Gas central heating	Mid/end terrace 2/3 storey	>90% of Welsh dwellings of this age are solid masonry	Possible basements
3D	1830-1910 urban [refurbished]	93-106m^2 [mid-end terrace]	Shallow stepped brick footings.	Brick terraced properties as above + 50mm IWI	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Ventilated suspended timber ground floor.	Gas central heating	Mid/end terrace 2/3 storey	>90% of Welsh dwellings of this age are solid masonry	Possible basements
3E	1830-1910 [Victorian and Edwardian legacy] rural	170m^2	shallow or no foundations	Solid walls, constructed from brick or stone sometimes with additional lime render and/or a limewash	Timber sash windows remained smaller in rural areas.	Traditional cut roof with overhanging eaves, natural slate tiles and cast-iron guttering. +25-100mm mineral wool at ceiling level	solid ground floor [flagstones or tiles on earth]	Gas central heating	Detached two storeys	>90% of Welsh dwellings of this age are solid masonry	Possible basements
3F	1830-1910 rural [Refurbished]	170m^2		Solid stone walls, as above, no additional insulation	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Solid floor – no insulation	Gas central heating	Detached two storeys	>90% of Welsh dwellings of this age are solid masonry	Possible basements
3G	1830-1910 rural [Refurbished]	170m^2	shallow or no foundations	Solid brick + 60-100mm EW	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Solid floor – no insulation	Gas central heating	Detached two storeys	>90% of Welsh dwellings of this age are solid masonry	Possible basements
3H	1830-1910 rural [Refurbished]	170m^2	shallow or no foundations	Solid brick + 50mm IWI	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Solid floor – no insulation	Gas central heating	Detached two storeys	>90% of Welsh dwellings of this age are solid masonry	Possible basements

4A	1919-1939	103m^2	Concrete strip foundations.	cavity walls: two independent leaves of brickwork tied together.	uPVC double glazed replacement windows	Traditional cut roof often with hipped ends, clay plain tiles. Some houses had torching [lime mortar under the tiles]. +25-100mm mineral wool at ceiling level	Timber floor joists protected from dampness.	Gas central heating	Semi-detached two storey	>80% of Welsh dwellings of this age have cavity masonry	[Between the wars when social housing was introduced]
4B	1919-1939 [refurbished]	103m^2	Concrete strip foundations.	Cavity walls with CWI	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Solid floor – no insulation	Gas central heating	Semi-detached two storey	>80% of Welsh dwellings of this age have cavity masonry	
4C	1919-1939 [refurbished]	103m^2	Concrete strip foundations.	Cavity walls with 60mm – 100mm EWI	uPVC double glazed replacement windows	+ 300mm mineral wool at ceiling level	Solid floor – no insulation	Gas central heating	Semi-detached two storey	>80% of Welsh dwellings of this age have cavity masonry	
5A	1945-1959 [Post-war recovery]	93m^2	Concrete strip foundations.	Traditionally built houses had mostly brick cavity walls. Early blockwork was also used for the inner leaf.	uPVC double glazed replacement windows	New techniques such as the TRADA truss introduced. Concrete tiles underlaid with felt and cast iron or asbestos guttering. + 25-100mm mineral wool at ceiling level	Thin concrete ground floor. No polythene dampproof membrane [DPM].	Gas central heating	Semi-detached two storey	>85% of Welsh dwellings of this age have cavity masonry	16% of Welsh dwellings were built between 1945-1964
5B	1945-1959 [refurbished]	93m^2	Concrete strip foundations.	As above + CWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Semi-detached two storey	>85% of Welsh dwellings of this age have cavity masonry	[WHCS states 62% have CWI]
5C	1945-1959 [refurbished]	93m^2	Concrete strip foundations.	As above + 60mm – 100mm EWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Semi-detached two storey	>85% of Welsh dwellings of this age have cavity masonry	

6A	1960-1979 detached	133m^2	Concrete strip foundations.	Most houses had cavity walls: block inner leaf almost universal and brick outer leaf.	uPVC double glazed replacement windows	Mostly prefabricated roof trusses, concrete tiles with felt and plastic guttering. 25mm insulation.	Concrete strip ground floor. Polythene DPM from mid-1960s.	Gas central heating	Detached two storeys	>85% of Welsh dwellings of this age have cavity masonry	More homes were built in the UK than at any other time; consequently, the variation of dwelling type is significant. 23% were built between 1965-1980
6B	1960-1979 semis	81m^2	Concrete strip foundations.	Most houses had cavity walls: block inner leaf almost universal and brick outer leaf.	uPVC double glazed replacement windows	Mostly prefabricated roof trusses, concrete tiles with felt and plastic guttering. 25mm insulation.	Concrete strip ground floor. Polythene DPM from mid-1960s.	Gas central heating	Semi-detached bungalow 1 storey	>85% of Welsh dwellings of this age have cavity masonry	More homes were built in the UK than at any other time; consequently, the variation of dwelling type is significant. 23% were built between 1965-1980
6C	1960-1979 purpose-built flats	57m^2 [Per unit]	Concrete strip foundations.	Most houses had cavity walls: block inner leaf almost universal and brick outer leaf.	uPVC double glazed replacement windows	Mostly prefabricated roof trusses, concrete tiles with felt and plastic guttering. 25mm insulation.	Concrete strip ground floor. Polythene DPM from mid-1960s.	Gas central heating	Purpose built flats 3 storeys	>85% of Welsh dwellings of this age have cavity masonry	More homes were built in the UK than at any other time; consequently, the variation of dwelling type is significant. 23% were built between 1965-1980
6D	1960-1979 Refurbished detached	133m^2	Concrete strip foundations.	As above + CWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Detached two storeys	>85% of Welsh dwellings of this age have cavity masonry	
6E	1960-1979 Refurbished detached	131m^2	Concrete strip foundations.	As above + 60mm – 100mm EWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Detached two storeys		
6F	1960-1979 Refurbished semis	81m^2	Concrete strip foundations.	As above + CWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Semi-detached bungalow 1 storey		
6G	1960-1979 Refurbished semis	81m^2	Concrete strip foundations.	As above + 60mm – 100mm EWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Semi-detached bungalow 1 storey		
6H	1960-1979 Refurbished flats	57m^2 [Per unit]	Concrete strip foundations.	As above + CWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Purpose built flats 3 storeys		
6I	1960-1979 Refurbished flats	57m^2 [Per unit]	Concrete strip foundations.	As above + 60mm – 100mm EWI	As above [Double Glazed PVCu]	As above + 300mm mineral wool at ceiling level	As above	Gas central heating	Purpose built flats 3 storeys		
7A	1980-1999 detached	173m^2	Deeper concrete strip foundations.	Cavity walls with aerated block inner leaf. Cavity typically 50 mm or 75 mm where partial cavity insulation is included.	Double glazed PVC-U windows, often casement style	Trussed rafters almost universal. Roofs ventilated at eaves. 100 mm roof insulation	Concrete floor, DPM and screed. Insulation rare.	Gas central heating	Detached two storeys	>85% of Welsh dwellings of this age have cavity masonry	

7B	1980-1999 semis	85m²	Deeper concrete strip foundations.	Cavity walls with aerated block inner leaf. Cavity typically 50 mm or 75 mm where partial cavity insulation is included.	Double glazed PVC-U windows, often casement style	Trussed rafters almost universal. Roofs ventilated at eaves. 100 mm roof insulation	Concrete floor, DPM and screed. Insulation rare.	Gas central heating	Semi-detached bungalow 1 storey		
7C	1980-1999 purpose-built flats	53m² [Per unit]	Deeper concrete strip foundations.	Cavity walls with aerated block inner leaf. Cavity typically 50 mm or 75 mm where partial cavity insulation is included.	Double glazed PVC-U windows, often casement style	Trussed rafters almost universal. Roofs ventilated at eaves. 100 mm roof insulation	Concrete floor, DPM and screed. Insulation rare.	Gas central heating	Purpose built flats 3 storeys		
7D Detached	1980-1999 [refurbished]	173m²	Deeper concrete strip foundations.	Increase CWI to 100mm	As above	Increase insulation to 300mm	As above	Gas central heating	Detached two storeys		
7E semis	1980-1999 [refurbished]	85m²	Deeper concrete strip foundations.	Increase CWI to 100mm	As above	Increase insulation to 300mm	As above	Gas central heating	Semi-detached bungalow 1 storey		
7F Purpose built flats	1980-1999 [refurbished]	53m² [Per unit]	Deeper concrete strip foundations.	Increase CWI to 100mm	As above	Increase insulation to 300mm	As above	Gas central heating	Purpose built flats 3 storeys		
7G	1980-1999 TIMBER FRAME	173m²	Concrete strip foundations.	modern platform timber frame with an outer leaf cladding of brick or rendered concrete block [50 mm or 75 mm insulation]	Double glazed PVC-U windows, often casement style	Trussed rafters almost universal. Roofs ventilated at eaves. 300 mm roof insulation	Concrete floor, DPM and screed. Insulation rare.	Gas central heating	Detached two storeys		By the early 1980s timber frame construction accounted for approximately 27% of all new housing in the UK
7H	1980-1999 TIMBER FRAME	85m²	Concrete strip foundations.	modern platform timber frame with an outer leaf cladding of exposed brick or rendered concrete block [50 mm or 75 mm insulation to the depth of the studs]	Double glazed PVC-U windows, often casement style	Trussed rafters almost universal. Roofs ventilated at eaves. 300 mm roof insulation	Concrete floor, DPM and screed. Insulation rare.	Gas central heating	Semi-detached bungalow 1 storey		There is no adaptation suggested for these dwellings
7I	1980-1999 TIMBER FRAME	53m² [per unit]	Concrete strip foundations.	modern platform timber frame with an outer leaf cladding of brick or rendered concrete block [50 mm or 75 mm insulation]	Double glazed PVC-U windows, often casement style	Trussed rafters almost universal. Roofs ventilated at eaves. 300 mm roof insulation	Concrete floor, DPM and screed. Insulation rare.	Gas central heating	Purpose built flats 3 storeys		There is no adaptation suggested for these dwellings

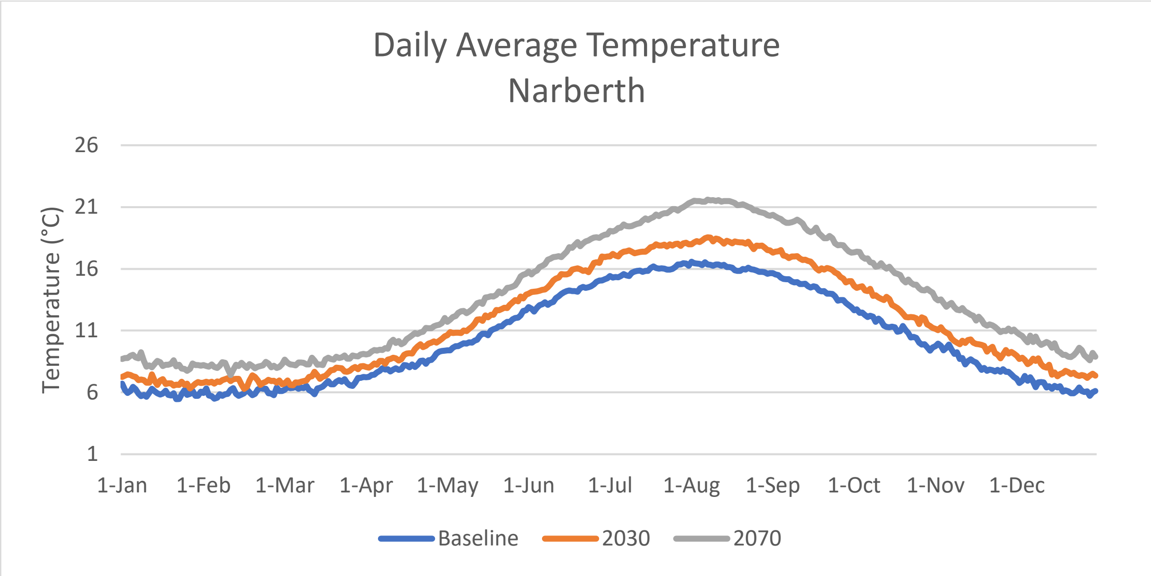
[37]

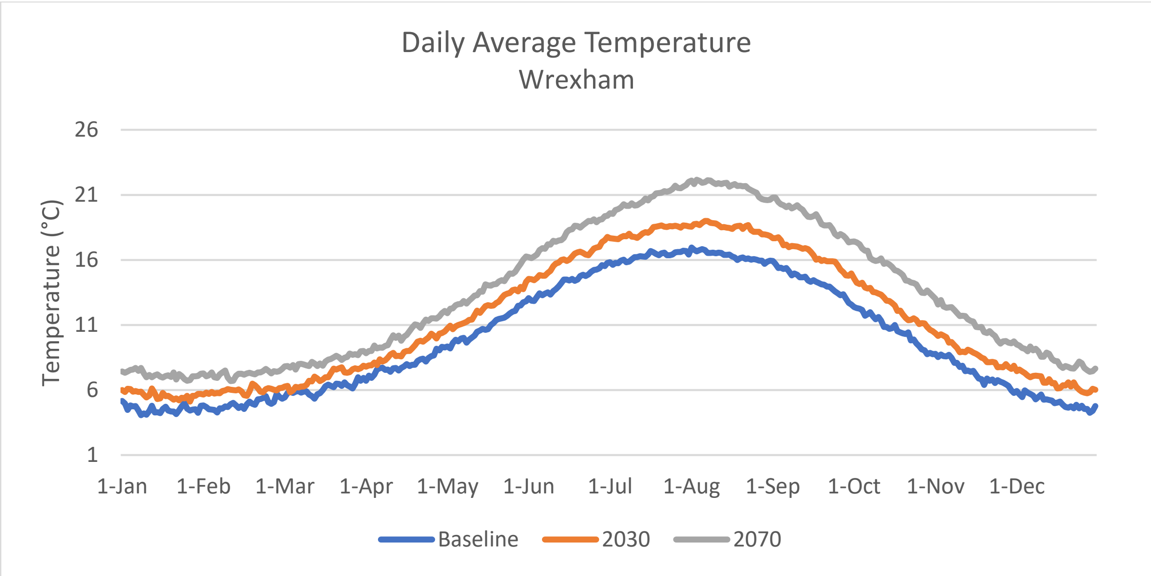
[37] **References:**

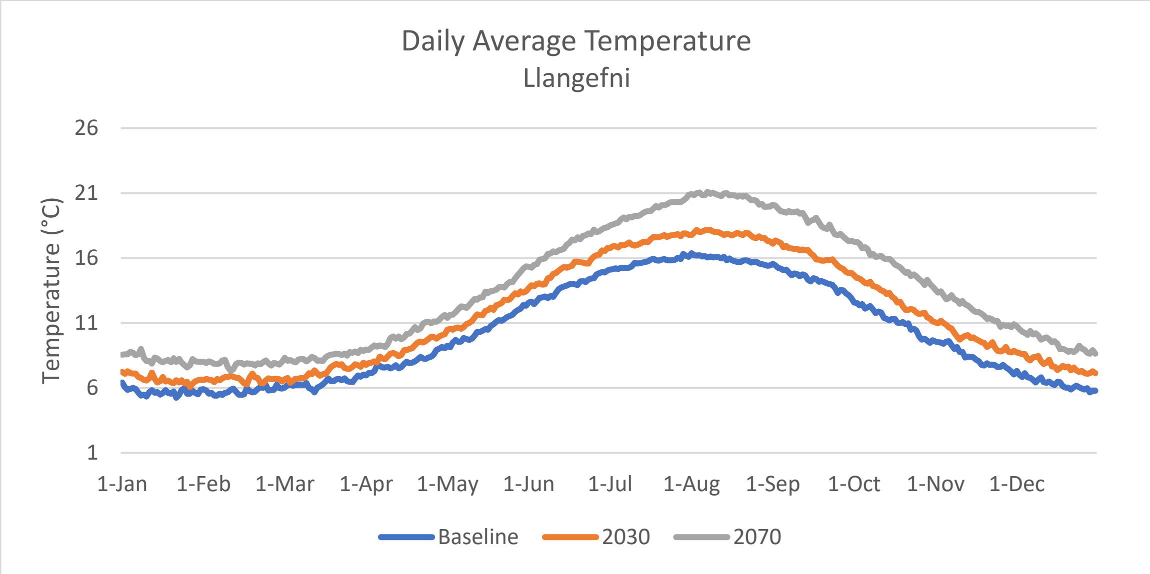
1. **BRE (2020). The housing stock of the United Kingdom. Available online: The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf (bregroup.com)**
2. **Welsh Government. (2018b). *Welsh Housing Conditions Survey*. Available online at: https://gov.wales/welsh-housing-conditions-survey**
3. **Welsh Government (2020). Welsh Housing Conditions Survey 2017-18: headline report. Available online: Welsh Housing Conditions Survey 2017-18: headline report (updated) (gov.wales)**

