Building resilience of roofing technologies in a changing climate

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FUTURE (P)ROOF

Building resilience of roofing technologies in a changing climate

FOREWORD

A roof is the first line of defence against the elements and plays an essential role in keeping a building wind and watertight. As the UK's climate is set to become wetter, warmer and experience more extreme weather events such as torrential rain and heatwaves over the next half-century, the way we build, maintain, and upgrade our roofs will become increasingly important.

That is why the NFRC Charitable Trust, the UK's charity dedicated to supporting the roofing industry, commissioned the University of Southampton to undertake this vital research under its Environmental Programme. Climate change is one of, if not the greatest, challenges we face as a society, and doing nothing is not an option. As this report makes clear, the risk of overheating, drought, and flooding is real. Doing nothing could lead to the loss of life and livelihoods, damage and degradation of built assets, as well as a negative impact on productivity.

The positive story from this research is that there are things we can do as an industry now to not only alleviate these risks but to maximise our roof spaces to ensure we are utilising it to the best of our ability. It has been said that almost every roof has the opportunity to tackle the climate emergency—whether that be through electricity generation through built-in solar PV, water harvesting through a blue roof, or reducing overheating through a cool roof, our industry has a solution.

The challenge now is to break down the barriers stopping us from achieving this potential. The government must create the right policy environment and incentives, and as an industry, we need to invest now to make sure we have the green skills needed. Critical to this will be ensuring there is sufficient funding available for the specialist training required to help the industry upskill in the many green technologies identified in this report. The NFRC Charitable Trust will help to play its part here where it can.

I would like to thank the University of Southampton and the team at NFRC for producing this important research.

Peter G Rogerson, OBE, FIoR
Chair, NFRC Charitable Trust

This research project, undertaken by the University of Southampton, investigates the impact that climate change will have on roofs covering the existing stock of buildings across the UK. It was commissioned by the NFRC Charitable Trust under the Trust's *'Sustainability'* charitable aim.

Whilst there has been a welcome focus recently on how the UK will achieve net-zero carbon emissions *(mitigation)* to keep global temperatures below 1.5 degrees, there has perhaps been less attention given to how to best prepare for the inevitable changes to the climate (adaptation).

The Committee for Climate Change (CCC) recently said that *"climate resilience remains a second order issue, if it is considered at all"* and that *"policies are being developed without sufficient recognition of the need to adapt to the changing climate"*.

This research helps to address this issue, as it relates to the built environment, specifically for the UK roofing sector, in both the residential and commercial sectors. It looks at outputs from the UK's climate change projections, then applies it to the context of both domestic and commercial roofing in the UK, and then makes a number of recommendations on what can be done to best prepare for these eventualities.

Overview of UK climate change

In a UK context from the mid-1970s to the Mid-2010s, there has been a:

- **4.5 per cent rise in annual mean rainfall.**
  The period from 2008 to 2017 was 4 per cent wetter than 1981 – 2000 and 11 per cent wetter than 1961 – 1990.
- **0.9 °C rise in average annual temperatures.**
  The top ten warmest years on record have all occurred since 1990.
- **9.2 per cent rise in sunshine levels.**
  This is most noticeable in winter and spring, where there is 14 per cent more sunshine than the 1961 average.
- **UK wide increases in extreme weather events.**

Looking ahead, these trends are set to intensify, and future climate projections suggest that what is considered to be an anomaly today will become the norm in future decades.

Broadly speaking, over the next half-century the UK is expected to:

- Experience warmer and wetter winters with hotter and drier summers.
- Have a higher frequency and intensity of extreme weather events, notably heatwaves and torrential rain.
- Have clearer skies in summer, but this will not be uniform across the UK.
- The frequency of storms, however, are not expected to increase.

Risks facing the UK from climate change

This research looked at a range of built forms from across 15 cities in the UK and how they are likely to be impacted by climate change. It identified flooding and overheating as the two greatest risks facing the UK from climate change.

Torrential rain and flooding

Higher levels of torrential rain will not only increase the probability of water ingress penetrating buildings through the roof fabric but will also lead to wider catastrophic flooding, the likes of which we have seen in recent years.

River, surface and groundwater flooding, as a result of extreme winter rainfall events and increases in average winter rainfall, is regarded as a medium building risk today by the Climate Change Risk Assessment (CCRA3), in terms of both building damage and productivity loss. This will rise to a high risk by 2080.

The CCRA estimates that 1.8 million people are living in homes which are in areas of significant river, surface water or coastal flooding, and those in the most deprived areas are at most risk.

Overheating

This research considers two thresholds for overheating between 25 and 28°C for the operative temperature of living rooms and 24 and 26°C for bedrooms.

Overheating is already a big problem in the UK, and it is expected to worsen in the future. Taking Islington, London as an example, its average temperature is expected to rise by 3.3 °C by the 2080s and its daily maximum temperature is expected to increase from 22.2 °C for the reference period to 27.9 °C for the 2080s.

This is a public health risk, especially for the elderly. According to the Committee for Climate Change, it is estimated that there are about 2,000 heat-related deaths each year in England and Wales. This number is expected to triple to over 7,000 by the mid-century as a result of climate change. It also has a productivity impact, as more and more people now work from home at least a few days a week, as well as it affecting the quality of sleep. The domestic sector is much more volatile than the non-domestic sector to overheating as families use their homes in a variety of ways.

Loft conversions and insulation are a popular way to create extra living space in the UK's small and expensive housing stock, but because of their typical loft characteristics (top floor, directly under roof) and usually of lightweight construction, loft conversions are prone to overheating. Islington and Plymouth were two cities in the study where lofts and dormer conversions were the most vulnerable to overheating, and this is predicted to cause serious issues by 2030.

Flats are also at risk, particularly those with overglazed single-sided ventilation. This is exacerbated by low thermal mass construction methods such as timber or steel-framed buildings. Certain public buildings such as schools, are also at risk, due to their construction type. A building that is marginal in terms of overheating risk today, will not perform appropriately in the future.

How roofing can help

Resilience can be defined as the capacity to recover quickly from extreme events. In terms of the built environment, this relates primarily to heatwaves, flooding, drought, cold, storms, and strong winds. Energy provision can also be included in this.

The question this research asks is, fundamentally, how can we ensure that roofs that we construct or retrofit today will be fit for purpose in 20, 30 or 50 years time?

The report finds several ways that roofing can contribute to building the resilience of the built environment, to adapt to these changes in our climate through the following technologies:

- **Conventional *(consolidated technologies).***
  These are technologies that are consolidated in the market currently in both the residential and non-residential sectors, such as enhanced levels of insulation and improving airtightness.
- **Cool *(highly reflective coatings).***
  A cool roof is one that is designed to reflect more sunlight and absorb less heat than a conventional roof, typically flat or low sloped. A highly reflective type of paint, sheet covering, tiles or shingles can be used to achieve this.
- **Green *(vegetated).***
  These are ballasted roofs that cover a conventional roof (typically flat) with a waterproofing later, growing medium (soil) and vegetation (plants),
- **Blue *(vegetated with enhanced stormwater attenuation capacity).***
  These are roofs that are designed to slow the drainage of rainwater collected above a roofs waterproof element, unlike conventional roof's which allow rainwater to drain quickly away from the roof.

All of these technologies have to be associated with adequate insulation to provide resilience against the cold.

When considering the two greatest risks posed to the UK from climate change, flooding and overheating, it is clear these technologies can help mitigate the effects. Roofs, particularly green and blue roofs, have the potential to address the impact of flooding both at the individual building level and the wider neighbourhood scale, through water attenuation. This should become a key issue for planning in cities where roofs must act as a rainfall run-off attenuator.

These technologies can also be used to contribute to the reduction of overheating risk and cooling demand during heatwaves. The research found that well-insulated roofs that were air tight and had enhanced night ventilation and a medium/light coloured roof, can significantly reduce the risk of overheating, even over the long term.

Therefore, in buildings prone to overheating risk, it will be necessary to consider the colour and reflectivity of the roof material, improve ventilation *(especially night ventilation)* and create hybrid forms of ventilation and mechanical cooling, particularly in buildings located in the South such as Plymouth and London. Elsewhere in the UK, the focus should be on increasing thermal capacity and optimising ventilation without the need for mechanical cooling.

Fabric first retrofits that involve increasing insulation levels are critical to reducing energy consumption and providing more comfortable winter conditions, but the design of these must consider the risk of overheating.

Across all of the locations considered in the research, in July peak conditions *(such as a heatwave)*, the net radiative balance is much lower for cool, green and blue roofs compared to conventional roofs, and this advantage was consistent across all the locations in the UK from South to North, helping to maintain a comfortable temperature in the buildings and reducing demand for air conditioning. These technologies also reduce local air temperatures, helping to lower the Urban Heat Island Effect.

Rooftop spaces can also play an active part in the energy system by incorporating renewable technologies such as solar PV, solar thermal and hybrid solar thermal and PV. For example, PV at scale on city roofs in Southampton could contribute to 25 per cent of the city's electrical demand. Another study found that Great Britain has the theoretical potential to generate 238 TWh/year from rooftop solar. In comparison, the UK had a total electricity demand of 330 TWh/year in 2020

Finally, anticipated changes to the UK's climate also highlight that the maintenance of roofs, particularly their drainage systems, will become ever more critical to help ensure fewer roof failures.

The report clearly demonstrates the whole UK roofing industry, including both pitched and flat roofing, has a huge role to play in helping the UK adapt and build resilience to climate change.

Barriers to building roofing resilience

There are a number of barriers to the adaptation of innovative roofing technologies, however, which are primarily at the policy, legislation and planning level. There are also financial barriers due to the higher cost of these technologies.

For the construction industry, there needs to be a greater investment in green skills and training.

Finally, as these new technologies develop they are being limited in their application due to constraints within the current building regulations and the approved document guidance that support those regulations. The sector must work with the Department for Levelling Up, Housing & Communities (DLUHC) to ensure this doesn't become a significant barrier.

Recommendations

Based on the findings of the research, NFRC, therefore, recommend the following:

FOR INDUSTRY

1. The roofing industry has skills gaps in the design and installation of new technologies. The industry must therefore embed and invest in green skills throughout the existing and future roofing workforce. Green skills can be used to help promote new entrants to the sector. Manufacturers have a key role to play here.
2. The roofing industry must review current apprenticeship frameworks to ensure they integrate the green skills needed by the sector and that these are available nationwide.
3. Roofing contractors should consider diversifying their business and upskilling their workforce to include green technologies. For example, roofers should take advantage of the uplift in Part L and offer Built-In Solar PV installation.
4. Designers should consider the reflectivity of the materials they are specifying when designing building types that are at risk of overheating.

FOR GOVERNMENT

5 The UK Government and the Devolved Nations should incentivise the retrofitting of public buildings to ensure they are prepared for a warmer and wetter climate. In particular, for schools, alongside these retrofit projects, pupils should be taught about the work and why it's important.

6 The Department for Business, Energy and Industrial Strategy (BEIS) should introduce a National Retrofit Strategy to support homeowners to retrofit their property to support resilience. This should also include insulation, measures to reduce overheating as well as supporting energy resilience through retrofitting Built-In Solar PV and solar thermal. This should be accompanied by guidance for homeowners.

7 The Department for Education and the Devolved Nations should review current construction qualifications to ensure they place more emphasis on green skills.

8 The Department for Environment, Food and Rural Affairs (DEFRA) should use this evidence as part of the 2022 UK Climate Change Risk Assessment and prioritise the use of cool, blue, and green roofs, as well as solar PV, as part of the National Adaptation Strategy. The Devolved Nations should do the same for their own risk assessments and adaptation strategies.

9 The Department for Levelling Up, Housing and Communities (DLUHC) should place greater emphasis on blue, green and cool roofs in the National Planning Policy Framework (NPPF), their planning policy guidance and design guide.

10 The Department for Levelling Up, Housing and Communities (DLUHC) should bring forward the Future Homes Standard for new build homes from 2025 to 2023 to ensure all new homes are built to a net-zero standard and include Built-In Solar PV.

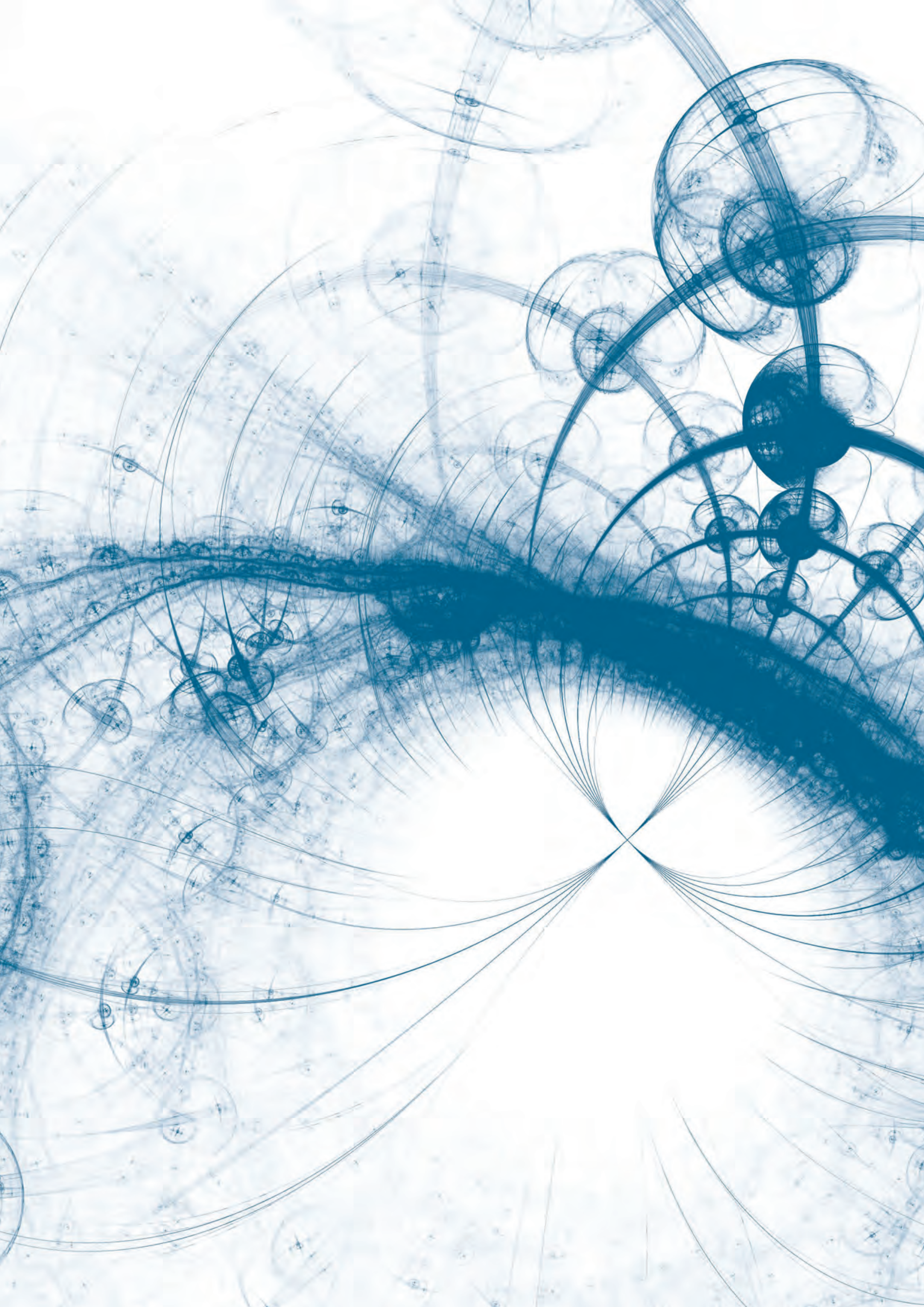
11 The Department for Levelling Up, Housing and Communities (DLUHC) should fast-track proposed changes to the building regulations concerning overheating and ensure these cover retrofitting, loft conversions and extensions, as well as new build.

12 The Department for Levelling Up, Housing and Communities (DLUHC) should update the Standard Assessment Procedure (SAP) to incorporate the insulating value of green roofs, and acknowledge reflective surfaces to encourage greater take up.

13 The Department for Levelling Up, Housing and Communities (DLUHC) should work with industry to ensure there is sufficient fire testing methodology and testing capacity for roof technologies such as green roofs and solar PV.

14 Each UK City and Local Authority at risk of overheating should develop an Overheating Strategy and utilise cool, blue or green roof technology as part of its solution through planning policy, similar to policies introduced in Philadelphia and Denver.

15 HM Treasury should develop financial incentives for commercial property owners to retrofit their buildings to become more resilient, such as by extending the Super Deduction policy to include buildings and structures.



