CLIMATE CHANGE ADAPTATION OF RETROFITTED SOCIAL HOUSING IN THE SOUTH-EAST OF ENGLAND

ARIANNA SDEI

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Abstract

This thesis is an investigation into the implications that a warming climate has for the housing retrofit programme recently completed at Rushenden on the Isle of Sheppey that was the subject of the EU Interreg research project IFORE (Innovation for Renewal, 2010-2014). The aim of this thesis is to inform UK public policy on social housing retrofit, as to whether we are pursuing the correct goal by retrofitting with insulation and air-tightness, a strategy to conserve heat, rather than one that would also combat summertime overheating. The community of Rushenden was used as a case study to develop a specific adaptation strategy for retrofitted social housing in the South-East of England.

Gaps in knowledge were identified relating to the role that insulation and air-tightness has in reducing or increasing the overheating risk, and the analysis of a wider range of shading strategies. The measures were discussed with sixteen households during completion of the adaptations questionnaire and three focus groups. Six households completed daily a longitudinal comfort questionnaire, over a period of two months. Monitoring of internal and external temperatures was carried out as part of IFORE but in addition questions about overheating were included by the author within the three IFORE questionnaires that were submitted to one hundred households during the timescale of the project.

Two models were built in ESP-r, a European standard building simulation tool: a single-storey and a two-storey house type. Dynamic thermal modelling, incorporating future weather files, was used to evaluate different specifications of insulation and air-tightness and the climate change adaptation measures. Future heating and cooling loads were calculated and the overheating risk was assessed using the adaptive comfort algorithm.

The first results from the simulations showed that the light type of retrofit installed by IFORE will reduce both the heating load and the cooling load in 2030s, 2050s and 2080s. On the other hand, a deeper type of retrofit that complies with the Passivhaus standard U-value for wall insulation, and air-tightness, will reduce the heating load but increase the cooling load. Despite reduction of overheating risk using the lighter type of retrofit, the living room of the single storey house will not meet the adaptive comfort set of criteria

and should be classed as "overheating". The installation of internal white, opaque roller blinds, will meet the adaptive comfort criteria and eliminate the need for cooling in both the single and two storey houses. The adaptation measures were discussed in terms of their practicality, affordability and the interaction between occupant and technology. The discussion arising from this work is to judge the wider application of its results as a guide to retrofit decision-making.

Table of Contents

Chapter 6: Discussion

Chapter 7: Conclusions

References

Appendix

List of Figures

List of Tables

List of abbreviations

IPCC: Intergovernmental Panel on Climate Change

DECC: Department of Energy and Climate Change

DEFRA: Department of the Environment, Food and Rural Affairs

TSB: Technology Strategy Board

IFORE: Innovation For Renewal

SNACC: Suburban Neighbourhood Adaptation for a Changing Climate

CREW: Community Resilience to Extreme Weather

CIBSE: Chartered Institution of Building Services Engineers

UKCIP: UK Climate Impact Programme

KTP: Knowledge Transfer Partnership

LCCP: London Climate Change Partnership

EST: Energy Saving Trust

CAR: Cambridge Architecture Research

UKCP02: UK Climate Projections 2012

UKCP09: UK Climate Projections 2019

ASC: Adaptation Sub Committee

CCC: Climate Change Committee

BRE: Building Research Establishment

TM52: Technical Memorandum 52

TM36: Technical Memorandum 36

ARCC CN: Adaptation and Resilience in a Context of Change Coordination Network

PAR: Participatory Action Research

CoP: communities of Practice

TRY: Test Reference Year

DSY: Design Summer Year

BSRIA: Building Services Research and Information Association

GAP: Global Action Plan

PFR: Planning For Real

SERR: Seasonal Energy Efficiency Rate

EER: Energy Efficiency Ratio

Statement by the author

The author is employed by the University of Brighton as a Research Fellow on the IFORE project. In the context of IFORE the author carried out some preliminary testing (pressure tests, thermographic tests) with the help of Professor Mike McEvoy. Independently, but in close collaboration with the University of Artois, the author modelled the seven house types in Rushenden (Kent) using ESP-r. She carried out dynamic thermal simulations of several low carbon retrofit measures applied to the houses in Rushenden and the analysis of the results. This informed the choice that was made by the housing association, Amicus Horizon, of which retrofit measures to install on their 100 houses.

The author actively participated in some of the community engagement activities and accompanied the Green Doctor during a few initial visits. The author wrote, with the help of a sociologist, Laura Banks, the questions regarding climate change and overheating that were inserted into the three IFORE questionnaires. These questionnaires were submitted to 100 residents (a few residents refused to take part in each survey) on three occasions during the length of the project.

The results from these questionnaires were analysed by Dr Paul Hanna. In the social engagement chapter the author used the graphs from Dr Hanna's IFORE report which represent the occupants' answers to the questions about climate change and overheating. The summertime comfort questionnaires, the adaptation questionnaires, focus groups and one-to-one interviews with children were carried out solely by the author with the support of the occupants' engagement team at Amicus Horizon.

The models of the two house types analysed in this thesis were constructed in ESP-r for this thesis to answer the main questions about climate change adaptation. They are more detailed than those originally built for the IFORE project as they are multi-zonal, room-by-room models and contain an air flow network. All the simulations run using these two models and presented in the analysis chapter are the original part of this thesis, were not used for IFORE or for any other purpose other than this thesis. Some of the information

used to build the models such as air permeability was taken from the initial measurements carried out by the author and Professor McEvoy.

Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

29-09-2015

Chapter 1. Introduction

"Resilience is, of course, a term derived from physics, describing the elasticity or ability of a material to return to its original form after having been subjected to an external stress. By analogy, resilience has come to be used in a wide range of fields to express the capacity of societies to recover from severe shocks, such as environmental destruction or economic crisis"

Daisaku Ikeda, (2014) Peace Proposal to the UN

1.1 Motivation

1.1.1 IFORE (Innovation for Renewal)

The European Union's carbon reduction goal for all its member states is, compared with 1990 levels, to cut 20% of its carbon emissions by 2020, 40% by 2030 and 80%-95% by 2050. (Climate Action, 2014). In order to respond to the global challenge to tackle carbon emissions and in accord with EU policy the Climate Change Act (2008) established a legally binding target to reduce the UK's greenhouse gas emissions by at least 80% below 1990 baseline year levels[1] by 2050, to be achieved through action at home and abroad (Carbon Plan, 2011). This made the UK the first country in the world to have a legally binding, long-term framework to cut carbon emissions (CCRA Evidence Report, 2012).

"Buildings constructed today will be there for the next 50 to 100 years. For example, 92% of the building stock from 2005 will still be there in 2020 and 75% in 2050. This is due to the very low demolition rates (about 0.5% per year) and new built construction rates (about 1.0% per year)" (EU, 2008)*.* A number of retrofit initiatives have been developed throughout Europe. In line with EU policy, Interreg (EU Regional Development Fund)

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[1] The 1990 baseline is the aggregate amount of: (a) net UK emissions of carbon dioxide for that year, and (b) net UK emissions of each of the other targeted greenhouse gases for the year that is the base year for that gas (Climate Change Act 2008). The base year is 1990 for carbon dioxide, nitrous oxide and methane, and 1995 for hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (Carbon Plan 2008).

funded the IFORE project (Innovation for Renewal), which had as one of its aim the low carbon retrofit of 100 social houses in Kent (UK). In order to achieve an 80% reduction in the carbon emissions IFORE aimed to enhance the carbon reduction achieved by the use of technical solutions with a change in the behaviour of the occupants in an effort to make them more responsible towards energy.

The technical solutions most commonly used in past and present low carbon retrofitting are insulation and air tightening. These techniques are commonly acknowledged to be the most suitable to reduce winter heat loss in existing housing in areas of the planet where there is a prevalent need for space heating (Professor Hiroshi Yoshino, private conversation). The author travelled to Japan with a research project funded by the Great Britain Sasakawa Foundation from 2008 to 2011 to monitor several examples of retrofitted traditional Japanese houses near Sendai, in the Tohoku region.

In accord with the current trend, and with the aim to conserve the heat in cold climates the IFORE houses in England and France have been retrofitted with insulation and air tightness. Different applications of these two techniques were adopted on both sides of the channel. In the UK the choice was made to adopt a "light" type of retrofit in accord with the limited finances available. A thin layer of insulation was applied to the external facades; the windows and the internal fabric were refurbished to increase the air-tightness. Renewable energy systems such as photovoltaic and solar thermal panels, air and ground source heat pumps were also used. Greater emphasis was put on the engagement of the residents and on their education with the aim to help them reduce their energy use.

This approach is different to a "deep" retrofit such as Passivhaus Enerphit that aims to dramatically reduce the energy used for space heating. IFORE gave more importance to occupants' education and engagement, less emphasis was given to the technical solutions that were used to reduce the heating demand. The "Retrofit for the Future" competition, the forerunner of IFORE that will be described in the Literature Review, had a far bigger budget than IFORE and "deep" retrofit solutions were preferred.

The author worked on IFORE as a research fellow with the University of Brighton between 2010 and 2014. She was involved in the energy assessment of the UK houses and in particular on the SAP (Standard Assessment Procedure) analysis, dynamic thermal modelling, and calculation of payback times for the retrofit measures. An assessment of the summertime overheating risk was not carried out during IFORE because the specific goal of the project was to reduce space heating demand and electricity use.

However, this aspect is particularly important since predictions of climate change suggest the likelihood of a future warming climate. The author explores herein the effects that the retrofit measures installed in the UK houses have on the summertime overheating risk at present and in the future. The following section describes in detail what the predictions of future climate change are and how they are likely to impact on retrofitted social housing in the South-East of England.

1.1.2 Climate change

"The heat wave that occurred in Northern France in August 2003 for a period of three weeks resulted in 15000 excess deaths" (NHBC, 2012). During that same summer, the heat wave resulted in over 2000 excess deaths in England and Wales. The greatest proportion of deaths occurred in the southern half of England, particularly in London (CCRA, 2012). The climate is already changing (Stern, 2010). We know from global temperature records [2] that the Earth has warmed by about 0.75 °C in the last century. The global-average temperature has increased over the past century and this warming has been particularly rapid since the 1970s (Met Office, 2011). From the 1970s to 1990s warming was faster than over the century as a whole, but the rise has slowed more recently (Met Office 2012).

The IPCC (Intergovernmental Panel on Climate Change) fourth assessment synthesis report (2007) affirms that there is very high confidence that the current warming is caused by human activity. The report believes it is very likely that anthropogenic activity has produced the changes in the climate that we are currently experiencing and has also increased the probability of heat waves. These changes will continue to increase into the

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[2] This includes air, ground and sea temperatures

future because global GHG emissions will continue to grow over the next few decades. That is why it is crucial to reduce energy demand as much as possible. It is virtually certain that the climate in the 21st century will warm (IPCC, 2007). Climate change is likely to lead to some irreversible impacts (IPCC 2007).

The report identifies two opportunities to tackle climate change: mitigation and adaptation. Mitigation helps emissions to stabilize; adaptation reduces vulnerability to climate change which is exacerbated by factors such as poverty (IPCC, 2007). While the challenge of mitigation is global, adaptation must take place mainly at the local and regional level (Stern, 2010). Despite this effort, emissions produced to date and those that will inevitably be produced in the future will cause the climate to change and the temperature to increase (IPCC, 2007). Winter energy use will reduce, which represents both a carbon and a financial benefit and in the summer there may be a risk of increased energy use and carbon emissions because of the uptake of air conditioning (CCRA, 2011).

In the UK, the heating degree-days to a base temperature of 15.5 °C calculated from the CIBSE/Met Office weather data have a distinct trend, showing a decrease through the period of the data, namely 1976–1995. The number of heating degree-days in both London and Edinburgh dropped by 20–30 degree-days per year, a drop of approximately 10% over the 15-year period covered by the measurements. This indicates that the climate has warmed even over the period of the CIBSE/Met Office data (CIBSE, 2005). The UK average temperature has increased by 1 °C since the mid-1970s (Jenkins *et al.,* 2011).

The IPCC synthesis report (2007) identifies six possible climate change scenarios belonging to four scenario families A1, A2, B1 and B2 (Figure 1.1). The different scenarios assume different economics, demographic and technological changes and resulting GHG emissions. "The A1 storyline assumes a world of very rapid economic growth, a global population that peaks mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T) and a balance across all sources (A1B). B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy. B2 describes a world with intermediate population and

economic growth, emphasising local solutions to economic, social, and environmental sustainability. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change." (IPCC, 2007). SRES is a Special Report on Emissions Scenarios that was published by the IPCC in 2000 (IPCC, 2007).
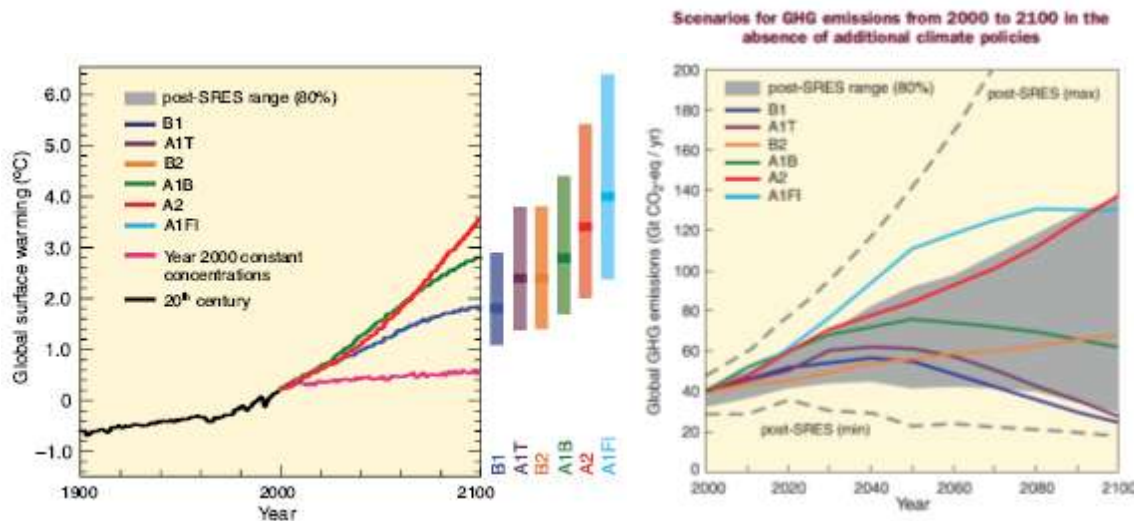
Figure 1.1: Climate change emissions scenarios, (Source: IPCC Synthesis report, 2007)

UKCP09 (UK Climate Projections, Murphy J. *et al,* 2009) uses A1F1, A1B and B1 scenarios from the IPCC synthesis report to establish high, medium and low emission scenarios for the UK (Figure 1.2). All scenarios are possible and none of them should be regarded as more likely to occur than the other (Gething, 2010). In addition to these three equally possible scenarios, there is for each scenario a range of probabilities that go from 90% (very likely) to 10% (very unlikely) to occur (Gething, 2010).

Overall for the UK, the scientific community agrees that in the future there will be warmer, wetter winters and drier, hotter summers. The South East of England is the region predicted to have the biggest increase in temperature. Figure 1.3 shows a plot of low, medium and high emission scenarios with the probability range from 10% to 90% for each scenario. Estimating regional changes is more difficult but the latest projections for the UK include increases in summer temperature of between approximately 1 and 8 °C in the South East of England by the 2080s (DEFRA, 2012).
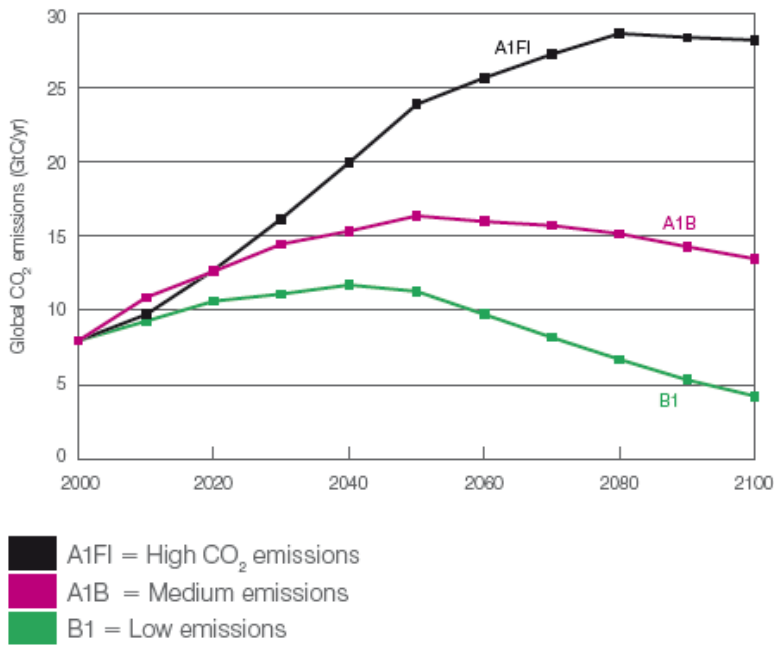
Figure 1.2: Three climate change emissions scenarios (Source: Gething, 2010)
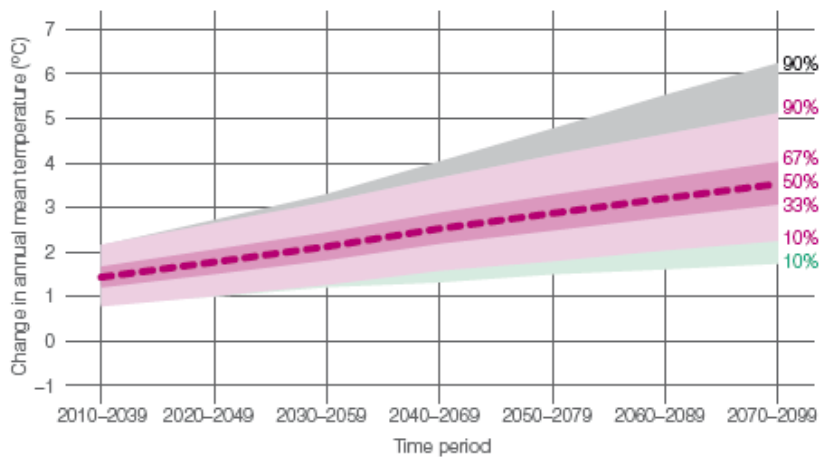
Figure 1.3: Annual mean temperature change in south east England (all scenarios)

(Source: Gething, 2010)

6

1.1.3 Mitigation and adaptation – climate change policy

Adaptation and mitigation are major subjects of the UK government agenda. **Mitigation**, through the reduction of greenhouse gas emissions, will contribute to risk reduction over the long term (100 years) and the Climate Change Risk Assessment (DEFRA, 2012) has shown that the consequences of a high emissions scenario are substantially greater for the UK than the low and medium emissions scenarios for the 2080s. Therefore, continued efforts to reduce global greenhouse gas emissions will benefit the UK as well as reduce the greater risks faced by vulnerable developing countries (DEFRA, 2012). **Adaptation** is needed to reduce the costs and damages of inevitable warming and to take advantage of opportunities that arise in a changing climate.

The energy demand of the built environment sector accounts for a significant amount of the UK's carbon emissions (DEFRA, 2012). For instance, space heating alone accounts for approximately 40% of all non-transport energy consumption (DECC, 2009). It is estimated by the UK Green Building Council (2007) that 70% of the existing building stock will still be in use by 2050 (DEFRA, 2012).

While we must take on the challenge of mitigation we must never lose sight of the importance of planning for and acting on adaptation now (Stern, 2010). Whatever happens to future greenhouse gas emissions we are 'locked in' to a certain amount of warming due to inertia in the global climate system (DEFRA, 2012). It is essential therefore to start planning for adaptation now while we focus on reducing our carbon emissions.