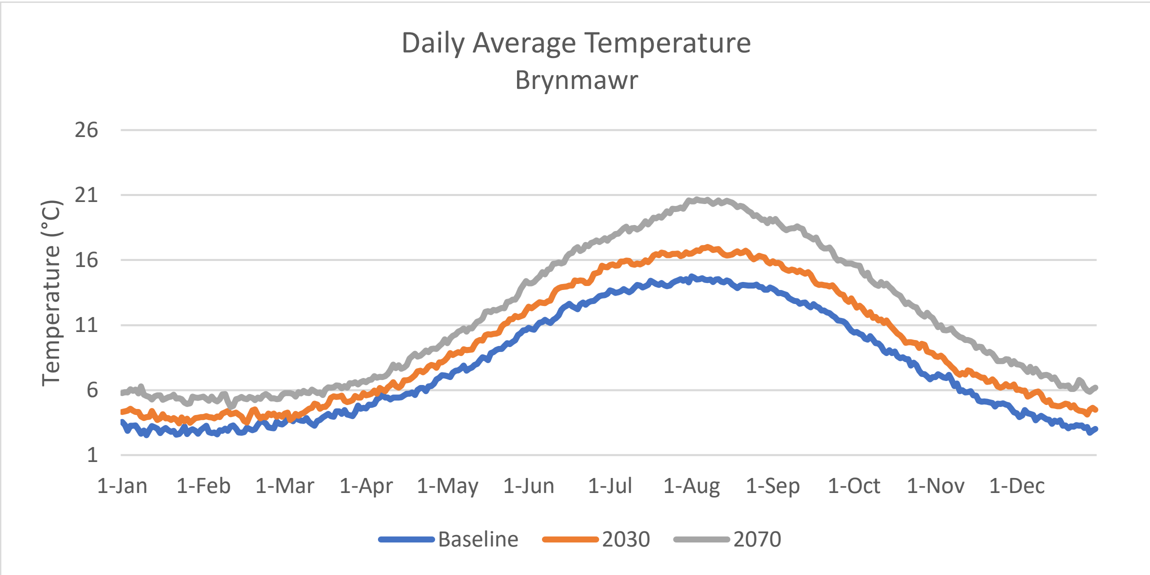
Appendix C: Additional Climate Vulnerability Modelling Results

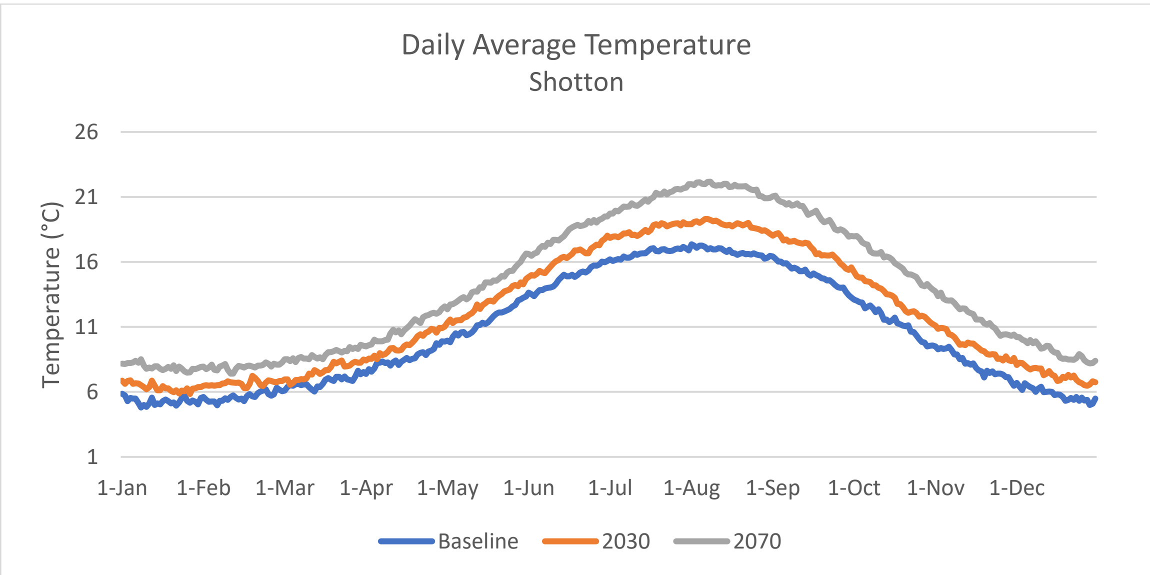
Annual Plot of Daily Average Temperature



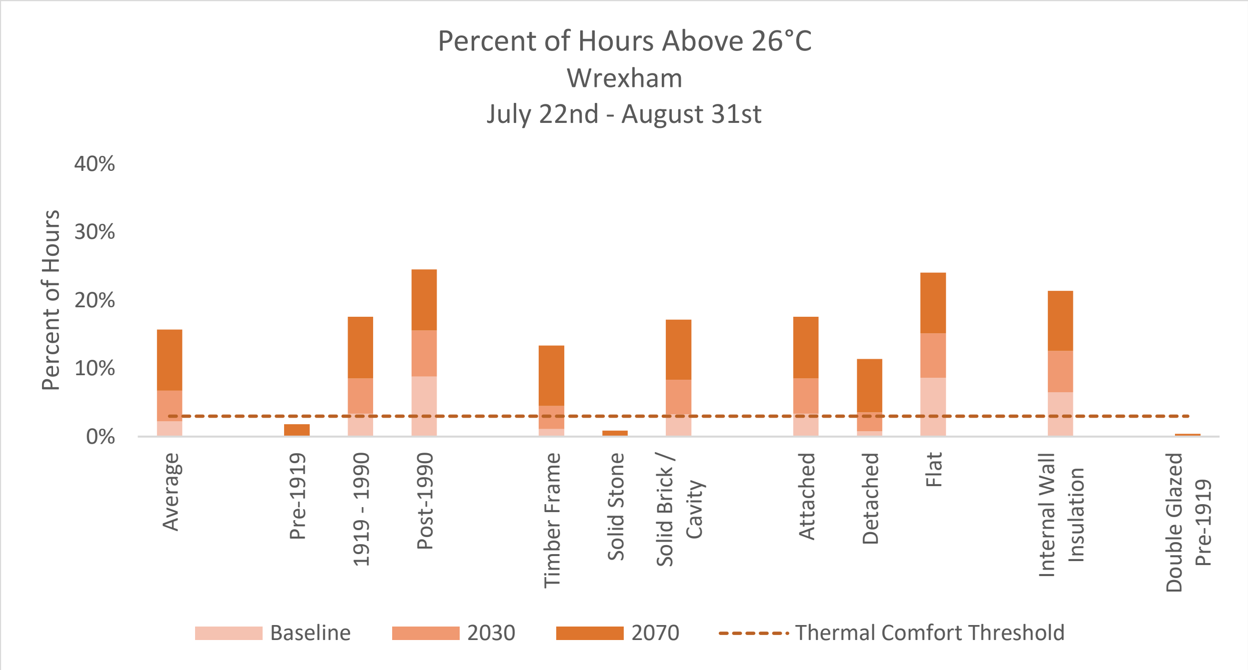


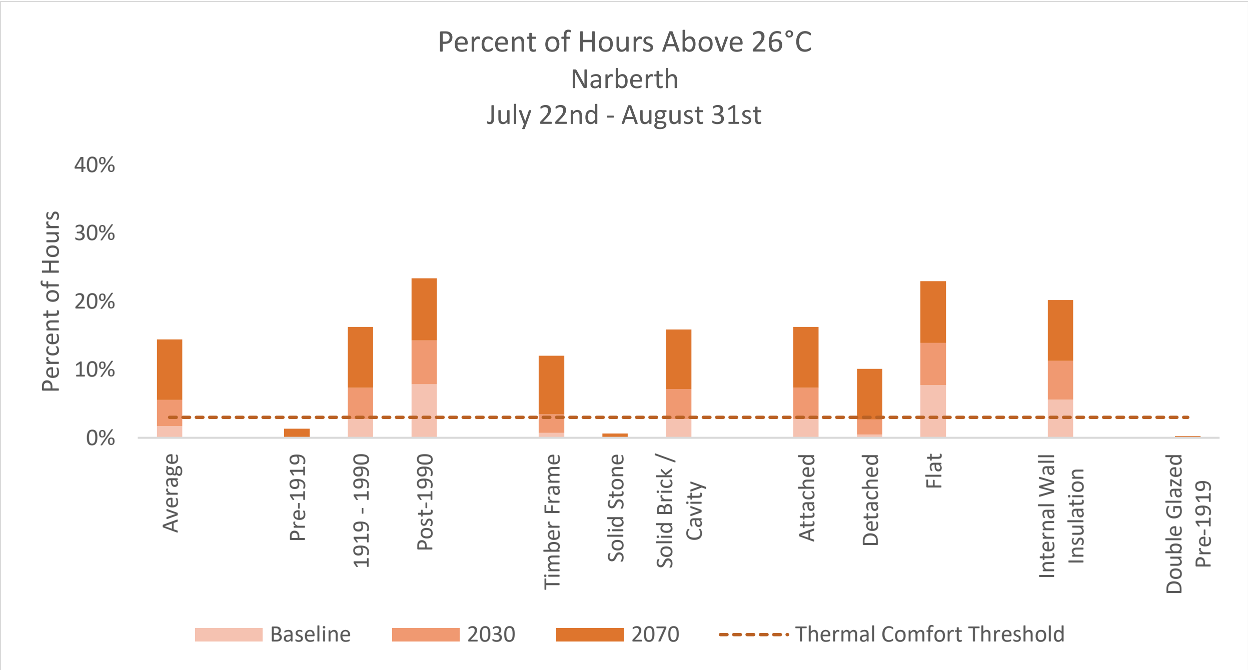

Daily Average Temperature
Llangefni
Temperature (°C)
26
21
16
11
6
1
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

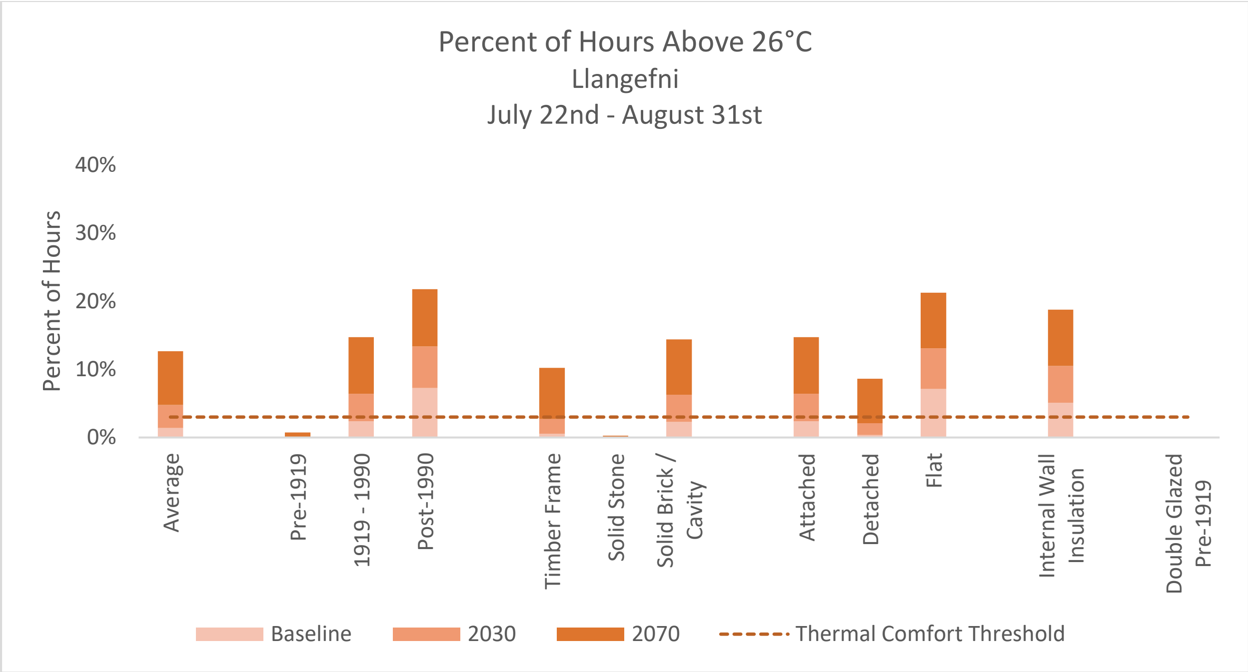

Daily Average Temperature
Brynmawr
Temperature (°C)
26
21
16
11
6
1
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

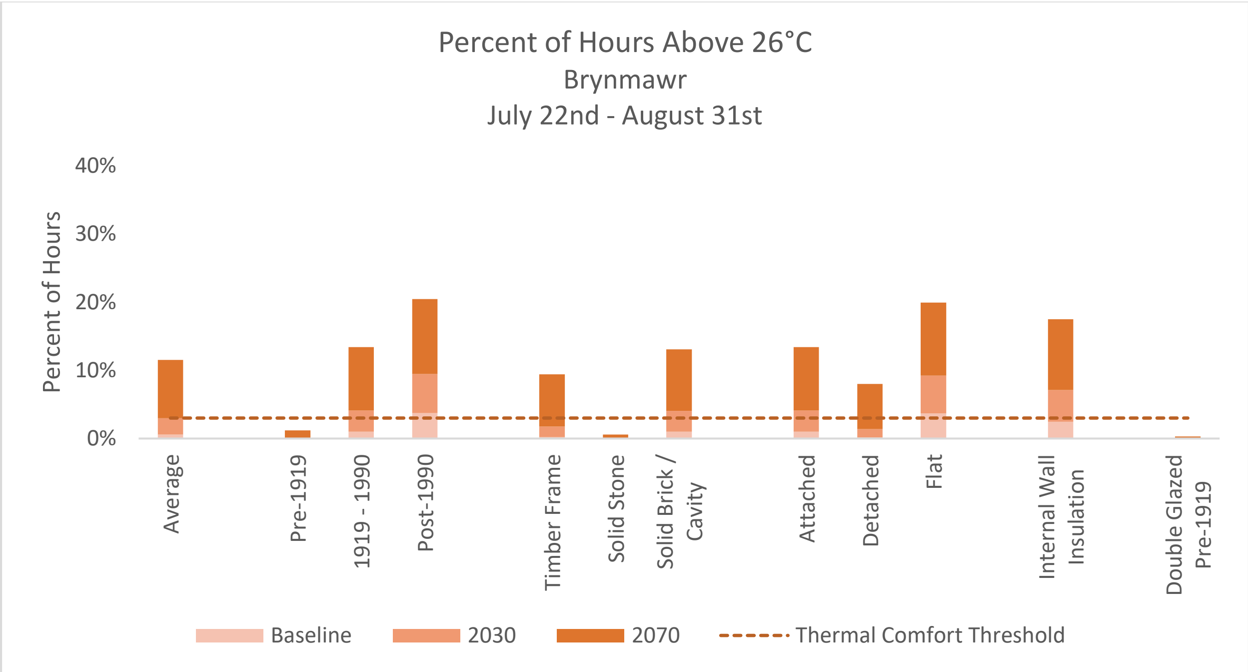

Daily Average Temperature
Shotton
Temperature (°C)
26
21
16
11
6
1
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