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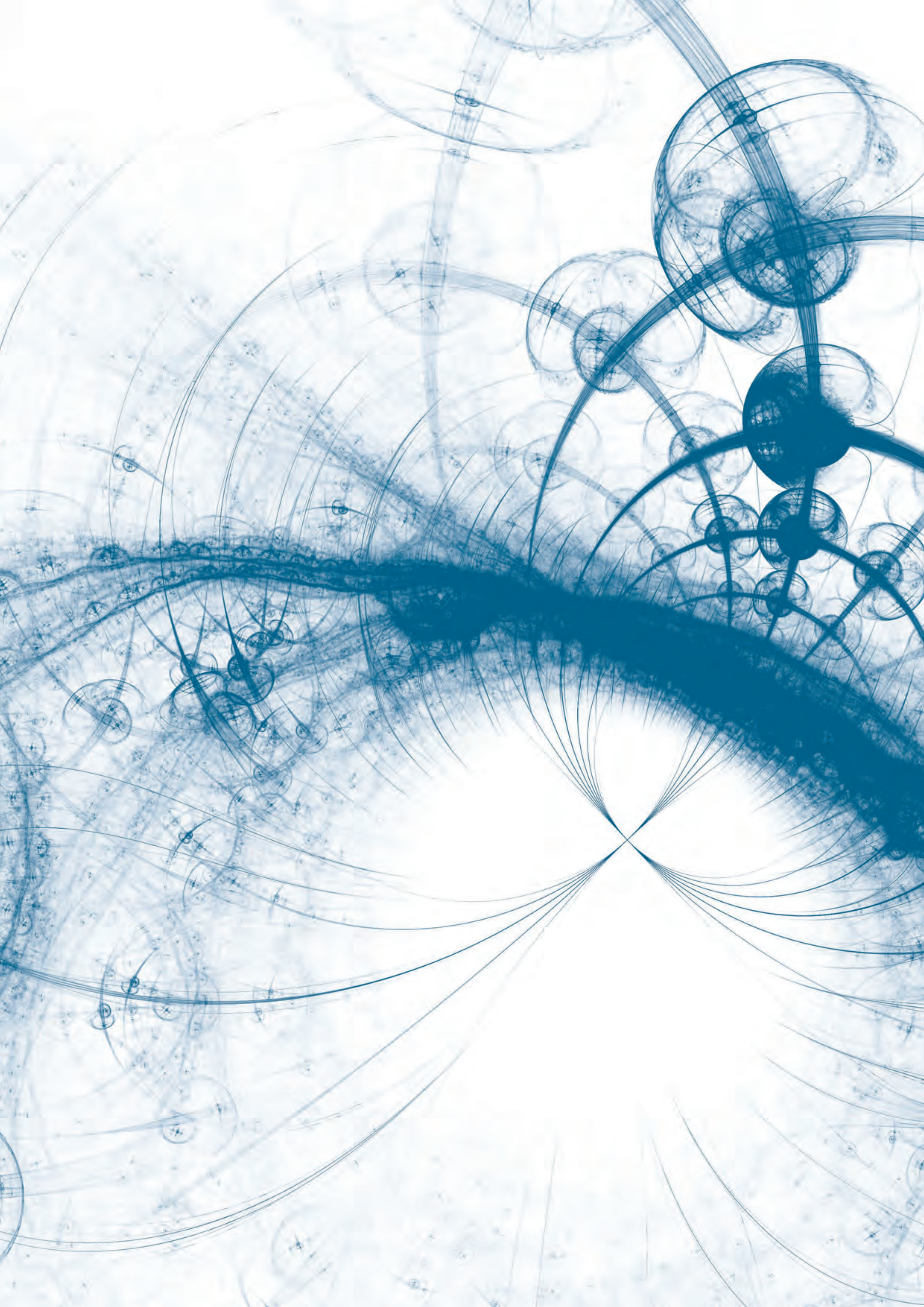

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Executive summary

Forecast of UK climate evolution

The UK is a leading country in terms of climate change projection modelling and provides high resolution (spatial) projections to support different sectors. UKCP09 and UKCP18 are the two most significant climate change projection updates released in the UK context, respectively in 2009 and 2018, with the most recent update in July 2021. UKCP18 projections are broadly in line with UKCP09 but now provide predictions with a higher resolution (2.2km grid square scale). Climate change projections take a probabilistic approach, allowing users to make predictions that are most relevant to their needs (i.e. average or peak, worst case scenarios, frequency, etc.), and are provided with percentiles of probability. UKCP18 reporting indicates that "winter is getting warmer and wetter" in the UK, but temperatures are expected to rise also in the other seasons, with a projected increase in frequency and intensity of heatwaves, which poses a particular challenge for the built environment. Furthermore, summer irradiance is expected to rise due to generally clearer skies on drier days. However, this effect is not uniform across the UK, because in some locations higher cloudiness may be expected because of the higher water vapour content of air. Additionally, in terms of rainfall, extreme daily precipitation increases proportionally to temperature and UKCP18 indicates that there is an increase in predicted peak rainfall (90th percentile) in a 24h period across the CIBSE weather station cities in the UK. Finally, with respect to wind, there are no compelling trends in storminess over the last four decades as measured by maximum gust speeds from the UK wind network, as shown in UKCP18 reporting. In terms of damaging storm windspeed projections, therefore, little change is expected. Nonetheless, because all of these projections are based on probabilistic scenarios, it is critical to track the actual evolution of climate and understand what the actual changes in terms of frequency and intensity are.

Building resilience to adapt to a changing climate in the UK context

Resilience can be defined as the capacity to recover quickly from extreme events. Buildings and communities have to find ways to deal with shocks and thus avoid disasters triggered by the environment. Technological improvements required to enhance the

resilience of buildings should also be considered from a sustainability perspective, where the emphasis is put on ways to reduce the impact on the environment. Major aspects to be addressed in relation to built environment resilience are heatwaves, flooding, drought, cold, storms and strong winds. All of these aspects are relevant for the UK climate context. Energy provision may be included as well, because of the increasing decentralisation of energy systems enabled by small scale renewable energy technologies and smart energy infrastructure. Roofing technologies can contribute to built environment resilience. In this study we consider conventional (consolidated technologies), cool (highly reflective coating), green (vegetated) and blue (vegetated with enhanced storm water attenuation capacity) roofs and we highlight how they can contribute to the reduction of overheating risk and cooling demand during heatwaves (conventional with medium-light coloured surfaces, cool with high reflective surfaces, green and blue by exploiting evapotranspiration of vegetation). All of them have to be clearly associated with adequate insulation (resilience in cold conditions). Furthermore, we indicate how green and blue roofs can help reduce the flooding risk in densely urbanised areas by means of improved storm water management. Roofs are not directly involved in drought risk mitigation; however, they can work in conjunction with rainwater storage and recovery systems. These can be realised contextually to the roof design or redesign and help to increase resilience against flooding risk. Additionally, all roofing technologies, if properly design and maintained, can provide adequate resilience against storm and strong winds. Finally, energy provision with Building Integrated Photovoltaic (BIPV) and solar roofs can provide energy resilience in a context of increasing electricity demand determined by heating and transportation electrification. It has to be stressed the fact that many of the benefits provided by roofing technologies go beyond the physical limit of the single building and have wider neighbourhood implications, among others Urban Heat Island (UHI) effect mitigation, flooding risk reduction and energy resilience at the community and local scale.

How can roofing technologies contribute to mitigate the impact of climate change?

The larger adoption of green and blue roof technologies can help reducing the flooding risk in highly urbanised areas and there is a large evidence base on the performance achievable from this point of view. Other benefits associated with these technologies include biodiversity and habitat, urban heat island effect mitigation and pollution reduction. Another fundamental issue in buildings is that of overheating and cooling demand which is caused by interacting factors such as increasing temperatures and frequency of heatwave events, urban heat island effect, the necessity to improve energy efficiency by means of higher insulation levels and incorrect design and operational practices. Recent research indicates that overheating is already a problem in the UK context and that it will worsen in the future. Appropriate roof design can give a relevant contribution to the reduction of overheating and cooling related risks, both for traditional residential building typologies and for non-residential typologies.

What are the barriers to the adoption of innovative roofing technologies?

There are a number of barriers to the adoption of innovative roofing technologies. Barriers exist primarily at the level of level legislation, planning and policy. Below that, barriers exist at the financial level, determined by the higher costs of some technologies. Finally, there is the need for specific green training and skills related to design and construction. Some actions to break down these barriers are proposed.

What actions can be done at the policy, industry and research levels to break these barriers down?

Research can provide evidence to inform policy and industry decision-making processes. At the policy level, it appears critical to fast track proposed changes to building regulations concerning overheating and to replicate the London Plan model for green roofs in other UK cities where overheating is a relevant risk. Furthermore, by facilitating planning permission processes, public authorities can encourage the installation of green and blue roofs. Blue and green roofs can play an important role in the UK's Sustainable Drainage Systems (SuDS) strategy and the importance of cool, green, and blue roofs should also be highlighted in the government's design guide. Homeowners should be given guidance on how to upgrade their roof to reduce overheating and flooding risk. At the industry level, NFRC should develop guidance for its members on how to make roofs more resilient to climate change, as well as collaborate with the Centre for Digital Built Britain to develop Digital Twin solutions aimed at addressing the issues highlighted in recent research. The benefits of flood prevention measures (as well as other co-benefits) extend beyond the physical boundaries of the building, and the capital investment has broader neighbourhood benefits. Current financing methods do not easily support such investments. However, there are ways to change tax policy, such as tax relief, to encourage such investments. Finally, even if the policies for planning and financing are in place, there is still one barrier to overcome: a lack of green skills. The roofing industry must speed up green training and skill development programmes that incorporate these increasingly important technologies.

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1 Introduction

This report examines the implications of the UK's changing climate for the residential and commercial roofing sectors. The report is supported by outputs from the United Kingdom's climate change projections programme (UKCP09, UKCP18), which are applied to the context of domestic and commercial roofing in the United Kingdom. In general, the UK is expected to have warmer, wetter winters and hotter, drier summers. Furthermore, the frequency and severity of extreme weather events, particularly heatwaves and torrential rain, are expected to rise. Torrential rain events will increase the likelihood of water ingress into buildings through the roof fabric, as well as wider catastrophic flooding, which is the primary climate change risk to the built environment in the UK. Rising summer temperatures have raised concerns about building overheating, which poses a public health risk, particularly in the residential sector. Because commercial buildings are more likely to use air conditioning, existing roof systems may result in otherwise avoidable increases in energy demand due to cooling.

In more general sustainability terms, shelter, access to food and warmth (and increasingly cooling) are fundamental requirements to sustain life. Climate change cuts across these fundamentals, whether it be from increasing frequency and extremes of weather, rising sea levels, or changes to the norms of the climate that we live in. The Environment Agency's recent report to HM Government (October 2021, [1]) is stark in its assessment of the impacts of climate change. Emma Howard Boyd, Chair of the Environment Agency, states "The climate crisis is global, but its impacts are in your village, your shop, your home. Adaptation action needs to be integral to government, businesses and communities too and people will soon question why it isn't – especially when it is much cheaper to invest early in climate resilience than to live with the costs of inaction." This Environment Agency report is set out across eight themes, all of which directly transfer to the roofing sector in the UK:

1. Thinking differently – 'business as usual' is not an option.
2. Collaborating adaptation works through partnerships.
3. Investing in change – adaptation needs public and private finance.
4. Working with nature – tackle the biodiversity and climate crises together.
5. Designing low carbon futures – support the low carbon economy.
6. Strengthening community resilience – support local adaptation for everyone.
7. Helping businesses prepare – flexible and climate-proof regulation and advice.
8. Stepping up to level up – show what it takes to live better with a changing climate.

If we consider roofs and the future climate, risks and impacts can be considered at the scale of the building, neighbourhood and even city scale. As indicated by the call to action of the Environment Agency report, all sectors must work together and roofing has a key role to play in the UK context. COP26 is increasingly seen as the last chance to keep global temperature rises close to 1.5 or even 2 ºC above pre-industrial levels, with current projections for rises of 3 ºC or more. The effects of climate change on temperatures, irradiance, rainfall, and wind patterns in a UK context are discussed in this report. This pattern is then applied to key aspects of built-environment resilience, specifically heatwaves, flooding, drought, cold, storm and strong winds and energy provision. Each of these resiliency aspects is associated with various roofing technologies, namely conventional, cool, green, blue roofs and the growing market for BIPV (Building Integrated Photovoltaic) roofs. As will be discussed later in the document, these roofing technologies can be applied to both residential and non-residential buildings. Figure 1 sets out the series of headline climate change effects and their associated risks and opportunities that relate to roofs. This report then describes climate change projections (and their interaction) across temperature, rainfall, wind and irradiance and the implications to UK roofing.

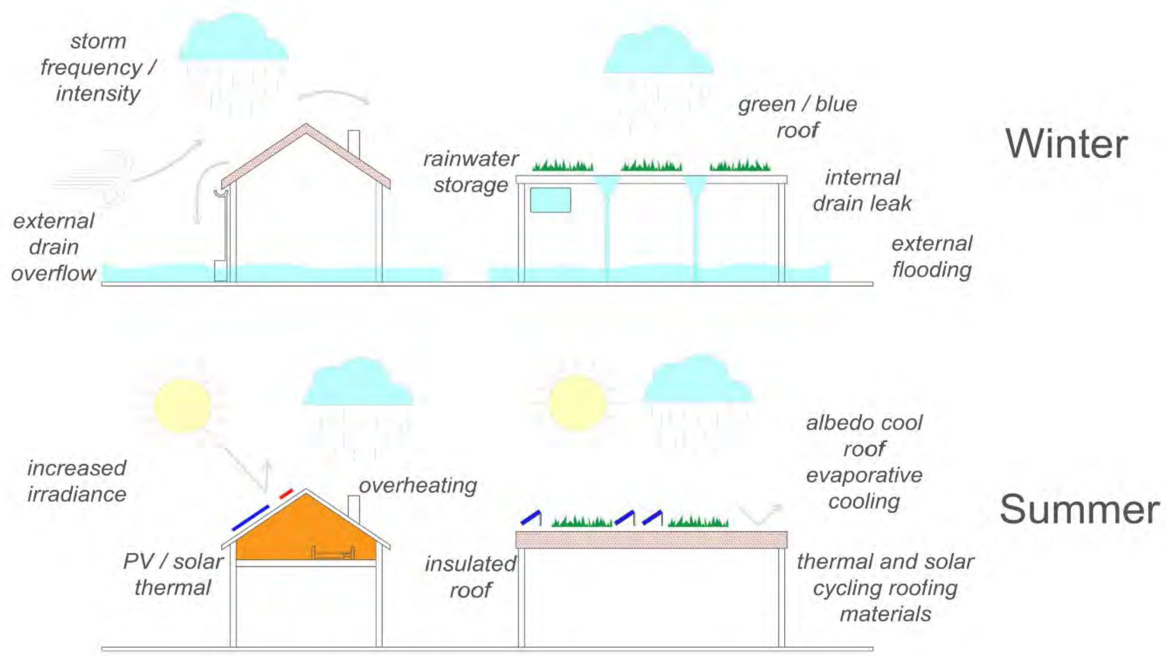

Figure 1: Climate change impacts and options for residential and commercial roofing.

Fundamentally, how can we ensure that roofs that we construct or retrofit today will be fit for purpose in 20, 30 or 50 years' time? Where, spatially, is the impact predicted to occur? Is it at the scale of the building, in terms of increased cooling loads or overheating risk, or is it at the scale of the wider neighbourhood in terms of catastrophic flooding or widespread water stress? Will increasing irradiance levels accelerate degradation rates of plastic in roofing materials? Roofing investments will have to be made to benefit not only the building owner, but the neighbourhood or region. Flooding, water scarcity, overheating these create impacts across multiple scales and sectors. Furthermore, the push towards net-zero has buildings at its core. Fabric first retrofits will incorporate roofs as a matter of course and must consider overheating risk in particular. New heating systems will be focussed around air source heat pumps supported by microgeneration, notably roof mounted or integrated photovoltaics (PV). The latest Independent Assessment of UK Climate Risk [2] and the Met Office State of the UK Climate Report [3] note that there are already clear patterns to the changing UK climate.

Table 1: Observed Changes to the UK climate [1].

Variable	Observed Change
Average annual temperature	+ 0.9 ºC rise from the mid 1970s to mid 2010s
Annual mean rainfall	+ 4.5% rise from the mid 1970s to mid 2010s
Sunshine	+ 9.2% rise from the mid 1970s to mid 2010s
Weather extremes	UK wide increase in extreme weather events Little evidence yet of change in extremes of rainfall
Sea level rise	UK rise of ~1.4mm per year since 1901.