1.1.4 Climate change adaptation

More extensive adaptation options are required to reduce vulnerability to climate change. There is high confidence that there are adaptation options that can be implemented at low cost (IPCC, 2007). The capacity to adapt is dynamic and is influenced by economic development. However, even a society with high adaptive capacities remains vulnerable to climate change at present (IPCC, 2007). Adaptation and mitigation can complement each other and together can significantly reduce the risk of climate

change; however neither adaptation nor mitigation can avoid all climate change impacts (IPCC, 2007).

The UK will continue to be vulnerable to severe weather, including cold spells, floods and droughts (DEFRA, 2012). The potential benefits of milder winter conditions are significant because there may be a large reduction in (for example) cold weather related deaths and detrimental health problems. This is therefore presented as an opportunity (DEFRA, 2012). However the numbers affected by cold weather will still be significant for the 2020s and fuel poverty issues will remain (DEFRA, 2012). Some risks, which are already a concern, have the potential to become more significant over the next 20-30 years. These include increases in summer mortality due to heat waves (DEFRA, 2012). Other potential risks are projected to become more significant by the latter half of the century; these include a greater demand for cooling.

Scenarios of climate change beyond 2012 take into account some of the uncertainties about future levels of greenhouse gas emissions, and suggest increases in the frequency of heat waves over the next 100 years in the South East of the UK, and less of an increase in the frequency in other regions (Kovats, 2008). Such heat wave temperatures have led to extensive installation of air conditioning in the United States (Kovats, 2008). There is a risk that as the outdoor air temperature rises, and the indoor environment becomes more uncomfortable in the summer as a result, there will be a greater need for cooling. This search for comfort may generally lead to more air conditioning units being sold which could mean an increase in CO_2 emissions and a further increase in air temperature.

An argument that is often used to delay decisions on climate change adaptation is that, in the long term, the UK government plan is to decarbonise the grid (DECC, 2009). Therefore, at some point in time, the sale of air conditioning units may well be justified by the fact that they use clean energy. However, this energy will be sold at a price and in the case of social housing this can imply an increase in fuel poverty. At present much less information about the cost of adaptation measures is available than that of mitigation (IPCC, 2007). Some basic indications of the cost of adaptation in retrofitted social housing are therefore needed, which is one of the outcomes of this research.

1.2 Health implications of overheating

Climate change will have consequences for the health of UK citizens (Kovats, 2008). The most obvious need at this level of risk is for elderly and ill people and their carers to be aware that these people are particularly vulnerable to heat stress (Flynn *et al.*, 2005), and to adopt protective measures that are common in Southern Europe in hot weather (Kovats, 2008). The Climate Change Risk Assessment analysis shows that there may be between 580 and 5,900 premature deaths per year by the 2050s in hotter summer conditions (without further adaptation of buildings or health services). The risks are greatest for vulnerable groups, such as the elderly, and in London and Southern England where the highest temperatures are likely to be experienced (DEFRA, 2012).

Vulnerable groups of people such as those affected by poverty, poor health and disabilities will tend to experience disproportionate negative effects from particular climate impacts. Social housing tenants are more vulnerable than other housing residents in these particular circumstances. This assessment concludes that social vulnerability to climate change is likely to reflect existing patterns of inequality (DEFRA, 2012). The CCRA evidence report (DEFRA, 2012) presents the overheating of buildings and the energy demand for cooling to be a threat with medium negative consequences by the 2020s and 2050s and high negative consequences by the 2080s.

The Health Protection Agency gives advice such as using an electric fan, shading with external shutters or thick curtains and opening the windows in the early morning while keeping them closed at night (Kovats, 2008). These measures, however, may not be enough in certain cases to ensure indoor comfort, and a rise in temperature may still lead residents to buy an air conditioning unit, which will be costly and carbon intensive.

The role of green infrastructure is essential. The living network of green spaces, water and other environmental features in both urban and rural areas can help to reduce extremes of temperature and manage water flows that affect buildings (DEFRA, 2012). In October 2011, the Green Infrastructure Partnership was launched, which will provide the opportunity to demonstrate the benefits that well-designed, high-quality green infrastructure can provide (DEFRA, 2012).

1.3 Research questions and objectives

The aim of this thesis is to analyse the houses in Rushenden retrofitted under IFORE in view of a future warming climate. There are many retrofit programmes and this thesis can be used to inform decision makers on how to retrofit social housing (e.g. to include adaptation measures in retrofit). This thesis provides an analysis of specific adaptation measures targeted at retrofitted social housing in the South-East of England. The measures have been discussed with the residents of Rushenden during some sociological studies. The practical applicability of each measure was tested during focus groups and questionnaires and suggestions were made by the residents about ways to overcome obstacles to adapt.

As with mitigating the effects of climate change, adaptation techniques can only go so far in ensuring comfort in the event of a heat wave. As Southern European populations know well, the implementation of techniques that reduce overheating are accompanied by a different way of living in the summer, spending more time in shaded and breezy outdoor spaces than indoors. In particularly hot regions, years of torrid summers have encouraged the development of a number of habits that people are now accustomed to, for instance, spending time along the coast and by the sea. These are now part of the tradition together with drinks and food that allow the population to cope better with dehydration. Therefore, both technical and community aspects need attention when adapting to a warmer climate. The underlying philosophical discussion is how to establish a synthesis between the environmental and the socio-economic contexts of climate change adaptation. This discussion forms one of the main aspects of this thesis, which as a result it progresses beyond the state-of-the-art, to include practical outcomes and recommendations.

The community of Rushenden is extremely vulnerable; it is formed of the elderly, single-parent families, unemployed singles and couples. Occupants with this social background are much more difficult to engage in a discussion on climate change because they have different priorities. The reality of Rushenden represents what the UK reality could be in a few years, with more elderly residents than there are now, increased life expectancy will make the population more vulnerable to a warmer climate.

The case of Rushenden is very extreme; there are more unemployed and more elderly than average. It reflects the reality of very deprived social housing communities in the UK. Occupants are often reluctant to participate in education programs. At present they do not think that they have an impact on the climate or that a change in climate is going to impact them. However, in the case of global warming, this particular group may not be able to quickly adapt to higher temperatures or to afford the price of air conditioning because of financial constraints. The occurrence of heat waves can therefore have a much higher health risk, early mortality and morbidity, especially in the case of the elderly. That is why it is so important to start talking about global warming at this time and to generate an interest in what can be done to re-establish comfortable living conditions.

While in Southern European countries these traditions have developed over time, in the advent of global warming, there may be no time to naturally develop different ways of living in Northern Europe. There is therefore a need to engage all spheres of society: planners, local authorities and communities in the discussion on climate change. The latest sociological research suggests participation as a way to initiate a transformative process where change is driven by the community supported by planners, architects and local authorities. In practical terms, local authorities may have to start offering certain types of services to the community that were not previously offered. Planners may need to start looking at outdoor spaces in a different way to make them more attractive and liveable in the hot summer months ahead. All actors: communities, architects, planners and local authorities will have to get together and establish common goals.

The problem of global warming, as has already been experienced in the recent past, poses a threat to present and future generations. The UK will see hotter and drier summers and warmer and wetter winters (DEFRA, 2012). There will also be an increase of extreme weather events including heat waves (DEFRA, 2012). This will especially affect the most vulnerable; the elderly, for instance, that tend to spend more of their time indoors (NHBC 2013) and social housing tenants that may not have the financial means to adapt their homes (LCCP 2013).

While IFORE, during its lifespan of 4 years (2010-2014), researched low carbon retrofit in 200 social houses, this thesis focuses on what will happen in 20, 40 and 50 years time to

the houses in Rushenden (Kent) as the temperature rises. It will build further understanding of the overheating risk in retrofitted social housing in the South East of England with lessons for other social housing communities.

As we mitigate the effects of climate change by making our houses more energy efficient, by adding a layer of external or internal insulation and by air tightening them, the risk is that in the summer the warm air from outside becomes trapped inside. This is because, houses are becoming more tightly sealed. Unless there is a natural ventilation strategy in place or the possibility to open the windows to purge ventilate by up to 10ACH (CIBSE, 2006), in a future warming climate, the houses are going to overheat. In cases where the window opening is restricted, in urban areas or in ground floor flats for instance, if the warm air cannot escape through ventilation, overheating will be a major issue.

The houses in Rushenden were built between 1945 and 1965 and since the average lifespan of UK housing is around 150 years we can assume that they will last until the end of this century. They have been retrofitted using insulation, air tightness and renewable energy systems. Due to financial constraints the retrofit was not as extensive as initially envisaged. The houses, in fact, have not been heavily insulated or air tightened, but there has been an improvement of these two parameters to allow for some energy savings. IFORE therefore offers a practical framework to study these theoretical aspects.

IFORE and the social housing in Rushenden are an example for many other social housing retrofit projects in the UK. The fabric of the housing and the social background and income of the residents is similar to other social housing developments throughout the country. The low-income social mix of the Rushenden residents, spanning from the single elderly to single-parent families or families with three to four children is characteristic of many other social housing developments in the UK, in particular the elderly occupying single-storey houses.

However, this thesis is not a sociological study, it is a technical and behavioural study aimed at finding recommendations to adapt the community of Rushenden to climate change. This work is an analysis of what academics, the construction industry and policy makers are currently thinking and doing about retrofit. As well as implementing technical

solutions, IFORE engaged the community in an education program that aims to reduce waste energy and is mainly targeted at the electrical devices in the homes. This seems to be the way forward in a social housing context, where residents are already in fuel poverty and gas for space heating is rarely wasted.

It is beyond the scope of this PhD to analyse whether the IFORE low carbon retrofitting reduced fuel poverty in Rushenden or whether it was successful in making the houses more comfortable in the winter. Broadly, this thesis is looking at the effects of low carbon retrofit measures in social housing and in particular at the potential for overheating in the summer at present and in the future. Using Rushenden as a case study that mirrors the circumstances of the residents of social housing throughout the country, it establishes adaptation options targeted at these particular houses and suggests ways to integrate them within the community and the low carbon retrofit.

This thesis focuses on overheating in dwellings and explores the relationship between housing, the occupants and the local community, calculating heating and cooling loads and overheating hours now and in the future to test different technical and behavioural adaptation options and establish whether they are valid for this particular social housing community.

Due to the socio-economic characteristics of social housing residents, an analysis of the cost of the adaptation measures and the payback times is included in this thesis. This does not take into account the effect of inflation on costs. However, in the future there may be widespread and energy-consuming adaptations to a warming climate e.g. the use of air conditioning. This is the reason why, as well as technical solutions, different ways of living in the summer are explored that can help alleviate the discomfort caused by overheating; collective services to the community run by the local council, for example, coaches that take the elderly to the seaside, do not require any extra fuel cost per household.

The author seeks to answer the following research questions:

Arising from analysis of the retrofitted housing at Rushenden

1. In the future, will the retrofitted social housing at Rushenden overheat to a greater extent than if the work had not been carried out?

2. If so, what type of retrofit, light retrofit or deep retrofit would tend to overheat more? For social housing (given limited financial resources) a reduced level of retrofit is the norm, how does that compare with deeper retrofit solutions (such as Enerphit) in terms of overheating risk?

3. If retrofit might increase the overheating risk, which measures are likely to cause this increase - more insulation, air-tightness, or both?

4. In which respects might the retrofit be helping to reduce the overheating risk, and which elements are the most beneficial?

5. How can these retrofitted houses be adapted to a warmer future climate?

6. How can a specific adaptation strategy be established for these houses?

7. What else the community can do to adapt to a warmer climate?

8. Which behavioural aspects adopted in other countries might be applicable to the south-east of England - offering extra comfort in the event of a heat wave?

The more general discussion arising from this study:

9. In terms of public policy for the retrofit of social housing in England, is the current approach, which is principally directed towards improving insulation and air tightness, the optimal strategy in view of climate change?

To fulfil the thesis aim and answer the research questions the author established the following set of objectives, using case studies to derive a list of measures that applied to retrofitted social housing in the South-East reduce the vulnerability of the community to overheating in the event of a heat wave.

1. To assess the heating and cooling loads and the overheating hours at present and in the future of two house types, representing the social housing community in Rushenden retrofitted under IFORE, using dynamic thermal modelling and the adaptive comfort equation.

2. To test different levels of insulation and air-tightness.

3. To find the maximum and minimum comfort temperature for this groups of residents using a longitudinal questionnaire.

4. To test adaptation measures using the models and the maximum comfort temperature derived by the questionnaires.

5. To discuss technical and behavioural adaptation measures with the residents of Rushenden using questionnaires, interviews and focus groups.

6. To insert the measures as discussed with the residents into the models and to establish combinations of measures that reduce or eliminate the overheating risk by 2030s using the adaptive comfort set of criteria.

7. To establish the payback times of the measures.

1.4 Scope of the study and thesis structure

The scope of this thesis is to inform UK policy on social housing retrofit and on the implications that insulation and air-tightness have on summertime overheating at present and in the future. It aims to present a method for the analysis of retrofitted social housing in the South-East of England in view of climate change. The analysis involved the evaluation by computer simulation of two case studies before and after the retrofit measures were installed using current and future weather files. Different specifications of insulation and air tightness were assessed. The heating and cooling loads were calculated for the case studies and the overheating risk was assessed using the adaptive comfort theory. A second part of the analysis consists of the assessment of a number of climate change adaptation measures that reduce the overheating risk in the event of a future warmer climate. A list of technical and behavioural adaptation measures was discussed with the residents during questionnaires and focus groups and the practical application of each measure was evaluated. The obstacles to adaptation were removed and the specific climate change adaptation measures targeted at the community of Rushenden were found. The return on investment was then calculated for the adaptation measures using cost-saving analysis.

The thesis is composed of seven chapters. Chapter two explores the relationship between mitigation and adaptation. It is divided into two main sections: the environmental context and the socio-economic context. In the environmental context the author presents

several national and international low carbon retrofit initiatives and focuses on the relationship between insulation, air tightness and overheating. It explains in more detail recent work on adaptation, and explores the overheating reduction methods of thermal mass, shading and ventilation. Through the critical analysis of existing studies the author identifies gaps in knowledge about the climate change adaptation of retrofitted social housing in the South-East of England that require further investigation.

The socio-economic context explores several participation techniques and presents several studies that successfully carried out community engagement activities. It is divided into initiatives for children and initiatives for adults. Among the initiatives for adults several examples on participation in the field of climate change adaptation are presented and analysed critically in relation to the occupant's engagement activities in Rushenden

Chapter three describes the methodology used to assess the heating and cooling loads and the overheating hours in the case studies and the adaptation options used to reduce the overheating risk. It starts by presenting the context in which the houses are located and it describes the future weather files used in the modelling. Here the author explores the characteristics of the houses before and after the retrofit works were carried out and presents a list of adaptation measure to be simulated in the models and discussed with the residents. It explores the methods used for the community engagement work and how it was carried out by the author in Rushenden. That is followed by considerations relative to the price of each adaptation measure.

Chapter four describes the field study. It presents the results from the questionnaires, the interviews with children and adults and the focus groups during which the adaptation measures are discussed. The first set of questions explores how the perception of summertime comfort has changed since the retrofit measures have been installed. The second questionnaire discusses several adaptation measures and at the same time the author carried out the summertime comfort questionnaire in order to identify the maximum and minimum maximum and minimum comfort temperature for the occupants in Rushenden. Three focus groups followed to discuss adaptation topics and the fourth

questionnaire was carried out with the children to discuss climate change and the legacy of the community engagement efforts.

Chapter 5 presents the results and analysis from the modelling. This chapter reveals the relationship between insulation, air-tightness and overheating in the two case studies. It then classifies each adaptation measure from the list established in the methodology and the reduction of the cooling load that each produces. The overheating risk is assessed for the case studies using the adaptive comfort criteria and the maximum temperature for this group of residents derived from the questionnaires. The best adaptation measures are identified with the help of the occupants' advice gathered during the engagement process.

Chapter 6 discusses the behavioural adaptations and how these can be applied to the case study and presents the cost-saving analysis. Common behavioural adaptations are presented and discussed in relation to the South-East of England. It develops the cost-saving analysis for the adaptations identified in Chapter 5. It explains the limitations of the study in relation to some of the physical measures analysed and the future weather files used in the investigation.

Chapter 7 summarises the findings and offers suggestions for further research in the field of climate change adaptation of retrofitted social housing. This chapter answers all the research questions presented earlier. The main finding of this research is that the retrofit done by IFORE in Rushenden reduces the future overheating risk when using the 2030s high emission scenario with 90% of probability. The use of white and opaque internal roller blinds combined with insect screens will eliminate the need for cooling in both case studies assuming that there will be a 2 °C increase in the average global temperature.

Chapter 2. Literature review

In the case, for example, of climate change, no place can be fully free from risk over the long term; the impacts will be felt by all present inhabitants of Earth and, further, by future generations.

Daisaku Ikeda, (2012), Environmental Proposal, Rio+20

2.1 Climate change risk assessment for the built environment

It is widely accepted that the world's climate is being affected by the increasing anthropogenic emissions of greenhouse gases into the atmosphere (DEFRA 2012). Even if efforts to mitigate these emissions are successful, the Earth is already committed to significant climatic change (IPCC, 2007). Due to the time lag between emissions and temperature rise, past emissions are expected to contribute an estimated further 0.2 °C increase per decade in global temperatures for the next 2-3 decades (IPCC, 2007), irrespective of mitigation efforts during that time period (DEFRA, 2012).

The Climate Change Act (2008) sets long- and short-term targets for the reduction of GHG emissions by 2050. However, it has been estimated that around 70% of the buildings, which will be in use in the 2050s already exist (UK Green Building Council, 2007). For the existing building stock it is vital to understand the impact of climate change before appropriate refurbishment and retrofit can be undertaken (DEFRA, 2012).

Climate change poses several potential risks to the built environment, due primarily to higher temperatures and changes in rainfall patterns (DEFRA, 2012). While warmer winters represent an immediate financial benefit, warmer summers present a danger because of the possibility of a massive uptake in air conditioning if no adaptation measures are put in place (DEFRA, 2012). Heating demand is projected to fall 15% by 2020, 30% by 2050 and 40% by 2080 under medium emissions scenarios, however, the demand for cooling is due to increase 50% by 2030, taking 2004 as the baseline.

Cooling degree days are projected to increase significantly during the twenty-first century, especially over Southern England. The 1961-1990 mean is simulated to be approximately 25 to 50 cooling degree days, whereas by the 2080s this has increased to between 125 and 175 (CCRA, 2012). The cooling demand will increase and this results in a potential rise from 0 in 2007 to 50 TWh per year by the 2050s for domestic cooling demand (CCRA, 2012). It must be stressed that these increases are primarily a response to increased wealth, although they do factor in future external temperature and climate change (CCRA, 2012).

A reduction in heating degree days results in a lower space heating demand and increased cooling degree days results in a higher cooling demand. The "UK climate projections science report" by DEFRA (2010) predicts changes to the climate by the 2080s in the UK, with all areas in the UK warming, more in summer than in winter. In parts of Southern England the average temperature increases by up to 4.2 °C as the mid estimate (between 2.2 and 6.8 °C at 10 and 90% probability levels, respectively). The summertime mean daily maximum temperature in parts of Southern England could increase by up to 5.4 °C (2.2 to 9.5 °C). Mean minimum temperatures could increase in the South by up to 4.1 °C in the summer (2 to 7.1 °C), and changes in the warmest day of summer range from +2.4 to +4.8 °C.