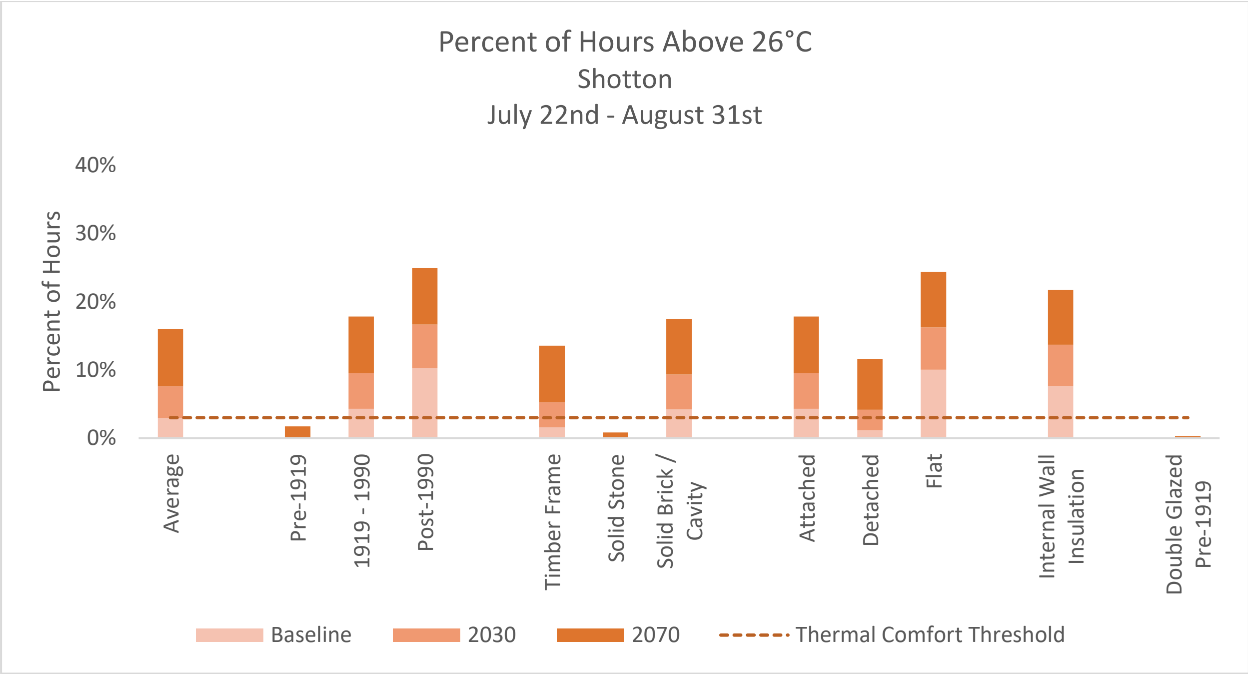
Overheating Risk Graphs



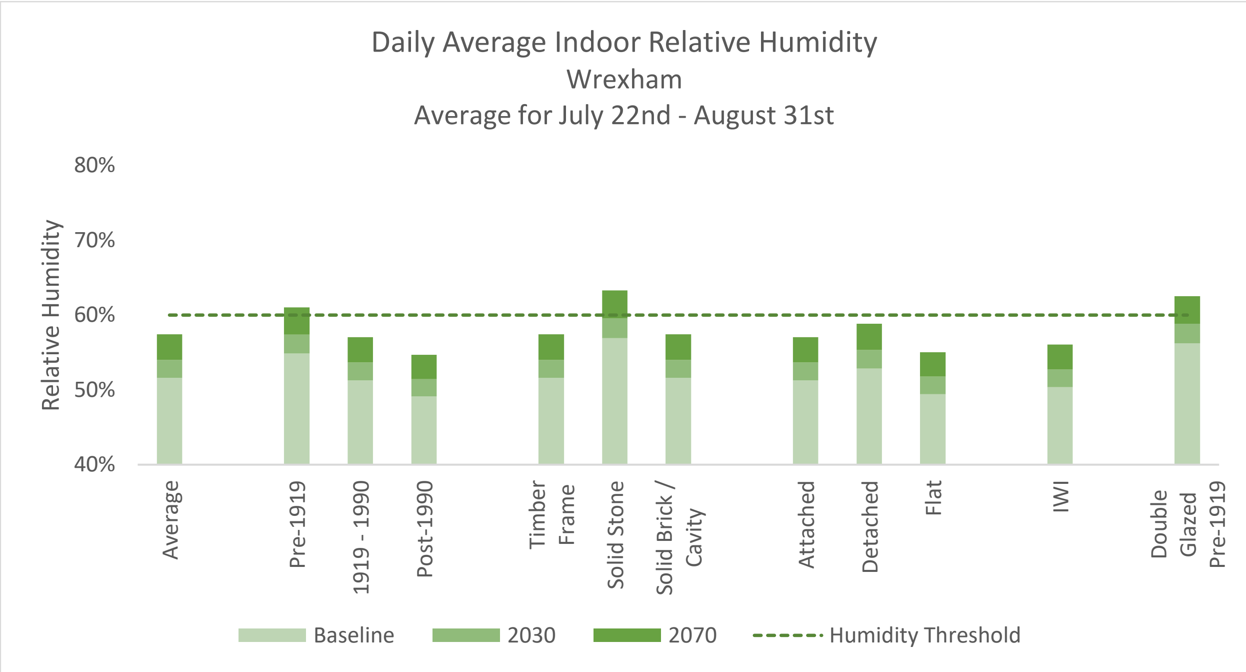


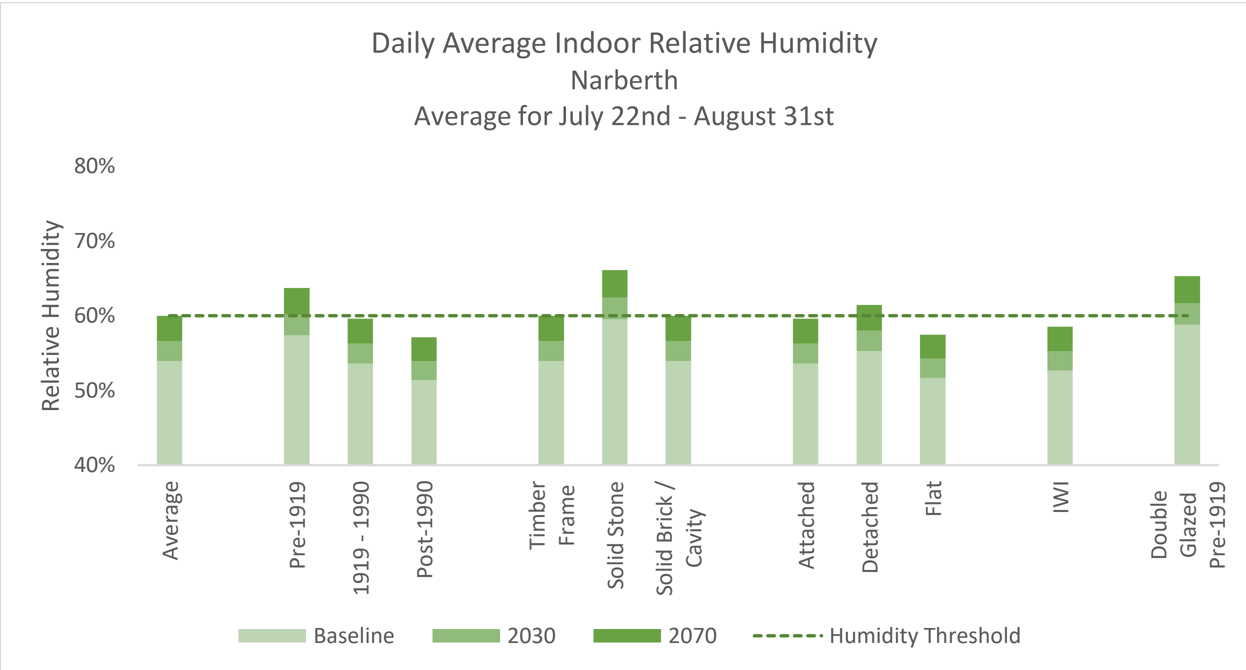

Percent of Hours Above 26°C
Llangefni
July 22nd - August 31st
Percent of Hours
40%
30%
20%
10%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
Internal Wall Insulation
Double Glazed Pre-1919
Baseline
2030
2070
Thermal Comfort Threshold

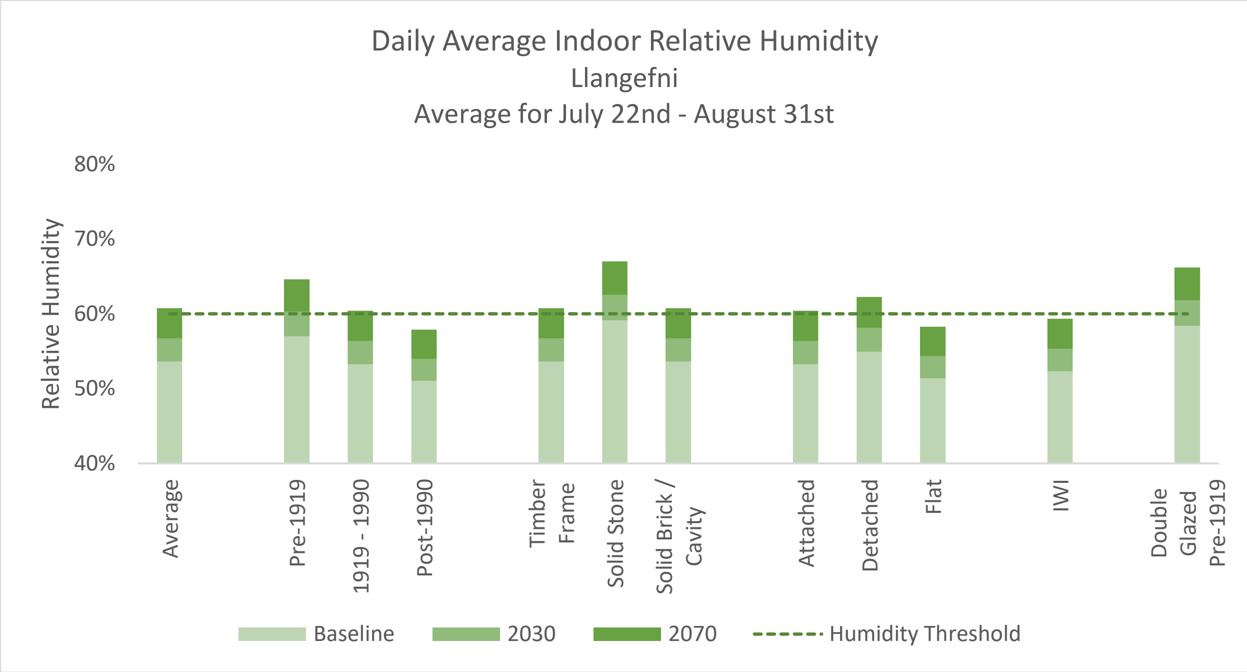

Percent of Hours Above 26°C
Brynmawr
July 22nd - August 31st
Percent of Hours
40%
30%
20%
10%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
Internal Wall Insulation
Double Glazed Pre-1919
Baseline
2030
2070
Thermal Comfort Threshold


Percent of Hours Above 26°C
Shotton
July 22nd - August 31st
Percent of Hours
40%
30%
20%
10%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
Internal Wall Insulation
Double Glazed Pre-1919
Baseline
2030
2070
Thermal Comfort Threshold

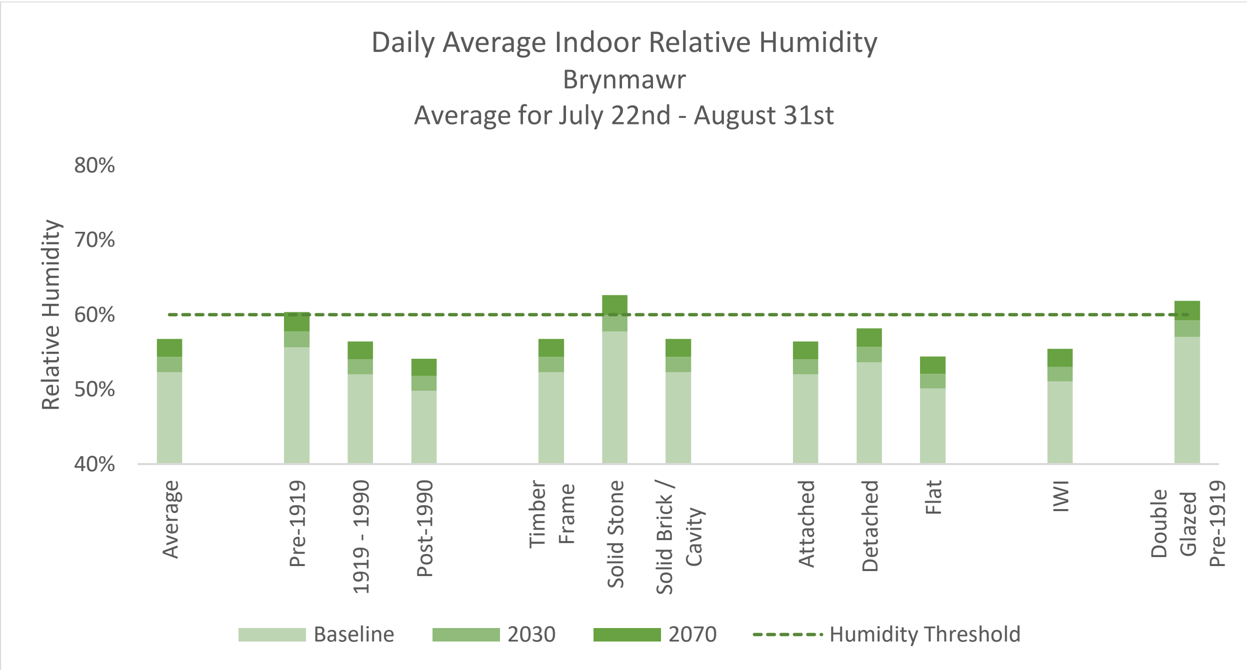
Daily Average Relative Humidity by Building Class



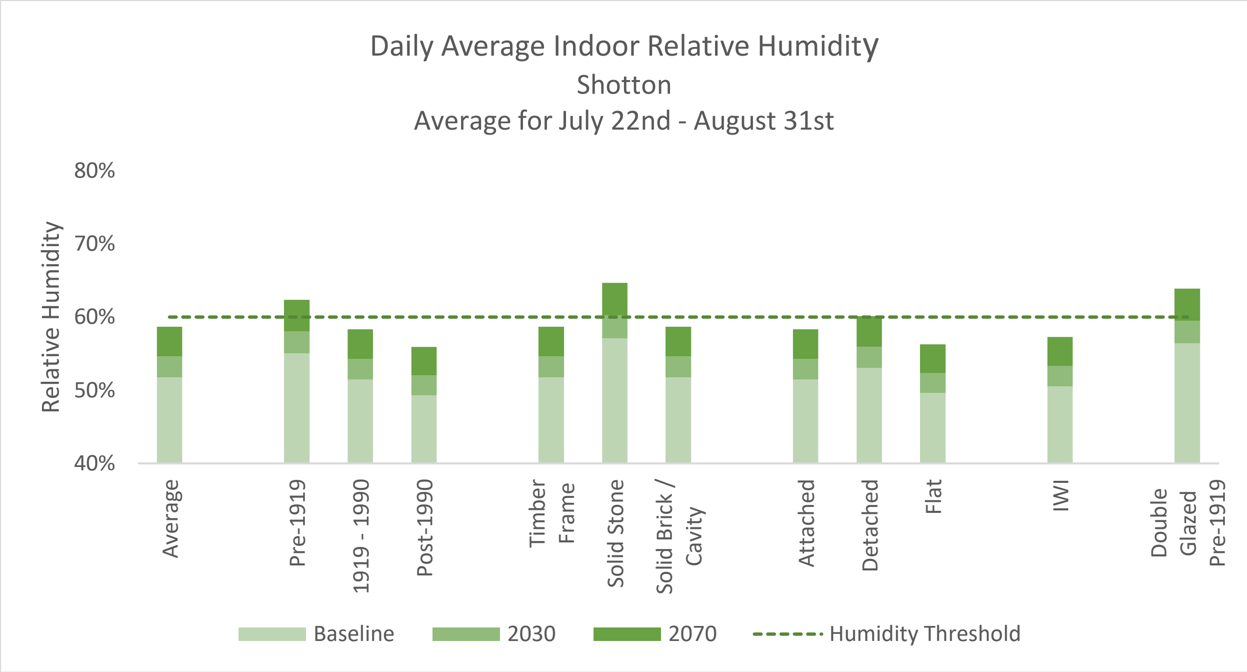




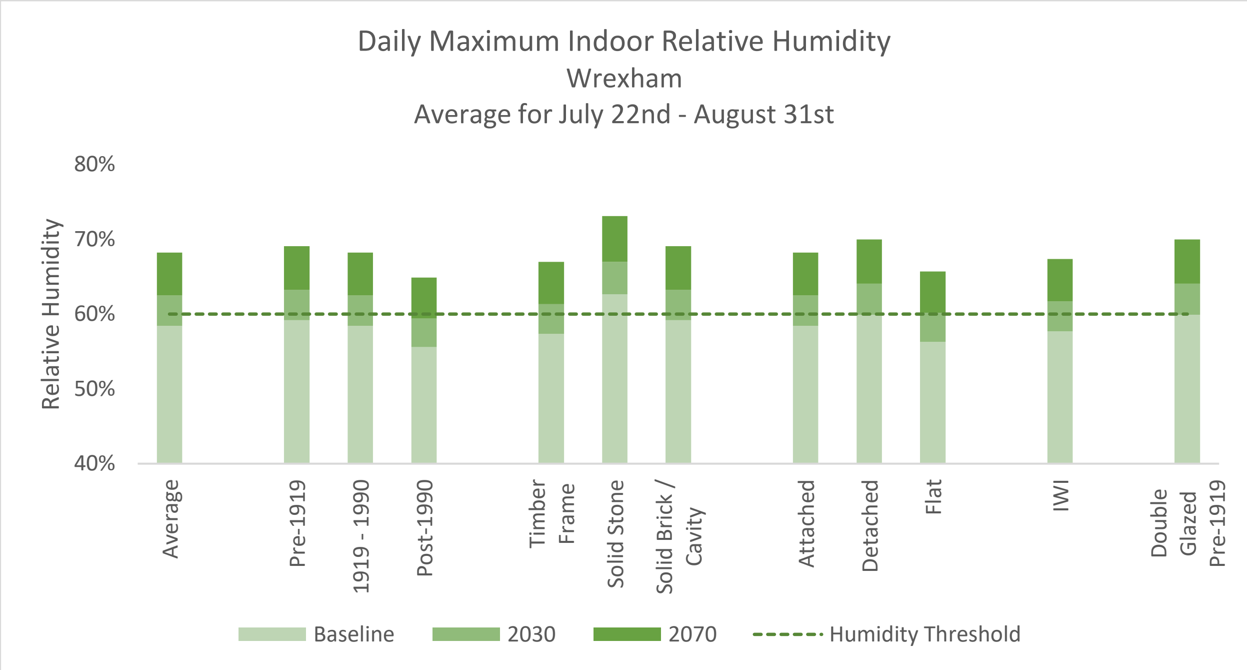
Daily Average Indoor Relative Humidity
Llangefni
Average for July 22nd - August 31st
Relative Humidity
80%
70%
60%
50%
40%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070
Humidity Threshold