The future climate projections for the UK suggest that in many cases what is considered as an anomaly today will become the norm in future decades. In essence, the UK will experience warmer wetter winters, with hotter drier summers. The built environment and roofing in particular, has a key role to play. Summer thermal stress will not only be in the form of overheating, but through drought and general water stress. The Environment Agency projects that public water supply will require an extra 3,400 million litres of water per day by 2050 if no action is taken. 1,150 million litres are directly associated with the need to make water supplies more resilient to drought. Rainwater collection and storage from roofs have a role to play here. Furthermore, around 50% of the national need for public water supply is in the South East which is already a region considered in drought.

In terms of significant risk pathways for the UK, the CCRA3 Interacting Risks project considers hazardous events, main impact candidates and a 2020 and 2080 timeframe [3]. Climate change as a driver of increasing summer temperatures and a reduction in summer rainfall, there is a medium risk for building overheating and loss of productivity, rising to a high in 2080 (p74, [3]). River, surface and groundwater flooding as a result of extreme winter rainfall events and increases in winter mean rainfall is seen as a medium building risk today (in terms of both building damage and productivity loss), rising to high risk by 2080.

2 Climate change and future weather evolution

The UK is a leading country in terms of climate change projection modelling and provides high resolution (spatial) projections to support sectors such as agriculture, insurance and the built environment. UKCP09 [4] and UKCP18 [5] are the two most significant climate change projection releases in a UK context, corresponding to 2009 and 2018, with the most recent update being in July 2021. The projections for the UKCP18 update are broadly in line with the previous UKCP09 release, but now provide predictions down to a 2.2km grid square scale [5]. The key summary for the United Kingdom is that "winter is getting warmer and wetter." The most recent decade's (2000-2017) UK observations were 0.3 ºC warmer than the 1981-2000 reference and 0.8 ºC warmer than the 1961-1990 reference. The top ten warmest years on record have all occurred since 1990. Rainfall has increased, especially in Scotland. The period from 2008 to 2017 was 4% wetter than the 1981-2000 reference period and 11% wetter than the 1961-1990 reference period [6]. Climate change projections in the United Kingdom take a probabilistic approach, allowing users to make predictions that are most relevant to their needs. Insurers, for example, are not concerned with the “average year”; rather, they consider the extreme and the change in intensity and frequency of which this may occur. Rainfall change projections and associated flooding are considered on the basis of the extreme in the context of building roofs.

In contrast, for an air-conditioned building, the change in average temperatures is critical because it allows the building owner to estimate the building's future carbon and energy costs. Naturally ventilated buildings necessitate a hybrid approach, as neither the typical (average) year nor an extreme heatwave (such as a 1 in 30 or 1 in 100 year event) are appropriate for assessing overheating risk. This issue is addressed in the UK for building simulation by using two types of weather files, the Design Summer Year (DSY) to represent a hot year and the Test Reference Year (TRY) to represent an average year. Climate change projections are presented as time slices from a reference baseline period. Historically, 1961-1990 was used as the baseline reference period, but in the United Kingdom, this has now been changed to 1981-2000 for most studies. The 2030s, 2050s, and 2080s are presented as future time slices. Users can select a rank ordered weather file from the modelling for each time slice, such as the 10^{th}, 50^{th}, and 90^{th} percentile. The 50^{th} percentile represents the time slice's middle warmest year, while the 90^{th} percentile represents one of the time slice's warmest modelled years. As a result, the 10^{th}, 50^{th}, and 90^{th} percentiles provide the local low, central, and high change projections.

According to the UKCP18 Science Overview Report [7]**,** flooding is already a problem as is overheating in flats – particularly in overglazed single-sided ventilation flats. This is exacerbated further by low thermal mass construction methods such as timber or steel framed buildings. Here the issue is to consider a building that is marginal in terms of overheating risk today, will not perform appropriately in the future.

2.1 Weather data files morphing and simulation of future climate

The University of Exeter's PROMETHEUS project provided the future climate weather files for this study [8,9]. Along with a baseline weather file (1960-1990), projections for 2030s, 2050s, and 2080s are used as the 10th, 50th, and 90th percentiles for both a typical (TRY) and Design Summer Year (DSY). The TRY is made up of 12 separate months of data, each of which was chosen as the most average month from the collected data. The TRY is used for energy analysis as well as to ensure compliance with UK Building Regulations (Part L). The DSY is a single continuous year as opposed to a composite made up of average months. The DSY is used to analyse overheating risk and represents a year with a hot but not extremely hot summer. Rainfall data projections are taken from the UKCP18 projections provided by the MetOffice [5]**.** The most recent decade (2008–2017) saw 6% more hours of bright sunshine in the UK than the 1961–1990 averages and 3% more than the 1981–2010 average. These trends are most noticeable in the winter and spring, when there is 14% and 11% more sunshine than the 1961-1990 average, respectively. There are no discernible trends in storminess over the last four decades, as measured by maximum gust speeds from the UK wind network. Nevertheless, the UK has the strongest wind climate in Europe and roof stability under wind loads remains a prime requirement. Figure 2 depicts an example of UKCP18 projection output.

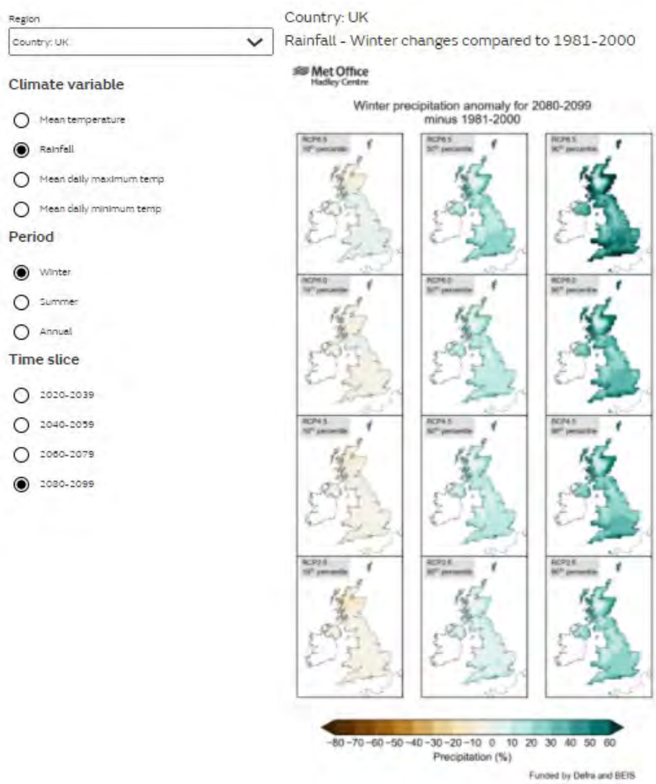

Figure 2: UKCP18 predicted rainfall changes compared to 1981-2000.

We have chosen 15 cities around the UK as the basis for the analysis of this report, providing broad geographical coverage encompassing cities with a range of rainfall, irradiance and temperatures. Figure 3 shows the UKCP09 DSY weather file for Islington, London. The average annual temperature is projected to rise by 3.3 ºC between the baseline (reference) period and the 2080s.

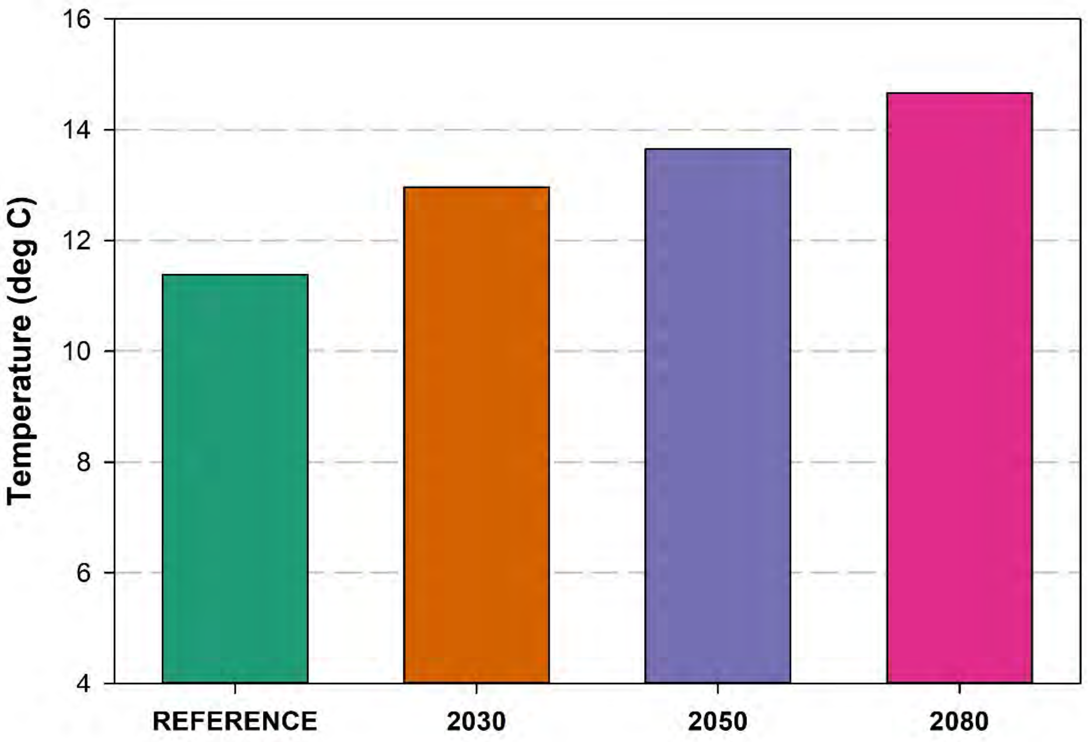

Figure 3: UKCP09 London Islington, 50th percentile projected Design Summer Year average annual temperature for reference period, 2030s, 2050s and 2080s.

Figure 4 shows the 15 cities across the UK for the same annual average temperature range of 4-16 ºC.

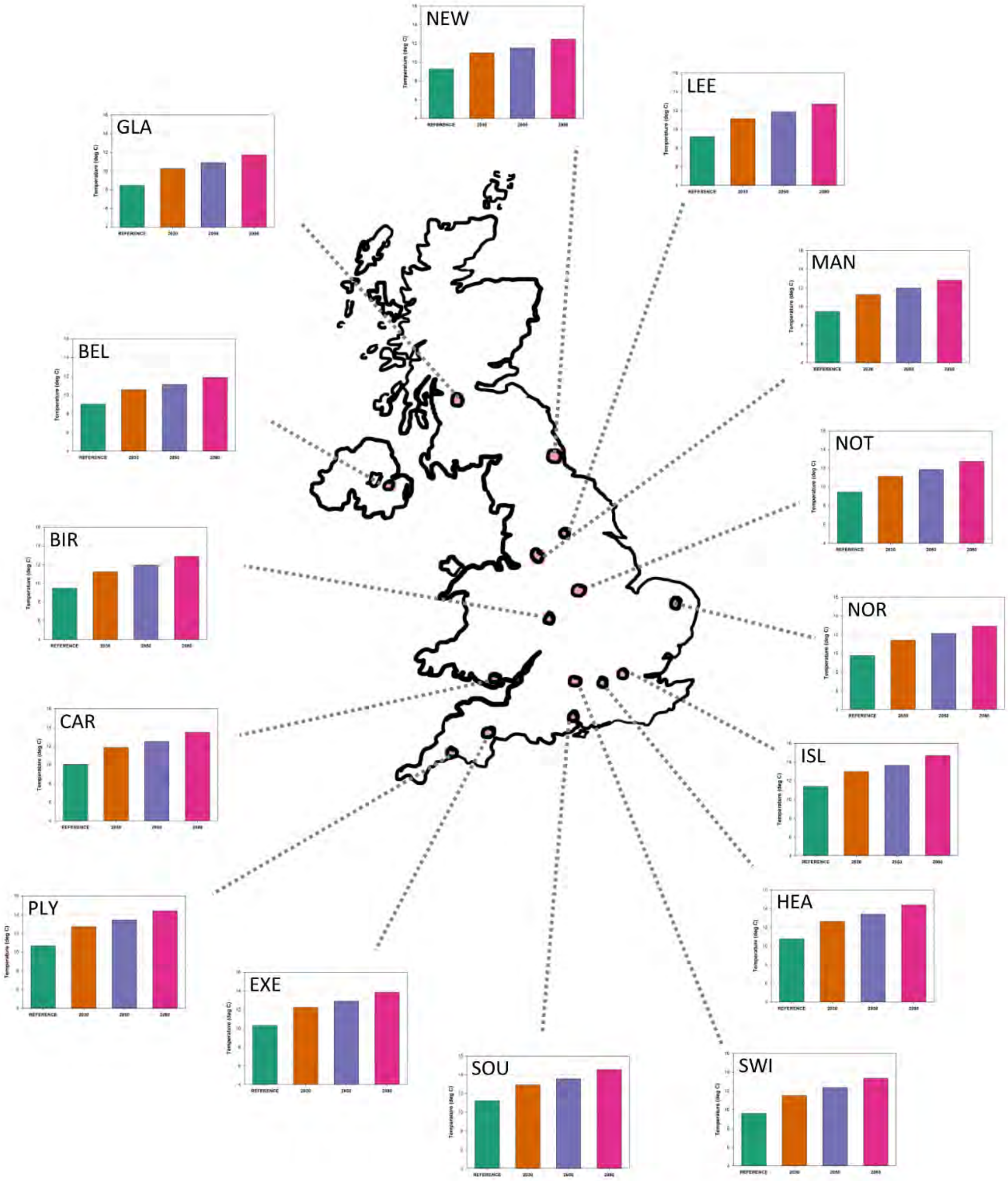

Figure 4: UKCP09 projections for future annual average temperature for a Design Summer Year (DSY), 50th percentile. Green BASELINE, Orange 2030s, Purple 2050s, Red 2080s. Temperature. 15 UK Cities as clockwise for 12:00 Newcastle (NEW), Leeds (LEE), Manchester (MAN), Nottingham (NOT), Norwich (NOR), Islington (ISL) - London, Heathrow (HEA), Swindon (SWI), Southampton (SOU), Exeter (EXE), Plymouth (PLY), Cardiff (CAR), Birmingham (BIR), Belfast (BEL), Glasgow (GLA).

In terms of future overheating risk, we clearly need to consider the summer period. Figure 6 shows the projected average daily maximum temperature for Islington for August for the reference, 2030s, 2050s and 2080s. A 12 degree y-axis range is again used to enable visual comparison between Figures 4 and 6. The average daily maximum temperature for Islington increases from 22.2 ºC for the reference period to 27.9 ºC for the 2080s, clearly indicating that cooling will be required.

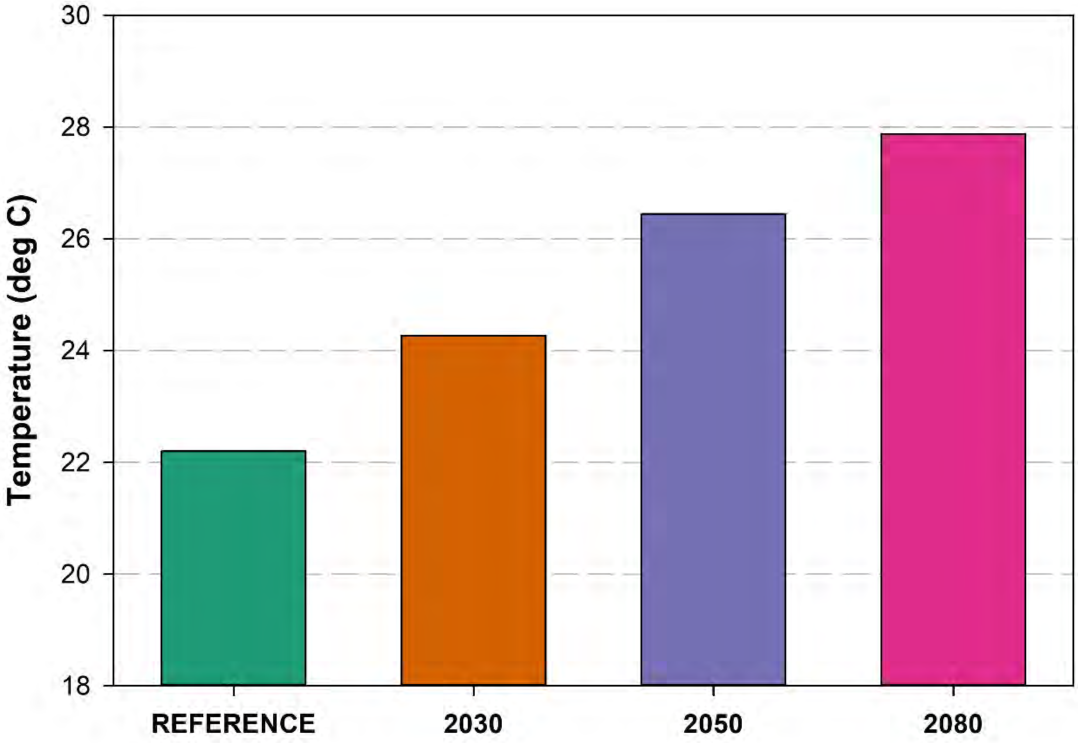

Figure 5: UKCP09 London Islington, 50th percentile projected Design Summer Year, August average temperature daily maximum for reference period, 2030s, 2050s and 2080s.