Precipitation in winter increases by up to 33% on the western side of the UK and in the summer decreases by 40% in the far South of England (50% probability). Relative humidity decreases by around 9% (-20 to 0%) in Southern England and the summer mean amount of cloud decreases by up to 18% (-33 to -2%) in parts of Southern England. It is very unlikely that an abrupt change in the Gulf Stream will occur this century (DEFRA, 2012).

2.1.1 Green areas

Building overheating and the Urban Heat Island effect are closely related to the effectiveness of green spaces (DEFRA, 2012). Spatial planning can make a big contribution both in terms of mitigation and adaptation and the role of green infrastructure can encourage designers to create environments where people want to live and work (DEFRA,

2012). Green spaces can offer cool shelter in the event of heat waves and help cool down the indoor environment through evaporative cooling. Green spaces can also improve flood resilience (DEFRA, 2012); the ASSCUE project (Gill *et al.*, 2007) showed that adding 10% green cover to areas such as the town centre could result in a cooling impact in the range of 2.2-2.5 °C.

Tree coverage was highlighted as a key means of providing shade and cooling effects. Recent work by CABE has sought to quantify and monetise the cooling capacity of green space (CABE, 2009) in producing a green infrastructure valuation toolbox (DEFRA, 2012). This work suggests that a 3% energy saving for each residential property within less than ten metres of trees is attributable to the shelter provided by the tree canopy (DEFRA, 2012). The shading effect of trees can therefore be tested in Rushenden.

Due to progressive relative aridity, the effective green area is due to shrink by 30% by 2080s under the medium emission scenario. The evaporative cooling effect of green areas is well recognized in reducing the requirement for air conditioning. Recent research funded by DEFRA identified several knowledge gaps in this area (Forest Research, 2010). "More detailed, statistically valid experimentation is necessary to improve understanding of the mechanisms by which vegetation cools the surrounding environment" (Bowler *et al.*, 2010). Recent research for DEFRA and the DCLG identified several knowledge gaps in the research field of green space and its potentially beneficial role in climate change adaptation (CCRA, 2012). In this dissertation the author explores the cooling effects of trees.

2.1.2 Fuel poverty and health concerns

Thermal comfort, or lack thereof, can have serious health implications, particularly for vulnerable members of the population. The document "Health effects of climate change in the UK" (Kovats, 2008) establishes a threshold temperature of 32 °C as the maximum limit for the London region. Modern lightweight insulated building envelopes and buildings with excessive south- and west-facing windows have the greatest risk of overheating. Older buildings, which have high thermal mass and smaller shaded windows, would be generally less vulnerable (DEFRA, 2012). The houses in Rushenden have a brick

and block construction, were built between 1944 and 1965 and in some cases have shaded windows. This study seems to suggest that the risk of overheating in Rushenden is lower than it is for more recent buildings with a lightweight construction.

Mixed mode buildings designed with passive cooling devices and back-up mechanical cooling are due to become more widespread. The adaptive comfort approach is not considered in the analysis reported by the Climate Change Risk Assessment (2012). To define the overheating risk for the built environment, the assessment use the temperature thresholds of 26 °C set up by CIBSE. The assessment uses external temperature as a proxy for indoor thermal comfort in naturally ventilated buildings. If the indoor comfort temperature related to the running outdoor mean, as suggested by Nicol *et al.*, (2008) in the adaptive comfort algorithm, were adopted by CIBSE the results presented by the CCRA would be different (CCRA, 2012). This aspect of the assessment suggests the use of the adaptive comfort approach in the calculation of the overheating risk in the specific case study of Rushenden.

"In terms of fuel poverty, present metrics focused on winter heating demands may need to be revised to consider cooling demands as well. This may be especially true for the elderly in providing assistance in summer heat events as well as in supporting energy efficiency programmes to reduce fuel costs in winter" (CCRA, 2012). The majority of the residents in Rushenden are currently elderly and in fuel poverty. They are therefore highly vulnerable to heat waves. In the future, the temperature rise and the consequent decrease in heating demand may help reducing fuel poverty in the winter, especially if the houses are retrofitted. On the other hand, the rise in cooling demand in summer may become a heavy burden that plunge them back into fuel poverty. The above statement from the CCRA therefore suggests that in this dissertation, the assessment of the future summer fuel cost of cooling is carried out for Rushenden.

2.2 Environmental context

The research activities carried out to answer the main questions of this thesis are: a literature study, thermal modelling, monitoring, survey questionnaires and consultation with the residents. The literature study includes topics related to retrofitted social housing in the UK and in Europe, the social context and the wider scientific and environmental context. It encompasses the 3 pillars of sustainability: environmental, social and economic.

2.2.1 Social housing context

There were 26.4 million households in the UK in 2012 (Office for National Statistics, 2012). Local authorities own 1.7 million homes while housing associations own and manage 2.4 million social rented homes in England (HM Government, 2011). This corresponds to around 16% of the total housing stock. "The majority (82%) of housing association homes were built after 1945" (DCLG, 2015). Among all social dwellings 1,289,000 were built between 1945-1965, including the Rushenden terraces. Most social housing homes are flats. Followed by terrace houses that total 1,322,000 dwellings, of which 547,000 are end-terraces, 775,000 mid-terraces, and 448,000 are bungalows. The floor areas of all dwelling types are less than 50 m² in 969,000 of the dwellings, between 50 m² and 69 m² in 1,402,000 dwellings, and between 70 m² and 89 m² in 1,244,000 (DCLG, 2015). The single storey houses in Rushenden belong to the second category and the two storey houses are part of the third group.

Overall, 9.6 million dwellings had cavity wall insulation in 2013: 48% of homes in the social sector (equal to about 1,956,000 dwellings), 44% of owner occupied homes and 24% of those in the private rented sector (DCLG, 2015). The majority of dwellings with cavity wall insulation was therefore in the social housing sector. 70% of the social housing sector or about 3 million dwellings had cavity walls. "The other types of wall structure include solid masonry, concrete, steel or timber, all of which are more difficult to insulate than cavity masonry walls" (DCLG, 2015). As an exemplar Rushenden is compelling since, having insulated brick and block cavity walls, it is representative of the majority of dwellings among all social housing in the UK. In 2013, 47% of all housing had 200 mm of

loft insulation. This includes the retrofitted terraces in Rushenden. The majority of UK housing in 2013 (70%) was in bands D and E. Before the retrofit the Energy Efficiency Rating Bands (EERB) in Rushenden were also D and E (see Appendix).

The total UK population was in 2013 equal to 64.1 million. Ten million people in the UK are over 65 years old (UK parliament, 2010), this corresponds to around 16% of the total population. The latest projections predict 5.5 million more elderly in 20 years time and 1.9 million, almost double in 2050 (UK parliament, 2010). In 2013-14 most common in the social rented sector were households containing a householder aged 65 or over (28% or 1.1 million) (DCLG, 2015). Therefore, currently the percentage of the UK population over 65 living in social housing amounts to 10%. This figure is destined to increase in the future with the prospect of an ageing population. One fifth (19% or 738,000) of social rented households included a householder aged 16-34, with 18% aged 35-44 and 20% aged 45-54. In Rushenden the percentage of elderly is higher than the national average as will be described later - in the Methodology Chapter (3) a case study illustrates a possible future demographic scenario considers an ageing population.

In 2012 there were 18.2 million families in the UK. Of these, 12.2 million consisted of a married couple with or without children (Office for National Statistics, 2012). The majority of families, 47% had only one dependant child at home at the time of the survey. 39% of families had two dependant children and 14% had three or more dependant children (Office for National Statistics, 2012). Dependant children are those living with their parents and either aged under 16 or between 16 and 18 and in full time education, excluding children aged between 16 and 18 and having a spouse, partner or child living in the household (Office for National Statistics, 2012). Among all tenures in the social rented sector, 8% are one family households with no children, 13.2% with children and 9.5% with no dependant children are (Office for national statistics, 2011). The majority (41%) of single parents with dependant children lives in social housing. Of all social renters, 23.5% are in full time work, 13.2% are in part time work and 8.6% are unemployed (DCLG, 2015). In 2013-14 the majority (41%) of the social rented dwellings were occupied by a single person, 26% by two people, 15% by three people, 10% by four, 5% by five and 3% by six or more people.

2.2.2 Intelligent Energy Europe (IEE) projects

NIRSEPES (New Integrated Renovation Strategy to Improve Energy Performance of Social Housing) had the goal to increase thermal efficiency by at least 30% by developing an integrated strategy for energy renovation in social housing. The project started at the beginning of 2006 and ended at the end of 2007. A key result is that a flexible, integrated and participative approach is expected to bring positive results in social housing retrofit. Activities targeted at raising awareness and educating residents were carried out through local forums with the aim of identifying the key issues and discuss the possibilities of energy retrofitting (NIRSEPES brochures, 2007). A participative approach was also adopted by IFORE and by the author in this thesis.

NIRSEPES analyses existing typical buildings in Spain, Greece and Germany with a view of comparing technological solutions for retrofitting and its cost-effectiveness (Intelligent Energy Europe, 2015). Key findings include minimal or no cost, low cost and moderate to high cost measures for heating and cooling loads reduction. Among the solutions for reducing the heating load there is thermal insulation of walls and ceilings, the replacement of windows and the installation of passive solar systems. It is suggested in the project brochure (2007) that natural ventilation/night ventilation can achieve a reduction of the cooling load by up to 20%. External shading of openings to the east, west and south orientations can reduce the cooling load by 20-30% and the installation of ceiling fans can further reduce the cooling load by up to 50%. The use of vegetation on roofs, facades and trees surrounding the buildings is suggested as a low-cost solution (NIRSEPES brochures, 2007). These common adaptation measures have also been tested within the case studies of Rushenden.

By 2020 all new buildings in Europe will have to comply mandatorily with the nearly zero energy buildings directive (nZEB) (Diacon and Moring, 2013). Powerhouse Europe (2012-2015) analyses selected case studies in Europe with the aim to establish best practice solutions for nearly zero energy social, public and cooperative housing. The project established four inter-Europe taskforces representative of different climatic regions, to carry out cost and consumption data analysis with the aim of building capacity and

confidence (Intelligent Energy Europe, 2015). The first taskforce worked on cold continental climates and the second on warm Mediterranean climates.

Some of the key findings of the first taskforce relate to concerns about the hidden cost of increased air-tightness. The additional costs of insulation and air-tightness with heat exchange for very low energy new buildings and passive houses add up to 6.7% for small buildings and 9.7% for large (compact) buildings and cannot be compensated by energy savings in the long run (Bauer and Vogler, 2013). Passive buildings differences in consumption are very small, cost implications will therefore play a big part in the definition of optimal standards of nearly zero energy buildings. Austrian housing associations prefer "simple" low energy buildings without the need for automated ventilation, for cost reasons and the complication of technical systems (Bauer and Vogler, 2013).

"Home energy use accounts for 25% of total energy consumption in the EU" (Diacon and Moring, 2013). The second taskforce reached similar conclusions to those of the first when solutions for nZEB social housing in warm Mediterranean climates were identified. Elements of the Passivhaus standard such as mechanical ventilation and highly insulated shells are inappropriate to warmer countries where there is a need for cooling (Pozzo *et al.*, 2013). The adoption of the Passivhaus standard can inhibit the benefits of thermal mass and cause excess heating in the summer months (Mediterranean House Manifesto, no date). Low-tech solutions that exclude mechanical ventilation in favour of the simple use of natural ventilation and thermal mass are suggested in the ten points Mediterranean House Manifesto (no date). The participation and education of residents is also an essential element of building nZEB in the Mediterranean.

It is suggested that the very stringent Passivhaus air-tightness target of 0.6 ACH at 50 Pa is very expensive to achieve and implies the use of a mechanical system. It was proved in Spain and Portugal that very low energy homes can be achieved without the need for active ventilation (Pozzo et al., 2013). The use of shading and external shutters is suggested to limit overheating. With a warming climate, northern European countries will experience temperatures relatively similar to those of the Mediterranean. The concerns expressed in relation to air-tightness, mechanical ventilation and super-insulation, need

to be taken into account when designing and retrofitting climate-resilient social housing in the South-east of England.

The Episcope project involves 16 countries and has the aim to improve the energy refurbishment process in the European housing sector (Intelligent Energy Europe 2015). EPISCOPE was launched in 2013 and was originally a three year project based on the previous IEE-funded TABULA database, a set of building typologies that identifies the most common types of housing by age and dwelling type for each country (Building 4 Change, 2/7/2015). Its scope has now been extended and includes the analysis of future scenarios of energy saving measures to meet energy and carbon targets in 2020, 2030 and 2050.

2.2.3 Current state-of-the-art on mitigation to climate change: UK low carbon retrofit initiatives

Recent retrofit initiatives include national competitions, several pilot projects run by housing associations and international projects. Several examples of retrofitted social housing were part of the competition "Retrofit for the Future" organized by Innovate UK. The competition was launched in 2009 and fully funded the retrofit of 86 social houses throughout the UK (Innovate UK, 2013). The project's goals were to set an example of retrofit throughout the country and cut carbon emissions by 80%, in line with the UK government's target (Innovate UK, 2013).

The Merton Parity Projects venture was commissioned by the London Borough of Merton in 2010 with the aim of analysing the potential for retrofitting the total housing stock in the borough (Parity Projects, 2010). The report produced by Parity Projects presents a thorough analysis of the entire housing stock of the borough, indicates basic retrofit measures for each house type and the corresponding payback times. The housing stock in Merton was built between about 1905 and about 1935 (Parity Projects, 2010) and it is therefore older than the stock in Rushenden. The three most significant building types in the borough are: terraced and semi-terraced houses, detached houses and flats in large blocks. The vast majority of the stock has a building fabric of solid brick wall. The stock

includes a small percentage of dwellings with empty or insulated cavity walls and new-build constructions.

As well as presenting retrofit measures such as adding cavity, internal or external wall insulation and analysing the carbon reduction that these measures provide, the report indicates that the occupants' behavioural change has the potential to reduce carbon emissions by 34%. This reduction was measured across different heating regimes and thermostat temperatures. Parity Projects also includes some renewable energy systems such as photovoltaic panels and analysed the benefit that the UK feed-in tariff would present to the residents and the project as a whole. The stock analysed totalled 78,056 dwellings, a much larger sample than IFORE. The occupancy profile for each dwelling type is not presented in the project's report. The payback times were calculated assuming that energy prices will not rise in real terms in the future (Parity Projects, 2010). Increases due to inflation are included in their calculation. The same assumption was made in the IFORE assessment when the payback times were calculated.

The Bristol retrofit project by Arup (2009) looks at the potential for retrofitting the private housing stock in the Bristol area. The dwellings types include Georgian and Victorian houses and terraces and flats, terraces, semi-detached and detached houses built between 1900 and 1980. The building fabric of the different types is derived from SAP (Standard Assessment Procedure) and it includes cavity walls which were generally introduced around 1930 (Arup, 2009). The study includes the implementation of standard retrofit measures such as cavity, external and loft insulation and draught proofing. The retrofit measures are assembled into four packages and then applied to the different house types consecutively. Three-bed detached houses built in 1945-1980 with cavity walls achieved the greatest carbon savings. The assessment includes an analysis of the cost of retrofit but does not calculate the return in investment.

A number of housing associations, Affinity Sutton, Gentoo and Worthing Homes have championed the retrofit of their building stock. The latter has developed the Relish project (Relish, 2014) in partnership with the University of Brighton. It involves the low-cost retrofit (£6500 per house) of social housing and it focuses on the importance of energy advice and the occupants' education programme.

The DEMScot project (CAR, 2009) studied the potential for retrofitting the Scottish housing stock and looked at the future of the houses up to 2050 and at future energy costs. It performed a cost–benefit analysis and calculated payback times. The age of the dwellings ranges from 1900 to 1997 and includes high performance new and upgraded dwellings. The most common wall constructions are solid walls and unfilled cavities. It is not clear from the project's report however, what percentage of the housing stock has cavity walls, solid walls or other wall construction. The dwelling types considered are: terraced house, semi-detached house, bungalow or detached house, tenement and flat. The housing stock was comprised of 2,291,414 dwellings in 2006 and includes social and private housing. The list of upgrades include, among others, cavity wall and loft insulation. The cost-benefit of each measure was estimated using a nominal discount rate of 10% by installing each measure individually in 2009 and discounting the future energy savings (CAR, 2009).

The IFORE project, inspired by the Retrofit for the Future competition and led by the University of Brighton has the ambition of leading the social housing retrofit process in Europe. The aim of IFORE is to reduce the carbon emissions of 100 social houses in the UK and 100 in France by 80% (McEvoy and Sdei, 2012). IFORE is achieving this retrofit target by the use of both traditional and innovative technical solutions and the education of the residents. In the UK a Green Doctor is a trained professional specializing in sustainable education who works with local residents. Also, an onsite occupants' engagement team informs the residents about energy reduction and involves the children of the community in order to leave a long-lasting legacy. IFORE offered the author a unique opportunity to work with a real community and test some adaptation measures targeted at social housing in the South-East. This was possible thanks to the existing structure in place in Rushenden and the willingness of the residents to participate in the study.

2.2.4 Current state-of–the-art on adaptation to climate change

While there is a large amount of regulation of how to mitigate the impacts of climate change, there is little on how to adapt buildings to a changing climate (Shamash, 2012). This is why, in terms of climate change adaptation, several projects funded by Innovate UK and various other government bodies have recently explored aspects related to this

subject. The UK Climate Impact Programme, funded by DEFRA, commissioned several reports on the subject of climate change adaptation. These studies form the basic references of this research. There is confusion about the role that insulation and air-tightness have in reducing (or increasing) the overheating risk. The author clarifies this matter in the Results and Analysis Chapter (5).

In 2005, Arup published the "Beating the heat report" that offers an overview of EU climate change adaptation strategies. It uses UKCP02 (UK Climate Projections 2002) to assess several case studies, among which are two residential buildings, using London, Manchester and Edinburgh weather data. It calculates numbers of occupied overheating hours using a temperature of 25 °C in bedrooms and 28 °C in the rest of the house, and proposes shading, high thermal mass, improving insulation and air tightness as the best strategies to reduce overheating in buildings. The two dwellings used as case studies are generic types: the first one was built using late 19th century standards and the second meets the 2002 Building Regulations (Arup, 2005). The 19th century house has four bedrooms and is semi detached. It has a brick and render façade and a medium weight - solid wall structure, it is not insulated and has poor air-tightness (Arup, 2005). The new built house has also four bedrooms and is detached. It has an insulated cavity wall structure and good air-tightness.

Both houses overheat considerably in the future and exceed the comfort threshold. The 19th century house overheats more in the bedroom and less in the living room than the new built house. Solar shading and mechanical ventilation (6 ACH) are applied to both models. The comfort threshold is failed in the bedroom of the 19th century house in 2020s and met in the new built house. The report states that this is due to the effects of the better insulation and air-tightness in the new built house. However, the new-build house is detached and has therefore an extra exposed surface that might help to dissipate the heat through air infiltration, convection and radiation.

The CIBSE TM36 report on "Climate change and the indoor environment: impact and adaptation" (2005) uses UKCP02 for the analysis of case studies of four residential building types. They are: 19th century semi-detached house, two storey new built house with three levels of thermal mass, 1960s flat and new built flat. The first two case studies

reported here are the same examples analysed in the "Beating the Heat" report by Arup (2005). The temperature thresholds for the analysis and the adaptation strategy adopted is also the same. The analysis is carried out using weather files for London, Manchester and Edinburgh.

