Article

Quantifying the Effects of Projected Climate Change on the Durability and Service Life of Housing in Wales, UK

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Abstract: This research aimed to provide the Welsh Government with measured and quantified climate vulnerabilities associated with housing building-fabric, including the potential financial cost of not planning for climate change. Wales's climate is projected to become warmer but wetter and it is known that hygrothermal impacts can accelerate deterioration, leading to damp and, subsequently, a loss of thermal performance. A stressor-response methodology was applied, which assumes that the exogenous stressors of solar flux, precipitation, and humidity have a direct effect on building-fabric performance. The resultant stressor-response values equate to the quantitative impact that a specific stressor has on individual specific building elements, presented as an adjusted service life and associated costs. Results show a modest reduction in the service life of building materials due to increases in and changing patterns of precipitation and subsequent moisture ingress. Although modest, with 1.5 million dwellings in Wales, the impact is significant. Advocating regular maintenance and repair will not only reduce the risks associated with changing weather patterns, but also encourage energy efficiency by improving the thermal performance of the building envelope. This will reduce the risk of adverse climate related outcomes, increased vulnerability to climate change, now or in the future.

Keywords: building materials; climate change; stressors; vulnerability

1. Introduction

Buildings exposed to weather and climate-related natural hazards attract much attention because of the immediacy of the losses. Nevertheless, cumulative degradation risks are also perceived to be increasing due to climate change. Although previous studies have discussed the implications of climate change impacts on older buildings in Europe [1], and the expected changes in the climate that are of importance to buildings in the UK [2], there is a paucity of studies that aim to measure or model the future impact of climate change on buildings, no studies have specifically looked at Wales and its buildings, and no studies have strived to measure of the impact of climate change on dwellings in Wales. This research project was commissioned by the Welsh Government, who have devolved competencies in policy areas relating to building standards, and aimed to identify quantifiable and measurable climate vulnerabilities for Wales's housing stock, and this paper focuses on building-fabric vulnerabilities.

Under the Climate Change Act 2008, the UK Government is required to address the challenges of climate change, including threats to infrastructure as well as health, economy and the natural environment. One important aspect of this is the climate vulnerabilities associated with buildings, including schools, hospitals, municipal buildings, public and private housing. In 2019, the Committee for Climate Change suggested that the UK's aging housing stock is "not fit for the future" [3] (p. 9), and Wales has the largest

proportion of aged dwellings in the UK, with 26% over 100 years old. Indeed, in the Committee for Climate Change's second Climate Change Risk Assessment (CCRA2) report of 2017 [4], they identified the existence of evidence gaps, the need to prioritise areas of research in order to fully understand the risks and the development of policy to manage the impacts of those risks, including risks to building-fabric from moisture, wind, and driving rain under future climate driven changes in weather patterns. In 2020, Natural Resources Wales (NRW) published their second "State of the Natural Resources" (SoNaR) report [5], where they set out flooding risks to buildings largely informed by the results of CCRA2. More recently, CCRA 3, published in 2021, identified further investigation is needed to understand risks to building-fabric. CCRA3 concludes that progress in adaptation policy and implementation is not keeping up with the rate of increase in climate risk [6].

Wales's climate is predicted to be warmer and wetter [7]. Changes in climate factors are expected to accelerate the deterioration of building materials and their detailing, including undermining binders and coating of building façades [8,9]. Climate change will undoubtedly have some impact of building-fabric performance and any acceleration in the erosion of building materials will depend on their inherent characteristics, as well as the prevalent climate stressor. The cyclical expansion and contraction of masonry and mortars are subject to the weathering cycle, which may alter because of climate change. For example, solid masonry walls that are characterised by higher surface water absorption coefficients and are more sensitive to exterior climate factors, such as rain and wind; but they will also react to solar radiation, which can reduce moisture accumulation considerably [10,11].

Simulating the onsite conditions of masonry structures subjected to rising damp and salts attack, due to daily and seasonal microclimate changes, as foreseen due to changing weather patterns, has established that building-fabric will be weakened in the long run, e.g., Franzoni et al. [12]. Differential expansion and shrinkage in various materials forming the building envelope can also be induced by temperature oscillation and temperature gradients across buildings [13]. Previous research by Facconi et al. has determined that daily temperature variations of circa 14 °C, or more, could induce cracking [14]. These daily temperature gradients are particularly harmful as they can induce strain accumulations in materials, which can lead to microcracking, which, in turn, can change the permeability of the outer surface and make them more susceptible to the adverse effects of wind-driven rain, as well as other sources of moisture [15]. Consequently, weakening building materials and strain values beyond reversible limits can create damage via creep (slow downward progression) and fatigue in many construction materials, including natural stone, concrete, and brick [16–18].

Studies on climate change and the effect that increased extreme rainfall events may have on building façades has renewed the scientific interest on determining the risk of accelerated surface erosion [19]. Among all extreme climate factors, wind-driven rain (WDR) impacts are likely to be the most pervasive across Wales and the UK. WDR can cause both surface erosion and weaken building-fabric. Nik et al.'s [20] investigation on the prospective impacts of climate change and WDR on buildings found that higher amounts of moisture will accumulate in walls in the future. In addition to WDR, moisture that diffuses across the wall as vapor was proven to be another main source of moisture accumulation.

Moisture related risks to the building envelope are found in buildings with large rates of moisture production or lack of ventilation. Wetted or damp building materials are usually contaminated by fungi and especially by moulds. Consequently, mould growth is one of the most common ways that moisture-induced deterioration manifests itself on buildings and the risk of mould growth increases considerably when the relative humidity of a construction material exceeds 80%. Many researchers have studied the relationship between diffusion, the transport of moisture across the building envelope, and indoor temperature and humidity, with a particular focus on mould growth. Mould growth negatively affects the durability of the building envelope, as well as the environmental quality

of the internal climate [21,22]. In addition to material type (and consequently material surface characteristics) the cleanliness of material surfaces are important considerations. Viitanen et al. [23] compared stone with timber and found that surface type and dirtiness of material has an influence on mould growth. In wood materials the finish of the surface was a critical factor, e.g., more mould growth was detected on planed pine sapwood than in edge-glued spruce board. Grant et al. [24] found that surfaces which are soiled or covered with a susceptible paint or paper do not need to become as damp for mould to develop. Climate change will inevitably impose new challenges for mould prevention, as well as other weather-accelerated building-fabric weakness.

2. Methodology

The main aim of this discrete piece of research was to identify quantifiable and measurable climate vulnerabilities for the building-fabric of Welsh dwellings, including an indication of the potential financial cost of not planning for climate change. A 2009 study by the World Bank on the economics of adaptation to climate change, published in 2010, estimated that urban housing costs could increase between USD 23.3 billion and USD 41.1 billion per year in the period 2010–2050 because of climate change impacts [25]. A failure to properly incorporate climate change factors into housing stock management decision-making could result in costly impacts, including roof and drainage issues, cladding and exterior façade deterioration, and issues with the foundation of buildings, among many others. It was intended that, evidence of vulnerability related to, the Welsh Government could create actionable strategies to prepare building owners and occupiers for projected climate change impacts on their dwellings and those that they manage.

The existing literature relating to climate change adaptation is primarily qualitative in nature, with an emphasis on specific case studies, broad recommendations, and hazard warnings. The stressor-response approach diverges from this literature base by considering the impact of incremental changes in weather patterns (e.g., wetter, warmer weather) in response to recommendations that indicate a broader, more holistic perspective would be beneficial and result in less vulnerability; therefore, reducing risks associated with climate change hazards, e.g., Berdica and Erath et al. [26,27]. Consequently, to determine the degree of climate change impacts on Welsh housing stock, a methodology, based on a stressor-response approach, was adopted after Chinowsky and Arndt [28].

2.1. Stressor-Response

The stressor-response approach utilises an assumption that exogenous factors or stressors have a direct effect on focal elements of a building, its materials and component parts. In this context, the exogenous factors considered were projected incremental changes to solar flux, precipitation, and humidity. The resultant stressor-response values were the quantitative impact that a specific stressor has on specific building elements, presented as an adjusted service life and associated costs. The procedure is detailed further in Section 2.4.