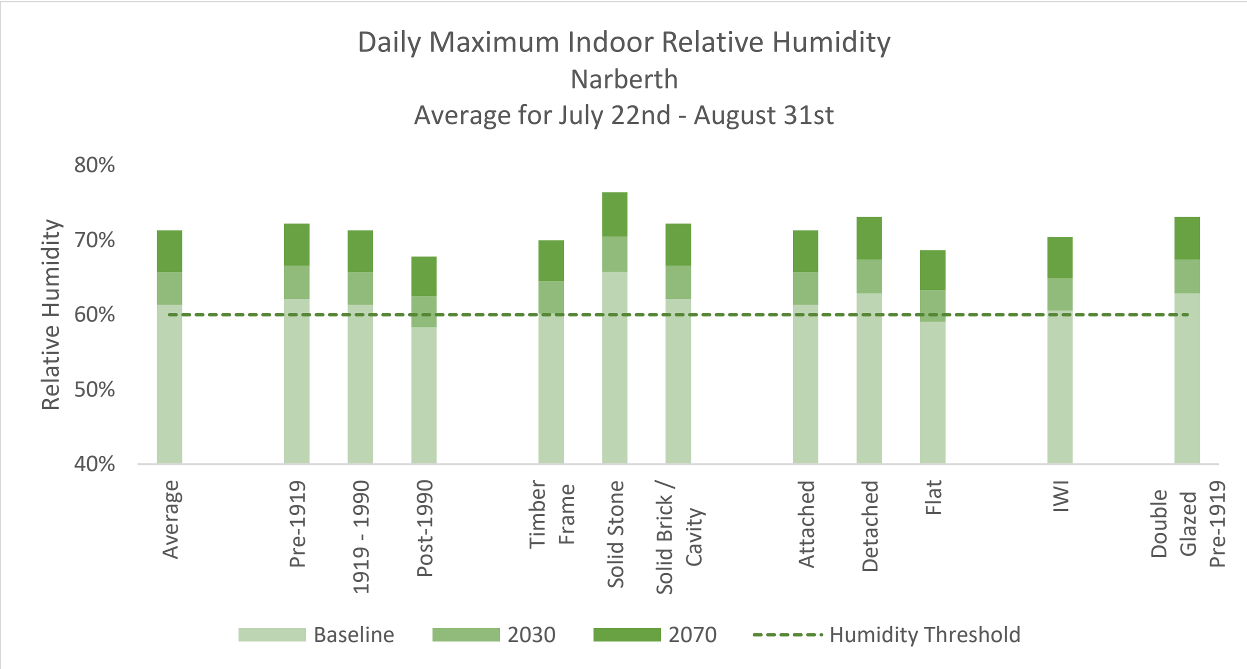


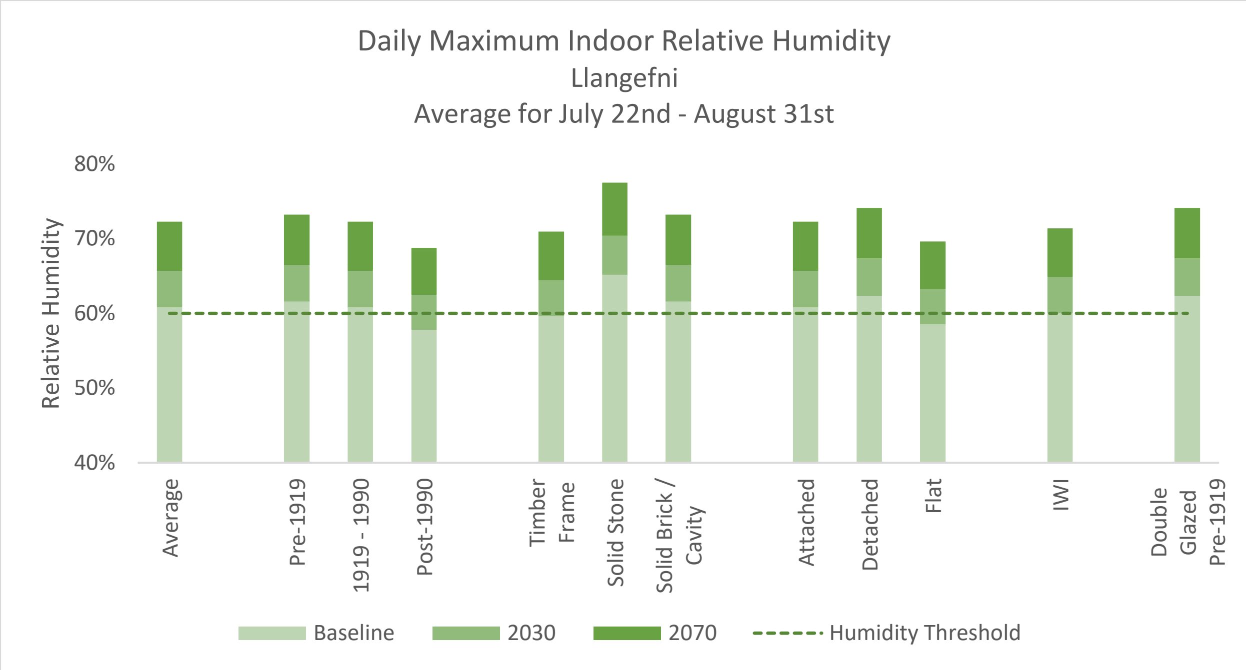
Daily Average Indoor Relative Humidity
Brynmawr
Average for July 22nd - August 31st
Relative Humidity
80%
70%
60%
50%
40%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070
Humidity Threshold

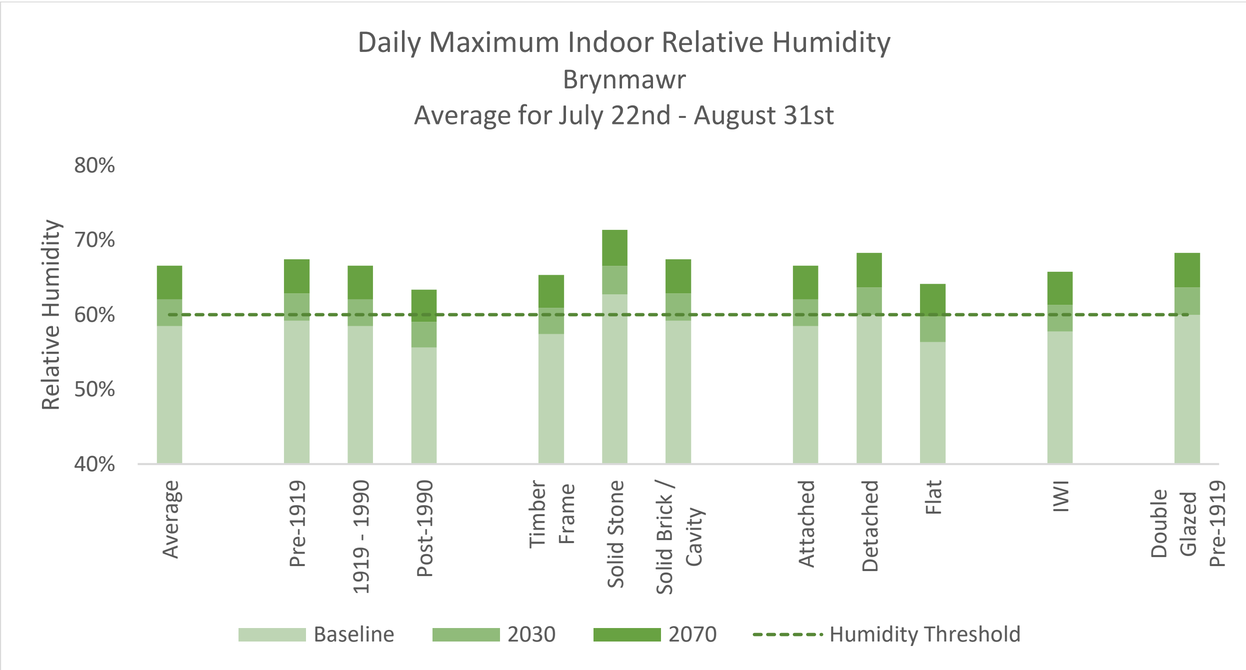

Daily Average Indoor Relative Humidity
Shotton
Average for July 22nd - August 31st
80%
70%
60%
50%
40%
Relative Humidity
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070
Humidity Threshold

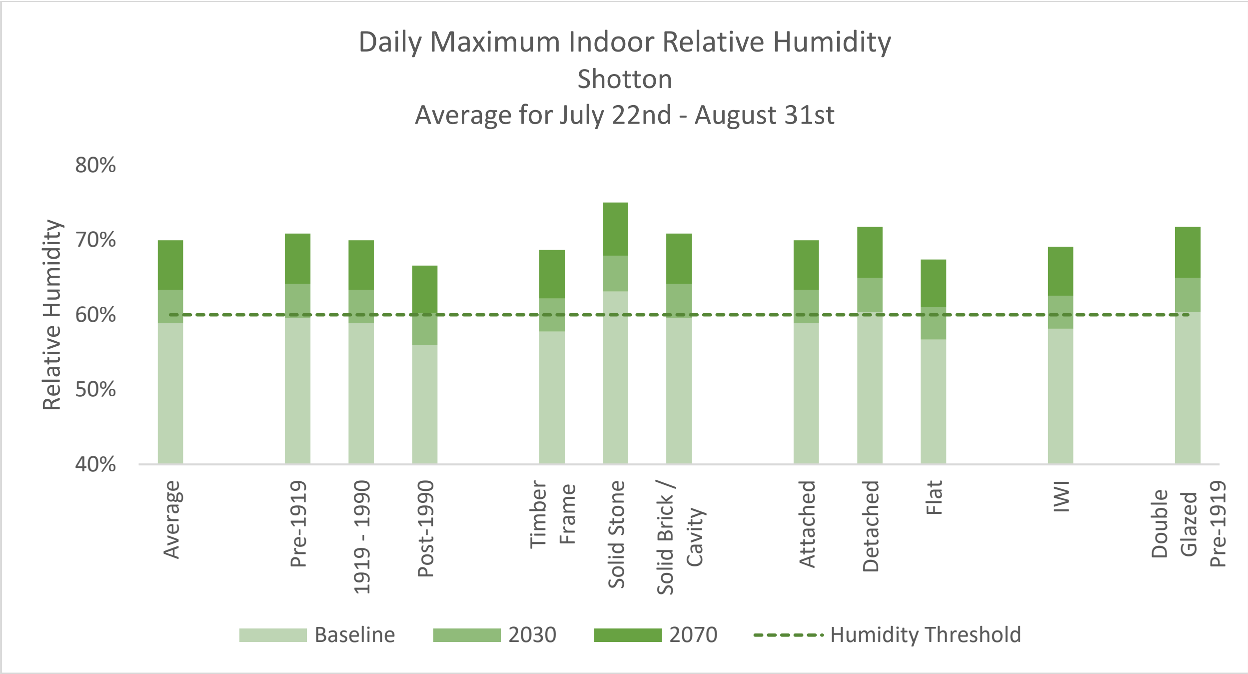
Daily Maximum Relative Humidity by Building Class



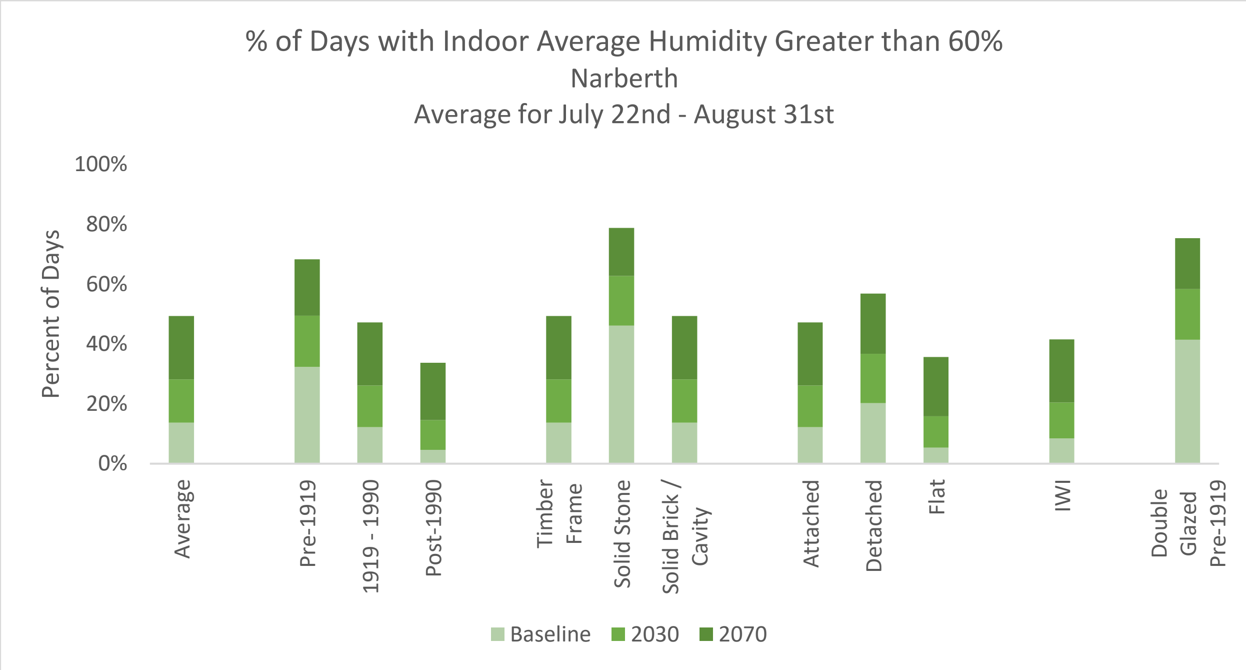


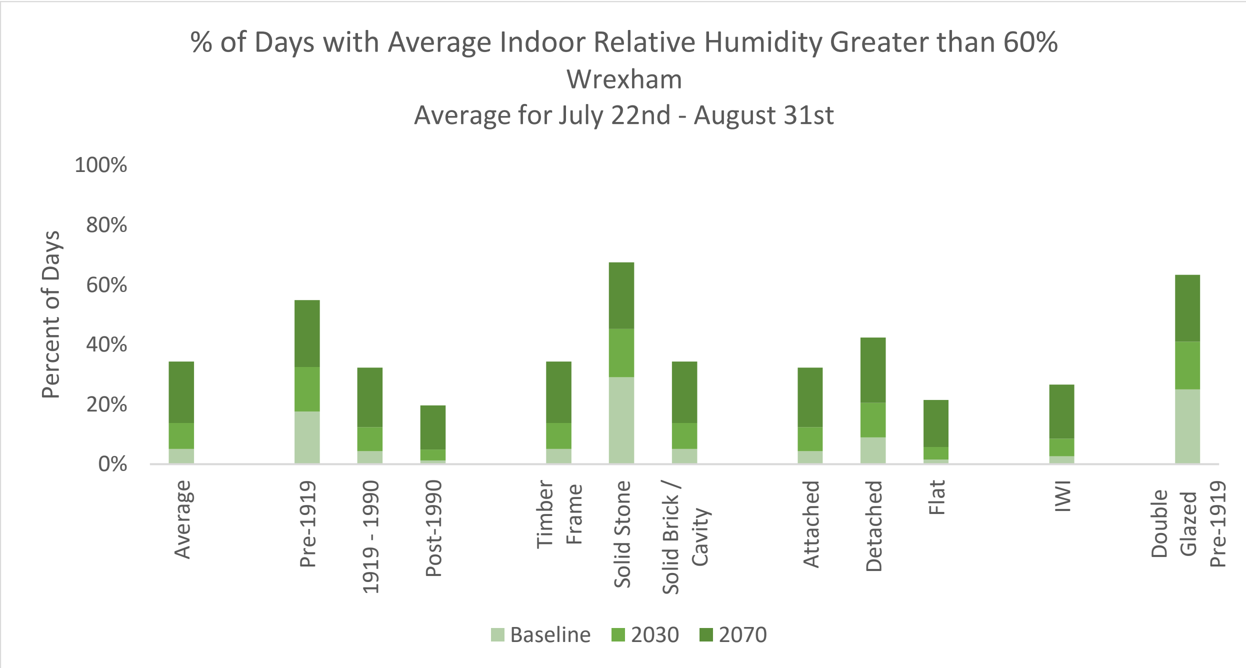

Daily Maximum Indoor Relative Humidity
Llangefni
Average for July 22nd - August 31st
Relative Humidity
80%
70%
60%
50%
40%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070
Humidity Threshold