The report also includes a graph of the energy required for cooling a medium thermal mass new-build house. In the un-adapted new-build house with high thermal mass the overheating hours are substantially lower than in the medium and light-weight examples. However the benefits of thermal mass fade as the temperature warms. When the shading and ventilation are applied the benefits of having high thermal mass are restored. The solar shading is very effective especially in the case of the high thermal mass house (CIBSE, 2005). The living room of the adapted high thermal mass house does not overheat up to 2050s, the bedroom however does overheat because of the lower threshold. It is now being recommended that the CIBSE Design Summer Years (DSYs) data are used to assess overheating risk as they provide a more stringent test of overheating risk than CIBSE's Test Reference Years (CIBSE A, 2006).   However, this document has been superseded by the CIBSE publication called TM52 (Nicol et al., 2013) on "The limits of thermal comfort: avoiding overheating in European buildings" that will be described later.

Recently, the Adaptation Sub-Committee published a progress report called "Managing climate risk to well-being and the economy" (2014) that includes a section on well-being and public health. This section includes several studies on climate change adaptation including heat related mortality and morbidity estimates. "The effects of increased mean temperature and population growth are projected to increase deaths in summer to approximately 7000 per year in the 2050s across the UK" (ASC, 2014). These estimates take account of a growing and ageing population but do not consider the "physiological adaptation that is likely to occur in response to gradual increases in summer main temperature" (ASC, 2014). Physiological adaptation is included into the adaptive comfort equations used in this thesis to calculate the overheating hours. With the prospects of an ageing population, more vulnerable people will be at risk in the event of heat waves in the future. Rushenden, with a percentage of elderly residents above the national average, represents a possible future snapshot of what reality in South-East England may be a few years time.

2.2.5 Climate data

The EPSRC (Engineering and Physical Sciences Research Council) funded a team based at the University of Exeter to work on the Prometheus project (Eames, 2010). The team used the UK Climate Projections 2009 data (UKCP09) in order to generate weather files that are suitable for use in building simulation programs (Mavrogianni, 2012). Hourly weather files, available online for downloading from the Prometheus project website, have been developed on a 5km grid over the UK (Eames, 2010), however, due to their probabilistic nature, that ranges from 10% to 90% and the different number of scenarios, there are 30 files plotted against each available location. It is therefore a challenge to choose which files to use in a modelling program to predict the impact that climate change will have on buildings.

There are various choices to be made about which climate data to use for research. The ProCliP KTP project, co-funded by CIBSE and UKCIP developed a method to aid weather data selection for use in design proposals (Shamash, 2012). ProCliP provides a number of graphs for different UK locations; a range of time periods; low, medium and high emission scenarios and five probability levels. The probabilistic climate profile (ProCliP) graph helps designers and engineers to obtain an initial review of climate projections at an early stage of the design process and to choose the most appropriate climate file during the modelling process.

The "Design for Future Climate" programme was launched in 2010 by Innovate UK with the aim of adapting new and existing buildings to climate change. The projects included a variety of large-scale building types, among which were schools, offices and housing, but not social housing (Innovate UK, 2010). The architect, Bill Gething, prepared the initial guidance to the programme (Shamash, 2012), and the report produced provides a basic tool to understanding the issues related to climate change for the built environment in the UK. It shows in great detail the three emission scenarios; it gives a detailed description of what the UK climate will be like by the end of the century and describes the UKCP09. Most of this data has been used in the Introduction to describe climate change scenarios in the UK.

The "Design for Future Climate" competition was launched with the aim of facing the challenge posed by the future climate as projected by the UK Climate Impacts Programme (UKCIP, 2014). All the projects that won the competition used the latest UKCP09 data to carry out the essential climate change risk assessment for overheating. UKCP09 was funded by DEFRA and provides detailed projections of the UK climate to the end of the century (Shamash, 2012). The climate change projections as shown by UKCIP and UKCP09 are all coherent with the work carried out by the IPCC. These projections are used in the form of weather files generated by the University of Exeter (2010) to assess the case studies in Rushenden.

In the 2011 "Design for Future Climate" competition the majority of risk assessments were carried out using the weather files for the Design Summer Years, high emission scenarios and a probability of 90% (TSB, 2012). This is because the current slow response in reducing CO_2 emissions is resulting in researchers and designers planning for the worst case scenario; the software used by the majority being the IES virtual environment. In this thesis, the author adopts this mainstream consensus by assessing case studies using the high emission scenario and a probability of 90%. In order to reduce GHG emissions from social houses and make them future proof to the overheating risk, a combination of both low carbon and adaptive retrofitting is needed. The following examples show the benefits of this combination and include several reports and government funded research projects.

2.2.6 Insulation and air-tightness

The effects of several adaptation measures, including insulation and air tightness, and the main strategies used in low carbon retrofit, are analysed herein. Some sources state that insulation protects against overheating and can be used as a valid adaptation measure, however, other sources state that well-insulated houses will overheat more than badly insulated houses. The author will explore several research papers to clarify what the role of insulation and air tightness is in adaptive retrofit. Compared with the section above that describes climate change adaptation initiatives, the author found some contradictions within the role that insulation and air-tightness have on reducing or increasing the overheating risk. Part of the Results and Analysis chapter is devoted to

resolving these contradictions and clarify what the role is of insulation and air-tightness in climate change adaptation.

A number of research papers have been published on the subject of insulation and the possibility that it may increase the overheating risk. For example, Maldonado (2005) when referring to office buildings asserts that over insulating may increase cooling energy needs. Chvatal reports that in housing, increased insulation of the envelope increases the overheating hours when solar gains are high and the shading factor is below 50-60% (Chvatal and Maldonado, 2005). When shading is high, high insulation decreases overheating (Chvatal and Maldonado, 2005). When the building is ventilated at night it can accept higher solar gains and less shading because night ventilation removes the heat accumulated during the day.

The paper "Control of overheating in well insulated housing" (Orme *et al*, 2003) focuses on residential buildings and shows, through the dynamic thermal modelling of four generic house types, semi-detached, detached, top floor flat and a town house, that the internal air temperature can be reduced by 2.5 °C below the external air temperature by using a combination of measures. The U-values assumed are as follow:

	W/m²K
Walls	0.25
Floors	0.16
roofs	0.22
Windows, glazed outer doors and roof lights	1.3

Table 2.1: U-values of building elements (Source: Orme *et al.,* 2003)

A first run of simulations was designed to measure the influence on overheating of surface density, solar protection, the percentage of glazing, glazing transmittance, thermal mass, thermal insulation, number of occupants, night cooling (fan), ventilation rate, roof albedo and heating demand. Different factors prove to have greater impacts in different rooms. The U-values adopted in the simulations are very similar to those of the retrofitted houses in Rushenden and they can be compared with those presented in the

Methodology chapter. The floor plans of the semi-detached house show cavity wall construction. It is not specified what level of air-tightness is used in the simulations. There are three levels of ventilation, low medium and high. The paper implies that extra insulation increases the overheating risk.

The second run of simulations tested the most important factors: solar gain, thermal mass, ventilation and incidental gain. In both the semi-detached and the detached houses a combination of all measures: high thermal mass, night cooling, solar shading, reduced internal gains, high roof albedo, is the most effective for all rooms. In the detached house, solar shading with external louvers results in the biggest reduction in overheating hours. The paper proves that high insulation increases overheating and that it was not possible to completely eliminate overheating in well-insulated dwellings. However, by applying a combination of measures the number of overheating hours becomes less than that of a dwelling built to 2002 Building Regulation standards.

The U-values used in the simulations are lower than those from 2002 Building Regulations and therefore are representative of a possible future when better insulation standards will be common practice in dwellings. The paper shows that the increased overheating risk of well insulated housing can be counteracted by a combination of adaptation measures. On the other hand, in "Estimating the impact of climate change and urbanization on building performance", Crawley (2008) states that low energy buildings will be the least affected by climate change with an impact of 10-15%. This is a contradiction that the author has clarified in the Results and Analysis Chapter (5) by simulating the effects of insulation and air-tightness on the overheating hours and cooling loads in Rushenden.

Mavrogianni A. *et al*, (2012) used dynamic thermal simulation (Energy Plus) to model 3456 combinations of dwelling types and characteristics representative of the London domestic housing stock. All buildings built before 1960 were modelled with solid brick wall and those built after 1960 with cavity wall. The air-tightness levels were specified as a function of age and the number of occupants in each dwelling as a function of the habitable areas. Since the terraces in Rushenden were built in 1945-64 and have a cavity wall structure it is difficult to compare them with those presented in this paper. However,

this study offers some indication of the effect of the insulation applied to the different building elements on the overheating risk.

The CIBSE Design Summer Year (DSY) weather data for London was used in the simulations to establish the base case and that was compared with the results using the weather data from the Prometheus website for the 2050s and a medium emission scenario with a probability of 50%. The method used was to model first the house types using the standard CIBSE DSY weather data and then show the effects of a low carbon retrofit on summertime overheating.

Mavrogianni found that the buildings that overheat considerably more than others are those built between 1914 and 1945. The combination of external insulation, retrofitted windows and loft insulation reduces average daytime living room temperatures by 0.76 °C. On the other hand, wall insulation and to a lesser degree floor retrofitting proved to increase living room temperatures. The combination of wall, floor, roof and window retrofitting is to decrease indoor temperatures, although in some dwellings the temperature increases.

Retrofitting of the roof/loft and windows only, however, appears to cause an overall reduction in overheating (Mavrogianni, 2012). She proved that the installation of some loft insulation slightly reduces the overheating risk, while wall insulation, especially internal wall insulation, increases it. "The most interesting finding that emerged from this analysis is that insulation interventions appear to reduce overheating risk" (Mavrogianni, 2012). However, in some cases, wall insulation increases the overheating risk of this stock since most of the houses have solid walls and the dwellings were insulated internally. In this case the use of night time ventilation is suggested. For this research it is very important to note that the results from the models, using climate change weather files, show that the impact of low carbon retrofitting measures on summer seasonal internal temperatures is limited (Mavrogianni, 2012).

Magrovanni's research contradicts the studies by Chvatal and Maldonado (2005) and Orme et al. (2003) that stated that better insulated houses are overheating more than poorly or non-insulated ones. The extent of air-tightness is not clear from the studies

analysed in this section since the value of the infiltration rate used in the modelling is not stated. The air-tightness level influences greatly the overheating risk and it is the combination of insulation and air-tightness that the author describes in more detail in the Results and Analysis Chapter in order to resolve these contradictions.

2.2.7 Lightweight versus heavyweight (thermal mass)

The report "UK housing and climate change" by Bill Dunster and Arup (2005) assessed the performance of lightweight versus heavyweight construction in housing. It suggests that summer behavioural patterns of people living in the UK will become closer to those of Southern Europe e.g. having an afternoon siesta. The use of high thermal mass that stores the heat during the day and releases it at night, when combined with ventilation, has been proved to significantly reduce indoor temperatures when compared with lightweight envelopes.

A four bedroom detached house built to the 2002 Part L Building Regulation standard of insulation and air tightness was modelled using three types of construction: lightweight, medium-weight and heavyweight (Arup *et al*., 2005). The house was assumed to be occupied by two adults and two children, unoccupied most of the day and occupied at the week end. The software used for the analysis was Energy 2, developed by Arup. The three models were run for London, Manchester and Edinburgh using UKCP02 medium and high emission scenarios for the 1980s, 2020s, 2050s and 2080s. The space operative temperature (average of the air and space surface temperatures) inside the heavyweight envelope is much more stable than in the other cases because of its high thermal inertia and is often below the peaks of maximum external temperature.

In terms of overheating hours, "in the living rooms, the performance improved broadly in line with the level of thermal mass, although all three buildings experience reasonably high percentage hours of overheating in at least one time slice. Significant levels of overheating of 28 °C (greater than 1% occupied hours) are predicted from the 1980s, 2020s and 2050s onwards, in the light, medium- and heavyweight cases, respectively. In the bedrooms there is much less difference between the thermal performances of the

three buildings. In fact, the lightweight house is marginally better than the other two cases, and the medium-weight house the worst.

This is because heat built up during the day is being retained during the day and reradiated at night in the heavier weight houses, while the lightweight building responds quite quickly at night to the cooling effect of ventilation air. However, all three buildings show significant levels of overheating of both temperature thresholds in all time slices including the 1980s." (Arup *et al.,* 2005). The houses in Rushenden can be compared with the medium-weight example.

Winter energy use by the 2080s is about 30% less of that used in the 1980s in all three cases. The heavyweight house has the highest heating energy use because of the slow response of the mass to an intermittent heating schedule. This latest result was also proved by the SNACC analysis and thermal modelling, which will be discussed later.

The adaptation options tested in all three types of house were controlled ventilation and solar shading. Cases in which 50% and 90% of the solar gain was excluded were also considered, e.g. as might be achieved using external blinds or shutters. A sensitivity analysis showed that the ventilation modelled, mechanical with a fixed rate of up to 12 ACH, was proved to be very effective in both the lightweight and heavyweight cases. Five ACH for given levels of shading was the threshold, after that an increase in ventilation proved to have little effect in reducing the number of overheating hours. In all cases the heavyweight house had the highest reduction in overheating hours.

The adaptation option that reduces solar gain by 95% and ventilates at 6ACH has the effect of dramatically reducing the overheating hours in both cases. The number of overheating hours remains relatively low up to the 2050s and the heavyweight house has the lowest percentage of overheating hours. In the bedroom, where before the adaptation the number of overheating hours was lower for the lightweight envelope, after the adaptation the heavyweight house has the lowest percentage of overheating occupied hours. This report proves that a house with a higher thermal mass benefits from a reduction in summer overheating, while it sees an increase in winter heating energy use (Arup *et al.,* 2005).

2.2.8 Cooling demand and the relationship between outdoor and indoor temperature

The paper "Forecasting future cooling demand in London" (Day *et al.,* 2009) shows that if CO_2 emissions from active cooling systems go unchecked, they could double by 2030 in London. The analysis was carried out for several types of air cooling systems: chilled beams, ground source heat pumps and bore holes. The paper analysed different scenarios of growth for the uptake of air conditioning systems, high and no climate change and improved efficiency. The analysis shows that a 10% uptake in mechanical cooling in the residential sector by 2030 could account for 10% of the total energy demand for the UK.

Although the residents of Rushenden are currently in fuel poverty, as the demand for cooling systems rises, the price of air conditioning equipment may fall. This may tempt the residents, especially the most vulnerable, to install an air conditioning unit or buy a portable cooling device to help them cope with heat waves. This action may not only be detrimental for the environment but also a threat to the health of the residents, as heat waves will be unpredictable, and the residents may well feel safe, when in actual fact they may not have enough money to run the unit to their needs. The paper proves that low-efficiency cooling systems as well as badly insulated houses dramatically increase total energy use. Due to the uncertainties associated with climate change, it is suggested here that high-efficiency cooling systems should be designed now instead of individual, low-efficiency units being installed when the need arises. The paper also highlights the need to develop good guidance on the best type of cooling system and establish a comparative environmental impact (Day *et al.,* 2009).

The paper "Changes in internal temperatures within the built environment as a response to a changing climate" (Coley *et al.,* 2010) shows that there is a linear relationship between increasing external temperatures due to climate change and the internal temperature. This means that as the external temperature increases, the overheating risk also increases linearly. "Over 400 different combinations of future weather, architecture, ventilation strategy, ventilation type (natural, mechanical and buoyancy driven stack ventilation), thermal mass, glazing, U-value and building use (house, school, apartment or office) were studied."

The scope of this work is to arrive at a set of coefficients that describe the response of any design to climate change. Lightweight and heavyweight envelopes with different thermal capacities were analysed and the thickness of insulation doubled to achieve a range of fabric thermal resistances from 0.11 to 0.44 W/m²K. Lightweight structures are more prone to overheating especially in the case of limited ventilation. "The form of the response to the perturbation of the weather file is always linear, regardless of the architecture, construction, ventilation type or use of building. Different buildings demonstrate different gradients and different climate change amplification coefficients" (Coley *et al.,* 2010). These coefficients enable one to carry out a cost-benefit analysis for different refurbishment options, however, it is not fully explained in the paper how they can be used for this purpose.

The paper identifies the response of all mechanically and naturally ventilated buildings. It investigates the response of a large number of buildings given a range of predictions of future climate (Coley *et al.*, 2010). It derives a set of coefficients that describes any design in relation to climate change, and suggests the use of these coefficients for the establishment of climate change resilience strategies. Future weather files were morphed using UKCP02 and the models were built with IES.

Two mathematical *climate change amplification coefficient* constants are defined: CT mean = δT internal mean / δT external mean and CT max = δT internal max / δT external max. They describe the response of any design to a changing climate (Coley *et al.,* 2009). As a result of the linear relationship between the two variables, if a building has, for example, CT mean = 1.5 and there is a 2 °C rise in the mean summertime temperature, then with great probability the increase in internal temperature will be 2 °C x 1.5 = 3 °C. It is suggested here that a CT mean < 1 could mean that the building is resilient. These coefficients are useful as they provide an initial idea of what the resilience to climate change is of a certain building fabric, type or use. However, this will not take into account the fact that a small increase in temperature over a long period of time could be potentially very dangerous for vulnerable groups of people (Coley *et al.,* 2010).

There is currently no agreement on design temperatures as a result of global warming. The IPCC fourth assessment report indicates that at mid-latitude there will be mean

temperature rises of ~4 °C over land under A1F1 (high emission) scenarios. However, research by Kevin Anderson (2011) suggests that these predictions underestimate the current emission trends and that the temperature rise could be far higher. Modelling by the Hadley Centre suggests that summertime temperatures such as the ones experienced in 2003 will be average by the 2040s (Anderson *et al.*, 2011). In this thesis the author has chosen to follow the mainstream way of thinking about future climate change as indicated by the IPCC. This is because all the research available on probabilistic future weather files follows this direction. This scenario has been adopted by the author when modelling the case studies in Rushenden and analysing their future overheating risk.

2.2.9 Shading

Nikoofard *et al.,* (2014) carried out a techno-economic assessment of Canadian housing and the effect of window shading on heating and cooling energy consumption and greenhouse gas emissions. In the assessment, Nikoofard *et al*. utilises ESP-r, the high resolution building energy simulation program also used by the author in this thesis. The space heating and cooling temperature set points were 21 °C and 25 °C, respectively.

In the paper, the Complex Fenestration Construction (CFC) model (Lomanowsky, 2008) is used to model venetian blinds. The base case house is assumed to be in Toronto and have no blinds, subsequently blinds were applied according to different parameters. The effects of slat angle, type, curvature orientation and control were evaluated.

Four different controls were applied to the shading:
1. In all seasons the blinds are closed during the night;
2. From October 8th to April 1st, the heating season, the blinds are open during the day;
3. From April 2nd to October 7th, the blinds are controlled using four different controls:
a. Automated lowering/raising of the blinds based on zone temperature;
b. Automated opening/closing of the blinds based on zone temperature with a change in slat angle;
c. Automated lowering/raising of the blinds based on the level of incident solar radiation;

d. Automated opening/closing of the blinds based on the level of incident solar radiation with a change in slat angle.

External blinds have the highest impact in reducing the cooling load, while internal blinds can increase the cooling load. Internal blinds always reduce the heating requirement, while external blinds increase or do not change the heating energy requirement. The implementation of external controlled blinds reduces the cooling load by up to 57% for a house located in Toronto, however it was found that external blinds also increase the heating load.

In conclusion the results of the simulations showed that "*adding ½ in. light aluminium venetian blinds on the indoors side of the windows with automatic control based on zone temperature would result in substantial reduction in energy and GHG emissions (2.3% of the Canadian housing stock)*". It was found that other types of shading can reduce the cooling requirements but can also increase the heating requirements (Nikoofard *et al.*, 2014).

Tillson *et al.*, (2013) in assessing the impact of summertime overheating identified some adaptation strategies for UK housing stock using SAP 2009 to carry out the calculation. The assessment was run using the data from the English Housing Survey 2009, which represents UK housing stock. It uses the static threshold of 28 °C to assess the overheating risk and the vulnerability of the housing stock.