The average daily maximum temperature across the 15 UK cities is shown in Figure 6. Glasgow is projected to have the lowest average daily maximum temperature for August of 23.2 ºC by the 2080s, an increase of 4.3 ºC. In contrast, Southampton is projected to have a daily average maximum temperature while in August 7.7 ºC higher at 28.4 ºC.

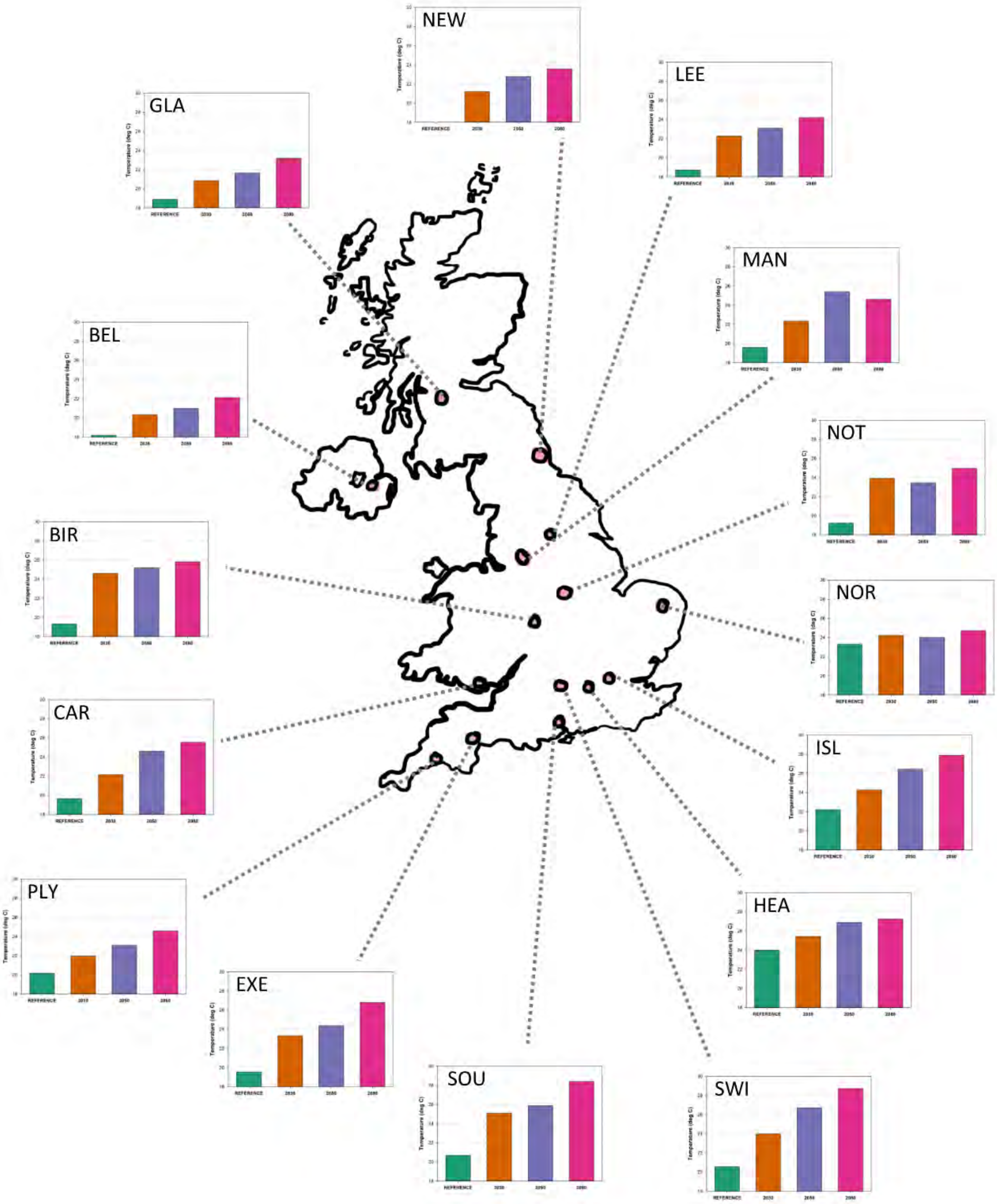

Figure 6: UKCP09 projections for future average daily maximum temperature for a Design Summer Year (DSY), 50th percentile for August. Green BASELINE, Orange 2030s, Purple 2050s, Red 2080s. Temperature. 15 UK Cities as clockwise for 12:00 Newcastle (NEW), Leeds (LEE), Manchester (MAN), Nottingham (NOT), Norwich (NOR), Islington (ISL) - London, Heathrow (HEA), Swindon (SWI), Southampton (SOU), Exeter (EXE), Plymouth (PLY), Cardiff (CAR), Birmingham (BIR), Belfast (BEL), Glasgow (GLA).

2.2 Comparison between present state and future projections

Here we present a synthetic outline of patterns of climate evolution in terms of temperature, solar radiation, precipitation, wind, and their relationship to extreme events such as heatwaves (temperature and solar) or storms (precipitation and wind), in order to highlight the evolution in comparison to the current trend.

2.2.1 Temperature and heatwaves

Whilst it is projected to become warmer as highlighted, the temporal patterns are also projected to change. There will be an increasing frequency and intensity of heatwaves which poses a particular challenge for buildings. Thermal mass is an effective climate moderator in buildings when there is a significant diurnal (day-night) change in temperature and overnight purge ventilation can be applied. Under conditions of prolonged heatwaves even high thermal mass buildings will become thermally soaked and their benefit will be reduced. For naturally ventilated buildings, which are particularly vulnerable to heatwave events, a range of DSY files are available to designers to assess both short intense and prolonged heatwave events.

2.2.2 Irradiance

Summer irradiance (sunlight levels) are expected to rise due to generally clearer skies on drier days. As a result, the rate at which exposed roofing materials degrade may be accelerated. Degradation of roofing materials such as UPVC guttering and certain flat roofs are sensitive to a combination of temperature and sunlight. UPVC degradation in sunlight undergoes both yellowing and photo bleaching at the same time (these two actions occur at different wavelengths) which results in excellent colour performance during environmental exposure. PVC photolytic degradation itself is sensitive to temperature, with higher temperatures increasing degradation [10]. Figure 8 shows the projected radiation anomaly (W/m^2) projected for the 2030s, 2050s and 2080s for UKCP18 rcp4.5 (a moderate development scenario) for June, July and August. The highest anomaly is for Wales (90th percentile, 2080s) at 32 W/m^2. To put this projected change into context, it is useful to compare London and Paris [11]. The average hourly horizontal irradiance (June, July, August) for London is 202 W/m^2 and Paris 219 W/m^2 (+8%). The Paris irradiance level is therefore 17 W/m^2 greater than London, which is a more than any of the projected 50th percentile anomaly increases. Tours, in the Loire Valley of northern France has an average June, July, August irradiance of 233 W/m^2, representing an increase of 31 W/m^2 compared to London. This is the same offset as the highest projected change for the UK, the 90th percentile projection for Wales in the 2080s. Roofing products which achieve the desired lifetime terms of combined temperature and UV degradation performance for a Northern France context today would therefore appear appropriate for the future UK climate to 2080 in term of irradiance and temperature stability.

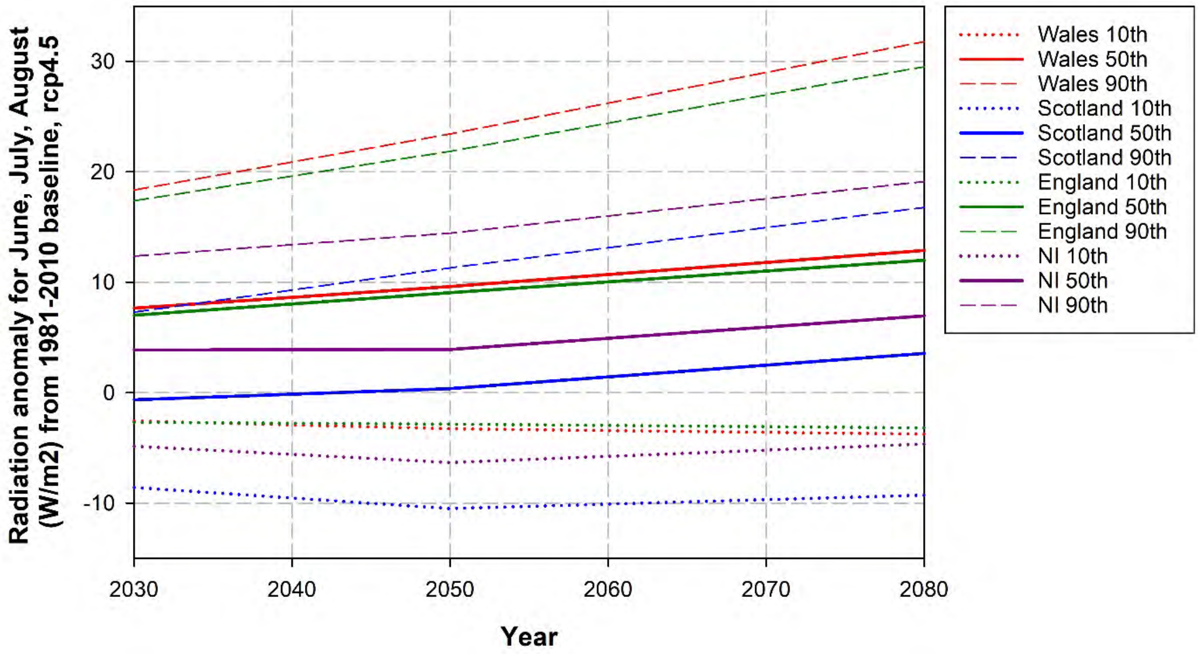

Figure 7: Radiation anomaly for June, July, August (W/m^2) from 1981-2010 baseline, rcp4.5 UKCP18. London has a current June, July, August horizontal radiation level of 202 W/m^2 [10].

2.2.3 Rainfall

Precipitation patterns projections for 12 UK cities is shown in Figure 8, indicating the UKCP18 24h peak rainfall event for 2021/2030/2050/2070 in the rcp4.5 scenario, 90th percentile [5]**.**

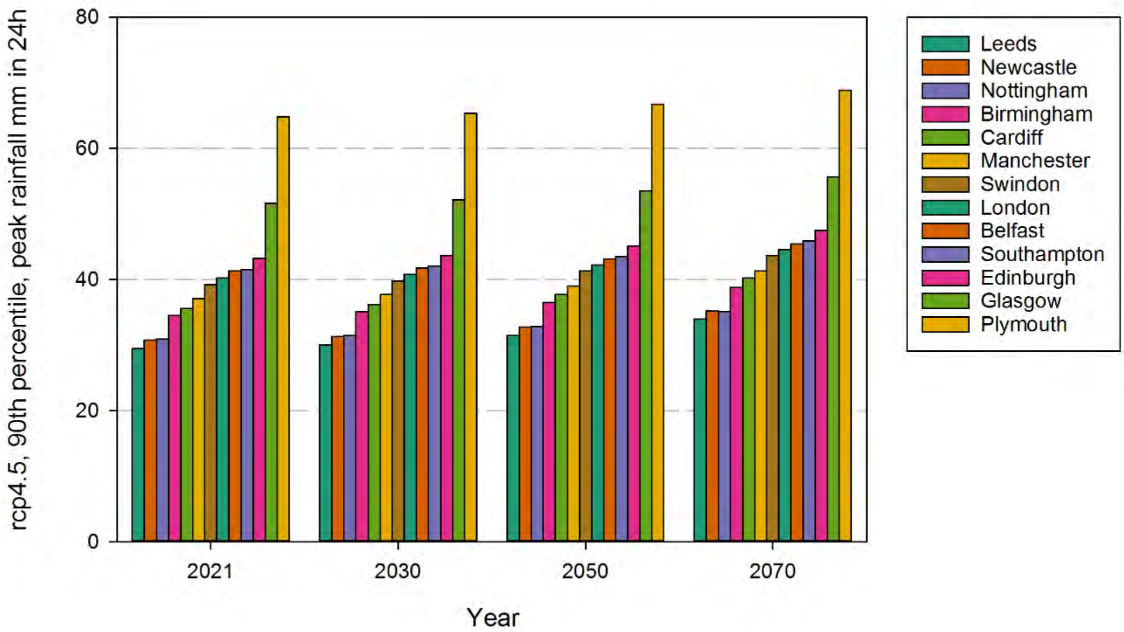

Figure 8: Precipitation patterns projections across the CIBSE weather file cities in the UK. Rcp4.5 90th percentile, maximum rainfall in a 24h period.

Extreme daily precipitation is considered to increase with temperature at a rate of 6.5% per K according to the Clausius– Clapeyron relationship between temperature and saturation vapour

pressure [12]. UKCP18 indicates that there is an increase in predicted peak rainfall (90th percentile) in a 24h period across the CIBSE weather station cities in the UK. There is a growing body of work looking at how extreme rainfall patterns (99th percentile) may change both temporally and in intensity as a result of climate change. Wasko and Sharma [13] showed that in Australia, rainfall patterns were changing as a result of climate change driven temperature changes. The observed relationship, known as scaling, indicates that the highest rainfall fraction of a temporal pattern scales positively with temperature, whilst the lowest fraction scales negatively with temperature. This scaling effect will clearly affect peak roof run off rates. The change in rainfall temporal patterns in a warmer UK climate was studied by Fadhel et al [14]. This work shows that for hourly storm events there is a statistically significant positive scaling for storm volume of 1.6% to 4.9% per ºC. Blenkinsop et al. [15] similarly showed that in the UK, the largest scaling value is seen in the summer season (6.9% per ºC), while for the other seasons it is lower: 3.2% per ºC for winter, 4.7% per ºC for spring, and 3.9% per ºC for autumn.
Design storms are still commonly used to assess flooding risk. However, this approach does not incorporate the scaling effects of temperature on rainfall profiles. In essence, the peak fractions of a rainfall profile will become peakier and the non-peak fractions less so with temperature. Fadhel [12] shows that summer and winter storms exhibit a different temporal temperature response. The largest scaling values were seen for hourly summer storms, the scaling factor declining as storm durations increased to 12h and then increasing again but still less than the short-duration storms. Summer flash flooding events can be considered a particular risk going forward. In contrast, in the winter season scaling factors for short duration storms were the smallest (<3h) increasing with the duration of the storm. Overall, when considering the scaling values of temporal patterns within individual storm events, it was found that there was a consistent positive scaling for the largest rainfall fraction and a consistent negative scaling for the smallest rainfall fraction. Therefore, consideration of peak rainfall in a 24h period alone, would clearly underestimate the potential of flooding risk.
With respect to the sizing of roof drainage systems we can refer to the standard BS EN 12056-3:2000 [16]. The standard considers the effective area of a roof by accounting for both vertical and horizontal (wind-driven) rainfall as shown in Figure 9. The flow rate from the roof (l/s) is simply the effective roof area (m^2) x rainfall intensity (l/s m^2).

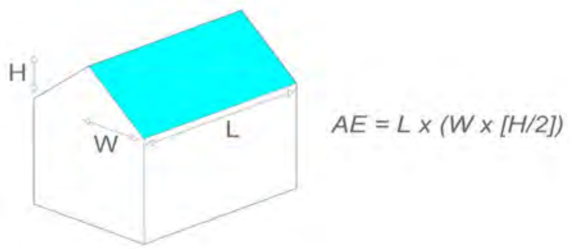

Figure 9: Effective area calculation for roof rainfall.

A simplified guide is available from drainagecentral.co.uk [17], with a comprehensive guide from HR Wallingford [18]. The position of the pipe to the gutter has a significant effect on the flow capacity of a rainwater system, with a centre outlet downpipe providing greater capacity. There is no standard rate of rainfall in the UK to use in calculations for roof drainage and a worst case storm of 0.021 litres per second per square metre is recommended by British Standards. In the event of an open gutter exceeding its design limits, the damage to a property will be relatively small. The issue at the building level, lies with internal drainage systems, most commonly found in commercial buildings where exceeding limits will result in damage to the building and loss of productivity. Flooding is the greatest climate change challenge facing the UK. Roofs have the potential to address the impact of flooding at both the individual dwelling/office/retail building and the wider community or neighbourhood scale. This will become a key issue for planning in cities where roofs must act as a rainfall run-off attenuator.