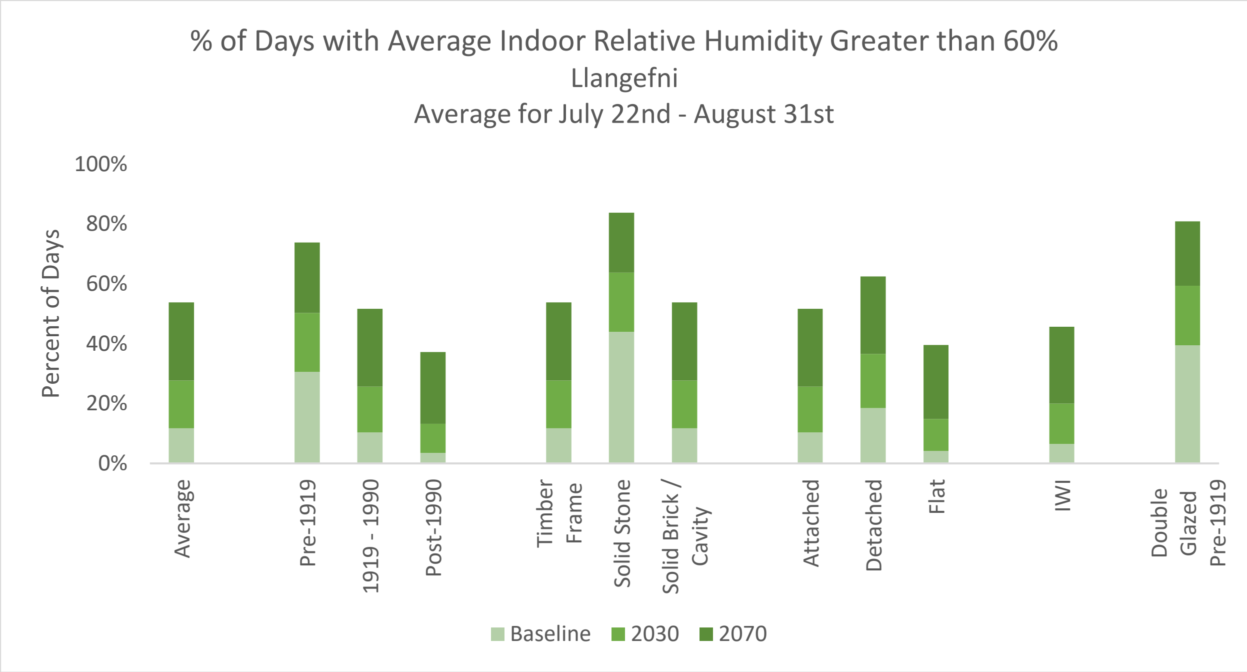

Daily Maximum Indoor Relative Humidity
Brynmawr
Average for July 22nd - August 31st
Relative Humidity
80%
70%
60%
50%
40%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070
Humidity Threshold


Daily Maximum Indoor Relative Humidity
Shotton
Average for July 22nd - August 31st
Relative Humidity
80%
70%
60%
50%
40%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070
Humidity Threshold

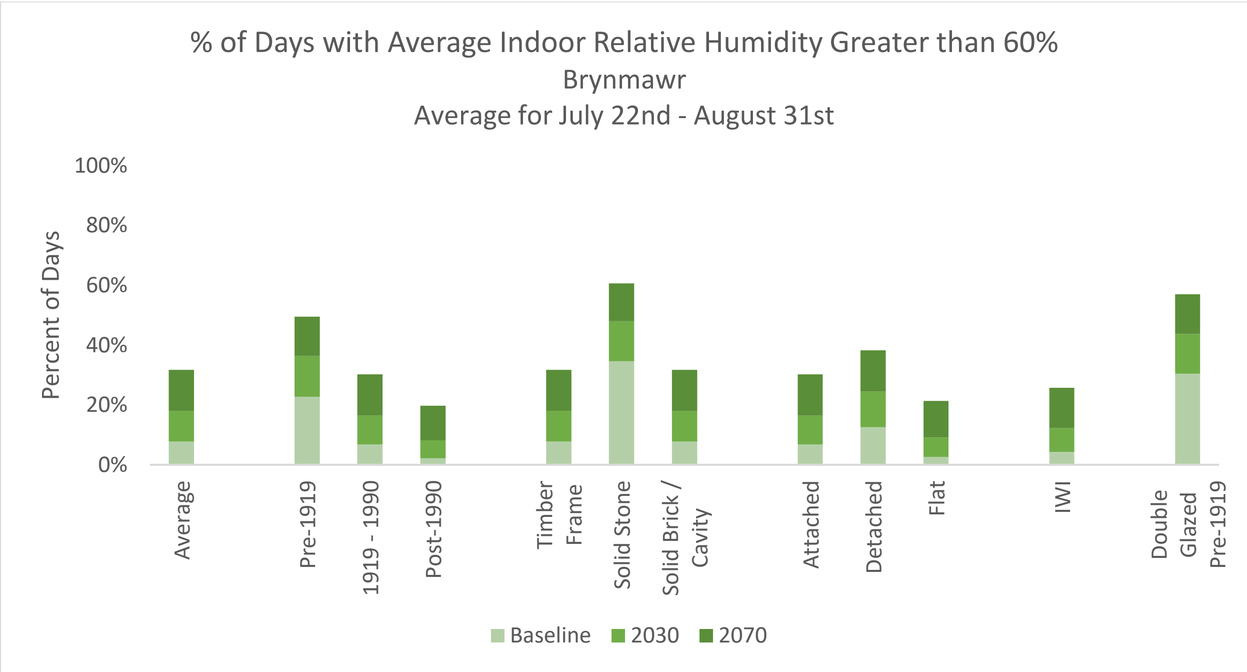
Percent of Days with Average Relative Humidity Above Threshold by Building Class



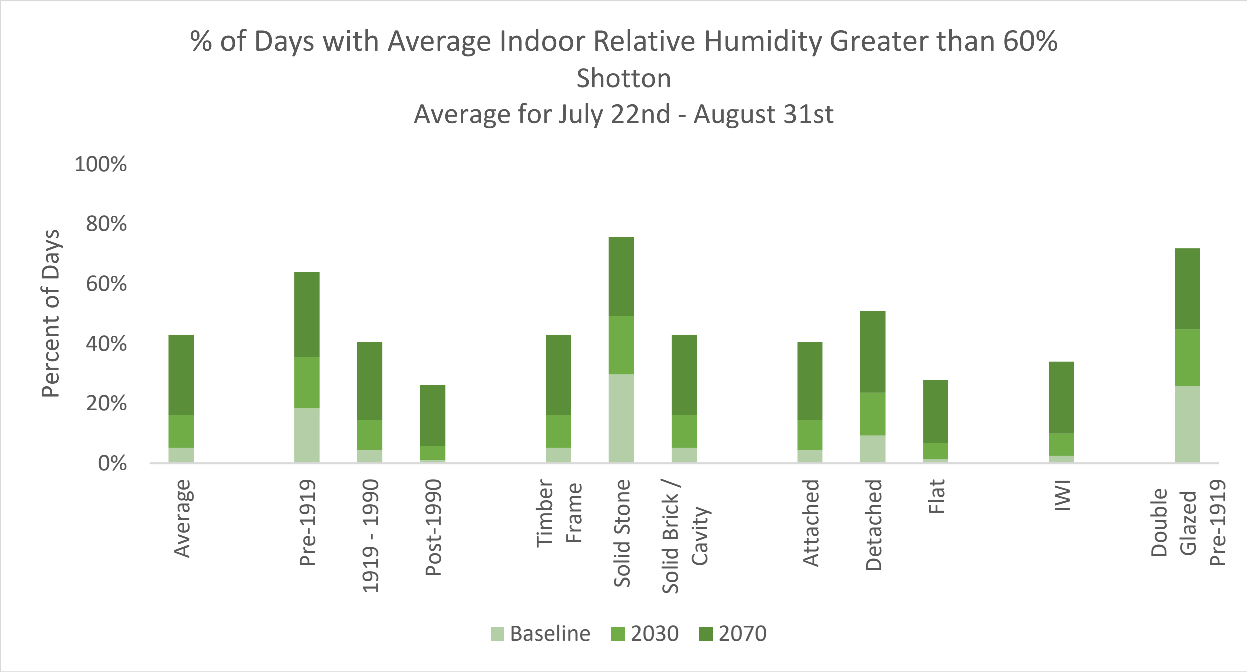




% of Days with Average Indoor Relative Humidity Greater than 60%
Llangefni
Average for July 22nd - August 31st
Percent of Days
100%
80%
60%
40%
20%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070

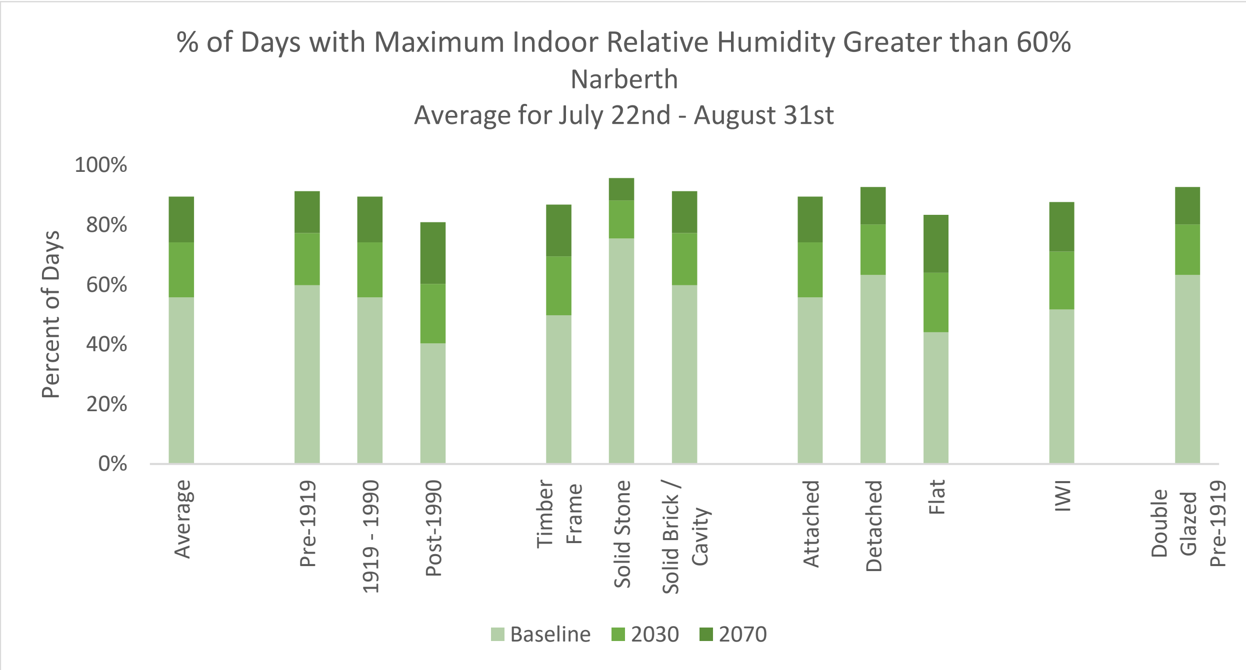


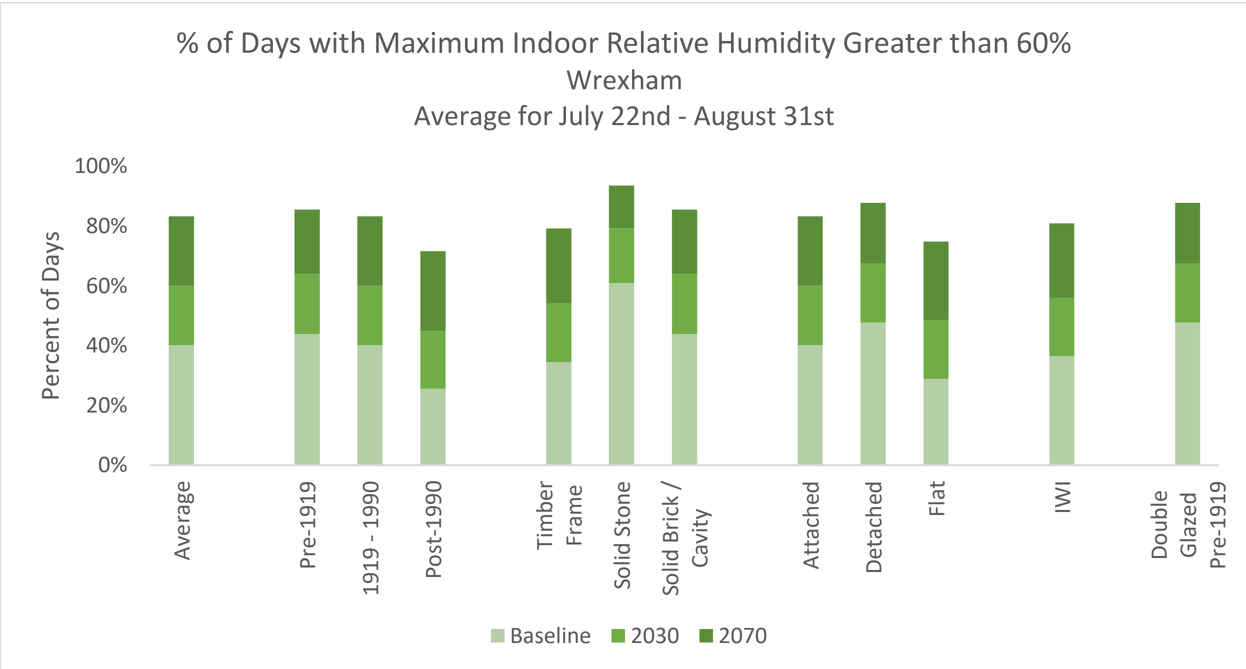
% of Days with Average Indoor Relative Humidity Greater than 60%
Brynmawr
Average for July 22nd - August 31st
Percent of Days
100%
80%
60%
40%
20%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070