It is useful to note that many shading types were assessed including simple net curtains, roman, venetian and roller blinds. There is a net increase in overheating when the age of the building and the construction of the external fabric changes from solid wall to cavity wall. Suggestions are made for using simple shading devices to retrofit existing buildings in preparation for climate change.

Akbari H. carried out extensive research in the United States since the 1990s about the potential cooling effect of vegetation, low albedo and trees. The experiments he carried out showed that the impact of shade trees in two houses in Sacramento resulted in a seasonal cooling energy savings of about 30% (Akbari, 2002). Huang *et al.*, (1997), showed

that increasing the urban tree cover by 25% can save up to 50% cooling energy in Sacramento. Saxena (2001) carried out a study using a new approach to the standard equations used by Huang *et al.*, (1987). He proved that the effect of evapo-transpiration from trees can result in a temperature reduction of up to 1.34°F when using the weather data for Phoenix, Arizona.

2.2.10 Total energy consumption and carbon emissions

The paper "Climate change and future energy consumption in UK housing stock" (Collins *et al.*, 2010) models, with many uncertainties, what the economic impact on households will be of climate change. It uses UKCP02 high emission scenarios (worst case) that assume a mean global temperature rise of 3.9 °C to model energy consumption up to 2080 (Collins *et al.,* 2010). Using the IES virtual environment they show that heating will continue to be the major load up to 2080 and changes in CO_2 emissions are very much more modest (Collins *et al.,* 2010).

The IPCC has highlighted that occupant behaviour or culture and consumer choice are major determinants of energy use in buildings (Collins *et al.*, 2010). It can be assumed that as the temperature in the UK will become as hot as it is in Southern European countries the use of air conditioning will be as widespread here as it is there (Collins et al 2010). Six dwelling types representative of the UK housing stock were modelled.

The modelling assumptions for the infiltration rate are fixed at 0.45 - 0.9 ACH; for the ventilation rate when the windows are open the models assume 1.0 - 2.5 ACH throughout. An average of the casual gains of different types of dwelling was used in order to generate heating and cooling loads representative of the national housing stock. The study includes a sensitivity analysis to changes in location, occupancy times, U-value, ventilation rate and temperature control set point. Simulations were run using future weather files to understand the changes in heating and cooling demand (Collins *et al.*, 2010).

The authors conducted studies to analyse the effect of regional climatic conditions, different occupancy patterns (family, single person), different house types and fabrics,

changes in natural ventilation provisions and heating set point temperatures. All models were given 1996 Building Regulation U-values as determined in the 40% house project (Collins *et al.,* 2010). The 40% house project was funded by the UK Tyndall Centre for Climate Change Research carried out by Boardman *et al.,* (2005). It studied the potential to achieve a 60% reduction of carbon emissions in the UK residential sector so that the typical house becomes a "40% House" (Boardman *et al.*, 2005).

CO_2 emissions are proven to fall by the 2050s because of the reduced heating load and remain stable throughout the 2080s because of the increase in cooling needed (Collins *et al.,* 2010). CO_2 reduction is very sensitive to occupancy pattern; reduced occupancy can reduce CO_2 emissions by up to 25%. The detached house, which is the largest consumer of energy, has the largest rise in cooling load and the highest fall in heating load by the 2080s. The purpose-built flat has the lowest consumption. The semi-detached house, the most common type in the UK, is between the two. All types have a gradual reduction in CO_2 emissions between the 2050s and 2080s.

Although an improvement in U-values results in lower heating emissions, cooling emissions are the same for non-retrofitted and retrofitted houses. Changing ventilation rates from 1ACH to 2.5ACH appears to have no effect on cooling demand, while the lowest ventilation rate reduced the heating demand by 30%. When increasing the cooling set point by 3.5 °C, the total CO_2 emissions reduce by 9% (Collins *et al.,* 2010).

Nationally, an uptake of air conditioning in 50% of the domestic buildings will nonetheless cause total CO_2 emissions (heating plus cooling loads) to reduce by 10% by the 2050s. The sensitivity analysis showed that occupancy time, ventilation rate and cooling set point temperature can be applied in an additive manner, and climate change does not influence the relationship between them. A variation of the above factors produces a great deal of difference in final CO_2 emissions, therefore dwellings in the same location and with similar construction can have very different energy consumption figures. The modelling assumes that no adaptation strategy is used (Collins *et al.,* 2010).

The above calculation presents many uncertainties; it uses a CO_2 conversion factor for electricity by the 2050s, which is lower than the current one but higher than that

predicted by the Committee on Climate Change. The proliferation of domestic air conditioning units in the USA shows that a rapid growth over a short period of time is also possible in the UK (Collins *et al.,* 2010) because a sudden rise in summertime temperatures could trigger the easy option of buying air conditioning units.

The ECODESIGN research project indicates that the uptake of reverse air source heat pumps will become popular in the UK and the sale of cooling only units negligible by the 2030s (Collins *et al*., 2010). Collins *et al*., indicates that as climate change occurs, heating demand will reduce 20% by the 2050s without any improvement to the current housing stock (Collins *et al.,* 2010). The challenge should be focused on reducing the heating energy demand of the existing building stock without compromising the design for increased cooling demand.

The sensitivity study showed that a well-insulated house was not significantly better at protecting against overheating than a poorly insulated one. By the 2050s, carbon emissions from space heating and cooling in dwellings appear to decrease by 10%. These levels rise again by the 2080s. The increase in domestic cooling will cause an increase in demand for the power network. If 50% of the households in the UK take up air conditioning, this will equate to 4TWh/year of electricity demand.

2.2.11 SNACC and CREW

The EPSRC funded a number of projects through the Adaptation and Resilience to a Changing Climate (ARCC) programme. One of them was the Prometheus project, which created weather files derived from UKCP09 (Shamash, 2012). The CREW and SNACC projects, the main references of this thesis, both touch on adapting retrofitted housing to climate change.

1. CREW (Community Resilience to Extreme Weather) was launched in 2008 and ended in 2011. It involved 14 Universities in the UK, used five south eastern London boroughs as case studies and investigated the opportunities and limitations of local communities' adaptive capacity (CREW project website) and the impact of adaptation on the communities studied. CREW generated

systematic, quantitative and holistic guidance for retrofitting UK dwellings to reduce overheating risk during heat waves, whilst at the same time minimising winter heating energy and considering the cost of retrofit (Shao, 2012).

The project team based at De Montfort University looked at four house types built using different construction methods typical of UK housing stock. The types studied were: a 19th century terraced house, 1930s semi-detached house, 1960s flat and a modern detached house. The study area was the South East of England, which is the UK region predicted to be at the greatest risk of overheating under future climate scenarios (Porrit, 2010).

All the building types were tested for daytime occupancy (elderly) and evening occupancy (families). The research found that overheating exposure will be greater for residents that are at home during the daytime, i.e. the elderly, unemployed and infirm. Overheating exposure of daytime occupied buildings could be over twice as much as that of daytime unoccupied buildings due to longer occupied hours (Shao, 2012). It indicates that the types of dwelling most vulnerable to overheating are the 1960s top floor flat and the detached house built in 2006. "Basically, top floor flats overheat due to excessive gains through the roof and modern houses overheat because heat is trapped in the house, as do highly insulated retrofit" (Shao, 2012). The project advocates the use of both mitigation and adaptation measures in design practice and regulation.

Tested mitigation measures include external and internal wall insulation, loft insulation and low–e triple glazing. Adaptation measures in combination with mitigation are light-coloured painted walls and roof, internal blinds, external shutters, curtains and night ventilation. Behavioural adaptation such as the "window rule", keeping windows closed when the outdoor temperature exceeds the internal temperature reduces heating exposure in the dwellings by 30% (Shao, 2012).

For semi-detached, terraced houses and ground floor flats, the CREW modelling work carried out with Energy Plus proves that overheating can be eliminated by using a combination of adaptation measures. Low-cost adaptation, such as light-coloured painted walls and roof, can increase heating energy in the winter. External insulation can reduce both overheating in the summer and heating load in the winter. A cost-benefit analysis of

the adaptation measures shows that a spend of £10,000 can result in a 90% reduction in overheating and over a 40% reduction in heating energy use. For the other types of dwelling, the top floor flat and the detached house, overheating exposure could not be eliminated using any of the combined adaptation measures. "The modern detached house is already well insulated and it is much harder to find adaptations that would lead to a reduction in winter heating energy use". The cost of adaptation options is dramatically higher (Shao, 2012).

The project's final report states that highly insulated retrofit can trap the heat in the house if is not combined with solar control and other measures i.e. ventilation, especially in the case of dwellings occupied during the day. The retrofit advice web toolkit (Figure 2.1) can help in deciding on the optimum combination of adaptation measures. It draws graphs of scattered plots where the percentage reduction or increase in energy use is indicated for each chosen combination of adaptation (and mitigation) measures. The tool also gives advice on the cost of each package of measures.

The U-Values of the houses in Rushenden retrofitted by IFORE are lower than those indicated by Part L of the 2006 building regulations. That means that, following the reasoning and outcomes from CREW the retrofitted houses may overheat more than the un-retrofitted ones. CREW suggests the use of adaptation measures to counteract the effects of insulation and air-tightness. The measures used are generic and not specific to any real community in the UK. However in this study it is not clear what element of the building structure is actually causing the overheating, whether it is the insulation or the air-tightness. The case studies in Rushenden are used herein to clarify this relationship and to investigate specific measures to adapt retrofitted social housing in the South-East.
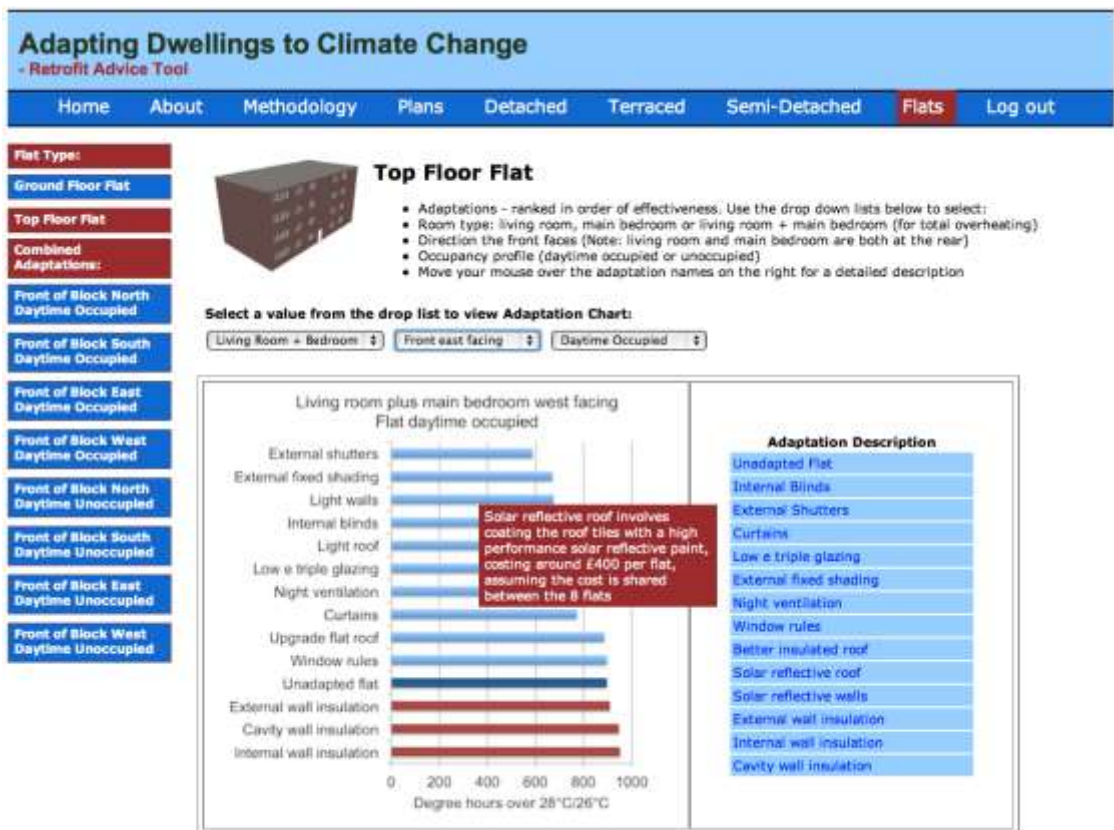
Figure 2.1: CREW retrofit advice web tool, (Source: CREW, no date)

"Most importantly this research work proves that if existing housing is retrofitted to the standard of detached houses built to 2006 Building Regulations in terms of insulation and air tightness, they will overheat as much as the latter. It is therefore essential to integrate the adaptation with mitigation and carbon reduction in order to avoid having a building stock, which is hard to retrofit and more expensive to adapt at a later date. It will be cheaper and it will prevent the risk of the quick–fix air conditioning option to integrate the mitigation retrofit with the adaptation" (Shao et al., 2012).

CIBSE guide A, the reference document in terms of regulation, published in 2006, recommends that for domestic properties the comfort threshold temperature of 26 °C for bedrooms and 28 °C for other living areas should not be exceeded for more than 1% of the occupied time (Porrit, 2010). "The problem with this approach is the lack of severity of overheating, because 1h at 29 °C would appear to be as bad as 1h at 35 °C" (Porrit, 2010).

CREW suggests an alternative to the way overheating hours are calculated by CIBSE and uses the method of degree hours where each degree centigrade over the threshold for an hour counts as an overheating hour (Porrit, 2010). The effect of a range of single and clustered interventions is then investigated. External shutters, followed by light-tinted walls and the window rule are the most effective single adaptations for the end-of-terrace house. "External insulation consistently outperforms internal insulation for total overheating exposure in all dwelling types, occupancies and building orientations considered" (Porrit, 2010). External and internal wall insulation is therefore used as an adaptation option that reduces the number of overheating hours. The paper implies therefore that the air-tightness can increase the overheating risk. This point is clarified by the author in the Results and Analysis Chapter.

In a Victorian terraced house, external insulation reduces the overheating hours by up to 43% and internal insulation reduces the overheating hours by up to 20% (Porrit, 2010). Internal insulation could lead to worse overheating in some cases and increase the overheating hours by around 20% compared to the base case of an end-of-terrace house with a living room with a west-facing window. However, internal insulation still has a role to play when combined with other adaptation measures (Porrit, 2010)

2. The SNACC project (Suburban Neighbourhood Adaptation for a Changing Climate) was launched in 2009 and ended in 2012. It involved the University of the West of England, Oxford Brookes and Herriot Watt Universities, White Design and Arup. SNACC (Williams *et al.*, 2012) identified six case studies taken from the three suburbs of Bristol, Oxford and Stockport. It tested over 100 adaptation options and established why adaptations are / are not being implemented. The residents of the six case studies were involved in a participative process through questionnaires and focus groups, as will be discussed in the following section.

The Oxford Brookes team has worked on the combination of adaptation and mitigation options in housing. At the end of 2012 they published and presented their final report "Suburban neighbourhood adaptation for a changing climate" (Williams *et al.*, 2012). Oxford was selected for the case study because of its location in the South East of England, the area predicted to be at a higher risk of overheating. The team carried out an

analysis of the overheating risk and established the extent of potential for overheating and variation in space heating (Gupta, 2012).

The project structured the climate change risk into hazard, vulnerability and exposure. The hazard is the potential for a climate change event to happen; exposure is the location and vulnerability is the impact on people, the elderly for instance. Four house types were investigated using IES: detached, semi-detached, mid terrace and a purpose built flat, because they are the most common types in the UK (Gupta, 2012).

The models, representative of the UK building stock, are, in the author's opinion, speculative and have no real context. The modelling, carried out for different construction types using specifications for houses built between 1919 and 1980 assumed different levels of occupancy for each house type. For instance, the mid terraced house was modelled with one working adult and two children and an adult at home, and the purpose-built flat had two pensioners living at home all the time.

Some of the concrete steps found to reduce or eliminate heat stress are: reducing the amount of clothing worn, improving hydration, opening windows and reducing internal heat gains. This study reviews most adaptation options for minimising overheating risk, which are divided into four key principles: microclimate, shading, internal heat control and ventilation. A review of these key principles and their mitigation potential is presented. By 2080, external shading is proved to be the most effective adaptation option, followed by high albedo surfaces and external insulation (Gupta, 2012).

The choice to use, during the modelling work carried out with IES, the high emission scenarios and TRYs files at a probability of 90% was taken because the current trend of carbon emissions is high. As the emission scenarios will be upgraded in the future and due to the unpredictability of climate change, Gupta poses the question of whether adaptation should be upgraded incrementally in the future (i.e. every 50 years). It has been shown by SNACC that space heating will continue to dominate space conditioning until the end of the century.

It has been shown that the location of thermal mass is critical to performance, for example, increased albedo, and the exposure of thermal mass on the ground floor and on the interior of the external walls was found to increase space-heating requirements. Floor and ceiling mass can reduce space heating and hours of overheating while external wall mass can increase, quite considerably, space heating requirements. Thermal mass is usually combined with night ventilation and one consideration for further research is whether the most vulnerable will be unable or unwilling to take up operational adaptation measures such as thermal mass and night ventilation, which require a level of user interaction (Gupta, 2012).

Four packages that combine adaptation options including external wall and loft insulation, low-e double glazing, high albedo exterior walls and roofs, exposed thermal mass and louvered shading are modelled and their performances plotted in a comparative graph. It is important to notice that in this study as well, insulation is modelled as an adaptation measure that reduces the overheating risk. Of all the packages investigated, the one that includes all adaptation options achieves the biggest reduction in overheating hours for all house types, although it slightly increased the space heating requirements because of the thermal mass exposure. None of the packages completely reduce the overheating hours for the 2030s onwards, and among the four house types the adapted semi-detached house has the biggest overheating reduction.

SNACC envisages the use of active cooling beyond 2030 because passive measures may not ensure comfort. A suggestion for further work is to carry out detailed analysis on adaptation and to test different thicknesses of insulation, for instance. The different performance of triple and double glazing, combined with external shading is also suggested as a topic for future research. The types and occupancy profiles investigated in CREW and SNACC are generic types and are not applied to any real case for verification and proof of the assumptions. So this thesis will continue this research by applying some of the adaptation measures investigated in CREW and SNACC to two house types in Rushenden with the aim of testing them on a real case.

All the research on adaptation exposed so far, including SNACC and CREW, used the comfort temperature thresholds of 25 °C in bedrooms and 28 °C in the rest of the house

to assess the overheating risk. However, that does not take into account the fact that people adapt over time to changes in temperature. Adaptive comfort theory, as explained in the following chapter, was developed to take into account the capacity of the occupants to adapt to their environment.

2.2.12 Adaptive Comfort

Comfort is a subjective area of study. Comfortable temperatures can vary from one group of people to another and in different building types. Many of the comfort standards are based on offices where comfort has an effect on productivity (Barraclough, 2011). In housing however, people can more easily adapt to their environment than in other building types. In housing, the building occupants can easily change their clothing, hydrate more, shower or move to a cooler room.

Adaptive comfort explains how people adapt to the environmental conditions they live in. It is based on the principle that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol, 2002). Adaptive comfort theory links the outdoor mean running temperature to the comfort temperature of a particular climate and for a particular group of people. Baker and Standeven (1995) identified adaptive opportunities, such as opening a window, changing clothes or drawing a blind that change the conditions which the occupants find comfortable.

Brager and de Deer in the late 1990s carried out a number of field studies in the USA with the aim of capturing different levels of comfort with different climates and expectations (CIBSE, 2005). The findings of these field studies were then incorporated in 2001 into the ASHRAE comfort standard for several locations in the US (CIBSE, 2005).