2.2.4 Wind

There are no compelling trends in storminess over the last four decades as measured by maximum gust speeds from the UK wind network (UKCP18 report). In terms of damaging storm windspeed projections, therefore, little change is expected. That is NOT to say that wind is and remains a key issue for roof design in a UK context. In addition, the increased thermal cycling of roof fixings due to rises in irradiance and temperature should be considered. Figure 10 shows the projected change in near surface windspeeds for 1900-2100 with respect to a 1981-2000 baseline [19].

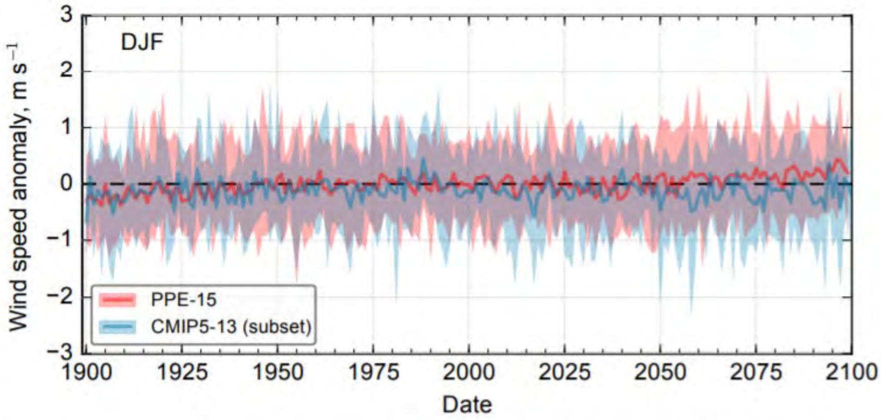

Figure 10: Global projections for changes in winter (DJF) mean near surface wind speed over the UK for 1900-2100 with respect to 1981-2000. The red line is the mean of the PPE-15 and blue line is the mean of the CMIP5-13. The red and blue shading represents the range of values from PPE-15 and CMIP5-13 respectively. Note that only 9 of the 13 models in CMIP5-13 have wind speed data for 1900-2100 [19].

3 Building resilience to adapt to a changing climate

As mentioned in the previous section, the UK has begun to experience more extreme weather events in the form of heatwaves caused by rising temperatures in recent decades. Rising temperatures have a direct impact on water vapour concentrations, clouds, precipitation patterns and streamflow patterns, causing either an abundance or a scarcity of rainfall. In relation to extreme events, what is resilience? We can define resilience as the capacity to recover quickly from these extreme events. Building and communities will have to find ways to deal with shocks and thus avoid disasters triggered by the environment. On the other hand, many of the technological improvements required to enhance the resilience of buildings also should be seen from the perspective of sustainability, where the emphasis is put on ways to reduce the impact on the environment.

3.1 Building resilience to adapt to climate change patterns

In order to be able to build resilience, it is important to define first the aspects of resilience that are of interest. In the built environment, major aspects for analysis are heatwaves, flooding, drought, cold, storms and strong winds, which are relevant for the UK climate context, as reported in Section 2. Energy provision is included because of the increasing decentralisation of energy systems with small scale renewable energy technologies. In Table 2 we correlate climate change patterns to resilience building.

Table 2: Building resilience to adapt to climate change patterns in the UK.

Resilience building	Temperatures	Irradiance	Rainfall	Wind speed
Heatwaves	Trend of increasing of average temperatures in summer conditions.	Moderate increase of solar radiation in summer in many locations, highest moisture content of air decreases direct solar radiation component in some cases.	-	-
Flooding	-	-	Increase of precipitation.	-
Drought	-	-	Risk of prolonged period with absence of rainfall.	-
Cold	Trend of increase of average temperature in winter conditions (in cold and temperate climate it is still necessary to heat even though the consumption will likely decrease).	Solar gains in winter months can be exploited in case of good passive design.	-	-
Storm and strong winds	-	-	Increase in rainfall related to these events.	Good design and maintenance practices at the state of the art are appropriate.
Energy provision	-	On-site energy technologies, PV and solar thermal.	-	-

3.2 Building resilience of roofing technologies

The problem of resilience building also affects roof technologies, which are a key component in buildings. In Table 3 we examine conventional roof technologies, cool roofs, green roofs, and blue roofs in relation to the resilience aspects introduced in Table 2. A basic definition of the different roof technologies considered is provided in Table 3. With the term "conventional roof" we indicate the technologies that are consolidated in the market and present in both residential and non-residential buildings, while "cool roofs" indicates the use of coatings which are made of white or special reflective pigments that reflect sunlight (short-wave radiation, high reflectance) and reduce infrared heat re-emission by the surface (long-wave radiation, low emissivity). In the summer, standard or dark roofs can reach high temperatures (e.g., 60 °C or higher). Under the same conditions, a cool roof could maintain a much lower temperature (e.g., 40 °C). These lower surface temperatures are critical, especially in light of climate change scenarios involving heatwaves and achieving longer lifetimes can be a potential advantage due to lower performance degradation. "Green roofs" are "vegetated roofs" with a growing medium (soil), and vegetation (plants), which can provide multiple benefits, as will be illustrated later, amongst others rainwater runoff retention [20,21]**.** It is worth considering that there could be a relevant difference between intensive[1] and extensive[2] green roofs, the former being used to create an accessible natural landscape as part of the building. Finally, blue roofs are building roofs that are explicitly designed to provide initial temporary water storage and then gradual release of stored water, typically rainfall. Blue roofs are built on flat or low sloped roofs in urban areas where flooding is a concern due to a lack of permeable surfaces for water to infiltrate or seep back into the ground. While the definitions given of a blue roof in literature can be fairly generic [22], in this document we will consider them to have a growing medium and vegetation, as in the case of green roofs.

Table 3: Roofing technologies definitions.

Roof technology	Description
Conventional	Technologies that are consolidated in the market and present in both residential and non-residential buildings. These roofing technologies are providing increasing levels of insulation and improvement of air-tightness, both in new build and retrofitted contexts.
Cool	A cool roof is one that is designed to reflect more sunlight and absorb less heat than a conventional roof. Cool roofs are typically flat or low sloped, but they can be adapted to steep roofs with highly reflective tiles or shingles. A highly reflective type of paint, a sheet covering, or highly reflective tiles or shingles can be used to achieve the reflective effect.
Green	Green roofs, also known as “vegetated roofs” or “living roofs”, are ballasted roofs that cover a conventional roof with a waterproofing layer, growing medium (soil), and vegetation (plants). Green roofs are typically flat or low sloped, with significant variations in the characteristics and thickness of the growing medium layer, which is determined by the type of vegetable species grown on the roof.
Blue	A blue roof is one that is designed to slow the drainage of rainwater collected above the roof's waterproofing element, unlike conventional roofs, which allow rainwater to drain quickly from the roof. Blue roofs are typically flat or low-sloped, with control devices that regulate drainage outlets, allowing water to be drained at a slower rate. While being designed for this specific task, they can have a growing medium (soil), and vegetation (plants) on top, similarly to green roof and have, for this reason, a similar thermal behaviour.

Finally, a topic which applies across all roofing technologies considered is the presence of renewable energy technologies. The use of a solar power generation technology (solar roof) in combination with the other options previously discussed, could help to maximise some of the benefits of a better roof design that we summarise in Table 4, highlighting pros and cons.

Table 4: Pros and cons of different roofing technologies.

Roof technology	Pros	Cons
Conventional	Better comfort and lower consumption in winter by means of improved insulation, while keeping the overheating effect under control. Medium-light coloured roofs can contribute to: • Maintain comfortable conditions in buildings, for buildings that are not air-conditioned. • Reduce cooling demand for buildings that are air-conditioned and related emissions due to electricity use. • Reduce local air temperatures (i.e. urban heat island effect).	Requires a substantial redesign of the roof. Can contribute to overheating if shading and/or solar control and ventilation are not possible. Medium-light coloured roof can result in: • Modest reduction of solar heating gains in winter.

[1] Intensive green roofs are designed to be accessed and to reproduce a natural landscape with a variety plant types. The needed relevant soil depth involves higher structural loads and design complexity.
[2] Extensive green roofs have generally a soil depth lower than 200 mm and can therefore have a lower structural weight. People generally seldom access them and vegetation requires less water and maintenance, making them financially more competitive, if a traditional narrow economic analysis is considered.

	• Reduction of heat released by air-conditioning systems. • Lower peak electricity demand, which can help prevent power outages.	• Potential glare effect for surrounding taller buildings.
Cool	Superficial reflective surface and improved insulation: • Maintain comfortable conditions in buildings, for buildings that are not air-conditioned. • Reduce cooling demand for buildings that are air-conditioned and related emissions due to electricity use. • Reduce local air temperatures (i.e. urban heat island effect). • Reduction of heat released by air-conditioning systems. • Lower peak electricity demand, which can help prevent power outages.	Superficial reflective surface results in: • Modest reduction of solar heating gains in winter. • Potential glare effect for surrounding taller buildings.
Green	Evapotranspiration and improved insulation: • Maintain comfortable conditions in buildings, for buildings that are not air-conditioned. • Reduce cooling demand for buildings that are air-conditioned and related emissions due to electricity use. • Reduce local air temperatures (i.e. urban heat island effect). • Reduction of heat released by air-conditioning systems. • Lower peak electricity demand, which can help prevent power outages. Reduce water runoff in extreme precipitation events, with the ability to slow the drainage and cope with peak flows. Reduced runoff water can prevent flooding in urban areas.	Increase in design complexity. Increase in weight structural load. Increase in capital cost. Increase in maintenance. Need for irrigation in case of water shortage, depending on the plant species grown.
Blue	Evapotranspiration and improved insulation: • Maintain comfortable conditions in buildings, for buildings that are not air-conditioned. • Reduce cooling demand for buildings that are air-conditioned and related emissions due to electricity use. • Reduce local air temperatures (i.e. urban heat island effect). • Reduction of heat released by air-conditioning systems. • Lower peak electricity demand, which can help prevent power outages. Reduce water runoff in extreme precipitation events, with the ability to slow the drainage and cope with peak flows. Specifically design to discharge over a long period of time (e.g. 24 h). Reduced runoff water can prevent flooding in urban areas.	Increase in design complexity. Increase in weight structural load. Increase in capital cost. Increase in maintenance. Need for irrigation in case of water shortage, depending on the plant species grown.

Many of the pros of roofing technologies could determine relevant benefits at the urban and community scale, including the reduction of Urban Heat Island (UHI) effect and flooding risk, as will be discussed in Section 3.3. Finally, in Table 5 we analyse the six resilience areas, introduced in Table 2, with respect to the four roofing technologies considered in Tables 3 and 4.

Table 5: Building resilience of roofing technologies in UK in future climate scenarios.

Resilience building	Conventional	Cool	Green	Blue
Heatwaves	Overheating/cooling/UHI risk mitigation by increasing the reflectance of roof surface (albedo) and	Overheating/cooling/UHI risk mitigation by increasing the reflectance of roof surface (albedo).	Overheating/cooling/UHI risk mitigation by increasing the evapotranspiration	Overheating/cooling/UHI risk mitigation by increasing the evapotranspiration

	increase of natural ventilation of roof.		determined by species growing.	determined by species growing.
Flooding	-	-	Ability to handle at least 10-20 mm rainfall events if properly designed.	Ability to handle 100-120 mm rainfall events if specifically designed.
Drought	-	-	-	-
Cold	Insulation improvement determined by insulating material/preventing condensation.	Insulation improvement determined by insulating material/ preventing condensation.	Insulation improvement determined by insulating material and additional insulation determined by the upper layers (i.e. growing medium, etc.).	Insulation improvement determined by insulating material and additional insulation determined by the upper layers (i.e. growing medium, etc.).
Storm and wind	Correct design, construction and maintenance are needed, following current standards.	Correct design, construction and maintenance are needed, following current standards.	Correct design, construction and maintenance are needed, following current standards.	Correct design, construction and maintenance are needed, following current standards.
Energy provision	BIPV and solar thermal integrated.	Optimised PV systems/solar thermal design, integrated/non-integrated.	Optimised PV systems/solar thermal design, integrated/non-integrated.	Optimised PV systems/solar thermal design, integrated/non-integrated.

Notably, the role of the roof in drought mitigation has not been included in Table 2 because it does not directly involve roof technologies. However, roofs can work in conjunction with rainwater storage and recovery systems, which can be realised contextually to the roof design or redesign and also help to increase resilience against flooding risk. In general, we can see how conventional technologies with increased insulation levels are essential components, but they must also be verified against condensation and overheating risk, as will be discussed in Section 4. Cool roofs have the potential to reduce overheating and cooling by increasing the reflectance (albedo) of the surface, and they can be a relatively inexpensive solution to these problems (with community scale implications as discussed in Section 3.3). Finally, by employing the evapotranspiration effect, green and blue roofs can provide similar benefits in terms of overheating and cooling. Furthermore, in the case of blue roofs, which are specifically designed to release water at a slower rate, they can make a significant contribution to reducing flooding risk in dense urban areas, even in extreme events. The final two solutions, green and blue, have a higher design complexity and costs (construction and maintenance), but they create benefits that are relevant both at the single building and at the community level, as discussed in the following section.

3.3 Resilience of roofing technologies from single buildings to communities

Improving the resilience of roofing technologies can have a positive impact across scales from the single building to entire communities. To begin with, improved thermo-hygrometric performance of the building envelope has a wide range of positive effects, ranging from reduced energy demand to increased comfort and health. Better acoustic performance also is generally associated with improved building components. Furthermore, as will be discussed in detail in Section 4, the appropriate design of roof technologies can help reduce overheating and cooling-related risks, including Urban Heat Island (UHI) effect. Furthermore, rooftop spaces can be an active part of the energy system by incorporating renewable energy technologies such as solar photovoltaic (PV), solar thermal, and hybrid PV/T (solar photovoltaic and thermal combined) into construction components (e.g. Building Integrated Photovoltaic, BIPV). The assessment of generation from PV technologies in roofs can be done with free modelling tools such as PV-GIS [11], but there are more complex options such as LIDAR. LIDAR can map roof geometries across a city and so, in conjunction with solar data assess shading risks on roofs. A LIDAR assessment of Southampton for example, showed that PV at scale on city roofs could contribute around 25% of the city's electrical demand [23]. Joshi et al. [24] conducted a high-resolution assessment of rooftop solar potential on a global scale and determined that the potential for Great Britain is 238 TWh/year. According to the study, this potential can be realised by utilising the entire roof surface and a PV generation system with a 10% efficiency. In comparison, total electricity demand in the UK in 2020 was 330 TWh/year [25], 4.6 % lower than in 2019 (346 TWh/year) [26], as a result of the response to the Covid-19 pandemic. The future projected rise in electrical demand, which is being driven in part by the electrification of heating demand in buildings and in part by electric vehicles as a response to decarbonisation targets, can be met at least partially by on-site renewable generation, given the large potential. Innovative business models, such as energy communities [27,28], can make these options more appealing and affordable, and this is part of the energy sector's ongoing R&D. Finally, technologies such as green roofs and blue roofs have higher design, construction, and maintenance costs. However, in addition to the previously mentioned benefits, they can provide additional benefits such as storm water management [29] and flood risk reduction, biodiversity and improved habitat, and air quality improvement. All of these factors are particularly important in densely populated areas and must be factored into cost-benefit assessment at the community level rather than at the single building level.

4 Resilience building in roofing technologies – Analysis of evidence and projections in future climate scenarios

First and foremost, the key characteristics of the building stock, including the key typologies, must be examined [30,31]. According to building stock studies, traditional built forms such as bungalows, detached houses, semi-detached houses, and mid-terrace houses will continue to make up a large portion of the building stock in the UK. Among these typologies, mid-terrace and flat developments with single-sided ventilation are amongst the most vulnerable to overheating.

The following section reports on some of the key characteristics of UK building stock, taking into account available evidence and future projections regarding overheating risk and increased cooling demand. In Section 4.1, traditional residential building typologies are discussed, which are typically characterised by pitched roofs, while in Section 4.2 we consider high-rise residential and non-residential, which are characterised by flat and low pitch roofs.