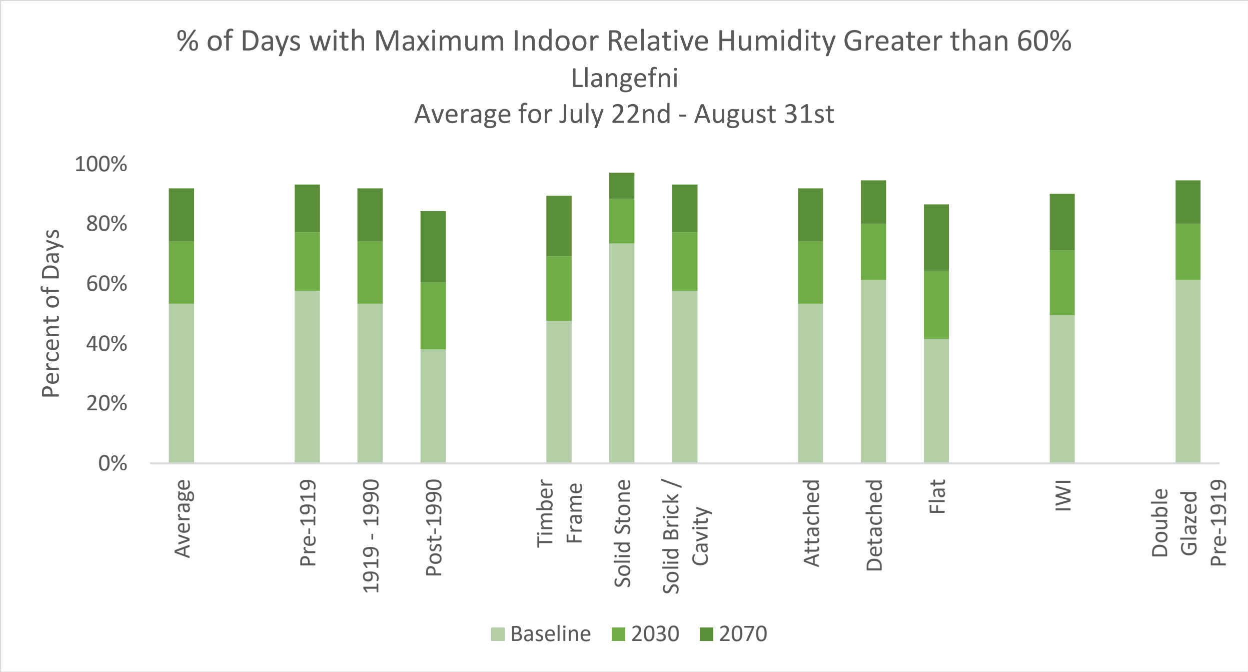


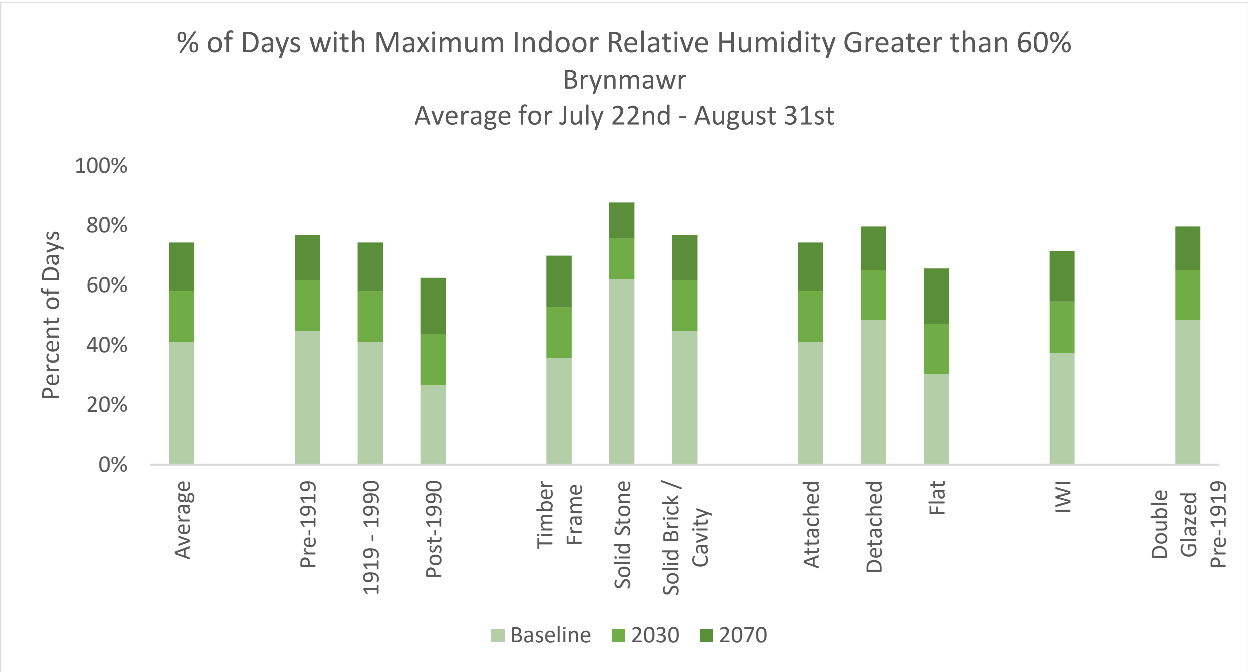
% of Days with Average Indoor Relative Humidity Greater than 60%
Shotton
Average for July 22nd - August 31st
Percent of Days
100%
80%
60%
40%
20%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070

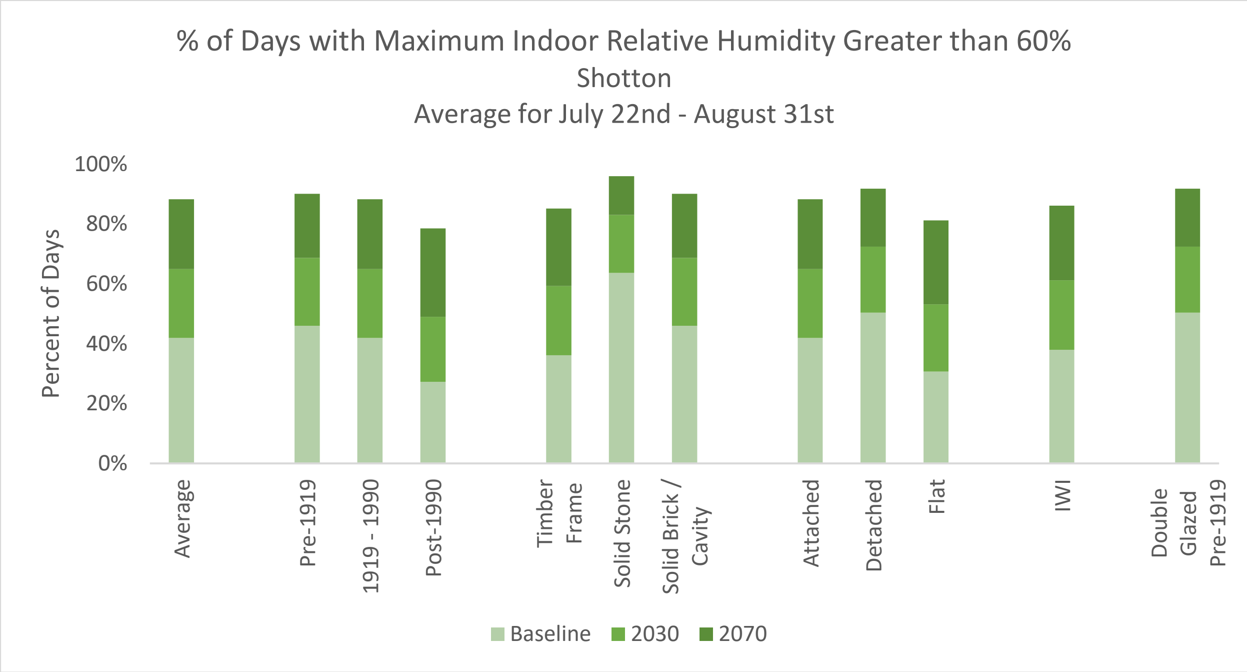
Percent of Days with Maximum Relative Humidity Above Threshold by Building Class



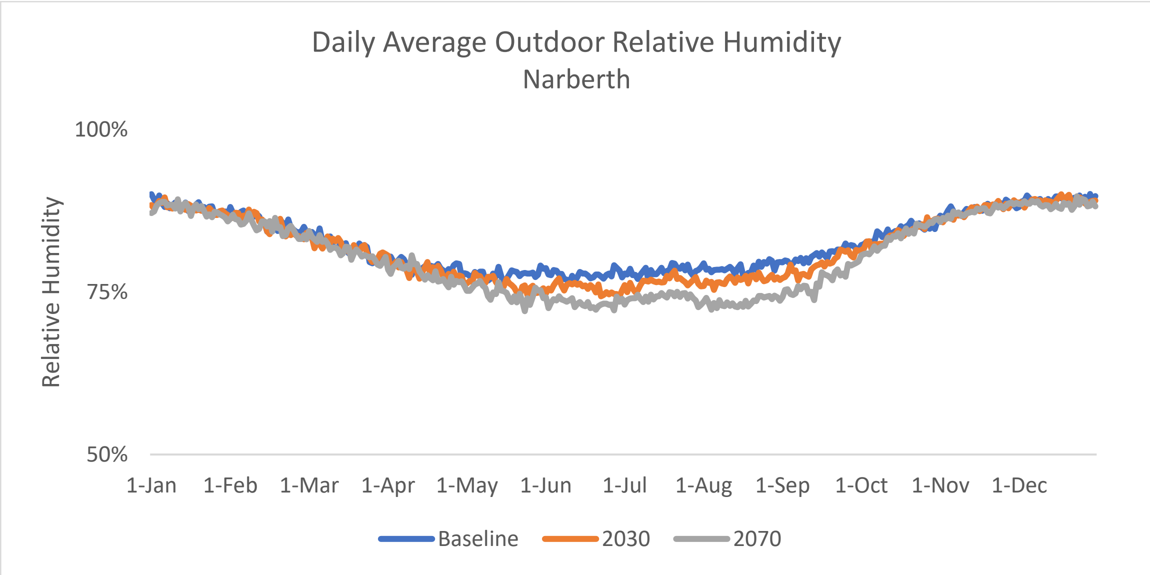


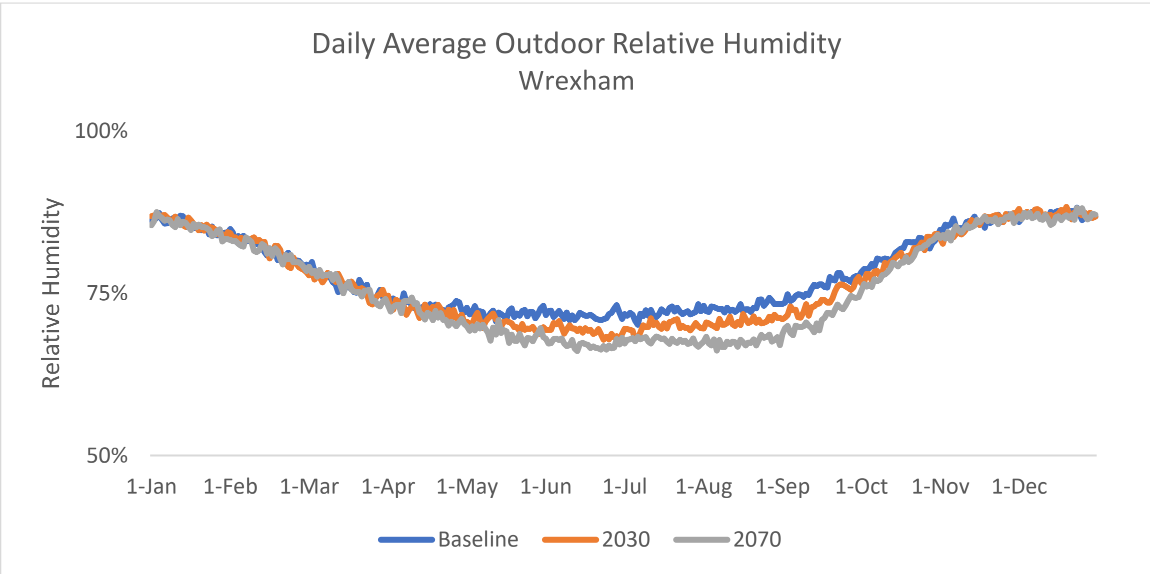

% of Days with Maximum Indoor Relative Humidity Greater than 60%
Llangefni
Average for July 22nd - August 31st
Percent of Days
100%
80%
60%
40%
20%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070

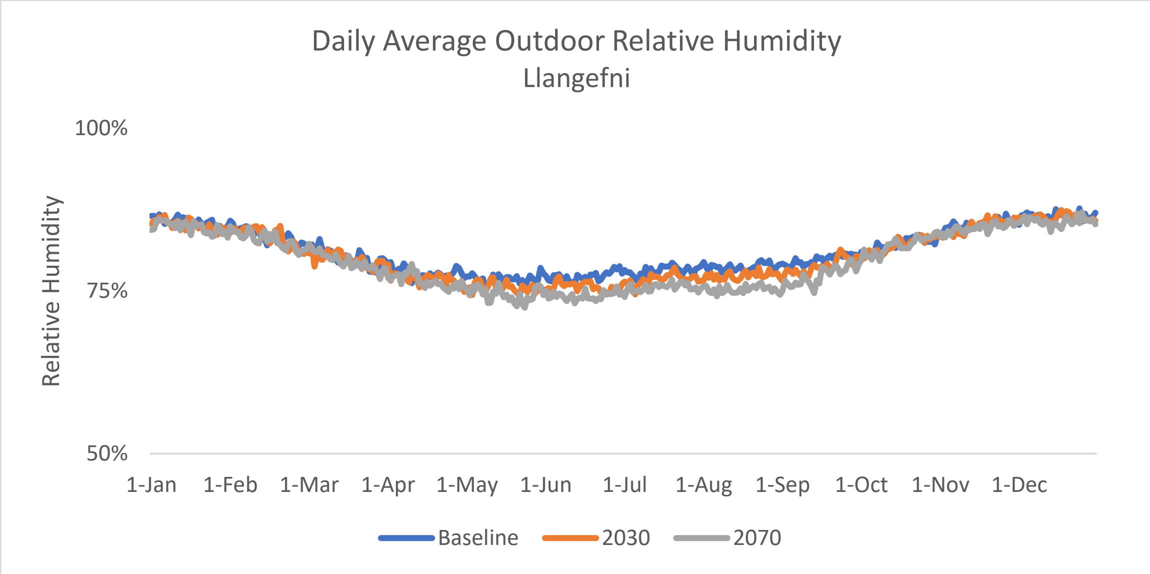

% of Days with Maximum Indoor Relative Humidity Greater than 60%
Brynmawr
Average for July 22nd - August 31st
Percent of Days
100%
80%
60%
40%
20%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070


% of Days with Maximum Indoor Relative Humidity Greater than 60%
Shotton
Average for July 22nd - August 31st
Percent of Days
100%
80%
60%
40%
20%
0%
Average
Pre-1919
1919 - 1990
Post-1990
Timber Frame
Solid Stone
Solid Brick / Cavity
Attached
Detached
Flat
IWI
Double Glazed Pre-1919
Baseline
2030
2070

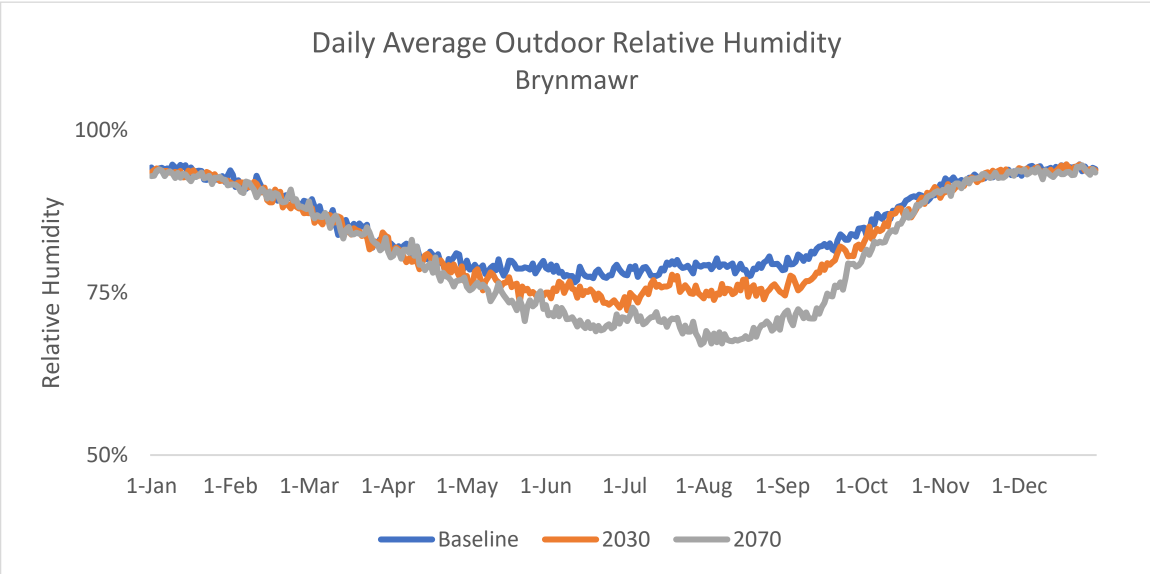
Annual Plot of Daily Average Relative Humidity