Adaptive thermal comfort is a function of the possibilities for change as well as the actual temperatures achieved (Nicol, 2002). Adaptive comfort theory was developed by Nicol and Humphreys in the early 1970s to challenge the steady-state method developed by Fanger of Predicted Mean Vote and Predicted Percentage Dissatisfied. The latter suggests appropriate indoor temperatures based on levels of clothing and metabolic rates (McCartney, 2002). Adaptive comfort theory explains that if people inside a building could

adjust their clothing, location or improve their control, then the range of comfortable environmental conditions would be amplified (McCartney, 2002).

Humphreys proved, by plotting the comfort temperature of surveys carried out worldwide against the running mean temperature at the time of the survey, that there is an almost linear relationship between the two variables in naturally ventilated buildings (Nicol, 2002). An Adaptive Control Algorithm (ACA) was developed by Humphreys and Nicol to link the running mean temperature and the comfort temperature.

The summary of several years of practice in thermal comfort studies is contained in the text book 'Adaptive Thermal Comfort' by Nicol, Humphreys and Roaf (2012). The text presents the different types of questionnaires, gives practical advice on how to approach the residents and explains how to analyse the data from the field study. One of the questionnaire samples explained in this text was adjusted by Nicol in 2012 and used by the author to assess the comfort level in Rushenden. There are several methods of reporting the results from the survey and they will be explored in this thesis.

The SCATs (Smart Controls and Thermal Comfort) project ran from December 1997 to December 2000 and was funded by the EU (McCartney, 2002). Oxford Brookes University acted as project leader and the consortium was formed by researchers in the following countries: the UK, France, Sweden, Greece and Portugal (McCartney, 2002). The aim of SCATs was to reduce energy consumption in air conditioned buildings by developing control systems that use adaptive comfort theory (McCartney, 2002).

The project carried out thermal comfort studies across Europe, developed control systems for both air conditioned and naturally ventilated office buildings and tested effects on energy use and thermal comfort. It used two types of questionnaire: transverse and longitudinal. The transverse questionnaire used the seven point ASHRAE scale; it assessed parameters such as clothing levels, humidity, air quality and activity level. It was conducted for a large number of occupants in a very short period of time to give a snapshot of what the comfort temperature is in mechanically ventilated offices. The longitudinal questionnaire is a shorter version and was completed by 15% of the subjects that participated in the transverse study. The occupants were asked to complete this second questionnaire every day for periods varying between 3 and 12 months (Nicol,

2002). The same longitudinal questionnaire was used in this thesis to derive the summertime comfort temperature in Rushenden.

Tessa Barraclough from The Peabody Trust wrote an MSc thesis for the Centre of Alternative Technologies (CAT) on overheating in retrofitted houses entitled "The risk of summer overheating in energy efficiency retrofitted UK domestic properties" (2011). She uses the adaptive temperature derived from the running mean as suggested by Nicol. Barraclough analysed the database of the Retrofit for the Future competition and carried out the overheating assessment for the houses after the retrofit measures were installed. She used both, the adaptive comfort equation and the overheating criteria set up by CIBSE (2006). She found that there is a significant amount of overheating in the Retrofit for the Future houses; 30% of the houses overheat, mostly in the bedrooms, where the temperature threshold (CIBSE, 2006) is lower. There are no data available for comparison before the retrofit, but overheating was never raised as being a problem before the retrofit work.

CIBSE published in 2013 the UK regulation following the European Standard on Adaptive Comfort called: "The limits of thermal comfort: avoiding overheating in European buildings" (CIBSE TM52, 2013). The principal author is Fergus Nicol and the document is a compendium of the studies on adaptive comfort carried out in Europe. TM52 (2013) contains formulas to calculate the operative temperature, the running mean of the outdoor temperature and the comfort temperature that is linked to the outdoor temperature. These will be explained in more details in the Methodology and the Results and Analysis chapters.

2.2.13 Surveys

A team from Loughborough University (Baizee *et al.*, 2013) carried out a survey, on a national scale, of 207 homes funded by the Engineering and Physical Sciences Research Council (EPSRC). The temperature was recorded for several house types built in different years since 1900 and located in 53 different local authorities. The recordings were collected from 22nd July to 31st August 2007, the warmest period of a relatively cool summer. Hourly air temperatures from weather stations across the country, measured by

the MET office, were also collected in order to analyse the internal data using the adaptive comfort algorithm. An assessment of the overheating hours was also made using the CIBSE guide static recommendation of not exceeding the maximum temperatures of 28 °C in the living room and 26 °C in the bedroom for more than 1% of the occupied time. Of the 207 homes some were heated during the summer and the data for 193 free running homes (using no heating or cooling devices) showed that the indoor temperature was generally between 21 °C and 25 °C with peaks of 30 °C. The more recent houses, those built after the 1990s, had the highest indoor temperature, while the houses built before 1919 had the lowest indoor temperature.

The warmest dwellings were in London, where the presence of the Urban Heat Island effect exacerbates the overheating, followed by dwellings in the South East (Baizee *et al.*, 2013). If we consider the type of dwelling in more detail, more living rooms in flats than in any other house type exceeded the static threshold. In older homes, with no insulation and solid walls, considerably fewer living rooms and bedrooms overheated than homes of more recent construction. In summary, the overheating analysis confirmed that newer houses and flats with lower fabric heat losses and built with cavity walls and insulation overheat more than older dwellings with higher heat losses and built with solid brick walls. The question of insulation and air-tightness and the role that these elements have in increasing (or reducing) the overheating risk arises from this study, is relevant to this thesis and is addressed in the Results and Analysis Chapter.

Top floor flats were those most prone to overheating among all the types of dwelling monitored. In contrast with the static study, the dynamic analysis that used the adaptive comfort criteria found that most of the houses were uncomfortably cool. The standard as discussed was designed for offices, and the authors (Baizee *et al*., 2013) argue that the comfort temperature in housing is actually lower than that derived from the algorithm because occupants in housing adapt more easily. This result, and especially the number of overheating hours derived from the standard CIBSE criteria, brings into question the way low carbon retrofit measures are added to existing old homes. If they are retrofitted with insulation and air tightness to 1990 or more recent standards they will overheat in a similar way to the latter. Baizee *et al*. (2013) undertook a very thorough study of overheating in UK housing and found that houses built with solid walls before 1919 do

not overheat as much as insulated houses built after 1990. This is in line with what the CREW project (Shao *et al.,* 2010) has found using modelling and simulation software. This is also the question investigated by the author in this thesis using as a case study the houses in Rushenden retrofitted under the IFORE program. The author has analysed in more detail the effects that insulation and air-tightness have on overheating in the Results and Analysis Chapter. The other aim of this thesis is to derive a specific adaptation strategy for Rushenden. What follows in Section 2.3 is an analysis of several participation initiatives and techniques that the author explores in order to elucidate how the occupants of Rushenden can be engaged in the discussion on climate change adaptation.

2.3 Socio-Economic context of the community of Rushenden

Socio–economic context is closely linked to the environmental context because people can generate very different energy demands depending on their understanding of how the building they live in operates. Therefore interacting with the residents, educating them and making them part of the energy reduction process is essential to the success of the project.

To avoid becoming overwhelmed by these feelings, it is crucial to be grounded—to find a standpoint from which one can sense the impact of one's actions and feel one is making concrete progress in transforming reality. This, in my view, is the role of the local community. A sense of responsibility toward the world or the future is not something that can be developed overnight, in isolation from the realities of daily living. If we cannot establish this within our immediate relationships and environment, we cannot hope to do so relative to the entire planet or the distant future.

The word "responsibility" indicates the ability or capacity to respond. It is through the persistent effort to strengthen and forge our capacity to respond to the evolving realities of the community that a sense of commitment toward all those with whom we share the planet and toward future generations is developed.

Daisaku Ikeda, (2012), Environmental Proposal to the Rio+20 Summit

2.3.1 Recent research on participation and climate change adaptation: BIOPICCC (Built infrastructure for older people's care in conditions of climate change) and SNACC (Suburban Neighbourhood Adaptation for a Changing Climate)

While there are several examples of collaboration between housing associations, local authorities and the community taking action on mitigation, there is little or no information available on how to involve communities and local governments in terms of adaptation. Engagement activities such as allowing the community to take ownership of local green spaces are examples of the empowerment of local people in the field of adaptation to climate change (Peter Matthews, Department of Communities and Local Governments, private conversation, 26-04-2012). Community involvement and developing ways to collaborate with the residents of Rushenden in the case of adaptation to climate change will be developed further in this thesis. An indication of how to do this can be found in recent UK projects.

BIOPICCC (Built infrastructure for older people's care in conditions of climate change) was a 3 year research project (November 2009 - October 2012), funded by the EPSRC, concerned with the adaptation and resilience of systems of care for older people at the community level and how to combine the knowledge of scientists, service providers and the general public to inform the development of community resilience to extreme weather events (ARCC 2012). The research was conducted by a multidisciplinary team based at Durham and Herriot-Watt Universities. BIOPICCC mapped the vulnerability (areas likely to have larger and growing populations of elderly people) and hazard (areas most affected by climate change events) to climate change throughout the UK up to 2030 using UKCP09.

It found that the variation of an ageing population and risk of extreme weather events will vary throughout the UK; it is therefore necessary to adopt local adaptation policies. "It is essential to prepare for the impact of disruptive weather events and build local community coping mechanisms and resilience" (Owen *et al.*, 2012). The work of BIOPICCC has helped to inform national guidance on adaptation to respond to the UK climate change risk assessment (Owen *et al.*, 2012). The work of BIOPICCC establishes the

importance attached within this thesis, to informing the community of Rushenden and building common solutions for coping with climate change.

In SNACC (2012), Dr Ian Smith and his team at the University of the West of England carried out research into particular local communities. His research focused on dealing with the issue of developing ways in which neighbourhood–centred communities can find neighbourhood-scale solutions to cope with climate change (Williams *et al*., 2012). The team carried out questionnaires and focus groups throughout the project.

The focus of their investigation was within suburban neighbourhoods of Oxford, Bristol and Stockport (Williams *et al*., 2012). The residents of private housing are the objects of the study. In general, most residents think that climate change adaptation is not a relevant issue because of their experience to date of how the climate is changing. Some residents are sceptical about climate change and they do not see overheating as an urgent threat and they believe they can address it when it becomes problematic (Williams *et al.,* 2012).

In order to establish the likelihood of the residents taking climate change measures on board they were presented with a number of mitigation and adaptation options. The residents were not very interested in the adaptation options presented to them, as they are not convinced about climate change and view adaptations either as unnecessary or think that behavioural adaptation will be sufficient (Williams *et al.,* 2012).

They were asked if they would be likely to take each option on board and their answers formed a traffic light table that included the likelihood of implementation for each option (Figure 2.2). The likelihood that the residents adopt the adaptation measures depends on a number of variables including initial cost, convenience, appearance, payback time and other environmental and lifestyle benefits (William *et al.,* 2012). Measures that produce additional benefits such as double/triple glazing and growing food were favoured (Williams *et al*., 2012).

Adaptation measures that are visually attractive and cheap such as solar film and wall greenery were preferred by the occupants. With the former, however, they had concerns

about potential damage to the property (Williams *et al.,* 2012). Residents were most likely to adopt an adaptation measure if its installation coincided with other building works, in order to minimise disruption (Williams *et al.*, 2012).

The first reason for carrying out adaptation measures is their low cost and the first limit to their implementation is their initial cost (Williams *et al.,* 2012). The residents quickly pointed out that behavioural measures such as opening the windows in the summer are derived from common sense and could reduce the need for technical measures. This is to be expected since they would have to pay for the measures themselves. In general, the residents interviewed preferred low-cost, convenient DIY solutions (K. Williams, SNACC final dissemination event, 23 October 2012).

Suburb typology	Inner historic	Pre-war Garden	Inter-war	Social housing	Car	Medium–high
Case study	St Werburghs	Summertown, Oxford	Botley Oxford	Cheadle Stockport	Bramhall Stockport	Horfield Bristol
External solar shading	✗	-	-	✗	✗	✔
Internal shutters		✗	✗	-	✗	-
External shutters	✗					
Solar film	✔	-	✗	✔	✗	✔
Wall greenery	✔		✔	-	✗	
Green roof	✗	✗	-	✗	✗	-
Shaded outdoor space	✗	✔	✔	✔	-	-
Water butt		✔	✔	✔	✔	✔
Rainwater harvesting system	✔	-	✗	✗	✗	✗
Internal thermal mass		✗		-	✗	-
White roof and walls		✔	✗	✗	✗	
Extend eaves		✗	✗	✗		
Lock-open windows	✔	✔		✔	✔	✔
Underpin house		✗	✗	✗		
Drought-resistant planting	✔					

Likelihood of implementation: Likely ✔   Mixed -   Unlikely ✗
Shaded areas: adaptation not tested in that case study

Figure 2.2: Traffic light table from SNACC (source: Williams *et al.*, 2012)

The residents were then asked what their views were regarding neighbourhood measures, the best mitigation options and which trees they would like to see in their neighbourhood. Neighbourhood adaptations were supported because the residents

believed they would make neighbourhoods more attractive (tree-lined streets, for example) (Williams *et al.,* 2012). There were mixed views on community cool rooms, which are rooms mechanically cooled that can serve the all community in the event of a heat wave, because the residents, in many cases, did not perceive the need for these facilities.

The residents were asked their views on who should be responsible for leading the change. Community groups, as well as residents that act as leaders, are important for the community to initiate and deliver adaptations. In the case of building adaptation measures the residents think their implementation should be the residents' personal responsibility. In the case of adapting public spaces the residents recognised the role of local authorities, such as the council, as the predominant authority responsible for change. They expressed concerns that the implementation of green areas in the neighbourhood would increase the cost of maintenance and, as a result, taxes would rise.

At the end of the final dissemination event held in London on the 23rd October 2012 the project leader Professor Kate Williams from the University of the West of England affirmed that what is to be done is to find better ways to talk about climate change. During the community engagement work, presented in the Field Study Chapter (4), the author is aiming to use some of the methods explored by SNACC towards making a step forward in establishing a dialogue with the residents of Rushenden on the subject of climate change adaptation. The results of these efforts are discussed in the following sections.

The houses analysed by SNACC includes both, privately owned and social housing. Social housing of the same type as the stock retrofitted by IFORE is included in the analysis. The social housing suburb in Stockport analysed in SNACC is very similar to Rushenden i.e. brick and block dwellings built in 1950. The report does not specify the type of occupancy included in the analysis, it stated that several occupancy patterns were analysed. The suburb of Stockport that includes social housing had the lowest overheating risk among all those analysed. The report states that mid-terrace houses will overheat before end-terraces with similar characteristics. In comparison with SNACC, this thesis offers the

analysis of more shading types, including trees and roller blinds to find specific solutions to the social housing in Rushenden that can be replicated to other communities in the UK.

In the case of the social housing tenants of Rushenden, financial considerations are the most important driver, as the majority of residents are in fuel poverty. However, in the case of social housing as opposed to private neighbourhoods, the housing association is the most important driver of change. The residents may therefore be more willing to accept adaptation measures on the grounds that the housing association is providing them at no cost to the residents.

2.3.2 Participation techniques

Some of the recent advice on climate change adaptation uses SNACC and CREW to draw conclusions on adapting retrofitted social housing with the aim of informing the UK policy on low energy housing retrofit of possible overheating risk (ARCC CN, 2013). Measures borrowed from Southern European countries, such as external shutters, that are reported to be the single most effective adaptation measure by SNACC, are not practical in the UK because windows traditionally open outwards. The residents of Rushenden, in fact, completely ruled out the above measure when they were asked by the author about it during one to one questionnaires (Chapter 4).

Therefore this research, through a social–economic study of participation and occupant engagement, offers the opportunity to look at the practical applicability of the most common adaptation solutions to the community of Rushenden. The outcomes can be extended to other retrofitted social housing in the South East and to other social housing communities with similar form, building fabric and occupants' patterns throughout the UK. Moreover, this research suggests behavioural change, borrowed from Southern European countries and presented to the residents as an option, can be adopted by the community to reduce the risk of heat stress. The technical modelling will be a way of testing the measures suggested by previous research and those that were selected by the residents as suitable.

Participatory techniques have been used within the community of Rushenden via focus groups to engage with the residents on the subject of climate change. Shading and ventilation, the main techniques used to reduce the overheating risk in the event of a heat wave can only go so far in enabling the occupants to achieve comfort and avoid the health risks, especially in the case of the elderly. In housing, in Southern European countries like Italy and Spain, some behavioural change is in place to cope with extreme summertime weather and heat waves. For instance in Italy, outdoor living is very popular in the summer especially by the sea where it is breezy and people can stay in the shade. Regular evening events are organized by the local council throughout the summer so that when it is too hot to sleep, local communities in towns or villages gather together in outdoor spaces. This galvanizes a sense of community and belonging.

Some of these behaviours only work in certain climates, for instance when there is a big variance between temperatures during the day and night. In the modelling chapter temperatures from a representative city in the South East of England are plotted using probabilistic weather files. In a future warmer climate, during hot summertime days, some behavioural change is envisaged in Rushenden. The English garden is a well established tradition in this country. In the Discussion chapter (6), these behavioural adaptation techniques and ways of living outdoors that are suitable to the South East of England will be presented in more detail.

In this section some participatory techniques are discussed and critically selected in order to find ways that they can be used to engage with the residents of Rushenden. The aim of these techniques is to change the way the residents think about climate change. At the moment, their view on this subject is mostly apathetic as is shown by past questionnaires undertaken by IFORE and presented in the Field Study Chapter (4). These other forms of engagement are aimed at enabling the residents of Rushenden to feel they can cope in the event of a heat wave.

"Participatory action research (PAR) is based on the principle that experience can be a basis of knowledge. At its heart is collective, self-reflective inquiry that researchers and participants undertake, so they can understand and improve upon the practices in which they participate and the situations in which they find themselves. The reflective process is

directly linked to action, influenced by understanding of history, culture, and local context and embedded in social relationships" (Baum *et al.,* 2006). PAR was used to tackle important health issues in rural areas and it involves a transformation, through the practical process of research; the researched becomes the researcher himself. The researcher becomes the facilitator of this process. It is a way of empowering communities (Baum *et al.,* 2006). The outcomes can be both qualitative and quantitative. This technique can be used in Rushenden in small group gatherings that discuss what can be done to mitigate and adapt to climate change, both on an individual level and collectively. These small groups have the potential to become the motor for changing the way the community perceives climate change and for changing the participants from apathetic to active.

PAR is not a method but it is an approach in which many different methods may be used: group discussion, interviews, diagramming, video, photography, art, surveys, mapping, the collection of environmental data, computer analysis of datasets, etc. (Pain *et al*., 2011). The ESRC funded project "Building Adaptive Strategies for Environmental Change with Land Use Managers", run by the University of Durham, involved stakeholders as well as academics. Several meetings between the Lune River Trust and researchers from the University enabled the identification of the main questions to be answered, carried out modelling, obtained feedback and came up with a toolkit. PAR in this context involved recurrent stages of planning, action and reflection, followed by evaluation (Pain *et al.,* 2011). The repetition of this process is what enables change. The seven themes that are central to PAR are: collaboration, knowledge, power, ethics, building theory, action, emotions and well-being. The main question can be clarified over one or several brainstorming meetings.

Etienne Wenger (1998) summarizes Communities of Practice (CoP) as "groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly". The learning that takes place is not necessarily intentional. Three components are required in order to be a Community of Practice: (1) the domain, (2) the community, and (3) the practice, and the practice is what they learn and use (Wenger, 1998). The domain needs to be a subject that the group of people share a concern or passion for, not simply an interest (Wenger, 2002). The community is the group of

participants that interact regularly with one another and share information. The practice means that the members are practitioners. Therefore CoP applies to groups of professionals for instance that share a common knowledge. In Rushenden the residents are not practitioners, however they have been informed through the IFORE project about energy saving measures by the on-site occupants' engagement team visits and many community events over the past four years. This approach may therefore offer some useful insight into establishing groups where the community can speak a similar language facilitated by the author who acts as a moderator.