4.1 Traditional residential building typologies

The UK residential housing stock has long been characterised by leaky, thermally inefficient buildings. Government retrofit programmes have focussed on addressing insulating properties, predominantly via cavity wall insulation and additional loft insulation to cold roof constructions. In parallel, there has been a gradual tightening of building regulations and associated energy calculations (SAP) to enhance the air tightness and thermal performance (U-value coefficient) of façade components and constructions. In recent years, increasing attention has been paid to summer overheating risk and this is now recognised as a growing problem [32]. Flat developments with single-sided ventilation and/or over-glazed facades have become common in the UK [33]. While these apartments may have addressed the winter heating season challenge, they have also created buildings with a high level of overheating risk in many cases because of the limited potential for cross-ventilation and the compact form. Furthermore, buildings with low thermal mass, such as those made of wood or steel, exacerbate the risk of overheating. It is clear how wooden frame lofts with limited natural ventilation are vulnerable to overheating, and how roof technologies play an important role here.

The first and essential step is to define what exactly is overheating. Overheating is a state of discomfort caused by an increase in internal temperature determined by the accumulation of warmth, determined by the balance between gains and losses. In terms of rules of thumb, CIBSE research suggests that most people begin to feel "warm" at 25 ºC and "hot" at 28 ºC [34] and there are different international standards [35]. In these standards, the assessment of thermal comfort has moved from rules of thumb to a deterministic approach and a more dynamic approach, such as the adaptive comfort method. The simulation results for overheating and adaptive comforts are dependent on the weather projections chosen [36] and can be considered as very restrictive in relation to the criteria reported in technical standardisation at the state of the art [37]. In this research, we consider as criteria to judge overheating the thresholds of 25 ºC and 28 ºC for the operative temperature in living rooms and 24 ºC and 26 ºC for bedrooms [38]. The basic recommendation is to have, in both cases, the number of hours above the two thresholds of respectively limited to 5% and 1% of occupied hours. The number of occupied hours is calculated for the period 08:00 to 22:00 for living rooms and the period 23:00 to 07:00 for bedrooms. Finally, CIBSE TM52 [39], applicable to all building typologies, and CIBSE TM59 [40], specific for homes, consider additional criteria that are not reported here.

4.1.1 Evidence on the impact of roofing technologies at present

As would be expected, the risk of overheating in buildings has received a lot of attention in recent years. Homes in normally temperate climates typically rely on passive design measures to deal with hot-weather events, rather than the mechanical means of ventilation and cooling used in commercial buildings. Furthermore, occupancy in the domestic sector is much more volatile than in the non-domestic sector, as families use their homes in a variety of ways.

The BRE report on the risk of overheating in housing [41], the BRE overheating in dwellings guidance [42], and the Zero Carbon Hub report on the solutions to overheating in homes [43].all review the evidence and discuss possible solutions and provide an assessment of the main influencing factors. What are the most important lessons for residential buildings? First, there is a size dependency, with smaller dwellings being more vulnerable to overheating risk.

Petrou et al [44] used statistical analysis to look for correlations between the factors that increase (or decrease) the risk of overheating in a large housing dataset of indoor temperatures and occupant and dwelling-type characteristics. One notable correlation was found between the size of a property and household vulnerability, with the latter increasing as the size of the property was reduced. Overheating is studied in both living spaces and bedrooms, with the latter being more vulnerable to overheating risk in many cases [33,38]. Loft conversion and insulation is a popular retrofitting measure to create extra living space in the UK’s small and expensive housing. Because of their typical loft characteristics – top floor (directly under the roof) and usually of lightweight construction – they are prone to overheating. Taylor et al. [45], for example, focused their research on loft conversion problems, and their findings revealed an increased risk of overheating in lofts when appropriate mitigation options are not considered, and climate change projections indicate the risk will increase in the future. Furthermore, De Grussa et al. [46], who studied the effectiveness of passive measures in mitigating high indoor temperatures in a real-life retrofitted apartment building in London, show how shading and ventilation (particularly night-time natural ventilation) can significantly reduce the risk of overheating in homes.

External shading is the most effective option for reducing solar gains and, as a result, the risk of overheating. Furthermore, external shading, such as shutters, can provide secure ventilation both during the day and at night, but they cannot always be used when windows are designed to open outwards. Other factors, such as noise and the potential reduction in daylight availability when external shading is used, must obviously be considered.

In general, the need to anticipate the potential impact of overheating in future climate conditions aims to address not only the issue of comfort in summer conditions, but also to reduce the risk of heat-related mortality during extreme weather events, when elderly people are more vulnerable [47] and will likely be even more vulnerable in the future [48]. What are the current limitations of simulation studies using future weather projections? More research in this area is needed in the future, given the underlying uncertainties [49], but simulation tools can give preliminary estimates of relevant effects and can be "calibrated" on available evidence, as will be illustrated in the next section.

4.1.2 Impact of roofing technologies in future climate scenarios

In this section, we provide the results of simulation for a typical mid-terrace house construction form with east-west orientation (particularly at risk of overheating), taking into account different roof types, such as loft conversion, dormer conversion, cold roof, and flat roofs, as shown in Figure 11 below.

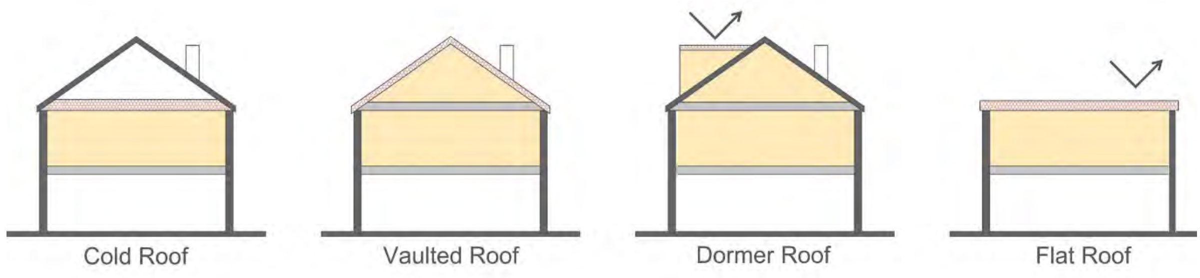

Figure 11: Different roof types for a mid-terrace house.

We consider well-insulated building envelopes and three forecasting intervals in this simulation case study: 2030, 2050, and 2080. We use Design Summer Year (DSY) weather data files with 50th percentile for the 15 UK cities listed in Section 2 for these forecasting intervals. Finally, we consider three simulation configurations for each roof type and forecasting interval, which are summarised in Table 6.

Table 6: Configurations for overheating simulations for a mid-terrace house.

Simulation configuration	**Description**
Baseline	Well-insulated and air-tight envelope but limited natural ventilation.
Configuration 1	Well-insulated and air-tight envelope and enhanced night ventilation.
Configuration 2	Well-insulated and air-tight envelope, enhanced night ventilation and medium/light coloured roof.

As recently reported in overheating research [33,37,49], the use of dynamic simulation for overheating risk assessment must be critically questioned, because actual conditions in the building depend on a variety of factors, including not only thermo-physical properties but also user behaviour. Nonetheless, they can be viewed as a tool for assessing the potential impact of future measures aimed at increasing building resilience in a "relative" manner (i.e. by comparing results with different configurations). In other words, the goal of the simulation study is not to provide absolute values, given the limitations of simulation techniques highlighted in recent literature and the uncertainty inherent in forecasts, but rather to provide a comparative analysis whose goal is to understand the impact of various technologies and measures in future scenarios. We consider a well-insulated and air-tight envelope as the baseline in all simulation cases due to its benefits in terms of energy consumption reduction and comfort in winter conditions. Following that, we present the findings of the analysis for four specific locations, namely Plymouth, London Islington, Nottingham, and Glasgow, in sequence South to North. The analysis takes into account the percentage of overheating hours for bedrooms at 24 °C and 26 °C, as explained in Section 4.1. The results indicate that and the ranges obtained from simulations in 2030 are substantially comparable with the ones indicated in other studies [38,45,49]. A well-insulated and air-tight envelope (baseline configuration) brings overheating risks if solar gains are not controlled and natural ventilation (especially night ventilation) is not exploited effectively. In fact, configuration 1 (higher night ventilation) and 2 (higher night ventilation and medium/light coloured roof surface) estimate a reduction of the overheating percentage hours, which is consistent from South to North in the UK. Looking more in detailed at the different locations selected, we can see how overheating is already an issue in 2030 for loft and dormer conversions in Plymouth (assumed to be well-insulated and air-tight as a baseline for 2030). For pitched cold roof and warm flat roof cases in configuration 2 (enhanced night ventilation and medium/light coloured roof) overheating is a moderately a problem in 2030 and it becomes progressively a more serious issue for 2050 and 2080.

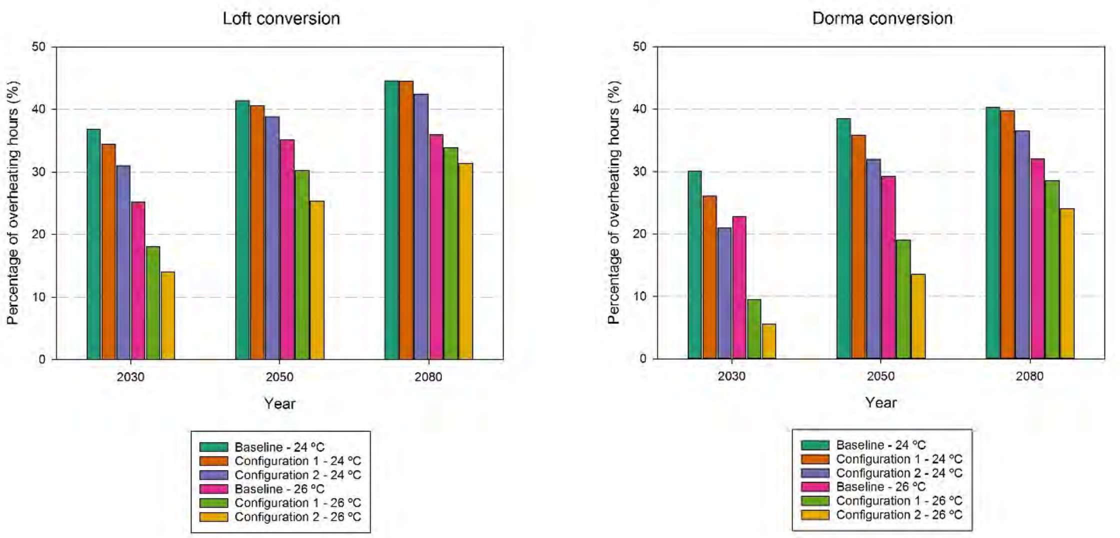

Figure 12: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – Plymouth – Loft and dormer conversion.

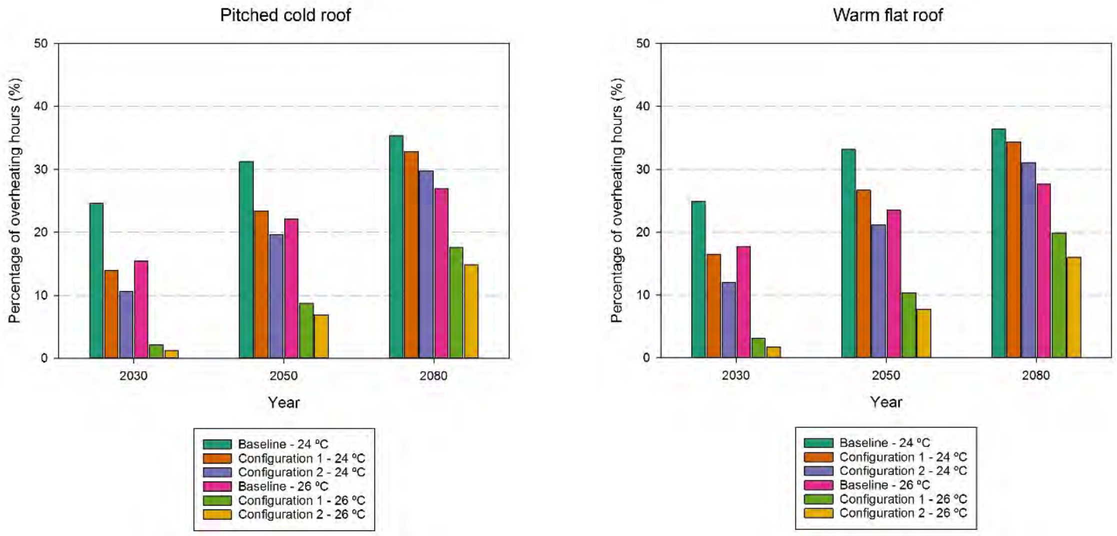

Figure 13: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – Plymouth – Pitched cold roof and warm flat roof.

In London Islington, we can see how loft and dormer conversions are the most vulnerable to overheating risk and this is predicted to cause serious problems by 2030. It is worth noting that pitched cold roof and warm flat roof cases in this location perform worse in terms of overheating when compared to Plymouth, and the enhanced night ventilation is less effective due to the higher summer temperatures caused by the urban heat island effect.

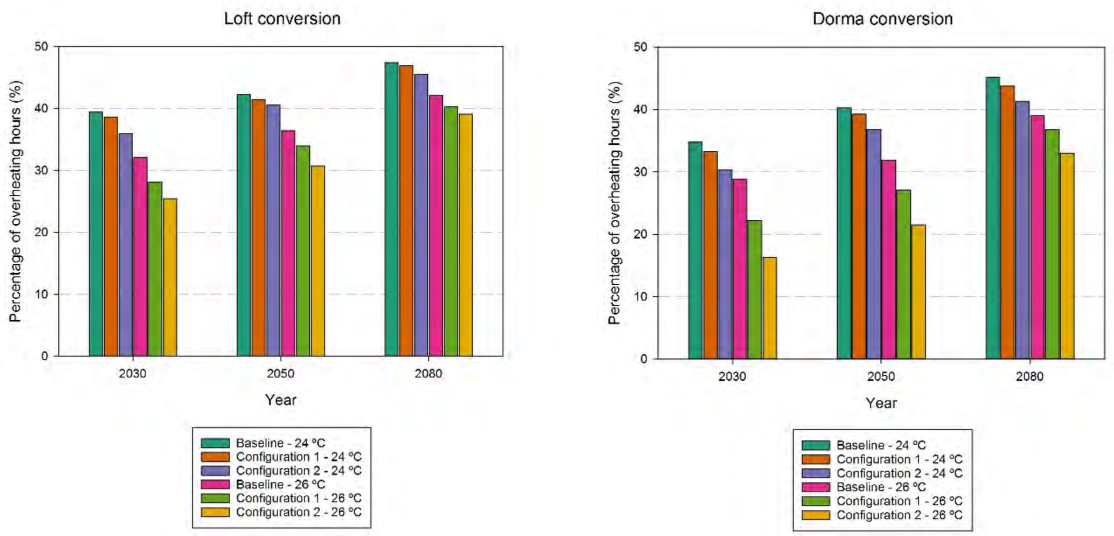

Figure 14: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – London Islington – Loft and dormer conversion.

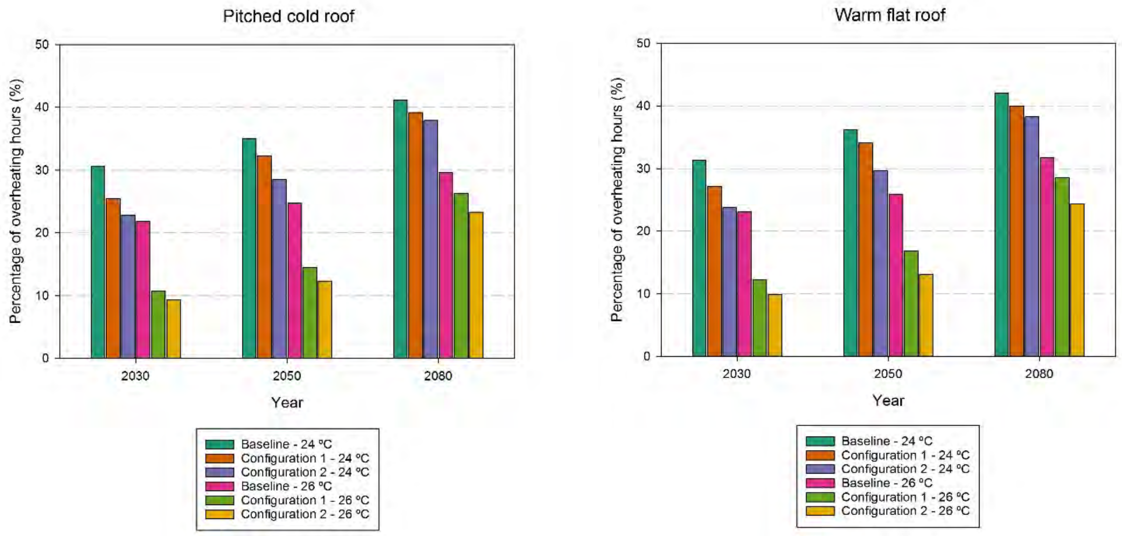

Figure 15: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – London Islington – Pitched cold roof and warm flat roof.