The systematic approach for determining the potential impacts of climate change on building-fabric involved three steps of analysis:
1. Climate model projections;
2. Existing building stock assessments; and
3. Analysis of climate change impacts on building components.

2.2. Climate Model Projections

The UK Climate Projections 2018 (UKCP18) local (2.2 km) projections for 12 Met Office Hadley Centre models (HadGEM3-GC3.05) under Representative Concentration Pathway (RCP) 8.5 [29] were used to inform the climate vulnerability modelling.

The Met Office [30] acknowledge that it is not possible to give a precise prediction of how weather and climate will change years into the future, so UKCP18 provides ranges that aim to capture a spread of climate response based on current knowledge and using a particular set of methodologies developed by the Met Office and collaborators [30]. RCP 8.5 is the only representative concentration pathway available for the 2.2 km scale data [31]. A Representative Concentration Pathway (RCP) is a Greenhouse Gas concentration (not emissions) trajectory, adopted by the Intergovernmental Panel on Climate Change (IPCC). When compared to the total set of RCPs, 8.5 is the highest scenario in assumed fossil fuel use, and thus corresponds to the pathway with the most greenhouse gas emissions [32]. Not only are the emissions consistent with RCP8.5 in close agreement with historical total cumulative CO_2 emissions (within 1%), but RCP8.5 is also the best match to mid-century, under current and stated policies; with still highly plausible levels of CO_2 emissions in 2100 [33]. RCP 8.5 is widely endorsed by the UK Met Office and the Intergovernmental Panel on Climate Change (IPCC) as an appropriate tool for considering risk and identifying future vulnerabilities.

Collectively, climate observations and projections can be used as a resource as well as a communication tool when planning for the future [30]. Although the projections represent the latest scientific understanding, it is important to note uncertainties in the projections.

Therefore, although our ability to simulate the climate is advancing all the time, models are not able to represent every possible climate characteristic [30]. Variables used in this study included a daily relative humidity (average), daily precipitation (average), and daily solar flux (average). The 1981–2000 time period was used as the baseline, whilst the 2021–2040 and 2061–2080 time periods were used for 2030 and 2070, respectively. Values presented represent the average year across the respective 20-year time period and the median model across the 12 climate models. The analysis periods for the building-fabric vulnerability metrics each include data for 1st January–31st December inclusively.

2.3. Dwelling Appraisal

The potential impact of climate change on building-fabric can be varied and extensive. As outlined above, variations in, e.g., precipitation and temperature will have characteristic impacts. The approach described in this paper aimed to isolate: the distinctiveness of potential impacts to the principal components of the building envelope; ones that have been detailed in the aforementioned research; have technical responses that can be accomplished through focused repair, maintenance, and adaptation or refurbishment upgrades; and that are crucial to building design life performance. The stressor-response considered impacts on replacement, repair, and maintenance costs, i.e., increases or decreases in recurring maintenance cost that would be incurred due to anticipated climate change, in order to achieve the design lifespan or service life. In each of these, the underlying concept, is to retain or extend the life expectancy of a dwelling.

2.4. Climate Stressors

Exposure to damp as a result of relative humidity and precipitation are analysed. One of the primary accelerators of the degradation of external cladding materials is exposure to damp [34–40]. Solar exposure is another important factor in the durability of many organic materials used in dwelling construction. Photodegradation is initiated by UV photons in sunlight and generally involves chemical reactions with atmospheric oxygen and/or water vapor, leading to brittleness. Elevated temperatures, such as those caused by solar absorption in dark materials, also lead to acceleration of harmful chemical reactions [39].

Numerous studies [34–40] have utilised the ISO 15686 Factor Method procedure [41–43] to calculate adjusted service life factors based on exposure to various climate variables. Factors from these studies were assigned to each year in the projected climate models based on a binary high or low exposure criterion for each climate variable. High or low

exposure was quantified as the change in the annual average value for the daily average humidity and solar flux, or the annual value in the case of precipitation, relative to the baseline for each building-fabric component. Factors representative of the mean year and median climate model were then applied to baseline service life values, as published in the British Standard 7543 [43], to find the adjusted service life under projected climate conditions. Three separate adjusted service lives were calculated, one for each climate variable, which were then used to calculate the percent change in maintenance and/or replacement costs for each building component. The building-fabric analysis is broken into three separate evaluations of vulnerability from solar exposure, from relative humidity, and from precipitation. Climate factors could not be combined since degradation data were only available for each climate variable acting independently. Note, not all building materials and components are affected by all three climate variables. Additionally, there are other climate variables not analysed that would likely have impacts on the durability of these building components, for example, wind (see research limitations section). Similarly, there may be other building-fabric components that were not analysed here, but that would be critical in a durability analysis of a dwelling where less conventional building materials and methods have been adopted.

In particular, the analysis aimed to quantify the impact that projected changes in solar exposure and damp (in the form of precipitation and relative humidity) will have on degradation rates of the six different building-fabric components shown in Table 1. Incurred costs are also included in the results. The costs incurred are from the increased maintenance necessary to retain the design life of the original building as degradation of the building occurs from climate change stressors.

Table 1. Building fabric components included in the building-fabric analysis along with the climate variables that impact each component's longevity.

#	Material/Component Classification	Impact from Climate Variables			Service Life [BS ISO 15686-8:2008]
		Solar	Relative Humidity	Damp	
1	Roof tiles [clay, slate, concrete]	√	√	√	30
2	Walls [brick, stone]		√	√	70
3	Render and mortar [lime, cement]	√	√	√	50
4	Masonry paint	√	√	√	20
5	Sealants	√		√	20
6	Window and Door frames	√		√	20

2.5. Adaptation Strategies for the Maintenance of Existing Buildings under Climate Change

The results of the climate vulnerability modelling were shared with representatives from across the Welsh Government, as well as other invited non-government public bodies, and a series of workshops convened between August and October 2021 to discuss the challenges associated with building-fabric deterioration, including the co-creation of adaptations that could be adopted to reduce building-fabric vulnerabilities in Welsh dwellings, comprising climate-responsive behavioural changes and building-fabric modifications.

3. Results

3.1. Climate Projections

Results were generated for six locations throughout Wales. The six locations are Cardiff, Wales's capital and the most populated city in Wales; the town of Narberth on the southwest coast in Pembrokeshire; the valley town of Brynmawr in the Brecon Beacons; Llangefni, the second largest town on the Ise of Anglesey in the northwest; Shotton, on the river Dee, which borders England; and the market town of Wrexham. The locations

were chosen to reflect a range of human settlement forms, for their geographic and socio-economic spread, as well as differences in for example, elevation and coastal proximity (see Figure 1).
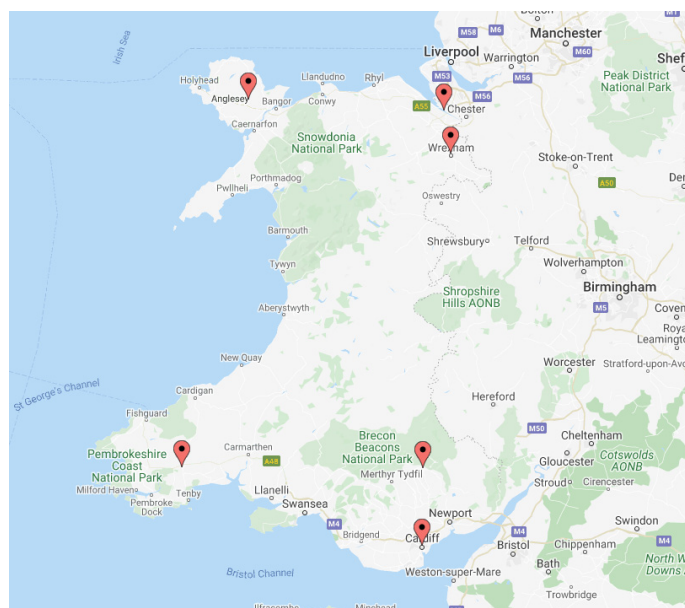
Figure 1. Locations in Wales, clockwise from the top left. [Llangefni, Shotton, Wrexham, Brynmawr, Cardiff, and Narberth].