Communities of practice as a method for community engagement implies that the community is sharing a practice or common knowledge. It can be likened to networking groups that spontaneously gather together to enhance their knowledge on a particular subject. A third party may be involved within the community as a facilitator, and particular attention in the communities should be given to the voices that are silenced by expertise. I asked Etienne Wenger, theorist of communities of practice, (private conversation, 1 May 2013) if his theory could be used with ordinary people. He replied that it would be possible and that the facilitation work would be targeted at understanding how the facilitator and the community could move forward together. This technique was used by the author to run focus groups in Rushenden that are described in the Field Study Chapter.

"Community participation: social development of the state" (Midgley *et al*., 1986) discussed if and how community empowerment can be driven by the state. In the case of Rushenden we can think of the state as being the local authority, the council. Concessions granted by authorities were largely secured by community participation (Midgley *et al.,* 1986). However in the past, participation was in some cases regarded as dangerous as it threatens the power of authorities (Midgley *et al*., 1986).

"Power, Process and Participation - tools for change" (Slocum *et al*., 1995) describes the role of women in community participation. Case studies are drawn from examples of African communities. It focuses especially on those that have been excluded from the decision-making process (Slocum *et al*., 1995), and describes a series of tools that enable change, such as focus groups.

2.4 Social engagement

"Social Engagement: the ability to work constructively within and between social groups to create more resilient and sustainable communities."

Juliet Millican, Community University Partnership Programme, University of Brighton

2.4.1 Definition

Social engagement implies the participation of the community in making the choices that concern the people living in it. In the field of low-energy buildings, over recent years, there has been a strong focus on occupant behaviour and social engagement. This is because it is the occupants who consume energy and not the buildings. When the community is engaged in low-energy projects and becomes part of the effort to reduce energy, it can learn, people become active drivers for change and change is long lasting.

In Rushenden and Outreau the social engagement teams have been working alongside the technical teams during the IFORE project. They organised cultural exchanges, sports activities and residents' visits between England and France; in Rushenden a few of the residents did not have a passport and had never left the Isle of Sheppey. Some of the residents have found training and employment through the project. All of these activities established an important link between the two countries and engaged the communities with the low carbon retrofit program.

The housing associations, Amicus Horizon and Pas-de-Calais Habitat, the residents associations, the community engagement teams and the residents were the main actors of the change. The targets are the residents living in the community rather than the buildings they live in. The original goal of IFORE was to reduce carbon emissions by 20% through a change in the way the residents use their homes. This chapter presents an overview of research methods and practices used in changing behaviour and introduces the sociological context and the role of the occupant.

2.4.2 Initiatives for children

In offices and schools two similar programs were run throughout the country and were organised by GAP (Global Action Plan), a small national charity. These were "Environment Champions", which took place in the workplace and "Action at Schools". Action teams of 20 employees, in the case of the "Environment Champions" program, or pupils, in the case of "Action at Schools", met regularly with a facilitator to design their own low-energy strategy.

School children, the majority from secondary schools, were supported by a lead teacher and were involved in exciting activities such as plays and writing songs (Hargreaves *et al.,* 2008). Children are much easier to influence than adults, which is why the education of children can have a positive influence on the behaviour of their parents. These activities resulted in a reduction in waste and increase in recycling of 43% in schools. The Eco Team household, a program designed to change behaviours within households (Hargreaves *et al.*, 2008) reduced their electricity by 7%, while in the workplace and schools the reduction was 12% (Hargreaves *et al.,* 2008). Hargreaves *et al.,* (2008) explain that since the message on environmental action from the government over the past 20 years was essentially targeted at recycling, reducing energy through behavioural change is more than just reducing waste.

The Queenborough and Rushenden regeneration project started in 2004 and resulted in a master plan that was adopted in November 2010 and is still in use. During the consultation process Planning for Real, an organisation running a nationally recognised planning process, was appointed by Swale Borough Council to undertake several exercises using specific participation techniques to involve the residents in the design process (Planning for Real, 2012). As part of this process, school children were asked to describe and draw the places where they would like to live and also to use their imagination to make physical 3D models. Their drawings were used to develop a master plan and a large model of the area was formed from several smaller models. The model-making process was an opportunity for both adults and children to study the history of their community and identify some of their concerns (Planning for Real, 2012). The model was discussed during the consultation process and used as a focus for anonymous feedback.

2.4.3 Initiatives for adults

The paper 'Social experiments in sustainable consumption: an evidence-based approach with potential for engaging low-income communities' (Hargreaves *et al.*,2008) describes research carried out since the 1990s by GAP, which started working with low-income communities to reduce their fuel and food poverty. GAP developed the *small changes* program to promote healthy eating, recycling and energy saving with local primary schools in Tower Hamlets, London (Hargreaves *et al.,* 2008). In 2006, GAP operated three programs based on these principles (Hargreaves *et al.*, 2008).

Eco Teams were formed, comprising of 5-6 people from the same neighbourhood and a facilitator, to create changes in the household. They met every month to discuss a specific subject e.g. transport, waste, water, energy etc. They identified what practical changes they could make to their daily routines and what the achievable limits are for individuals.

After the discussions, the members of the group tried out the changes discussed and did some "homework" on the subject for the following month. They regularly reviewed the impact their behavioural changes were having (Hargreaves *et al.*, 2008). The groups were recruited from different regions of England between 2002 and 2008 (Hargreaves *et al.,* 2008) and further research is evaluating the impact that the Eco Teams have had on the reduction of household waste (Hargreaves *et al.,* 2008). During the focus groups carried out in Rushenden the author investigated how the residents could practically adapt to a warmer climate (Chapter 4).

"The original Harland and Staats (1997) study demonstrated that the changes in domestic routines in the Dutch Eco Team households remained in place for two years after the end of the intervention" (Hargreaves *et al.,* 2008). The intervention however is long, and long-lasting change needs up to nine months of engagement to take place and a great deal of participation by the residents. This meant that only the most enthusiastic households took part in the program. Residents' measurements and feedback were also essential to enable Eco Team members to measure their impact (Hargreaves *et al.,* 2008). The bottom-up methods described seem to have a very good outcome with low-income communities like Rushenden for instance. The author participated in the community

engagement activities organized by the on-site team in Rushenden such as home visits and community fairs. The author used the existing structure in place in Rushenden to run one-to-one interviews and focus groups to discuss specific themes concerning climate change adaptation (Chapter 4).

GAP action teams are able to improve local knowledge through three types of intervention. First, homework stimulates personal research through social media, members of the family and friends. Second, knowledge of environmental issues emerges from the group's discussions. Third, measurements help the residents to understand their own environmental impact. GAP's approach of facilitated action teams does not impose knowledge on the groups but starts by acknowledging what the groups are doing and asks what realistic changes can be made. GAP's participants belong to the same neighbourhood and can influence one another. GAP believes that peer influence can be much more powerful in establishing a positive change and energy savings. The involvement of school children, the activities of growing vegetables in community gardens that then are cooked and eaten by the community can leave a long-lasting legacy. This is especially important for low-income communities where a large portion of income is spent on heating and electricity; energy saving, in this case, leads to an increase in well-being (Hargreaves *et al.,* 2008). These activities were carried out in Rushenden as part of IFORE by the community engagement team. The participation of residents in these activities enabled the author to establish a communication with them based on a shared knowledge about energy saving.

The paper "Effecting durable change: a team approach to improve environmental behaviour in the household" (Staats *et al.,* 2004) explains the complexity associated with establishing a long-lasting effect on pro-environmental behavioural change. The process that leads behaviour to forming habit comprises three stages: information, feedback and the creation of a supportive environment. The establishment of a supportive environment is particularly important and it was proved that small group discussions, rather than lectures, are much more effective in establishing habits. Therefore focus groups are a valuable method for behaviour change.

A member of the neighbourhood was appointed as a block leader with the task of informing the residents about recycling facilities. This technique was much more effective than information leaflets, which suggests that face-to-face exchanges have longer-lasting effects of establishing habits. On pro-environmental behaviour, the opinion of a respected friend or someone in the family is often very effective and pledging to achieve a target in the future has also proved to generate long-lasting changes in behaviour (Staats *et al.,* 2004). Global action plans and the establishment of Eco Teams is described as an effective method for long-term changes.

Case studies were carried out at different points in time, in 1994 and 1996, to assess the long-lasting effect on pro-environmental behaviour of the participation of Eco Teams on the Dutch population. The questions were essentially the same and regarded 38 different behaviours as well as the weight of solid waste produced, and gas, electricity and water consumed. Data for gas consumption was corrected for variations in weather conditions using the degree day method (Staats *et al.,* 2004). Comparisons were made with a subset of the Dutch population that was not part of the program and the results showed that the Eco Team participants improved their pro-environmental behaviour for up to two years after the program ended. Behavioural change has been addressed during IFORE. The community engagement team established a relationship of trust with the residents. They tried to help them to resolve day-to-day problems related to energy saving. They introduced the author to the residents who agreed to take part in the questionnaires and focus groups. The community engagement team was an intermediary between the author and the residents in the discussion on climate change adaptation.

The paper "Promoting Sustainable Behaviour: An Introduction to Community-Based Social Marketing" (McKenzie-Mohr, 2000) highlights the difficulty in establishing behavioural change. Although it is generally acknowledged that energy and carbon savings are determined by the way occupants use buildings, the field of environmental psychology is little understood by programme planners and governments (McKenzie-Mohr, 2000). Before 2000, most programs that focused on promoting sustainable behaviour were information intensive.

Two perspectives are currently used in these campaigns. The first is based on the assumption that information about the effects people's behaviour has on the environment determines a positive change in behaviour. The second assumes that economic reasons function as deterrents for people's waste and incentives to install low-energy measures such as insulation. However, several low-energy programs based on media campaigns in Canada and the US to promote, for instance, the use of insulation had no effect, because they were based on advertising. While the proliferation of information through media and the use of advertising, based on traditional marketing techniques, are "easy" ways to pass on the message and can alter consumer preferences regarding a certain product, they are not generating a change in behaviour (McKenzie-Mohr, 2000).

The field of community-based social marketing was developed in Canada to respond to the challenge of generating new sustainable behaviour. The first step of this methodology is to assess the benefits, in terms of carbon reduction, of changing a particular behaviour, for example, installing insulation or changing transport methods. The second, very important step is to uncover the barriers to behavioural change dictated by several factors such as the climate, physical barriers etc.

To identify barriers, preliminary research needs to be carried out to decide which behaviour to promote. Observations, surveys and focus groups can be used to identify what the causes are of differences between "individuals that engage with the activity and those who do not" (McKenzie-Mohr, 2000). The third step is identifying whether the resources exist to overcome these barriers (McKenzie-Mohr, 2000). The same was done by the author during focus groups, the aim was to identify barriers currently in place to adapt to a warmer climate. Discussion was directed towards possible solutions to overcome these barriers and suggestions by the residents were encouraged during the discussion (Chapter 4).

Community-based social marketing promotes the direct measurement of environmental change e.g. energy use (McKenzie-Mohr, 2000). Piloting strategies before implementation is a very effective way of achieving the target, and several organisations in Canada have used this method to successfully encourage behavioural change. Case studies show that

in the case of backyard composting, the establishment of a social norm was encouraged by placing a decal on the garbage boxes of those in the community who were already composting. In the case of reducing lawn water usage in the summer, a preliminary study on the barriers was followed by door-to-door home visits by a student employee on a bicycle, while a control group was also informed by information leaflets (McKenzie-Mohr, 2000). Results showed that those who received a home visit and practical information on how to reduce their lawn watering were able to reduce watering by 54%, while the control group increased watering by 15%. From this study the habit of reducing water usage was encouraged by home visits. The Green Doctor in Rushenden has carried out a series of 3 home visits to each resident part of the IFORE project with the aim to encourage behavioural change. "The role of a Green Doctor is to provide local business and residents with information and support on reducing household (or commercial) energy consumption and thus save money for the residents" (Hanna *et al.*, 2014).

"Collective self and individual choice: The effects of inter-group comparative context on environmental values and behaviour" (Rabinovich *et al.*, 2012) asserts that by characterising and stereotyping a group of individuals, the individuals identify with the group and start acting in a way that is in line with the stereotype. This can lead to behavioural change. Inter-group comparisons between environmental and non-environmental groups, for example, serve to establish a stronger stereotype. In-group stereotyping is also a valid way of establishing behaviour change by comparison between individuals. Comparison manipulations were considered to be effective in changing the environmental stereotype within the group (Rabinovich *et al*., 2012). By involving the community of Rushenden with the low-energy initiatives IFORE has helped the residents to identify as a low-energy community.

Rabinovich *et al*. (2012) demonstrated that inter-group comparisons with groups believed to be less environmentally friendly promotes a more environmentally friendly in-group stereotype and therefore a "greener" behaviour. To prove this concept several experiments were carried out by first of all asking the participants to rate their level of sustainable behaviour compared to another group. After this, the participants were asked to pick up leaflets on environmental awareness; those who rated themselves more environmentally aware picked up more leaflets than those who rated themselves to be

less environmentally aware. This seems to suggest that in this case relative perception tends to become absolute. This paper shows that creating an identity which is more environmentally friendly can help to promote a more sustainable behaviour within a group.

2.4.4 Environmental psychology

Environmental psychologists formulate practices and strategies to change the behaviour of individuals (Uzzell *et al.*, 2009). Informing people about environmental problems has proved not to be effective as a behavioural change strategy as also demonstrated by providing information to people on the effects of smoking and poor diet on health. Therefore, environmental psychology looks at the wider economic structures that lead to the creation of unsustainable societies. It considers individuals, society and the environment as intrinsically linked and focuses on changing the causes of unsustainable behaviours rather than on the behaviour itself.

The paper 'Modern Institutions, Phenomenal Dissociations, and Destructiveness toward Humans and the Environment' (Worthy, 2008) argues that alienation from the environment produces destructive behaviour. It is, in fact, difficult in our society to relate where the products we use come from, as they are processed and manufactured in a way that produces something that we do not recognise. In Rushenden for example, it is necessary that the people become aware of their own environment in order to adapt to climate change.

Eco-psychology investigates the causes of the alienation between humans and nature and asserts that this instigates negative emotions. Instead, by re-establishing this connection with nature, humans can discover that it is possible to live a materially simple life with beauty (Environmental Psychology, 2014). This is relevant to Rushenden because in social housing the occupants necessarily have a low-income lifestyle.

Poverty is not necessarily an accompaniment to environmental degradation. Gardening activities for adults and children were facilitated by the IFORE community engagement team with the intention of strengthening the relationship between the occupants and the

environment. This relationship seems to be quite strong already especially among the elderly, who make up a large part of the population in Rushenden. The occupants look after their surroundings and in return they gain a sense of belonging and satisfaction that enhances their life experience.

2.4.5 Fuel poverty

Climate change will affect the poorest and most vulnerable since, amongst other things, they have less resilience to rising energy costs and tend to live in poorer quality, less efficient housing (Scott, 2010). The social housing in Rushenden is inhabited by residents currently living in fuel poverty. DECC (Department of Energy and Climate Change) states that fuel poverty is a measure of the occupant's ability to provide an adequate level of warmth at 21 °C in the living area and 18 °C in other occupied rooms (DECC, 2012). A person is considered to be in fuel poverty if (s)he spends more that 10% of their income on fuel. The Climate Change Act established the need to set a series of carbon budgets which chart the course to achieving the long-term 80% reduction in CO_2 emissions by 2050. The 4th carbon budget, which runs from 2023 to 2027, acknowledges that fuel poverty will increase as a result of increased energy prices by 2020, more so than was originally envisaged (DECC, 2012).

DECC's Statistics show that fuel poverty has decreased over the past 2-3 years (DECC, 2012). This is a result of a combination of increased income and energy efficient measures and the installation of energy efficient boilers. Fuel poverty however increases with energy prices therefore it is crucial to gain an understanding of future energy prices.

There are three factors affecting fuel poverty: energy prices, income and the energy efficiency of the house (DECC, 2012). Among these three, low income seems to be the single-most influencing factor. Most of the residents of Rushenden are currently on income support, are single parents, unemployed or elderly. Will an increase of 2 °C (or more) in temperature cause a change in fuel poverty in Rushenden? In order to answer this question the author will carry out a basic cost-saving analysis of the different retrofit measures per household compared to an uptake of air conditioning.

2.4.6 Calculation of payback times

A calculation of the payback times of the adaptation measures used in the case studies in Rushenden as well as a comparison of the cost of air conditioning and the adaptation measures will be carried out in this thesis. The aim of this exercise is to understand the financial benefits of adaptation to climate change and whether the residents of Rushenden, already in fuel poverty, will be able to adapt.

The report "Your home in a changing climate" prepared by Arup for the Three Regions Climate Group was published in 2008. The three regions incorporate London and East and the South East of England, where the impact of climate change will be the greatest. It assesses effective measures to adapt the existing three regions' housing stock in terms of flooding, water stress and overheating. It advocates a combination of mitigation and adaptation options in retrofitting. Across the three regions most of the housing stock was built between 1851 and 1994. In the East and South-East regions most of the prolific construction period is between 1965 and 1984 while in London the stock is older with more than 50% having been built before 1944 and 30% between 1919 and 1944 (Arup, 2008).

The report highlights the 600 deaths in London during the heat wave of 2003 and states that effective adaptation options are currently available. In recent history, in fact, overheating has been responsible for the highest number of deaths in the three regions (Arup, 2008). It suggests the use of passive measures such as enhancing natural ventilation, reducing internal gains and solar gains through the windows. The use of insulation to keep the heat out is advocated when combined with ventilation, especially at night.

The cost of a typical adaptation package that includes awnings on south and west facing windows, night ventilation, ceiling fans in each room (active) and external surfaces painted white was estimated to be around £16,000. When mitigation options have already been installed the price is halved by £8,000. A table that includes several adaptation options such as awnings and shutters ranks their price range into low (£1-100) medium (£100-1000) and high (over £1000). The use of trees is recommended on west

and east facades where sun angles are low, while retractable shading is recommended on south facing elevations. The price for adaptation indicated by the report is high and difficult to afford in the case of social housing. The author in Chapter 6 proposes low-cost solutions that are affordable in social housing in the South East.

A 1930s three-bedroom semi-detached house, with cavity wall, single glazing, minimal insulation and occupied by a family of five was modelled. A range of adaptation measures were adopted for each of the three key impacts of flooding, water stress and overheating in order to show that these techniques are currently available on the market. Using UKCP02, the study shows that overheating hours above CIBSE 2006 comfort temperatures are going to be 30% of the total occupied time by the 2050s in the bedroom and 50% in the living room. The combination of summer adaptation measures, described above, totalling £16,000 was applied to the house, together with some light retrofit winter measures such as cavity wall insulation, low-e double glazing and loft insulation. By using this combination of measures the overheating hours were almost totally eliminated.

Adaptation needs to be addressed locally while mitigation requires both local and global actions (Arup 2008). The choice of appropriate retrofit adaptation measures will vary according to location, the local climate (current and future) and the building type involved (Arup, 2008). The type of tenure will affect the response of the households to the impact of climate change (Arup, 2008). Social landlords are in many ways in the best position to oversee adaptations, having control over estates and blocks, access to capital, and incentives to maintain the quality of the accommodation (Arup, 2008).