Nottingham has a lower risk of overheating than Plymouth and London Islington. In fact, the ranges of values for overheating hours (both with 24 and 26 ºC thresholds) obtained in Islington for pitched cold roofs and warm flat roofs (i.e. the cases generally less exposed to overheating) are similar to those obtained in Nottingham for loft conversion (i.e. the case generally more exposed to overheating). This behaviour is consistent across the time intervals studied (2030/2050/2080). Furthermore, pitched cold roofs and warm flat roof cases in Nottingham have a low risk of overheating in 2030, but this risk rises steadily in 2050 and 2080.

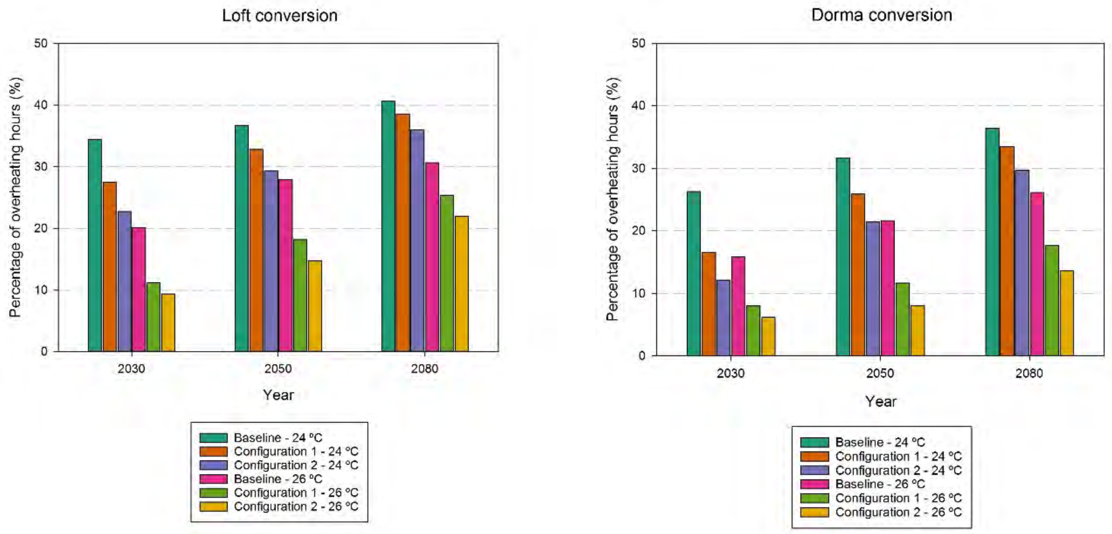

Figure 16: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – Nottingham – Loft and dormer conversion.

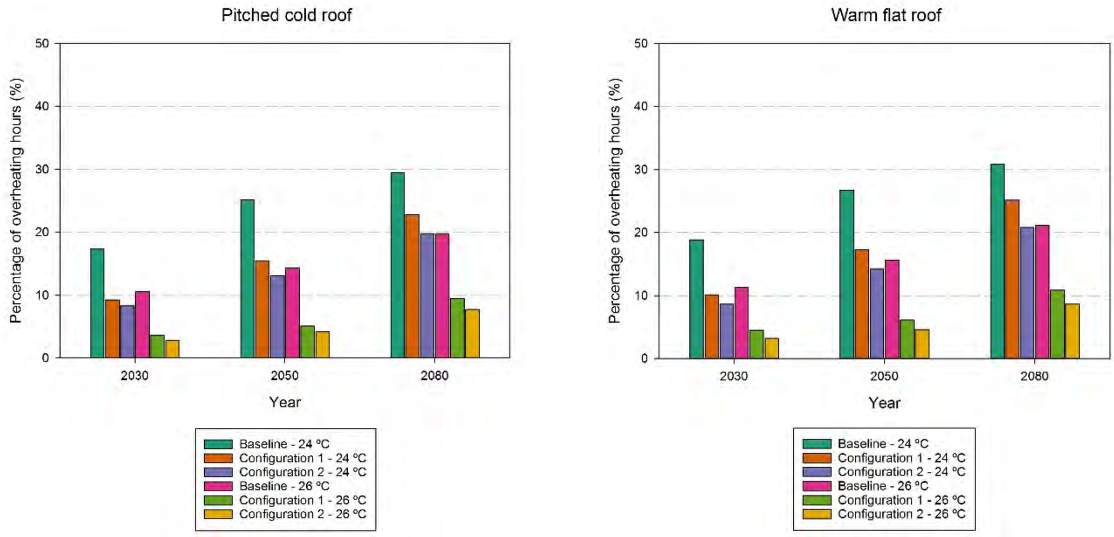

Figure 17: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – Nottingham – Pitched cold roof and warm flat roof.

Finally, in Glasgow in 2030, overheating is not a major concern for configuration 2 (enhanced night ventilation and medium/light coloured roof), even for loft and dormer conversions, which are the most vulnerable in all other locations. However, due to rising temperatures, it may become more of a problem in 2050 and 2080. On the other hand, for pitched cold roof and warm flat roof cases, configuration 2 can significantly reduce the risk of overheating even over the long-term.

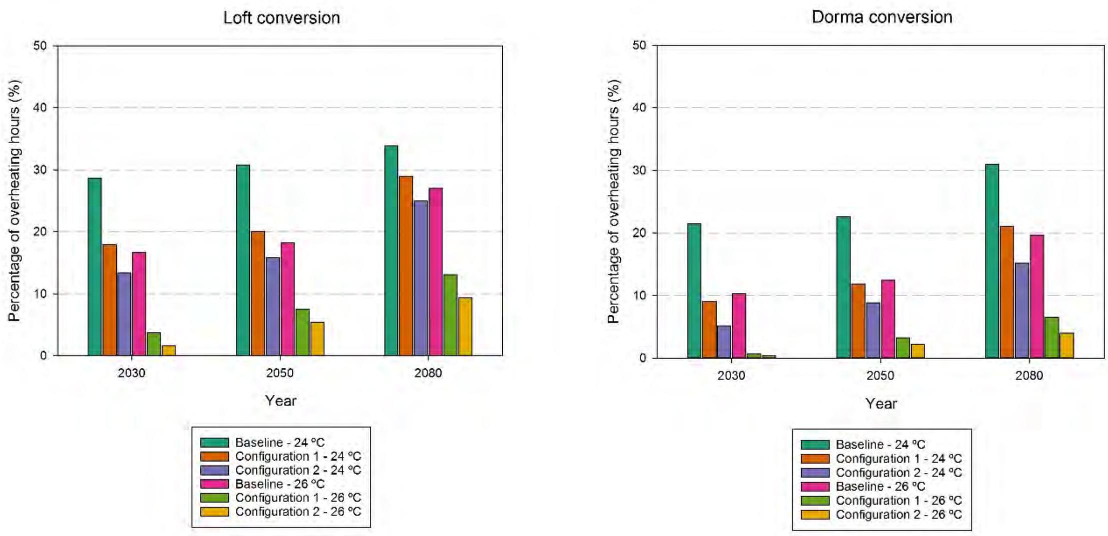

Figure 18: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – Glasgow – Loft and dormer conversion.

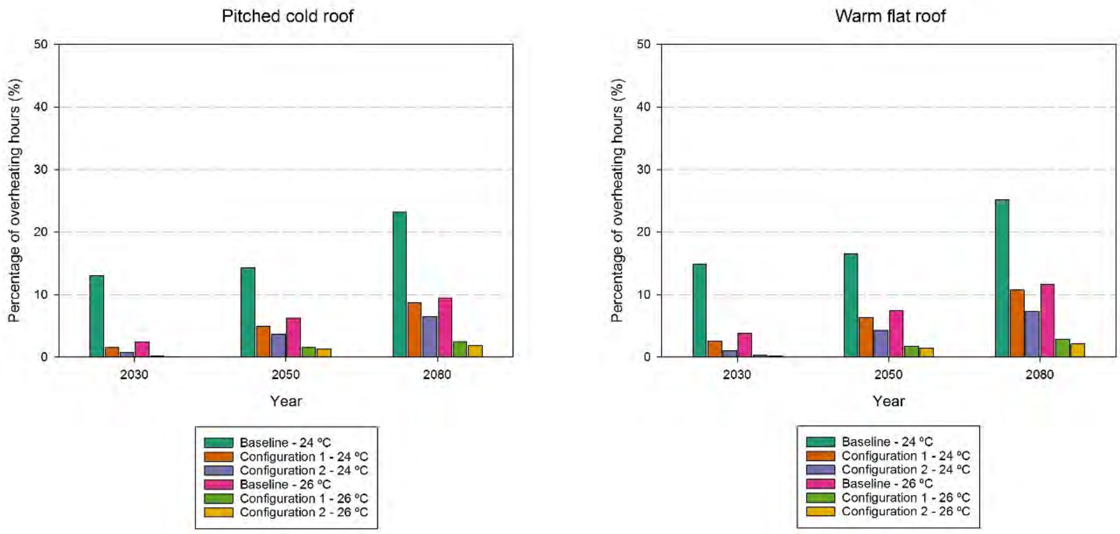

Figure 19: Percentage of hours of temperature above 24ºC and 26ºC for a bedroom for different roof types – Glasgow – Pitched cold roof and warm flat roof.

While the cases considered here are particularly prone to overheating risk, the impact of a good roof design is relevant and can contribute to the reduction of this risk. Another important consideration is that all the percentage ranges given are progressively increasing in the future scenarios (2030, 2050, 2080), confirming the fact that this will be an important issue to be considered in policies. What we can clearly see is that, in buildings prone to overheating risk, it will be necessary to improve ventilation (especially night ventilation) and create hybrid forms of ventilation and mechanical cooling, at least for locations in the South, such as Plymouth and London Islington. In the other locations selected, Nottingham and Glasgow, other measures focused on increasing the thermal capacity and optimising ventilation further may be sufficient and avoid the need for mechanical cooling.

In general, we can see how simulations in configuration 2, i.e. with a well-insulated envelope combined with, enhanced night ventilation and medium/light coloured roof can contribute to the reduction of overheating risk. Further improvements could be achieved potentially by even higher ventilation rates, higher thermal capacity of construction components and a light coloured roof surface. Finally, for cases more exposed to overheating risk, at least in the long-term perspective, it will be probably necessary to provide some devices for cooling, at least to mitigate peak conditions.

4.2 High rise residential and non-residential building typologies

In this section, we look at the impact of roof technologies that are suitable for flat and low slope roofs, as well as non-residential and high-rise residential buildings. As a result, the following section compares the role of cool, green and blue roof technologies to conventional ones in the prevention of overheating, cooling and urban heat island effect.

4.2.1 Evidence on the impact of roofing technologies at present

We can begin by reviewing the evidence pertaining to cool roofs. The idea behind 'cool' roofs is to make roof surfaces more reflective to sunlight (for example, by painting roofs a lighter colour), lowering local temperatures. Because of the urban heat island effect, this is especially useful in urban areas. This effect is caused by a lack of moisture and vegetation in cities compared to rural landscapes, as well as the fact that urban building materials store heat. During heatwaves, daytime temperatures in cities can reach dangerously high levels, causing serious health effects and increasing the risk of death. Heat-related mortality can thus be reduced by implementing this solution, as demonstrated in case studies conducted in the United Kingdom [50] and other EU regions [51]. Cool roofs have higher albedo values than asphalt and tar surfaces, which means they reflect more sunlight. Materials with high albedo values[3] (as discussed in Section 3.2) keep you cooler in the summer because they reflect more solar energy than materials with low albedo values.

The ability of green roofs to reduce urban heat island is not dependent on albedo, but rather on converting absorbed sunlight into water vapour via evapotranspiration [52]. The evapotranspiration effect of green roofs is dependent on the type of vegetation species as well as precipitation and irrigation, which should keep the level of moisture in the ground under control to allow for the mitigation of urban heat islands [53]. However, if we consider the problem in terms of heatwaves, when there may be less precipitation and a lack of water demand for irrigation, they may become less effective when compared to cool roof solutions. The hydrological behaviour of green roofs, on the other hand, is particularly interesting in relation to extreme precipitation events, and studies conducted in UK climate conditions indicate a potential retention capacity of around 20 mm of water for typical solutions [54]. The effect of run-off water reduction [55] is particularly important in the selection of this solution. Another important consideration is the additional insulation effect on the roof, which is determined by the growing medium used [56], which has a lower thermal conductivity than normal ground [57]. The growing medium layer's thermal conductivity is determined by its moisture content, which is determined by irrigation, precipitation, and evapotranspiration. Because of the variation in the thermal conductivity of the layer, the resulting thermal transmittance of the green roof is dynamic [58], and simulation techniques can be used to understand the behaviour on a yearly basis [59]. The effect of this variation on the annual energy performance balance [60] is determined by the previously specified factors (precipitation, irrigation, evapotranspiration). The effectiveness of green roofs in reducing energy consumption in various climates has recently been reviewed [61], indicating how green roofs perform well in multiple conditions, showing particular benefits in terms of cooling load reduction [62]**.** Another potential benefit is improved urban air quality due to particulate matter mitigation [63], as demonstrated in UK urban case studies [64], and other benefits have previously been mentioned in Section 4 but are not detailed here. Returning to the hydrological behaviour of green roofs, they may be unable to cope with extreme water events if their water retention capacity is insufficient (see rainfall data reported in Section 3), and specific solutions can be designed to slow the release of rainwater into the drainage system via a restrictive flow outlet. In this case, we use the term blue roof to describe a solution that combines some of the benefits of green roofs with the ability to discharge water from an extreme precipitation event over a longer period of time, typically a 24-hour period.

Finally, blue roofs are thus specifically designed to reduce runoff water with a potential retention capacity of up to around 100 mm, making them compatible with extreme precipitation events such as those described in Section 3. The benefits of this behaviour can be assessed using measurement and modelling [65] to determine their cost/benefit ratio in relation to the increased design complexity and cost.

[3] Albedo is a measure of the diffuse reflection of solar radiation out of total solar radiation, measured on a scale ranging from 0 to 1. 0 corresponds to a black body that absorbs all incident radiation and 1 to a body that reflects all incident radiation.

4.2.2 Impact of roofing technologies in future climate scenarios

In this section we present the results of simulations for four different flat roofing typologies, namely conventional, cool, green and blue. These roofing technologies have been introduced in Section 3.2. As described in Table 7, all of them are well-insulated and green and blue roofs have slightly lower thermal transmittance (i.e. a better insulation level), determined by the additional construction layers. It is worth noting that the thermal behaviour of green roofs and blue roofs is potentially similar, but we have decided to distinguish them by considering a higher thickness of the construction component for the blue roof compared to the green roof. All the solutions considered in this case are flat and low pitch.

Table 7: Configurations for flat and low pitch roof simulations.

Simulation configuration	Description
Conventional roof	Well-insulated conventional flat roof with dark coloured surface.
Cool roof	Well-insulated conventional flat roof with light coloured surface.
Green roof	Well-insulated green-roof component, lower thermal transmittance compared to conventional and cool roof determined by the additional layers of the construction component.
Blue roof	Lower thermal transmittance determined by the additional construction layers.

Similarly to the simulations presented in Section 4.1.1, we consider three forecasting intervals, 2030, 2050, 2080 and we use Design Summer Year (DSY) weather data files with 50^{th} percentile for the 15 UK cities listed in Section 2. Finally, for each roof type we consider two operating conditions, July average day and July peak day. This month has been selected because of the higher irradiance level, which is the most relevant component with respect to the net radiative energy balance. With the term net radiative energy balance, we indicate the energy entering the building and contributing as a heat gain (therefore contributing potentially to overheating and/or cooling demand, depending on other building characteristics). The net balance considers the solar irradiance component entering as a heat gain minus the thermal radiative exchange with the sky vault.

We present the simulation findings for four specific locations, namely Plymouth, London Islington, Nottingham, and Glasgow, in the same order as in Section 4.1.1. As with the simulations presented in Section 3.1, the goal of this study is not to provide values that can be used as a reference in an absolute way, but rather to understand what the relative advantage of one technology over another is. In all of the locations we can see how in July peak conditions (e.g. in a heatwave event) the net radiative balance expressed in W/m^2 (average power on a daily base over surface area for the roof) is much lower for cool, green and blue roofs compared to the conventional ones. This advantage is consistent in all the locations considered in the UK from South to North. In contrast, the average July condition presents in some cases an increase (e.g. Plymouth), while in other cases a reduction (e.g. London Islington) of net radiative balance, determined by the reduced direct solar radiation component due to higher cloudiness. However, in all cases the advantage of cool, green and blue roofs over conventional ones is clear. Finally, since the net radiative balance considers solar radiation and sky vault radiative exchanges, we can see how this may evolve over time, but with variations that are much smaller compared to the ones determined by temperatures and discussed in Section 4.1.2.