All six locations experience the highest daily average solar flux in the warm months as presented for Cardiff in Figure 2. Looking forward to 2030 and 2070, the daily solar flux is projected to increase in all locations, with the largest changes from baseline expected in the warmer months from May to September. The daily solar flux, averaged over the whole year, is also projected to increase in all locations, as shown in Figures 3 and 4.
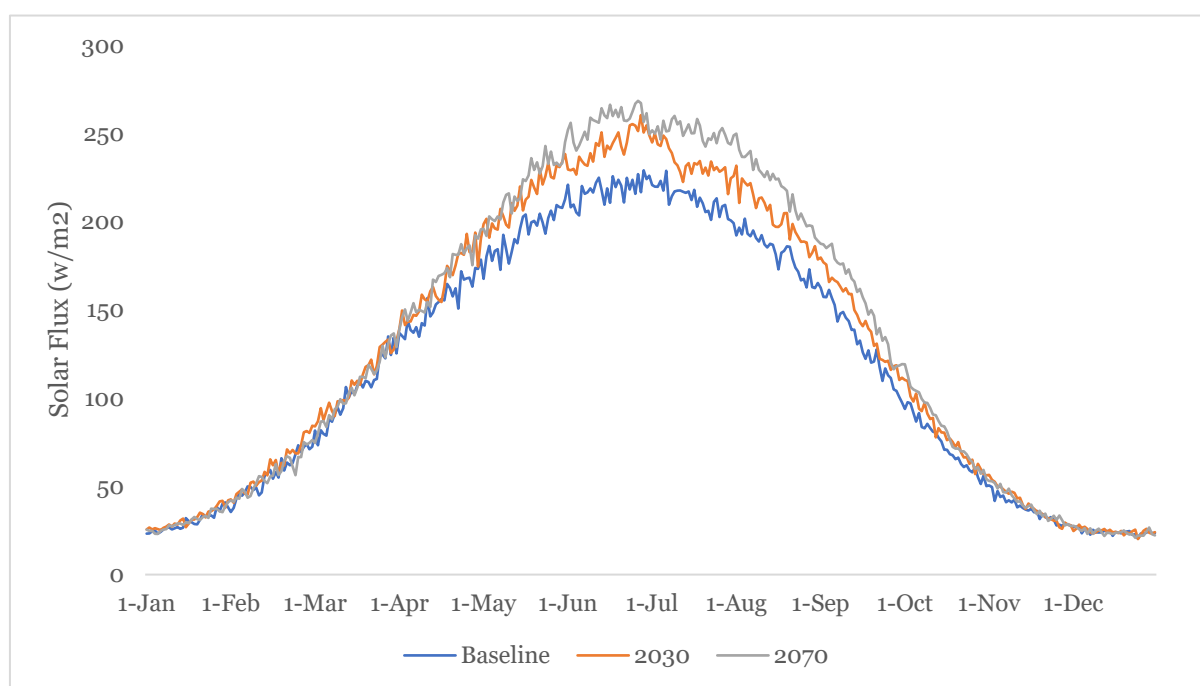
Figure 2. Annual profile of daily average solar flux in Cardiff for baseline, 2030 and 2070.
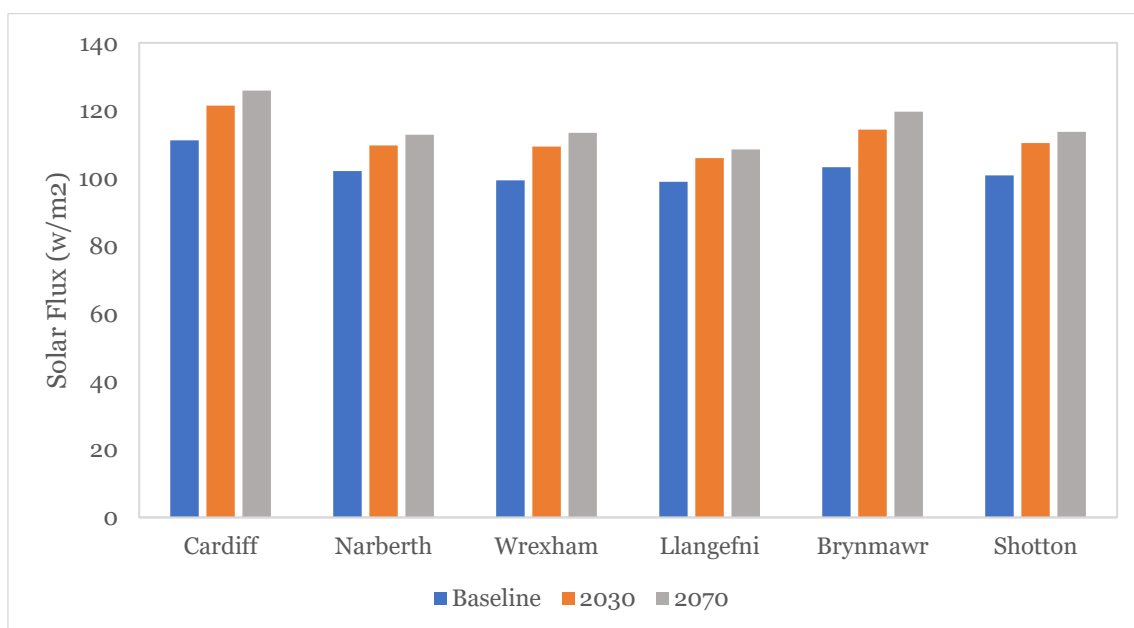
Figure 3. Daily average solar flux averaged over the study period for six locations throughout Wales for baseline, 2030 and 2070.
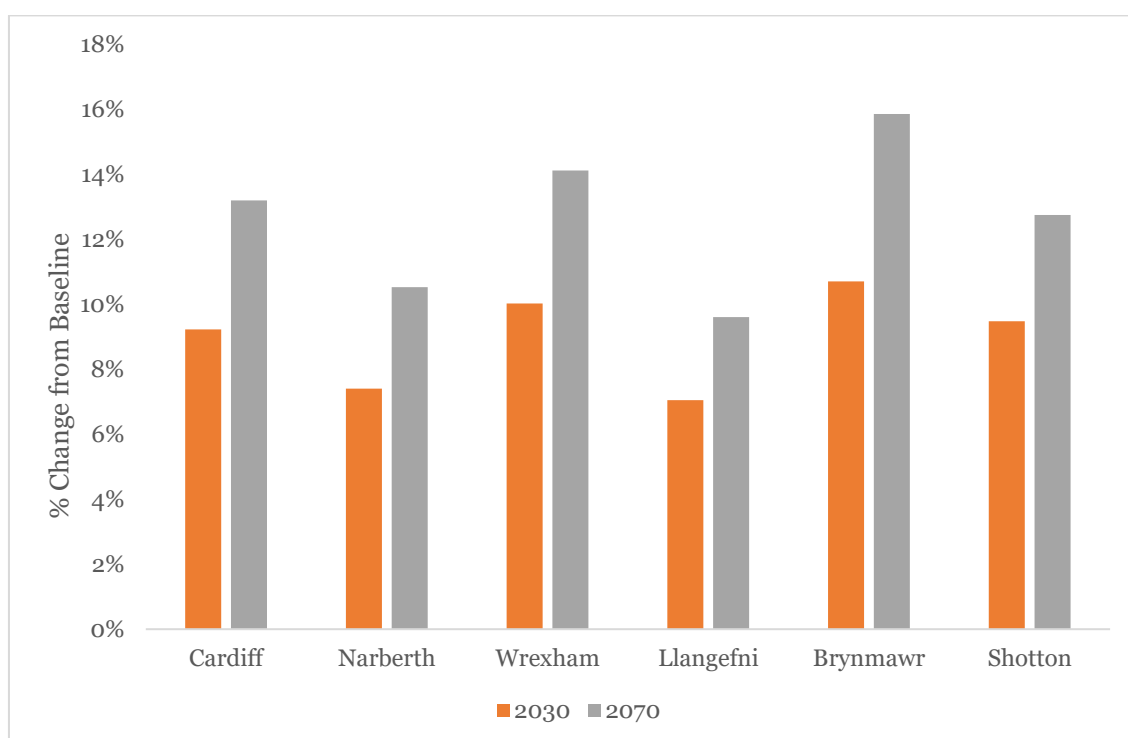
Figure 4. Change in average daily solar flux for 2030 and 2070.