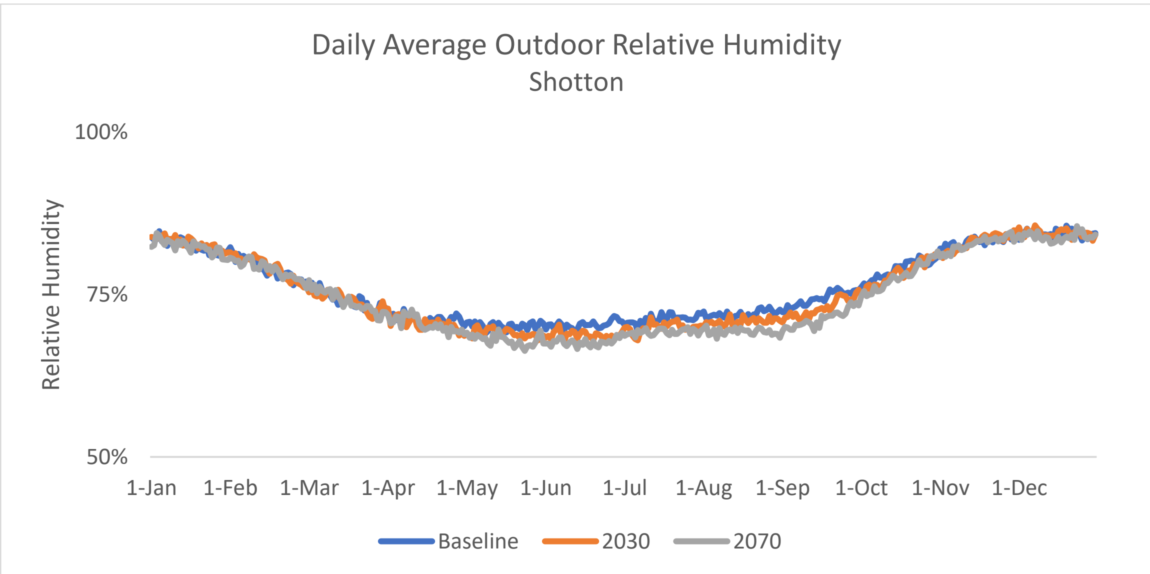




Daily Average Outdoor Relative Humidity
Llangefni
100%
75%
50%
Relative Humidity
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

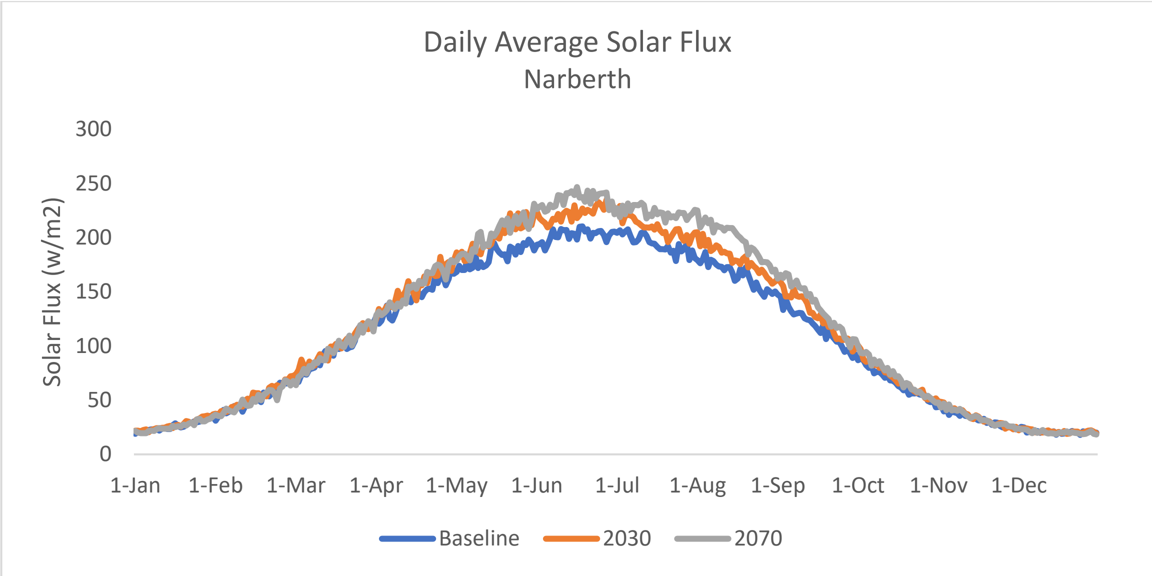


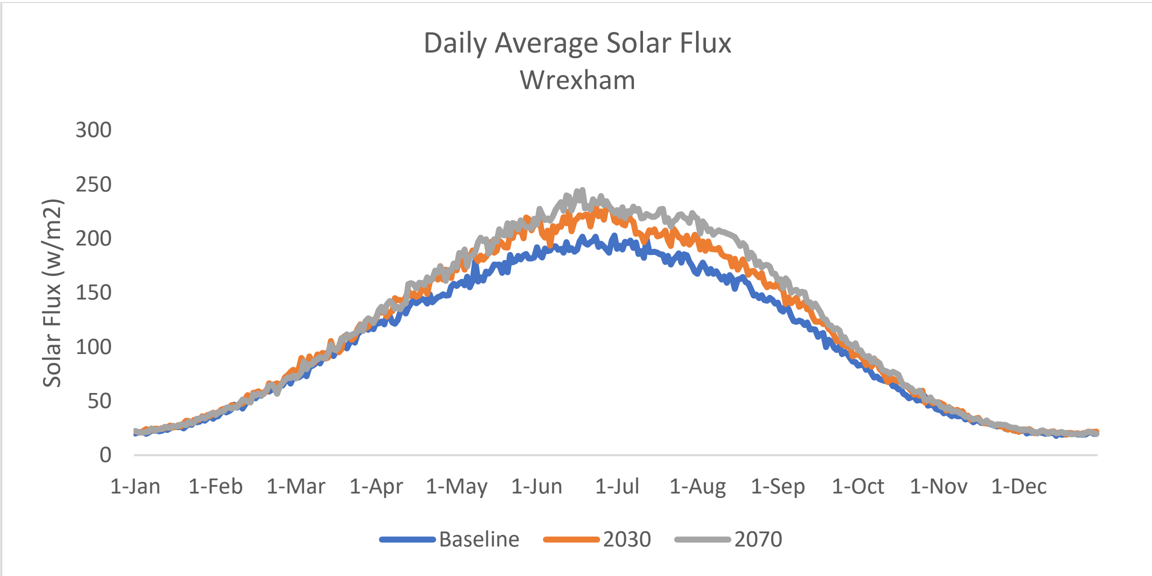
Daily Average Outdoor Relative Humidity
Brynmawr
100%
75%
50%
Relative Humidity
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

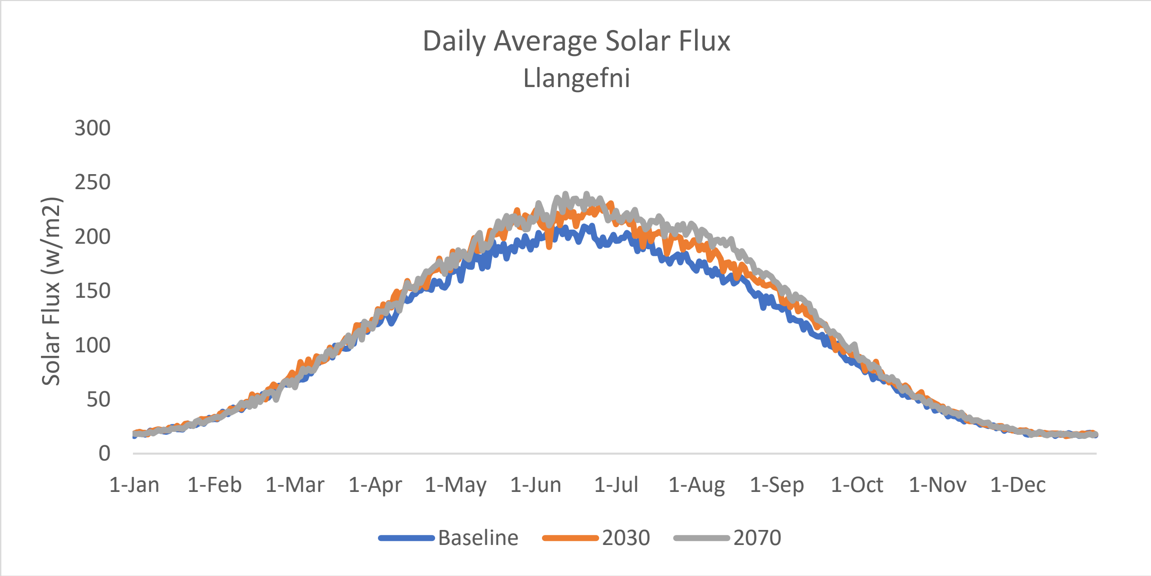


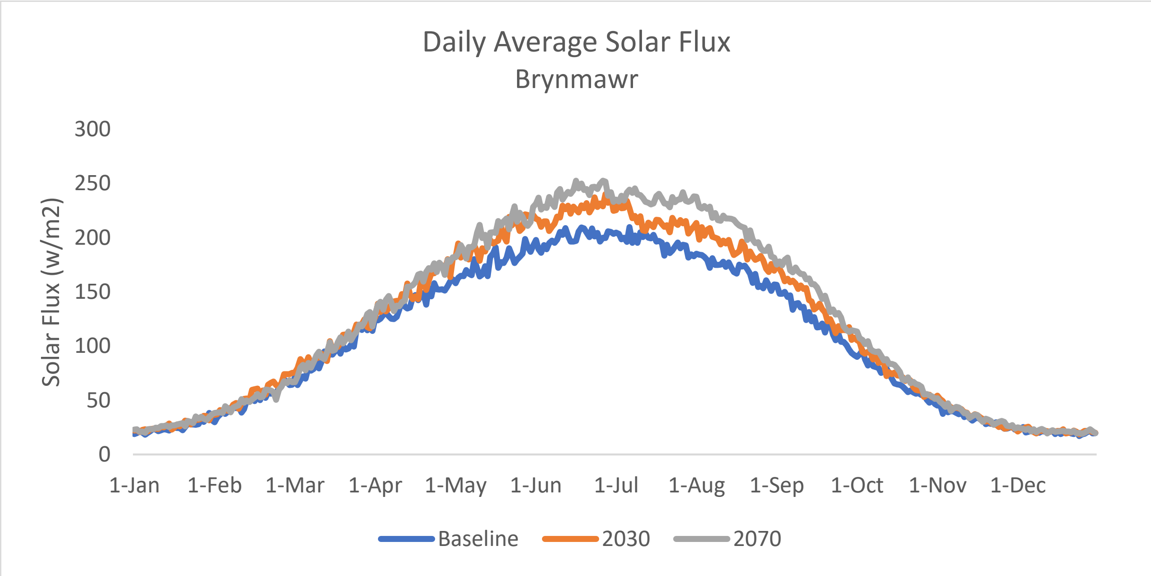
Daily Average Outdoor Relative Humidity
Shotton
100%
75%
50%
Relative Humidity
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

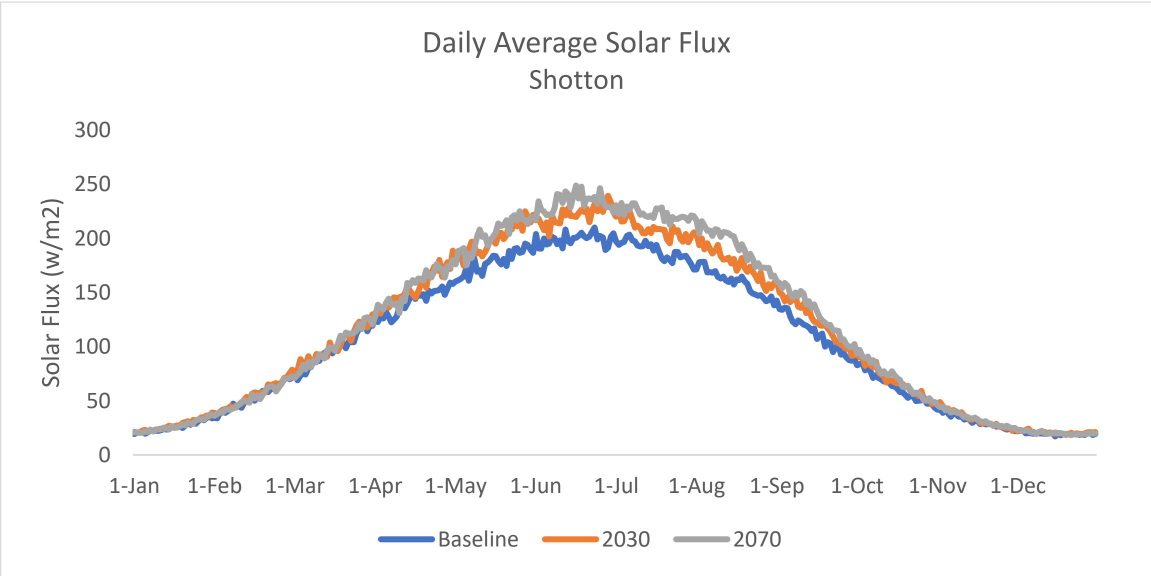
Annual Plot of Daily Average Solar Flux



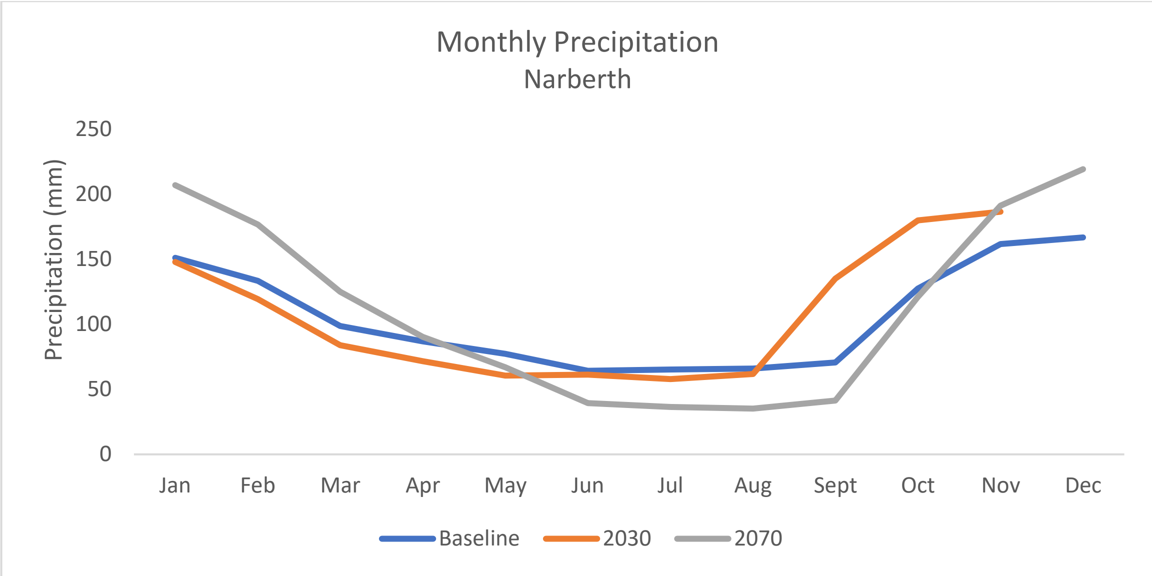


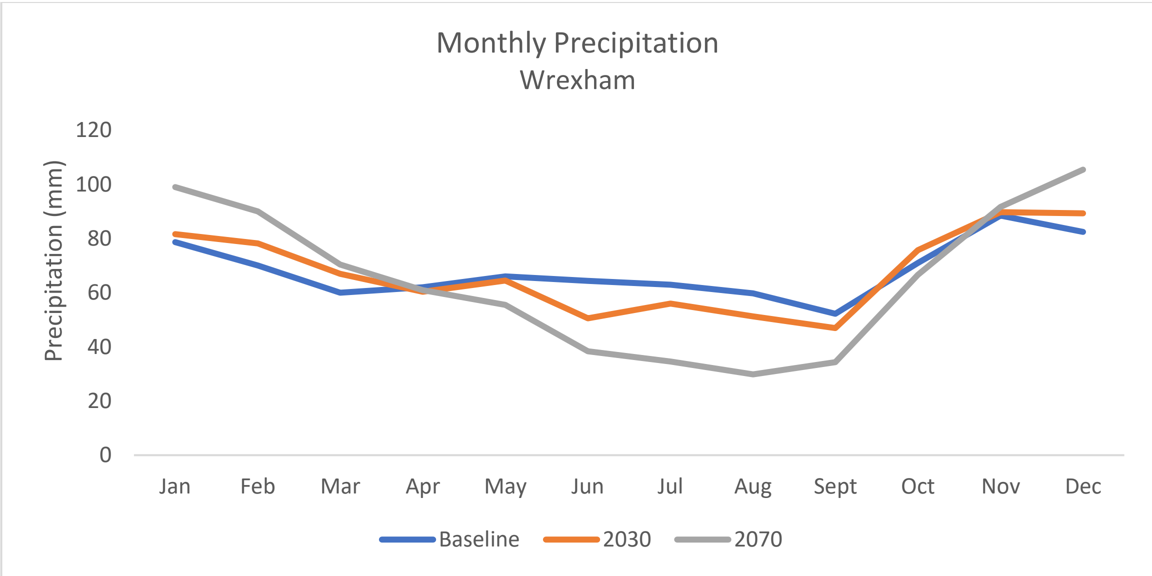

Daily Average Solar Flux
Llangefni
Solar Flux (w/m2)
300
250
200
150
100
50
0
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