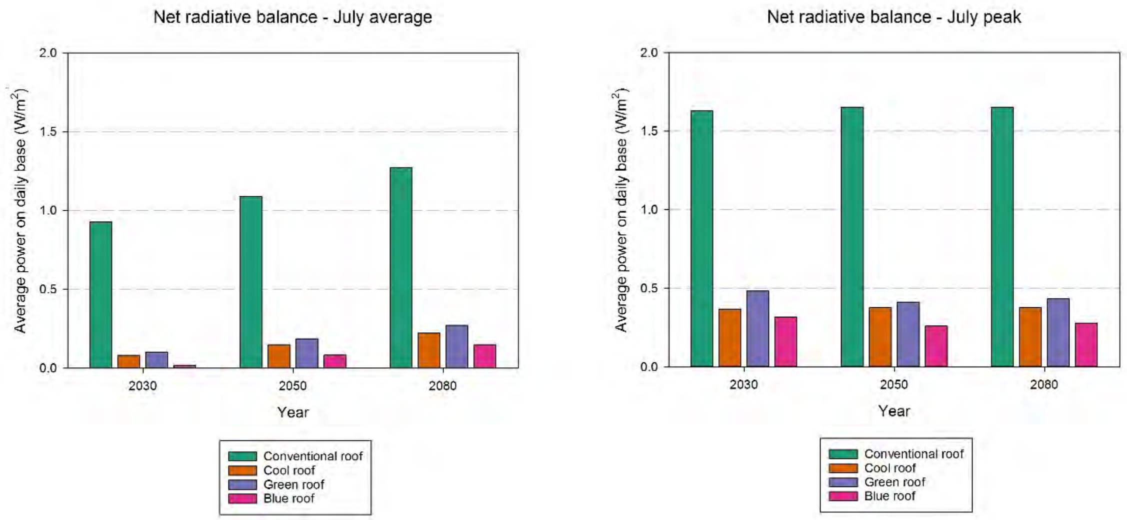

Figure 20: Net radiative balance of different roof types – Plymouth.

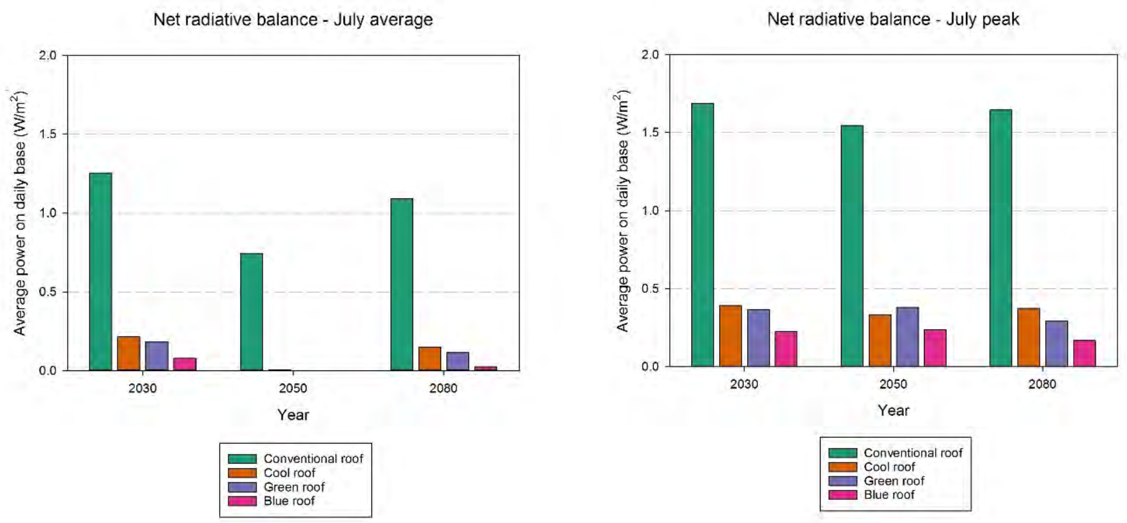

Figure 21: Net radiative balance of different roof types – London Islington.

In terms of radiative balance, the July peak daily conditions for the selected locations in the South of the UK, Plymouth and London Islington, are not considerably different from those for Nottingham and Glasgow. Locations in the South are typically characterised by higher temperatures than those in the North, and are therefore more vulnerable to the Urban Heat Island effect and overheating risk. It is still worth considering the potential issues associated with heatwaves in Northern locations, at least in the medium to long term, due to the uncertainty of temperature pattern evolution.

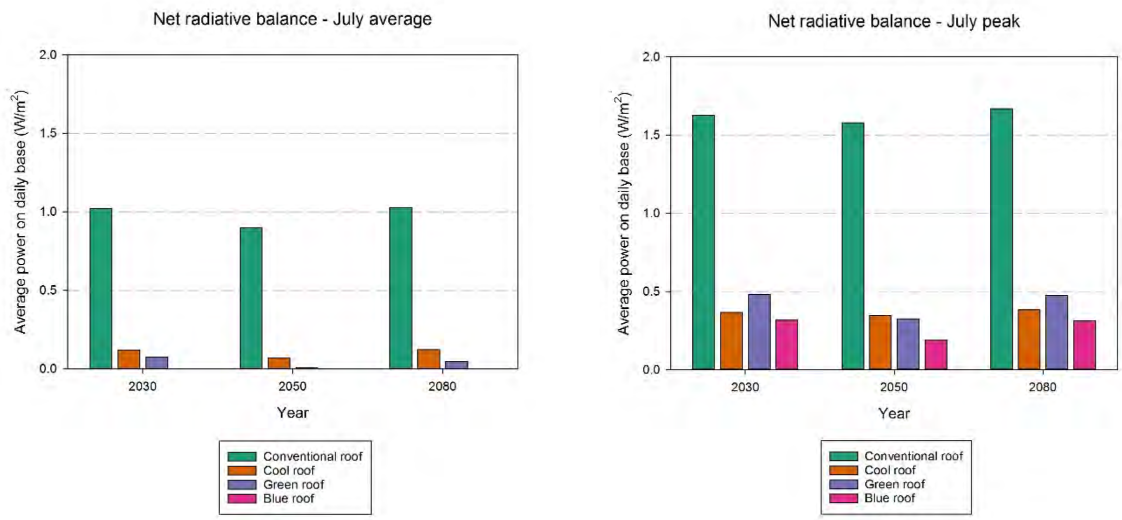

Figure 22: Net radiative balance of different roof types – Nottingham.

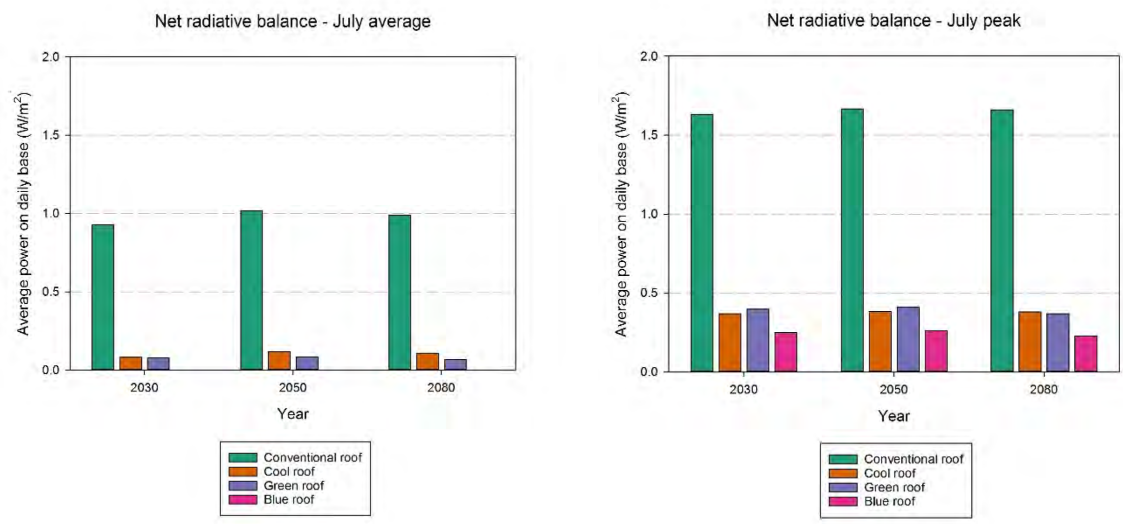

Figure 23: Net radiative balance of different roof types – Glasgow.

4.3 Future research on roofing technologies resilience

Following the evidence gathered and the results of the analysis of future climate evolution and its impact on building resilience, we can outline some potential areas for research and innovation. Firstly, effective re-inventing of the traditional built form for resilience, taking into account the results of field studies and simulations, for example regarding the size and type of openings to improve passive cooling, given the constrained nature of built form evolution and the systemic nature of overheating problem. Furthermore, an analysis of common errors that can reduce building performance in terms of energy, comfort, and durability (starting from roofing insulation and condensation in a hotter and wetter climate). Additionally, innovative and low-impact materials for roofs and structures (e.g. phase-change materials to increase thermal capacity): their feasibility should be demonstrated through techno-economic analysis and their sustainability should be demonstrated through Life Cycle Assessment (LCA). Another important area of research is the optimal integration of renewable technologies in roofs, which involves finding a balance between the maximisation of energy provision to the user, reduction of overheating and/or cooling, aesthetics, waterproofing, and durability. In this regard, innovative business models for energy communities may present interesting opportunities while also contributing to community-level sustainability.

In terms of roofing technologies, a better characterisation of surface albedo and reflectance, particularly through field-testing, is critical to ensuring the actual achievement of high performance in summer conditions. Furthermore, the ability to collect temperatures and other data using “on-board” sensors (i.e., installed in roof construction components) could ensure first-hand information, and the cost of these monitoring technologies is rapidly decreasing. Finally, it appears that the ability to characterise the long-term performance evolution of technologies using sensors and appropriate data analytics (e.g. digital twins) in the monitoring process is ever more important. Long-term data may be extremely valuable in understanding the actual impact of climate pattern evolution, as well as ensuring a solid knowledge base to improve design and operational practices, which are deeply intertwined with innovative business models focused on energy provision and with future developments in the circular economy context.

4.4 Recommendations

The temperature, irradiance, rainfall, and wind patterns presented in Section 2 have a direct impact on resilience, as described in Section 3.1 for buildings in general and in Section 3.2 for roofing technologies in particular. Furthermore, in Section 3.3, we discussed how the benefits of roofing technologies extend to the community level. Finally, in Section 4, we analysed the available evidence with respect to the problem of overheating and cooling needs, which represents one of the key risks for buildings in the future, given the implications in terms of use of building spaces, comfort and heat-related mortality, especially for an ageing population. The simulations conducted are based on the forecast of future climate for years 2030, 2050 and 2080 with 50th percentile, so they represent an “average” future condition, not the most severe. On the other hand, dynamic simulation methods, whilst being the state of the art approach, present limitations regarding the prediction of overheating risk [49]. Acknowledging the limitations and uncertainties inherent to long-term predictions and simulation, we can see nonetheless how an appropriate roof design can give a relevant contribution to the reduction of overheating and cooling related risks. This is both for traditional residential building typologies, largely characterised by pitched roofs, and for non-residential typologies, largely characterised by flat and low pitch roofs. As described in Section 4.3, there are numerous potential areas of improvement for roofing technologies that can increase resilience and sustainability in the built environment. The empirical characterisation of roofing technology performance through long-term monitoring appears to be one of the most important issues for ensuring first-hand information about the changes caused by the evolution of climate patterns. The cost of sensors is rapidly decreasing, and it is possible to consider "on-board" monitoring technologies for roof components, which will most likely be an essential feature, particularly in a circular economy context where extended lifetime, re-use, and recycling of materials are critical issues. More broadly, medium and large-scale field studies comparing the actual lifetime of roofing technologies to the certified predicted life expectancy would aid in addressing the durability and replacement rate issues for roofs in the UK context. Finally, monitoring technologies are already widely used to track the performance of renewable energy technologies in buildings (e.g., BIPV), and synergies for the development of innovative building components, as well as their business models, are possible.

Research can provide evidence to inform policy and industry decision-making processes. In terms of policy and legislation, it appears critical to fast track proposed changes to building regulations concerning overheating for new builds and extend these to pre-existing buildings [66] and to replicate the London Plan model for green roofs in other UK cities, particularly in the South, where overheating is a greater risk. Furthermore, by facilitating planning permission processes, public authorities can encourage the installation of green and blue roofs. Besides that, in densely populated areas, blue and green roofs can play an important role in the UK Government and Devolved Nation's Sustainable Drainage Systems (SuDS) strategy. Finally, the importance of cool, green, and blue roofs should be highlighted in the UK government's design guide [67], and homeowners should be given guidance on how to upgrade their roof to reduce overheating and flooding risk.

At the industry level, the National Federation of Roofing Contractors (NFRC) should develop guidance for its members on how to make roofs more resilient to climate change, as well as collaborate with the Centre for Digital Built Britain to develop Digital Twin solutions aimed at addressing the issues presented in Sections 4.1, 4.2, and 4.3. It should be stated unequivocally that the benefits of flood prevention measures (as well as other co-benefits mentioned in this report) extend beyond the physical boundaries of the building, and that the capital investment has broader neighbourhood benefits. Current financing methods do not easily support such investment. However, there are ways to change tax policy, such as tax relief, to encourage such investments. For example, it could be proposed that the government's Superdeduction tax relief be extended to include green and blue roof work in order to allow full capital expenditure tax relief. Furthermore, when determining how to lend to infrastructure projects, the National Infrastructure Bank should consider climate resilience, as well as funding projects to help reduce the impact of flooding and overheating through roofing technologies.

Finally, even if the policies for planning and financing are in place, there is still one barrier to overcome: a lack of skills. The roofing industry must speed up training and skill development programmes that incorporate these increasingly important technologies.

5 Conclusions

Climate change projections in the UK (UKCP18) are available today with downscaled models that provide a higher level of resolution in the data. This data can be used to identify the key problems for a short, medium and long-term perspective and enable decision making to increase resilience. This is particularly relevant in the built environment because buildings are long-term assets. Climate-change patterns have been discussed in relation to temperature and heatwaves, irradiance, rainfall and wind. The trend of increases in temperatures and of heatwaves appears to be the most relevant issue, together with the flooding risk determined by extreme rainfall events. A moderate increase in irradiance is predicted in many locations due to clearer sky conditions, while there is no forecasted change in peak wind gust speeds. The evolution of these patterns has an impact in terms of building resilience and six areas were identified: heatwaves, flooding, drought, cold, storm and wind, energy provision. Increased insulation levels are necessary to reduce energy consumption and provide more comfortable winter conditions, but appropriate design strategies must be pursued to limit the risk of overheating, which can have dramatic consequences in particular during heatwaves. Regarding flooding, green and blue roofs can give a relevant contribution in case of extreme events of short duration, especially in urban and densely populated areas. Rainwater storage and recovery, realised contextually to roof redesign, can be a measure to reduce the impact of drought and flooding. Finally, energy provision through rooftop solar technologies, photo-voltaic in particular, is crucial due to the possibility to supply a relevant quota of electricity demand, which will increase because of the increasing electrification of heating and transportation**,** determined by decarbonisation policies. At present PV is often applied to support energy compliance in new buildings. Partial roof coverage with PV is commonplace and this can change. The costs of a full roof coverage (corresponding to a higher installed PV power) are marginal when a roof is replaced; these sunk costs (construction labour, scaffolding, etc.) can be harnessed. The problems of overheating and cooling were analysed more in depth because of their relevant implications (e.g. usage and comfort, heat related, mortality, higher energy consumption, etc.) from single buildings up to community scale (e.g. urban heat island effect, anthropogenic heat release, etc.). What was found is that an appropriate roof design, both in residential and non-residential buildings contexts, can give a significant contribution to decreasing risks and to improving resilience. Finally, different key areas for future research have been identified, indicating the need for empirical characterisation of roofing technology performance through long-term monitoring, which appears to be one of the most important issues for ensuring first-hand information about the changes caused by the evolution of climate patterns. It is possible to consider "on-board" monitoring technologies for roof components, which will most likely be an essential feature, particularly in a circular economy context where extended lifetime, re-use, and recycling of materials are critical issues. Further, medium and large-scale field studies addressing the durability and replacement rate for roofs in the UK context would provide robust evidence for future policy actions in the sector. These principles are already part of the state of the art of renewable energy technologies in buildings (e.g. BIPV) but can be extended to other roofing technologies as well, given the rapidly decreasing cost of sensors and data analytics.

6 Acknowledgements

We would like to thank James Talman, Gary Walpole, Philip Campbell and other roofing professionals connected to NFRC for the useful comments and valuable insights.

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