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

Across all six locations the daily average relative humidity is highest in the winter months and lowest in the summer months. This is demonstrated for Cardiff in Figure 5.
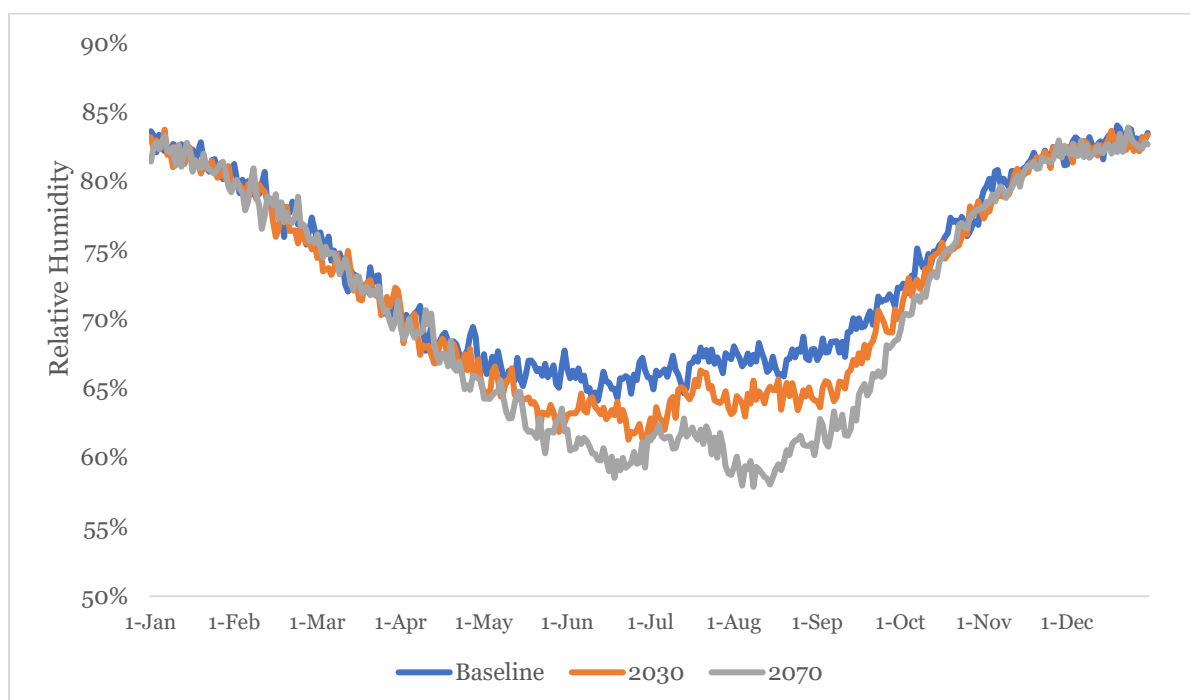
Figure 5. Annual profile of daily average outdoor relative humidity in Cardiff for baseline, 2030 and 2070.

As can be seen for Cardiff, and which holds true for all locations, the largest relative humidity changes from baseline to 2030 and 2070 are seen in the warmer months from May to September. During this period the relative humidity is projected to decrease from baseline. Although the biggest change is in the summertime relative humidity, the daily relative humidity is also projected to decrease when averaged over the whole year, as shown in Figures 6 and 7. The biggest decrease in average daily outdoor relative humidity is projected in the high elevation location of Brynmawr, with a 1.6% decrease by 2030 and a 3.7% decrease by 2070.
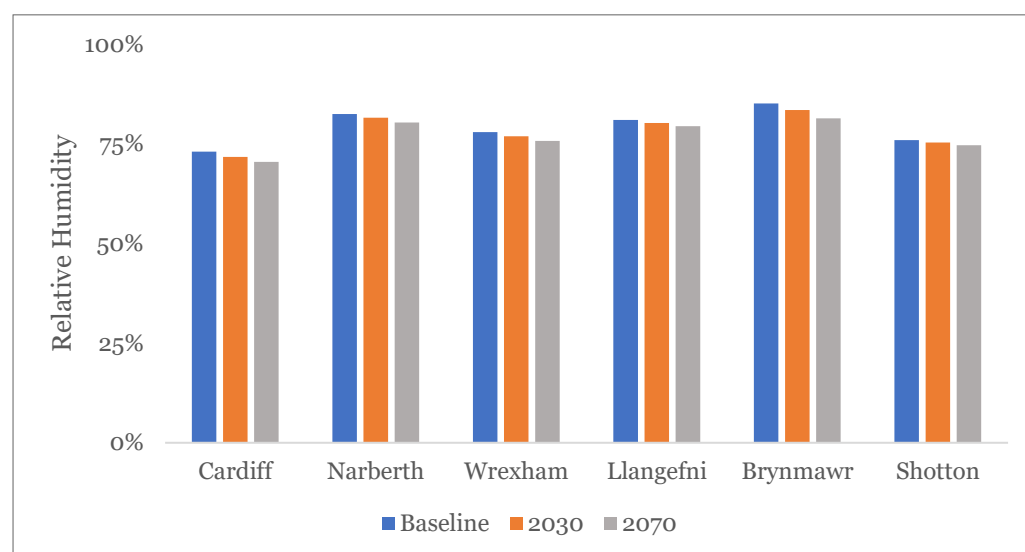
Figure 6. Daily average outdoor relative humidity for baseline, 2030 and 2070.
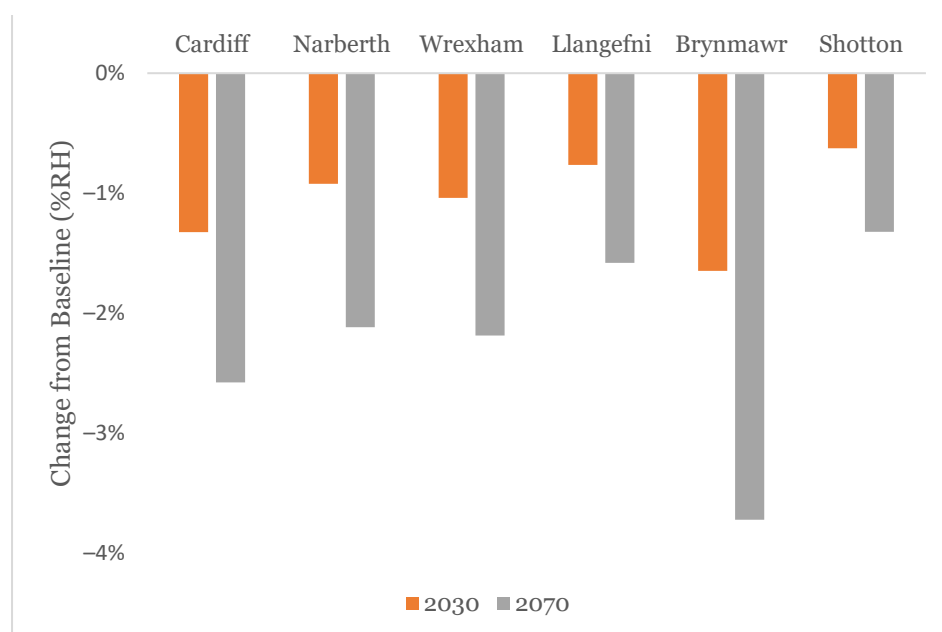
Figure 7. Change in average daily outdoor relative humidity for 2030 and 2070.