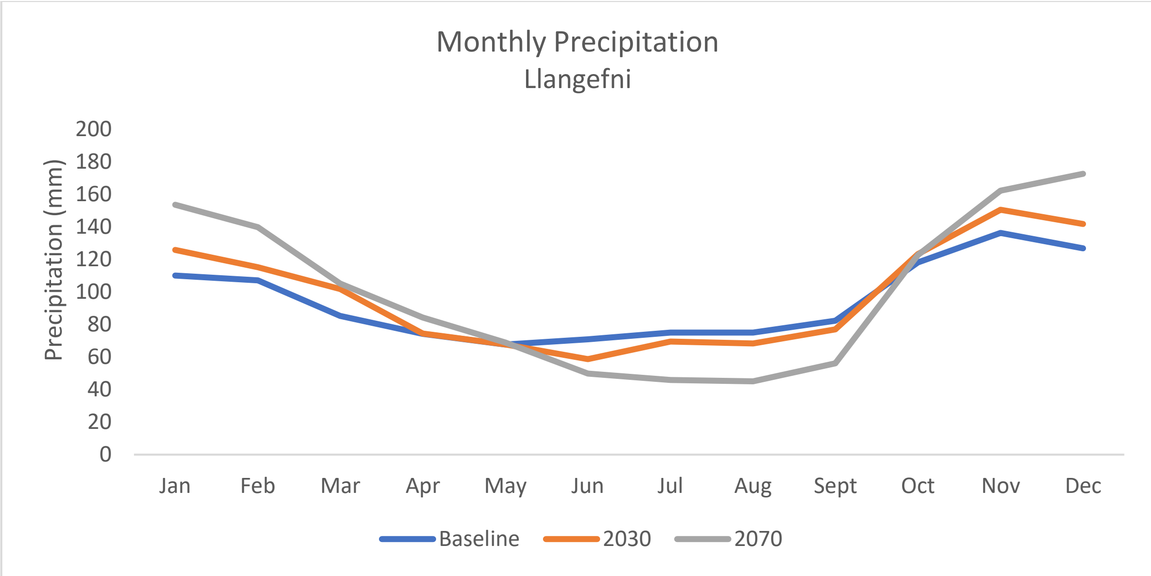

Daily Average Solar Flux
Brynmawr
Solar Flux (w/m2)
300
250
200
150
100
50
0
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070


Daily Average Solar Flux
Shotton
Solar Flux (w/m2)
300
250
200
150
100
50
0
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
1-Oct
1-Nov
1-Dec
Baseline
2030
2070

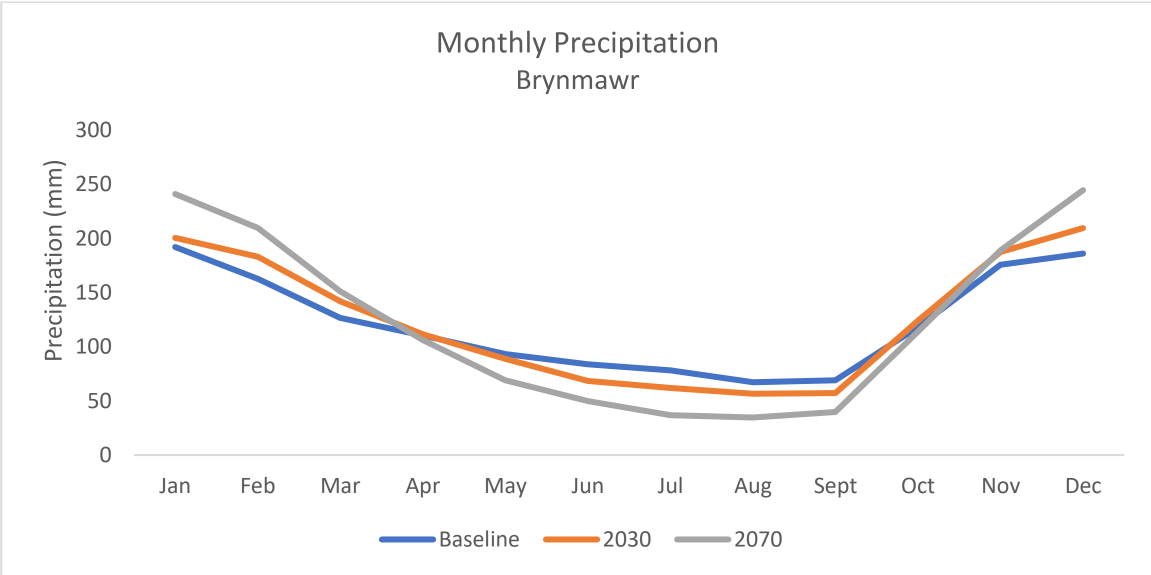
Annual Plot of Daily Average Precipitation



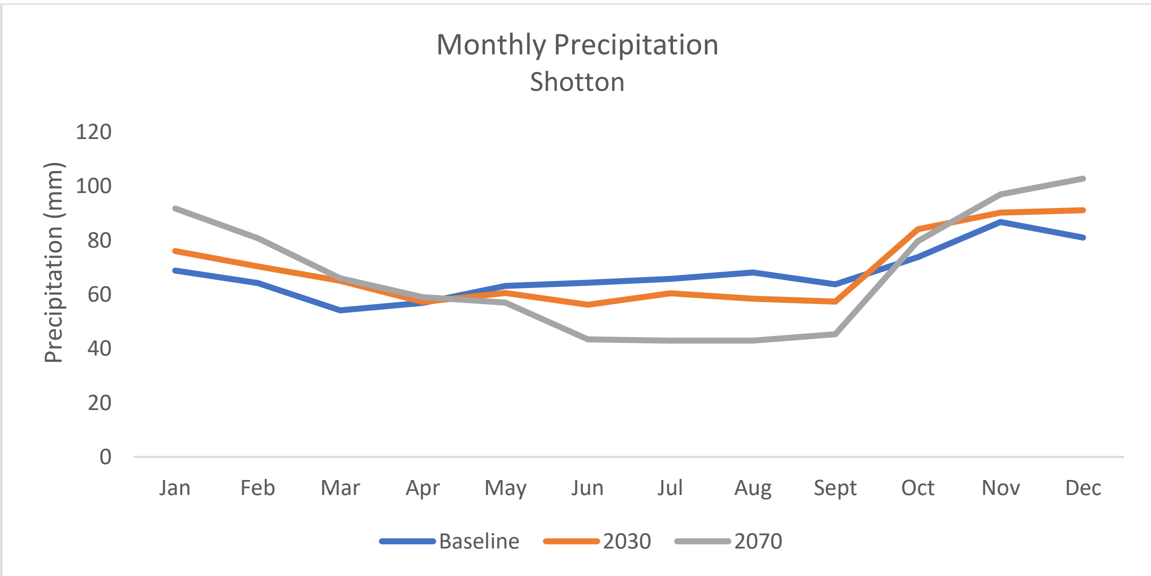




Monthly Precipitation
Llangefni
Precipitation (mm)
200
180
160
140
120
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec
Baseline
2030
2070



Monthly Precipitation
Brynmawr
Precipitation (mm)
300
250
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec
Baseline
2030
2070



Monthly Precipitation
Shotton
Precipitation (mm)
120
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec
Baseline
2030
2070

Building Fabric Degradation Tables

Building Fabric Degradation Results for: Narberth													
Material / Component	Solar Flux	Relative Humidity	Precipitation	Forecast Level of Deterioration	Baseline Service Life	Adjusted Service Life Change from Baseline (Years)				Change from Baseline Cost			
						Solar Flux	Relative Humidity	Precipitation	Total	Solar Flux	Relative Humidity	Precipitation	Total
2030													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.5	0.9	-0.2	-0.8	5.2%	-3.1%	0.8%	3.0%
Walls (brick/stone)		Low	High	Moderate	70		2.2	-0.6	1.7		-3.1%	0.8%	-2.3%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.5	1.6	-0.4	-1.3	5.2%	-3.1%	0.8%	3.0%
Masonry Paint	High	Low	High	Moderate	20	-1.0	0.6	-0.2	-0.5	5.2%	-3.1%	0.8%	3.0%
Window & Door Frames	High		High	Severe	20	-1.0		-0.2	-1.2	5.2%		0.8%	6.0%
2070													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.7	1.3	-0.6	-1.0	5.8%	-4.0%	2.1%	3.9%
Walls (brick/stone)		Low	High	Moderate	70		2.9	-1.5	1.5		-4.0%	2.1%	-1.9%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.8	2.1	-1.0	-1.7	5.8%	-4.0%	2.1%	3.9%
Masonry Paint	High	Low	High	Moderate	20	-1.1	0.8	-0.4	-0.7	5.8%	-4.0%	2.1%	3.9%
Window & Door Frames	High		High	Severe	20	-1.1		-0.4	-1.5	5.8%		2.1%	8.0%

Building Fabric Degradation Results for: Wrexham													
Material / Component	Solar Flux	Relative Humidity	Precipitation	Forecast Level of Deterioration	Baseline Service Life	Adjusted Service Life Change from Baseline (Years)				Change from Baseline Cost			
						Solar Flux	Relative Humidity	Precipitation	Total	Solar Flux	Relative Humidity	Precipitation	Total
2030													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.7	1.0	-0.2	-0.9	5.8%	-3.3%	0.8%	3.3%
Walls (brick/stone)		Low	High	Moderate	70		2.4	-0.6	1.8		-3.3%	0.8%	-2.5%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.8	1.7	-0.4	-1.4	5.8%	-3.3%	0.8%	3.3%
Masonry Paint	High	Low	High	Moderate	20	-1.1	0.7	-0.2	-0.6	5.8%	-3.3%	0.8%	3.3%
Window & Door Frames	High		High	Severe	20	-1.1		-0.2	-1.3	5.8%		0.8%	6.6%
2070													
Roof Tiles (clay/slate/concrete)	High	Low	Low	Mild	30	-1.7	1.4	0.1	-0.2	5.8%	-4.5%	-0.3%	1.0%
Walls (brick/stone)		Low	Low	Mild	70		3.3	0.2	3.5		-4.5%	-0.3%	-4.8%
Render & Mortar (lime/cement)	High	Low	Low	Mild	50	-2.8	2.4	0.1	-0.3	5.8%	-4.5%	-0.3%	1.0%
Masonry Paint	High	Low	Low	Mild	20	-1.1	0.9	0.1	-0.1	5.8%	-4.5%	-0.3%	1.0%
Window & Door Frames	High		Low	Moderate	20	-1.1		0.1	-1.0	5.8%		-0.3%	5.6%

Building Fabric Degradation Results for: Llangefni													
Material / Component	Solar Flux	Relative Humidity	Precipitation	Forecast Level of Deterioration	Baseline Service Life	Adjusted Service Life Change from Baseline (Years)				Change from Baseline Cost			
						Solar Flux	Relative Humidity	Precipitation	Total	Solar Flux	Relative Humidity	Precipitation	Total
2030													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.5	0.7	-0.5	-1.3	5.3%	-2.3%	1.9%	4.8%
Walls (brick/stone)		Low	High	Moderate	70		1.7	-1.3	0.4		-2.3%	1.9%	-0.4%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.5	1.2	-0.9	-2.2	5.3%	-2.3%	1.9%	4.8%
Masonry Paint	High	Low	High	Moderate	20	-1.0	0.5	-0.4	-0.9	5.3%	-2.3%	1.9%	4.8%
Window & Door Frames	High		High	Severe	20	-1.0		-0.4	-1.4	5.3%		1.9%	7.1%
2070													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.6	1.3	-0.7	-1.0	5.6%	-4.0%	2.4%	3.9%
Walls (brick/stone)		Low	High	Moderate	70		2.9	-1.6	1.3		-4.0%	2.4%	-1.6%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.6	2.1	-1.2	-1.7	5.6%	-4.0%	2.4%	3.9%
Masonry Paint	High	Low	High	Moderate	20	-1.1	0.8	-0.5	-0.7	5.6%	-4.0%	2.4%	3.9%
Window & Door Frames	High		High	Severe	20	-1.1		-0.5	-1.5	5.6%		2.4%	8.0%

Building Fabric Degradation Results for: Brynmawr													
Material / Component	Solar Flux	Relative Humidity	Precipitation	Forecast Level of Deterioration	Baseline Service Life	Adjusted Service Life Change from Baseline (Years)				Change from Baseline Cost			
						Solar Flux	Relative Humidity	Precipitation	Total	Solar Flux	Relative Humidity	Precipitation	Total
2030													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.7	1.3	-0.3	-0.8	6.1%	-4.1%	1.1%	3.1%
Walls (brick/stone)		Low	High	Moderate	70		3.0	-0.7	2.2		-4.1%	1.1%	-3.0%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.9	2.1	-0.5	-1.3	6.1%	-4.1%	1.1%	3.1%
Masonry Paint	High	Low	High	Moderate	20	-1.2	0.8	-0.2	-0.5	6.1%	-4.1%	1.1%	3.1%
Window & Door Frames	High		High	Severe	20	-1.2		-0.2	-1.4	6.1%		1.1%	7.2%
2070													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.7	1.7	-0.5	-0.5	6.1%	-5.5%	1.6%	2.2%
Walls (brick/stone)		Low	High	Moderate	70		4.1	-1.1	3.0		-5.5%	1.6%	-3.9%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.9	2.9	-0.8	-0.8	6.1%	-5.5%	1.6%	2.2%
Masonry Paint	High	Low	High	Moderate	20	-1.2	1.2	-0.3	-0.3	6.1%	-5.5%	1.6%	2.2%
Window & Door Frames	High		High	Severe	20	-1.2		-0.3	-1.5	6.1%		1.6%	7.7%

Building Fabric Degradation Results for: Shotton													
Material / Component	Solar Flux	Relative Humidity	Precipitation	Forecast Level of Deterioration	Baseline Service Life	Adjusted Service Life Change from Baseline (Years)				Change from Baseline Cost			
						Solar Flux	Relative Humidity	Precipitation	Total	Solar Flux	Relative Humidity	Precipitation	Total
2030													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.7	0.6	-0.2	-1.3	6.1%	-2.1%	0.8%	4.9%
Walls (brick/stone)		Low	High	Moderate	70		1.5	-0.6	0.9		-2.1%	0.8%	-1.3%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.9	1.0	-0.4	-2.2	6.1%	-2.1%	0.8%	4.9%
Masonry Paint	High	Low	High	Moderate	20	-1.2	0.4	-0.2	-0.9	6.1%	-2.1%	0.8%	4.9%
Window & Door Frames	High		High	Severe	20	-1.2		-0.2	-1.3	6.1%		0.8%	6.9%
2070													
Roof Tiles (clay/slate/concrete)	High	Low	High	Moderate	30	-1.7	1.3	-0.1	-0.5	6.1%	-4.0%	0.3%	2.3%
Walls (brick/stone)		Low	High	Moderate	70		2.9	-0.2	2.8		-4.0%	0.3%	-3.8%
Render & Mortar (lime/cement)	High	Low	High	Moderate	50	-2.9	2.1	-0.1	-0.9	6.1%	-4.0%	0.3%	2.3%
Masonry Paint	High	Low	High	Moderate	20	-1.2	0.8	-0.1	-0.4	6.1%	-4.0%	0.3%	2.3%
Window & Door Frames	High		High	Severe	20	-1.2		-0.1	-1.2	6.1%		0.3%	6.4%