Precipitation trends exhibit a more varied set of projections by location and time period. In general, the wettest times of year across all locations are the colder months, as seen in Figure 8 for Cardiff. Looking forward to 2030 and 2070, the colder months are projected to see an increase in precipitation, while the warmer months are projected to see a decrease in precipitation. However, on an annual scale, the trends are not as unanimous across locations as they are for the other climate variables. Cardiff, Narberth, Llangefni, and Brynmawr are projected to experience an increase in annual precipitation by 2030 and then another increase by 2070 (Figure 9). Conversely, in 2030, Wrexham is projected to see 0.7% more annual precipitation than baseline, but 1.7% less annual precipitation than baseline come 2070. Furthermore, Shotton's annual precipitation is projected to stay close to baseline levels for both projections, with a 0.6% increase from baseline by 2030, followed by a drop to 0.2% above baseline by 2070 (Figure 10).
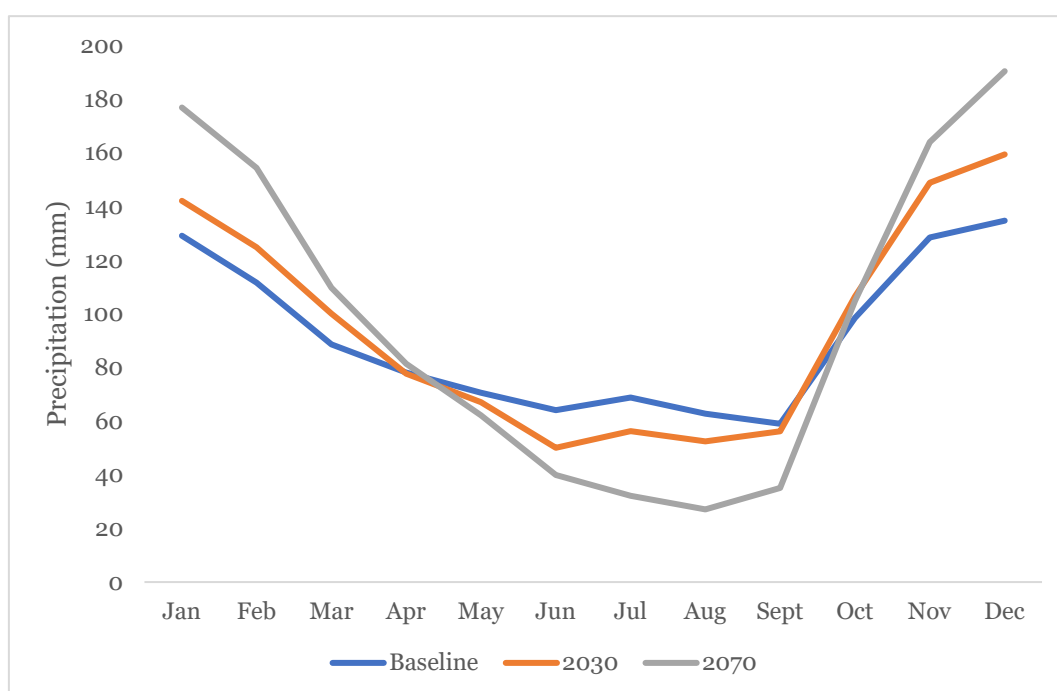
Figure 8. Annual profile of average monthly precipitation in Cardiff for baseline, 2030 and 2070.
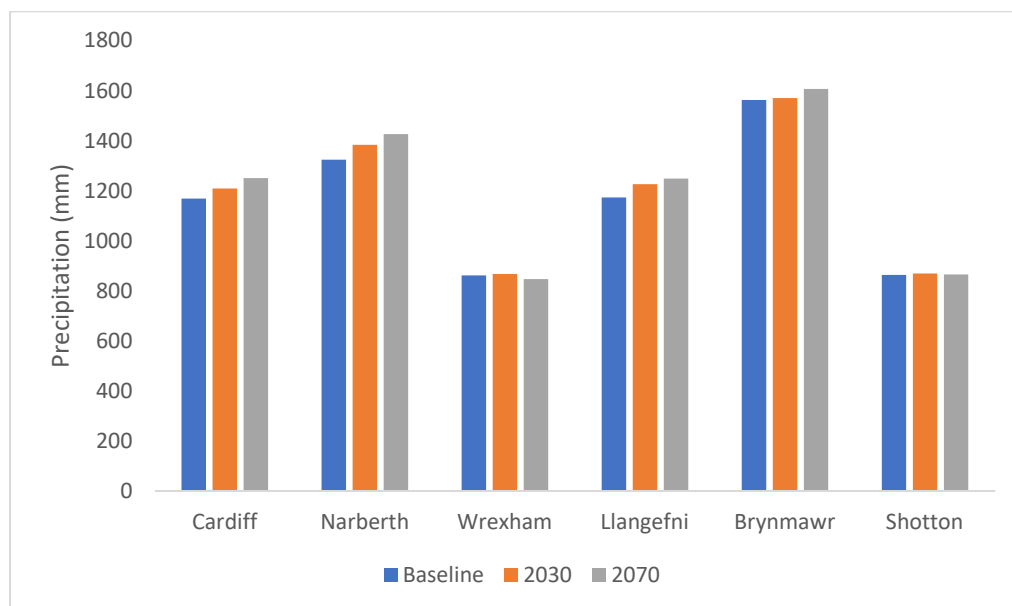
Figure 9. Average annual precipitation for six locations throughout Wales for baseline, 2030 and 2070.
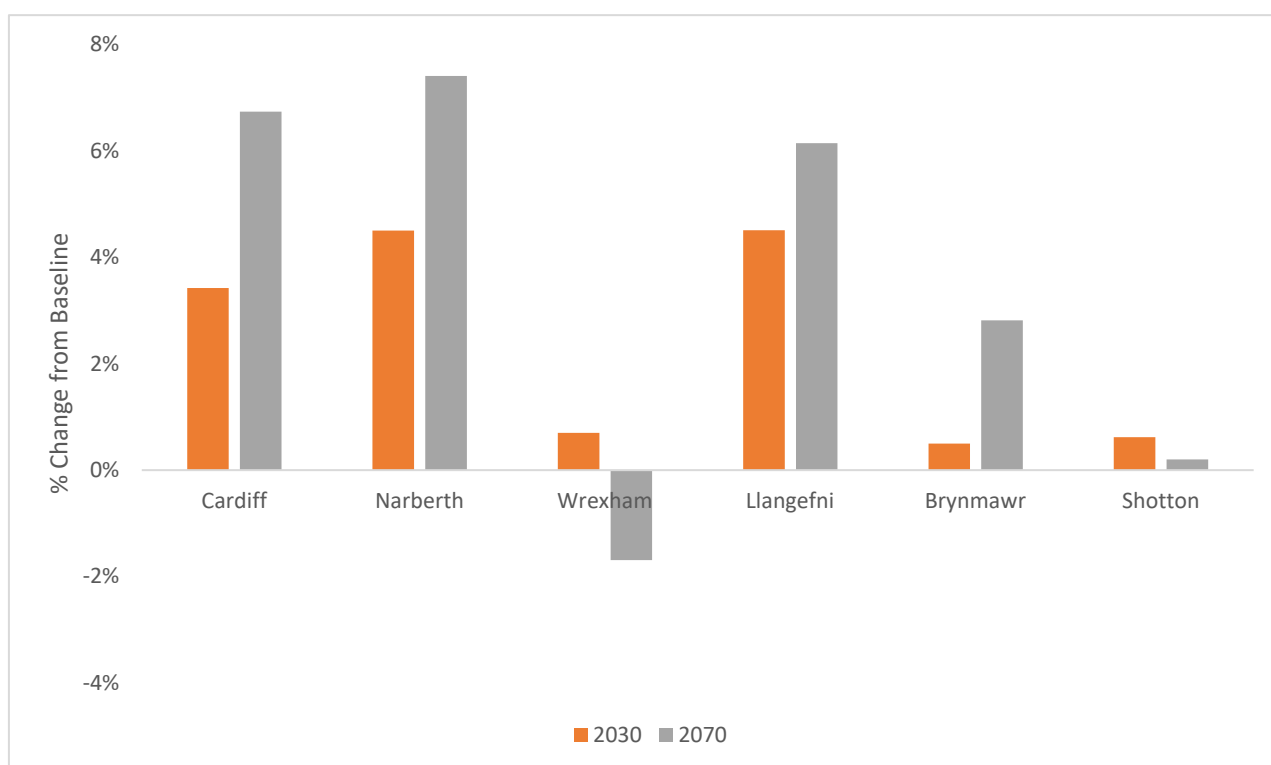
Figure 10. Change in average annual precipitation for six locations throughout Wales for 2030 and 2070.

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

3.2. Building Fabric Deterioration

Table 2 presents the forecast level of deterioration and adjusted service lives for five building-fabric components in Cardiff. No data were available for sealants, therefore this has not been included in the analysis. The forecast level of deterioration for each climate variable is deemed "High" if the resulting adjusted service life for a given climate variable is projected to be lower than baseline, and "Low" if it is projected to be higher than baseline. The level of deterioration for each climate variable is rolled into a single forecast level of deterioration, as shown in Table 2, which is deemed "Mild" if only one of the three climate variables shows "High" deterioration, "Moderate" if two show "High", and "Severe" if all three show "High". The adjusted service life values are calculated using the solar flux, relative humidity and precipitation climate projections presented above. The percentage change from baseline costs represent the costs associated with the change in the number of replacements that are projected to be necessary in comparison to the baseline service life of the given building component. Blank spaces correspond to building components that were not found to be impacted by the corresponding climate variable. In Cardiff, solar flux and precipitation are projected to increase from baseline to 2030, and then again from 2030 to 2070. This leads to adjusted service lives for these two climate variables in 2030 and 2070 that are lower than the baseline, and replacement costs that are higher than baseline. Conversely, relative humidity in Cardiff is projected to decrease, which leads to increases in adjusted service life and a decrease in replacement costs.

Table 2. Results for building-fabric degradation analysis for Cardiff showing deterioration classification, adjusted service life, and change in cost for 2030 and 2070.

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

Table 2 provides an indication of how that component may fare under the combined stresses of the climate variables. For example, by 2030, the roof tile service life is projected to decrease by 1.9 years as a result of increased solar flux degradation, an increase of 1.1 years as a result of decreased relative humidity, and a decrease of 0.3 years as a result of increased precipitation. These service life changes equate to a 6.7%, −3.6%, and 1.1% change in in replacement costs, respectively. The total across the adjusted service life values for the climate variables applicable to roof tiles gives an estimated decrease in adjusted service life of 1.1 years, indicating an overall trend towards a decreased service life when

all climate variables are considered. It is important to note that degradation data are only available as it pertains to single climate variables, and not for the impact of multiple climate variables simultaneously. For this reason, totalling the change in service life and cost across each climate variable simply gives an indication of impact trends, while more work is needed to accurately assess the impact from the combination of climate variables.

3.3. Financial Implications

The financial implications of these adjusted service lives for individual building materials and components have been calculated and presented in Table 3. Meanwhile, cost implication results were generated on a per-dwelling basis as an average across the 6 locations and are presented in Table 4. Dwelling costs are generated for a typical Welsh dwelling, including a typical value for the exterior façade and roof area, number of windows, percentage of area needing replacement for each building component, amongst other characteristics. The costs presented represent a change from baseline. Per-dwelling costs represent those incurred over the lifespan of the respective building material. For this reason, costs between building materials cannot be compared since they are likely to be incurred over different timespans.

Table 3. Adjusted service lives for change in replacement costs by dwelling over the life of the building material.

| Building Fabric Component # | Materials or Component | Impact from Climate Variables | | | Service Life | Replacement and Maintenance Cost | | | | |
		Solar	Relative Humidity	Damp		Component	Unit Cost	Unit	% Surface Area	Dwelling Cost
1	Roof Tiles (clay/slate/concrete)	x	x	x	30	Plain shingles/tile, e.g., concrete	£30	1 M²	10%	£334
2	Walls (brick/stone)		x	x	70	Repointing brickwork/stonework (with cement mortar)	£25	1 M²	50%	£5272
3	Render and Mortar (lime/cement)	x	x	x	50	Lime/Cement render average	£50	1 M²	50%	£10,544
4	Masonry Paint	x	x	x	20	Exterior masonry paint, e.g., all weather protection with biocide	£25	15 M²	100%	£703
5	Sealant	x		x	20	Waterproof filler/sealant	£3	10 M		£30
6	Window and Door Frames	x		x	20	Wooden casement window replacement	£325	1		£2800

Table 4. Change in replacement costs by dwelling over the life of the building material.

Material/Component	Solar Flux	Relative Humidity	Precipitation
2030			
Roof Tiles (clay/slate/concrete)	£20	−£10	£4
Walls (brick/stone)	-	−£161	£56
Render and Mortar (lime/cement)	£619	−£323	£112
Masonry Paint	£41	−£22	£7
Window and Door Frames	£164	-	£30
2070			
Roof Tiles (clay/slate/concrete)	£20	−£15	£5
Walls (brick/stone)	-	−£232	£73
Render and Mortar (lime/cement)	£635	−£464	£146
Masonry Paint	£42	−£31	£10
Window and Door Frames	£169	-	£39

3.4. Climate Vulnerability Modelling Limitations

This study aimed to inform a deeper understanding of the vulnerability of the Welsh housing stock to a changing climate. Although the methodology described above achieves detailed results that can help inform repair and maintenance, there are limitations to the analysis. The grid for the UKCP18 wind data is offset from the other variables for the local (2.2 km) projections. As a result, it could not be used as an input for this analysis. However, the studies referenced in the ISO 15686 factor method include many impact areas which affect a building component's service life, of which the most relevant to climate change are exposure to WDR and exposure to moisture. Although WDR was not an option, exposure to moisture, which is impacted by high relative humidity and increased precipitation, is; both were available in UKCP18 local (2.2 km) projections, i.e., with the correct grid.

A building's exterior fabric is made up of many different materials, each uniquely impacted by a variety of climate variables. A group of six building-fabric components were chosen in this study as they represent the principal elements of Welsh dwelling construction. However, even for this limited selection of building-fabric components there is an absence of available data on definitive climatic thresholds and the associated impact on durability if that threshold is breached. The published durability factors were defined for qualitative thresholds, typically binary in nature, such as "moderate" or "severe" or, in the case of solar exposure, by compass orientation. As such, the lowest of the published durability factors (having the most impact on service life) was assigned for a given climate variable if it was projected to increase from the baseline and the highest durability factor was assigned if it was projected to decrease from the baseline. Additionally, data are absent on the combined effect of multiple climate variables on any of the building-fabric components. For example, a single adjusted service life could not be calculated for a component from the combination of high solar exposure, high precipitation exposure, and low relative humidity exposure. Instead, separate adjusted service lives were presented for each of the three climate variables for each building-fabric component. Additionally, while there are likely additional climate variables that impact the durability of these building components, only three were analysed because of data and project scope limitations. It is important to note that the other climate variables which may have detrimental impacts, including extreme events, principally manifest in Wales in the form of high winds, storms with concentrated downpours, and associated events, such as flooding.

If future work is able to establish service life factors that are tied to quantified climate thresholds, these could be integrated into the methodology outlined here. The result would be a better understanding of the impact that changes in each climate variable have on the service life of each building component. Additionally, it would be useful if future research focused on establishing service life factors for additional climate variables and for a combination of climate variables on a single building component.

Building fabric cost implications were calculated assuming a typical Welsh dwelling, as detailed above. Each building component was also assigned a per-unit replacement cost and a percentage of building material in a typical dwelling needing replacement at the end of its service life, as presented in Table 4. A more tailored replacement cost figure for a specific building or portfolio of buildings can be garnered in practice if the building's characteristics are used in place of the representative values.

3.5. Applying Climate Vulnerability Modelling

Building fabric vulnerabilities have been established for solar flux, relative humidity, and precipitation, measured using an adjusted service life. This information aims to inform repair, maintenance, and refurbishment planning. The building-fabric vulnerability results can be applied, alongside with established knowledge and understanding of building-fabric performance, and associated deterioration mechanisms, to better inform frequency of repair and maintenance to mitigate further damage. For example, Table 5

provides a summary of known deterioration mechanisms and severe event safety measure requirements [41,42,44]. This knowledge can be used alongside known climate vulnerabilities and associated costs, repair, and maintenance routines [Tables 2–4], to plan building maintenance and repair, including any adaptations that might be required, in this instance materials and components reflect those for a pre-1919 terraced sandstone dwelling in Cardiff.

3.6. Adaptation Strategies

If the Welsh government, building managers, and individual dwelling owners are to avoid the anticipated expense of climate change, government policy must give people agency to better manage extreme hazard risks but also cumulative degradation impacts, i.e., provide individuals, property managers, and the wider building and construction industry with legislation and tools, including appropriate skills and training, to better understand the hazards and risks, and to maintain and adapt domestic properties. Figure 11 provides a summary of building-fabric vulnerabilities as identified in the research and proposes climate-responsive behavioural changes for improved maintenance, and subsequent repair and adaptation resolutions based on both the literature [45] and the aforementioned workshops.

It is recognised that climate vulnerabilities, and therefore maintenance, repair, and adaptation priorities, will also be contingent on a dwelling's location, orientation, age, and construction typology, and influenced by previous interventions including energy efficiency measures, such as external, internal, and cavity wall insulation. Additionally, it may be necessary to prioritise extreme event modifications, such as those associated with flood risks. Consequently, it is understood that not all the challenges outlined in Figure 11 will be pertinent to every dwelling. However, the results of this research highlight the importance of climate-responsive behaviours and the value of regular maintenance and repair as a first defence to climate change. For example, regular maintenance of building envelopes will both reduce material deterioration and improve building performance and could potentially mitigate the need for additional energy efficiency measures, for example. Climate-responsive behavioural adjustments, as well as and building-fabric modifications, may be required, but the regular maintenance and timely repair are low-cost decisions and start with attitudes and behaviours towards building upkeep; and can be considered as a time investment in prevention, rather than a more costly investment to remedy a problem.

Table 5. Known material and component deterioration mechanisms and severe event safety measures to inform repair, maintenance, and adaptation works.

Material/Component	Deterioration Mechanisms	Severe Event Safety Measures
Solid stone or brick	❖ Masonry deterioration is associated with excessive moisture content. ❖ Water ingress, wet-dry cycles, freeze–thaw cycles, rain splatter at base of walls. ❖ Discolouration (staining) micro-cracking, biological/organic growth. ❖ Relative humidity < 75% can escalate crystallisation–hydration cycles, so drier, hotter summers could be a potential threat, especially for carbonate and sandstone *but no estimate is yet available related to their correlation* [44].	❖ WDR and heavier downpours will require more regular maintenance of stone/brickwork ❖ Address micro-cracking to reduce moisture ingress ❖ Increased impact likely on northerly elevations.
Painted render	❖ Water ingress, wet-dry cycles, freeze–thaw cycles, rain splatter at base of walls.	❖ Address cracking to reduce moisture ingress.

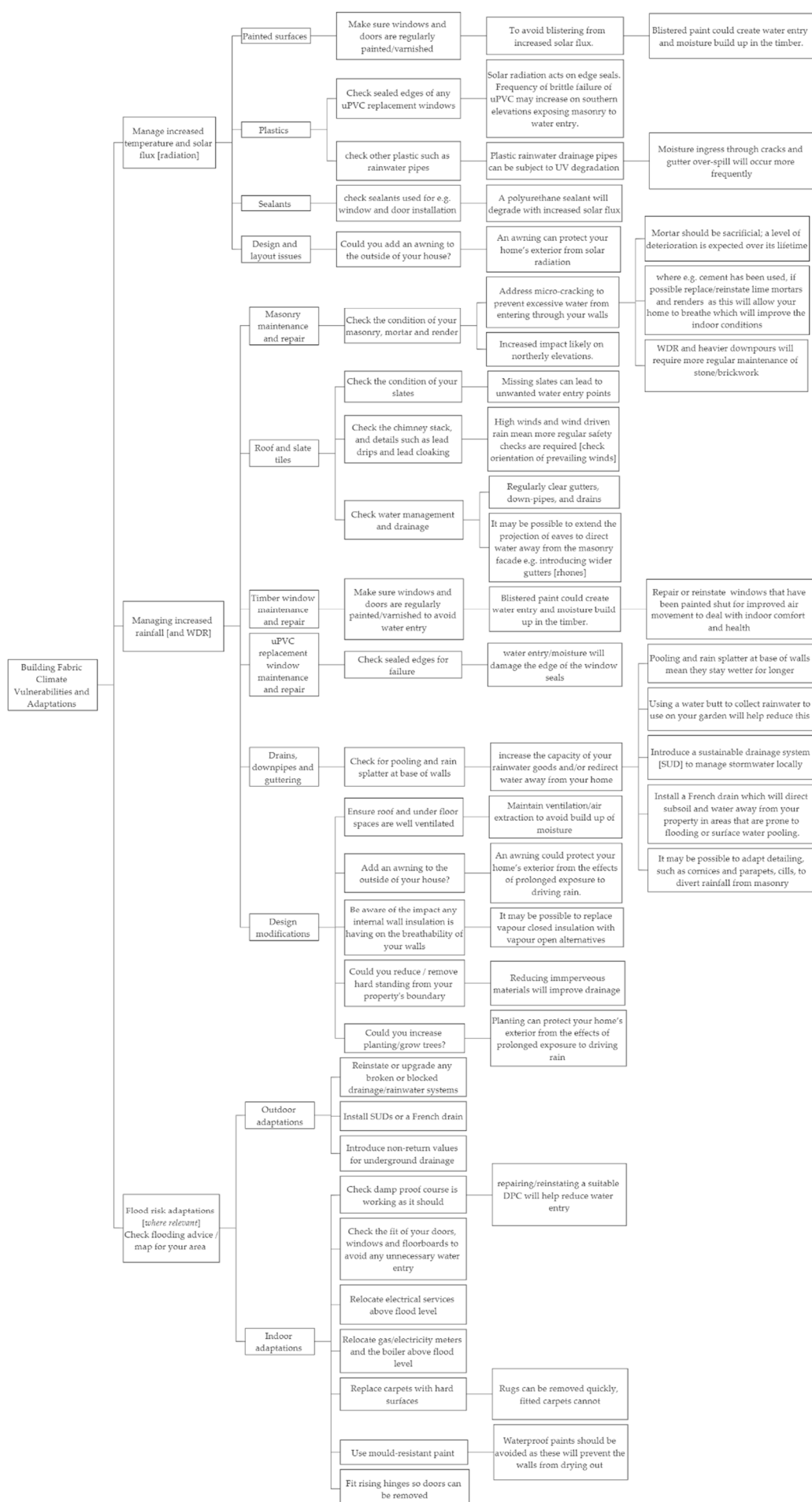|		
	❖ Discolouration (staining), cracking, biological/organic growth. Loss of strength may also occur. ❖ A reflective/pale coating can prevent walls exposed to sunlight reaching a critically high temperature [41]	❖ Increased impact likely on northerly elevations.
Painted/treated timber (window frames and doors)	❖ Solar radiation and moisture lead to erosion or stains and blistering of varnish/paint, that allow timber saturation ❖ With high solar flux, increased blistering will occur on painted timber on south facing elevations increased frequency of repair. ❖ If level of moisture is raised >20%, rot can damage frames [42]	❖ Frequency of repaint/retreating will increase on southern elevations.
uPVC replacement window frames and doors	❖ Moisture, atmospheric gases, and solar radiation acts on edge seal.	❖ Frequency of brittle failure of uPVC may increase on southern elevations.
Lime/cement mortar repointing	❖ Mortar should be sacrificial; a level of deterioration is expected over its lifetime	❖ Repointing the mortar more regularly will reduce moisture ingress in stone/brickwork ❖ Increased impact likely on northerly elevations.
Roof—slate tiles	❖ Rare delamination of poor-quality slates (usually fixings/supporting timbers that deteriorate before the slate tiles themselves)	❖ High winds/WDR, more regular safety checks required including chimney stack (check orientation of prevailing winds)
Decorative ceramics	❖ Moisture in backing or adhesives	❖ WDR and heavier downpours will require more regular maintenance of ceramic tiles
Guttering uPVC	❖ Plastic rainwater drainage pipes can be subject to UV degradation and physical impacts during maintenance access. ❖ Moisture ingress through cracks and gutter overspill will occur more frequently	❖ WDR and heavier downpours will require more regular maintenance of gutters, joints, and drainage
Drains	❖ Pooling and rain splatter at base of walls	❖ Heavier downpours will require more regular maintenance of grates and drainage
Sealants	Moisture, atmospheric gases, and solar radiation. A polyurethane sealant will degrade in sunlight, whilst a silicone sealant will be virtually unaffected. Hardening, chalking, crazing, cracking, and reverting all suggest the sealant needs replacing.	Frequency of replacement of polyurethane sealant will increase on southern elevations

Mind map: **Building Fabric Climate Vulnerabilities and Adaptations**

- **Manage increased temperature and solar flux [radiation]**
  - **Painted surfaces**
    - Make sure windows and doors are regularly painted/varnished → To avoid blistering from increased solar flux. → Blistered paint could create water entry and moisture build up in the timber.
  - **Plastics**
    - Check sealed edges of any uPVC replacement windows → Solar radiation acts on edge seals. Frequency of brittle failure of uPVC may increase on southern elevations exposing masonry to water entry.
    - check other plastic such as rainwater pipes → Plastic rainwater drainage pipes can be subject to UV degradation → Moisture ingress through cracks and gutter over-spill will occur more frequently
  - **Sealants**
    - check sealants used for e.g. window and door installation → A polyurethane sealant will degrade with increased solar flux
  - **Design and layout issues**
    - Could you add an awning to the outside of your house? → An awning can protect your home's exterior from solar radiation

- **Managing increased rainfall [and WDR]**
  - **Masonry maintenance and repair**
    - Check the condition of your masonry, mortar and render
      - Address micro-cracking to prevent excessive water from entering through your walls
      - Increased impact likely on northerly elevations.
      - Mortar should be sacrificial; a level of deterioration is expected over its lifetime
      - where e.g. cement has been used, if possible replace/reinstate lime mortars and renders as this will allow your home to breathe which will improve the indoor conditions
      - WDR and heavier downpours will require more regular maintenance of stone/brickwork
  - **Roof and slate tiles**
    - Check the condition of your slates → Missing slates can lead to unwanted water entry points
    - Check the chimney stack, and details such as lead drips and lead cloaking → High winds and wind driven rain mean more regular safety checks are required [check orientation of prevailing winds]
    - Check water management and drainage
      - Regularly clear gutters, down-pipes, and drains
      - It may be possible to extend the projection of eaves to direct water away from the masonry facade e.g. introducing wider gutters [rhones]
  - **Timber window maintenance and repair**
    - Make sure windows and doors are regularly painted/varnished to avoid water entry → Blistered paint could create water entry and moisture build up in the timber. → Repair or reinstate windows that have been painted shut for improved air movement to deal with indoor comfort and health
  - **uPVC replacement window maintenance and repair**
    - Check sealed edges for failure → water entry/moisture will damage the edge of the window seals
  - **Drains, downpipes and guttering**
    - Check for pooling and rain splatter at base of walls → increase the capacity of your rainwater goods and/or redirect water away from your home
      - Pooling and rain splatter at base of walls mean they stay wetter for longer
      - Using a water butt to collect rainwater to use on your garden will help reduce this
      - Introduce a sustainable drainage system [SUD] to manage stormwater locally
      - Install a French drain which will direct subsoil and water away from your property in areas that are prone to flooding or surface water pooling.
      - It may be possible to adapt detailing, such as cornices and parapets, cills, to divert rainfall from masonry
  - **Design modifications**
    - Ensure roof and under floor spaces are well ventilated → Maintain ventilation/air extraction to avoid build up of moisture
    - Add an awning to the outside of your house? → An awning could protect your home's exterior from the effects of prolonged exposure to driving rain.
    - Be aware of the impact any internal wall insulation is having on the breathability of your walls → It may be possible to replace vapour closed insulation with vapour open alternatives
    - Could you reduce / remove hard standing from your property's boundary → Reducing immperveous materials will improve drainage
    - Could you increase planting/grow trees? → Planting can protect your home's exterior from the effects of prolonged exposure to driving rain

- **Flood risk adaptations [where relevant] Check flooding advice / map for your area**
  - **Outdoor adaptations**
    - Reinstate or upgrade any broken or blocked drainage/rainwater systems
    - Install SUDs or a French drain
    - Introduce non-return values for underground drainage
  - **Indoor adaptations**
    - Check damp proof course is working as it should → repairing/reinstating a suitable DPC will help reduce water entry
    - Check the fit of your doors, windows and floorboards to avoid any unnecessary water entry
    - Relocate electrical services above flood level
    - Relocate gas/electricity meters and the boiler above flood level
    - Replace carpets with hard surfaces → Rugs can be removed quickly, fitted carpets cannot
    - Use mould-resistant paint → Waterproof paints should be avoided as these will prevent the walls from drying out
    - Fit rising hinges so doors can be removed

Figure 11. Building fabric vulnerabilities and adaptations.

4. Discussion and Conclusions

This research has explored known building-fabric deterioration mechanisms and climate hazards, risks, and stressors. The results of the study offer a set of quantifiable and measurable climate vulnerabilities associated with housing building-fabric. The objective being to address evidence gaps identified by the Welsh government, which included risks to building-fabric from moisture, wind, and driving rain under future changes in weather patterns. Climate change will undoubtedly influence how we manage the physical condition of our homes in the future, if it is not already. In general terms, Wales will experience warmer but wetter weather that will bring certain challenges for building upkeep, especially considering the high proportion of older properties, over a quarter of which are more than 100 years in age. Certainly, the need to repair, and in some cases rebuild, due to damage caused by changing precipitation patterns, including WDR, which may lead to more severe storm events and consequent flooding, will become more prevalent.

The climate vulnerability modelling asserts there will be a modest reduction in the service life of building materials due to increases in and changing patterns of precipitation and subsequent moisture ingress. Although modest, with 1.5 million dwellings in Wales, the impact is significant. To that end, climate change will alter existing building-fabric performance, as identified in the climate vulnerability modelling. For example, solid masonry walls, the standard way to build in the late 1800s and early 1900s, are characterised by higher surface water absorption coefficients and are more sensitive to exterior climate factors, such as rain, wind, and solar radiation. Changes in climate factors are expected to accelerate the deterioration of masonry and detailing and undermine binders and coating on buildings [8,9]. Wall orientation will also make a difference and some building façades will require more attention than others, as south-facing walls dry out quicker than north-facing walls, the higher solar flux reducing relative humidity significantly [46].

Previous interventions or retrofits may also impact on the performance of buildings as weather patterns change, for example adding insulation to a property has been found, in some cases, to result in interstitial condensation, surface condensation, mould growth, and even decay, the effects of which could be expediated by climate change [47]. Meanwhile, the risk of mould growth increases considerably when the relative humidity of a construction material exceeds 80%. Buildings susceptible to damp, both now and under future climate projections, will most certainly require additional attention. Hygrothermal impacts, including repeated wetting, drying, freezing, and thawing of building-fabric, can cause problems such as damp, condensation, and mould growth, resulting in loss of thermal performance, and may even lead to premature material failure. However, advocating climate-responsive behaviour through regular maintenance and repair, will not only reduce the risks associated with changing weather patterns, but also encourage energy efficiency, by improving the thermal performance of the building envelope. This will reduce the risk of adverse climate related outcomes, and increased vulnerability to climate change, now or in the future.

Investment in climate adaptation, alongside associated skills and training, is crucial. Certainly, a review of recent government policy and published academic literature shows that climate change mitigation and associated carbon reduction targets remain to be the primary climate change objective for the design and construction industry. However, known building-fabric performance and the result of the climate vulnerability modelling indicate that climate-responsive modifications, resulting in more regular maintenance, timely repair, and appropriate adaptation, have the ability to steady any decline in service life associated with climate change and has the potential to reduce projected costs associated with a decrease in building-fabric service life.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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