In order to achieve comfortable temperatures in hot summers, adaptation measures must be planned and installed in advance (Arup, 2008). In contrast, air conditioning units are readily available, inexpensive, and can be easily installed (Arup, 2008). Air conditioning has negative consequences in terms of noise, waste heat and carbon emissions. This report shows that the need for air conditioning can be eliminated by 2050 using passive and low energy adaptation options (Arup, 2008).

In terms of future energy generation, the Carbon Plan (HM Government, 2011) sets out how the UK will achieve decarbonisation within the framework of the UK's energy policy

and sets up scenarios for UK electricity generation to 2050. By the 2030s the mix of electricity generation will be composed of up to 20GW from nuclear, 10GW from fossil fuel with carbon catchers and 50GW from renewable technologies. On the heating side for the building sector the plan envisages the use of air and ground source heat pumps and district heating. By the 2050s the energy mix is predicted by the outputs of the 'core' run of the cost-optimising model (MARKAL) to be 33GW of nuclear, 45GW of renewable (mainly offshore and onshore wind farms) and 28GW of fossil fuel with carbon catchers. The UK energy demand will have to be half what it is today. With the aim of decarbonising the power supply sector the UK has commissioned a study (HM Government, 2010) to devise three extra pathway scenarios for electricity production. A prediction of future costs of energy generation is currently being reviewed by the UK Energy Research Centre (UKERC).

The UK Energy Research Centre is reviewing the studies that aim to predict the future cost of electricity taking into account the four pathways envisaged by the Carbon Plan (HM Government, 2011). More precise information regarding future energy prices is required at this stage to make an informed evaluation of what the financial impact will be in the future on households. Current energy prices will be used by the author at this stage of the evaluation of adaptation measures taking into account that, as well as for mitigation, the payback time argument may not be rewarding if based on current energy prices.

"Your social housing in a changing climate" (London Climate Change Partnership, 2013) presents some very basic cost benefit analysis of simple adaptation options for the borough of Barking and Dagenham run by Richard Lupo from Sustainable Homes. The London Climate Change Partnership (LCCP, 2014) has published two short reference documents: "Business case: incorporating adaptation measures in retrofit", "A checklist for retrofit measures to incorporate when planning a retrofit".

Both documents are based on the case study of the two social housing blocks in the London borough of Barking and Dagenham that were equipped with adaptation measures. These comprise external blinds incorporated in triple glazing windows, external cladding, light external colouring and extractor fans (LCCP, 2014). The overheating

protection measures did cost £6,500 per home. The current savings were estimated to be 28 £ per property per year using a figure of 220 kWh for the cooling required for July and August in the bedroom and the living room (LCCP, 2014). An electricity charge of 12.5 p /kWh was used in the calculation.

2.5 Conclusions from the literature review

Overheating may pose a risk to the health of UK citizens in the advent of global warming. Two strategies for tackling carbon emissions, that cause global warming, were identified: mitigation and adaptation. Since climate scientists affirm that even if emissions were reduced to zero today (or were reduced by the effects of the mitigation measures) we would still experience the effects of past emissions. It is therefore essential to consider adaptation measures together with mitigation. This concept can be effectively put into practice through a combination of low carbon retrofit and adaptive retrofit measures. Several gaps in current knowledge were identified, those relating to green infrastructure and the mechanisms in which vegetation cools its surroundings.

UK regulation and legislation is reflecting global efforts to mitigate CO_2 emissions. Several social housing low carbon retrofit projects have been launched over the past five years in the UK and abroad, such as IFORE, which have involved the use of technical solutions combined with education and raising the energy awareness of the residents. However, with regard to regulation pertaining to adaptation to climate change and resident participation, knowledge is still lacking; further research is required on occupant interaction, engagement and participation as part of the adaptation process.

Several projects and government funded research programmes were launched to explore adaptation options in housing. CREW (Shao *et al.,* 2012) and SNACC (Williams *et al.,* 2012) were identified as the main references on this subject. The role of external insulation was proven to have beneficial effects on both fronts: reducing carbon emissions and reducing overheating hours. However, gaps in knowledge were identified relating to understanding the best combination of insulation and air tightness, a wider range of shading, and the use of behavioural adaptations.

There is some contradictory evidence within the literature review regarding the role that insulation and air tightness have on reducing (or increasing) the overheating risk. Several studies (Arup, 2005; Crawley *et al.*, 2008) affirm that insulation and air-tightness help in reducing the overheating, and some others (Maldonado, 2005; Orme *et al.*, 2003;) say that it makes overheating worse. The author has clarified the role that insulation and air tightness (or a combination of the two) have in altering the overheating risk in the social housing of Rushenden (Chapter 5).

The calculation of overheating hours as established by CIBSE (2006), (28 °C in the bedroom and 25 °C in the rest of the house) is used to assess the overheating risk for several examples. However, this definition does not take into account the fact that occupants adapt over time to environmental conditions. The European Standard (CIBSE TM52, 2013) uses adaptive comfort theory to produce a comfort algorithm for naturally ventilated offices. This algorithm links the running mean of the external temperature to the comfort temperature, however, a specific adaptive comfort algorithm for housing has not been developed and this is therefore a gap in knowledge. The author established what the comfort temperature is for this group of residents using the same longitudinal questionnaire that was used to derive the adaptive comfort algorithm.

Past and previous research on mitigation takes into account occupant engagement practices that are becoming necessary to ensure that the low carbon retrofit targets are achieved. However, very few climate change adaptation initiatives include examples of participation. SNACC and BIOPICCC involved the residents in the discussion on climate change. The research outcomes highlight the need to find better ways to talk about climate change adaptation.

IFORE's community engagement officers used a number of techniques that involved initiatives for adults and children to enable the occupants in the community to reduce their energy use. These activities include the energy champions initiative, the growing of vegetables in community gardens, the organization of community fairs and the green doctor's visits. The author used the existing structure created by the community engagement team during IFORE to carry out the questionnaires and focus groups used in this dissertation to discuss the adaptation options with the residents.

Participatory Action Research (PAR) is an approach to research that sees "the community under study participate actively with the researcher throughout the research process from the initial design to the final presentation of results and discussion of their action implications" (Whyte *et al.*, 1991). PAR can be adopted in Rushenden with the help of focus groups whereby the discussion is facilitated by the author. Elements of the communities of practice theory were used by the author to structure focus groups and the discussion on adaptation with the residents (Chapter 4).

Generic examples of the costs of adaptation were identified in CREW (Shao *et al.,* 2012) and in the "Your home in a changing climate" report (ARUP *et al.,* 2012). However, detailed payback times for adaptation options were not fully explored in these examples and is a subject for further research. In order to assess the payback times of adaptation options it is necessary to calculate the relative reductions in cooling energy that the adaptations produce.

Chapter 3. Methodology

3.1 Introduction

The behaviour of the occupants as well as their adaptive capacity will determine how much cooling energy they need in their homes. Depending on the occupants' understanding and degree of energy awareness there will be different energy demands, which is why it is very important to consider the wider socio-economic context. Several methods are used in this thesis to assess the adaptation measures in social housing: surveys and questionnaires, dynamic thermal modelling and monitoring of the environmental data.

A brief overview of all the methods used in this thesis to answer the main research questions is discussed herein. Qualitative and quantitative research practices were used during the analysis of the data. The calculation of payback times was used to assess the cost of adaptation measures and packages.

The question of whether the houses in Rushenden will be comfortable in a future climate is answered by simulating different scenarios, using probabilistic weather data, within the models. While seven house types were modelled by the author for IFORE to calculate the heating consumption before and after retrofitting, two types are assessed herein for overheating. This is because there are two main types of house in Rushenden: single and two storey.

Dynamic thermal modelling is used to calculate the cooling loads and overheating hours. Since the levels of insulation and air-tightness were modified during the retrofitting, in the models, the author calculated the cooling loads and overheating hours before and after the low carbon retrofit measures were installed. The adaptations, applied to the models of the houses retrofitted with insulation and air tightness, are then added to the models and the reduction of overheating hours and cooling loads are calculated at present and in the future. The results of the simulations are analysed using adaptive comfort model (CIBSE TM52, 2013).

3.2 Context

Rushenden is a small social housing development on the Isle of Sheppey, in the borough of Swale in Kent, in the South East of England. Most of the houses are owned by the housing association Amicus Horizon. As a result of the "right to buy" some of the houses were bought by the residents so typical terraces are composed of a mix of social and owner-occupied houses. Within Rushenden, the IFORE project has selected 100 dwellings on the east side of Rushenden Road, the main road that cuts the development in two. The development is composed of single-storey bungalows occupied by the elderly and two-storey family houses. The houses selected were grouped into 7 main types (Figure 3.1).

The houses were built in the 1940s, 1950s and 1960s. The single-storey house types 1, 2 and 3 do not differ substantially between one another apart from in their dimensions and their layout. House type 2 is the most recent and the best in terms of thermal performance. This is also true for the two-storey house types 4, 5, 6 and 7, however, house type 7 seems to be the most recent but is the worst in terms of air tightness and thermal performance (Appendix B.1, B2). Before the retrofitting the appearance of the development was very homogeneous because of the use of traditional brick cladding and roof tiles (Figure 3.2).

After the retrofitting the development has changed considerably, as external insulation has been rendered using a colour palette chosen by the residents. Overall, a thickness of 60mm of phenolic foam was applied to the existing external layer of bricks; photovoltaic panels have been installed on most roofs where the orientation was favourable and, at present, the tenants benefit from the feed–in tariff run by the government. The pepper potting is a result of the owner-occupied houses interspersed with the social housing that have not been retrofitted under IFORE. The thermal bridges that were created at the junction of the retrofitted and unimproved houses reduced the extent of the energy saving that could be achieved by the retrofit. However in the modelling this was not taken into account (Figure 3.3).
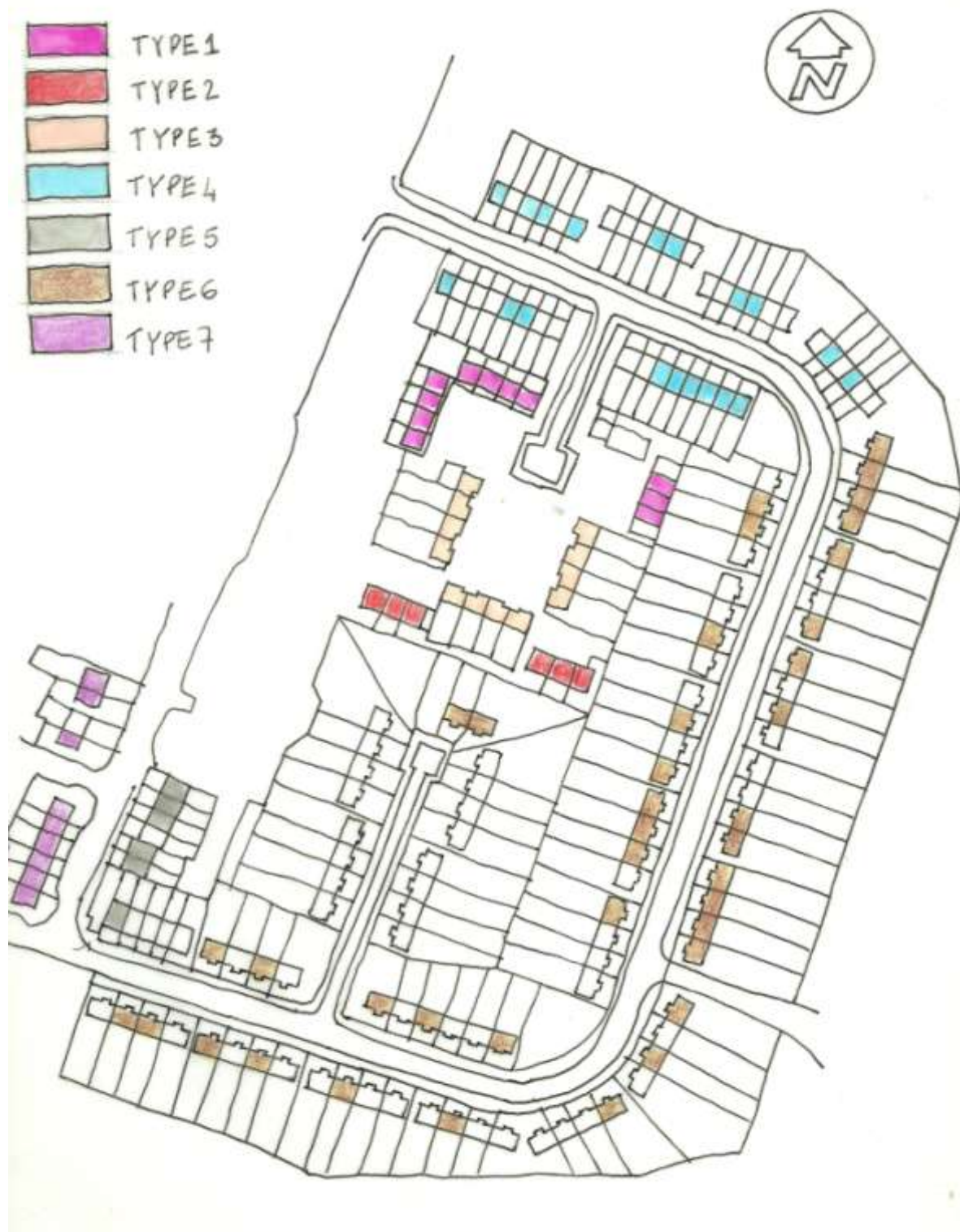
Figure 3.1: Housing development in Rushenden with identification of the 7 house types

Figure 3.2: View of the un-retrofitted houses in Rushenden

A few solar thermal panels were also installed for testing. Generally, the existing twenty year old PVCu window\s have been refurbished by replacing the rubber gaskets and weather seals and only the components that were defective such as the air vents, glazing or handles were replaced (IFORE NL n.3, 2013). Ground and air source heat pumps have also been installed on house type 2.

Some innovative technologies have been installed: supply–air windows and trombe walls. They have been developed and manufactured in France; the French IFORE houses are installing them into a prefabricated timber cladding system that was tailor-made for the project and which includes the external insulation. The design has been modified to fit the houses in Rushenden and these technologies are being exported to the UK. A trombe wall has been installed on a bungalow.

Figure 3.3: View of the retrofitted houses in Rushenden

The closest town to Rushenden is Queenborough (Figure 3.4). Queenborough is the oldest town on the isle of Sheppey and it is located in North Kent, to the south of the Thames Estuary (Queenborough and Rushenden Masterplan, Context, 2010. Because of the nature of the site, the proximity to the sea and street layout Rushenden is particularly windy. Climate files for Dover, located in the same region just forty miles to the south east, are available from the Prometheus website and are used in the modelling to represent a climate similar to Rushenden and typical to the South East of England.

Figure 3.4: Location of Rushenden (Source: Google maps)

3.3 Occupants

"The Queenborough and Rushenden Regeneration will provide new houses and flats for a wide range of people, communities facilities and services, a school, jobs employment space, new open spaces, pedestrian parks and a new marina" (Queenborough and Rushenden Masterplan, Executive summary and Introduction, 2010). The Masterplan has been subject to extensive public consultation over a number of years. The involvement of the community and in particular the children was enabled by the "Planning for Real" (PFR) process (Queenborough and Rushenden Masterplan, Executive summary and Introduction, 2010). Planning for Real is an organization that developed a method for occupant engagement. They asked the children and the community at large to build models and do drawings of how they envisaged their built environment and green spaces to be (Planning for real, 2012).

Rushenden "has broad roads and gardens are generous but lacks any other basic amenities necessary to make a good community" (Queenborough and Rushenden Masterplan, Context, 2010). In Rushenden social rented housing comprises 43% of the total housing stock. This is particularly unusual when compared to an average of 15% across Swale and 14.5% across Kent which is not very far from the 16% national average of social housing reported in the literature review. This results in a concentration of people with a low income (Queenborough and Rushenden Masterplan, Context, 2010).

In Rushenden the current demographic is mainly composed of the elderly and unemployed. The results from the second questionnaire carried out by the Green Doctor and analysed by Dr Paul Hanna using SPSS show that from over 80 households (20 were not able to be contacted), 38 are elderly and retired (Table 3.1). Rushenden with a large percentage of elderly residents is a snapshot of what the future may look like given a nationally ageing population. Only 6 households are in full-time employment and 6 work part time. The unemployed account for 21 households and 9 are long-term sick (Table 3.1). This means that the occupants in 68 of the households surveyed are currently at home during the day. In December 2014 the percentage of unemployed was 5.5% nationally (Office for National Statistics, 2015). Around 45% of the UK social tenants between 16 and 64 years old are working (Gregory and Todd, 2012). Therefore the case of Rushenden in terms of number of unemployed is not too unusual when compared with the national social housing average. However the high percentage of elderly residents increases the vulnerability of the community of Rushenden to heat waves.

The 28 households with a single occupant contain mostly elderly and 16 households contain a couple only. Single parents total 16 households and 19 are couples with children (Table 3.2). Since the population of Rushenden is mainly composed of the elderly or single unemployed, a large number of the IFORE residents, equal to 44 households, have no children living at home.

Employment status	Frequency	Percent	Valid Percent	Cumulative Percent
Full-time employed	6	6.0	7.5	7.5
Part-time employed	6	6.0	7.5	15.0
Unemployed	21	21.0	26.3	41.3
Retired	38	38.0	47.5	88.8
Long-term sick	9	9.0	11.3	100.0
Total	80	80.0	100.0	
Missing	20	20.0		
Total	100	100.0		

Table 3.1: Current employment status in Rushenden (Source: Green Doctor's second questionnaire of the IFORE houses)

Who do you live with?	Frequency	Percent	Valid Percent	Cumulative Percent
I live alone	28	28	35.3	35.4
Spouse or partner only	16	16	20.3	55.7
Spouse or partner and children (under or over 18)	19	19	24.1	79.7
With children only (under or over 18)	16	16	20.3	100
Total	79	79	100	
Missing	21	21		
Total	100	100		

Table 3.2: Who do you live with? (Source: Green Doctor's second questionnaire of the IFORE houses)

3.4 Thermal modelling

Dynamic thermal simulation is used to evaluate current and future projections for heating and cooling loads and overheating risk in two types of house, a single storey and a two storey. ESP-r is the software being used in the IFORE project to evaluate the energy reduction from the low carbon retrofit measures and the research tool used in this thesis to assess the climate change adaptation. The author used ESP-r to simulate two base-case models using different climate change scenarios, occupancy patterns and adaptation options. ESP-r is an open source energy modelling software (Clarke, 2001) that has been validated using industry standard methods and with regard to EN 15265.

The terraces in Rushenden have two main orientations, the main axis facing south-east-north-west and north-east-south-west. Manor Road, where most of the IFORE houses are

located, has a "C" shape that connects Rushenden road, the road that cuts into two the development, on both sides. With the aim of modelling the worst-case scenario, the single-storey house type (Figure 3.5, 3.6) has the living room and the bedroom facing south-west rotated by a 30° angle to the east – west axis where there is a high risk of overheating. Moreover, the windows facing this orientation are difficult to shade because of the low angle of the sun. In this case the only way to shade is to have a frame "consisting of a horizontal overhang and a vertical fin oblique at 45° towards the south" (Givoni, 1994). The area of the single storey house type (type 2) is 50 m² and its volume is 110 m³.

Type 4 (Figure 3.7, 3.8), the most energy-efficient house type in Rushenden was chosen amongst the four existing two-storey house types. Type 4 is the smallest of the two storey house types and the one that is most comparable with the single storey in terms of footprint. It is a two bedroom house; the living room has single orientation facing south-west and the kitchen faces north-east. The two bedrooms are on the second floor; one is at the front facing south-west and one is at the back facing north-east. The area of type 4 is 72.2 m² and its volume 159 m³.
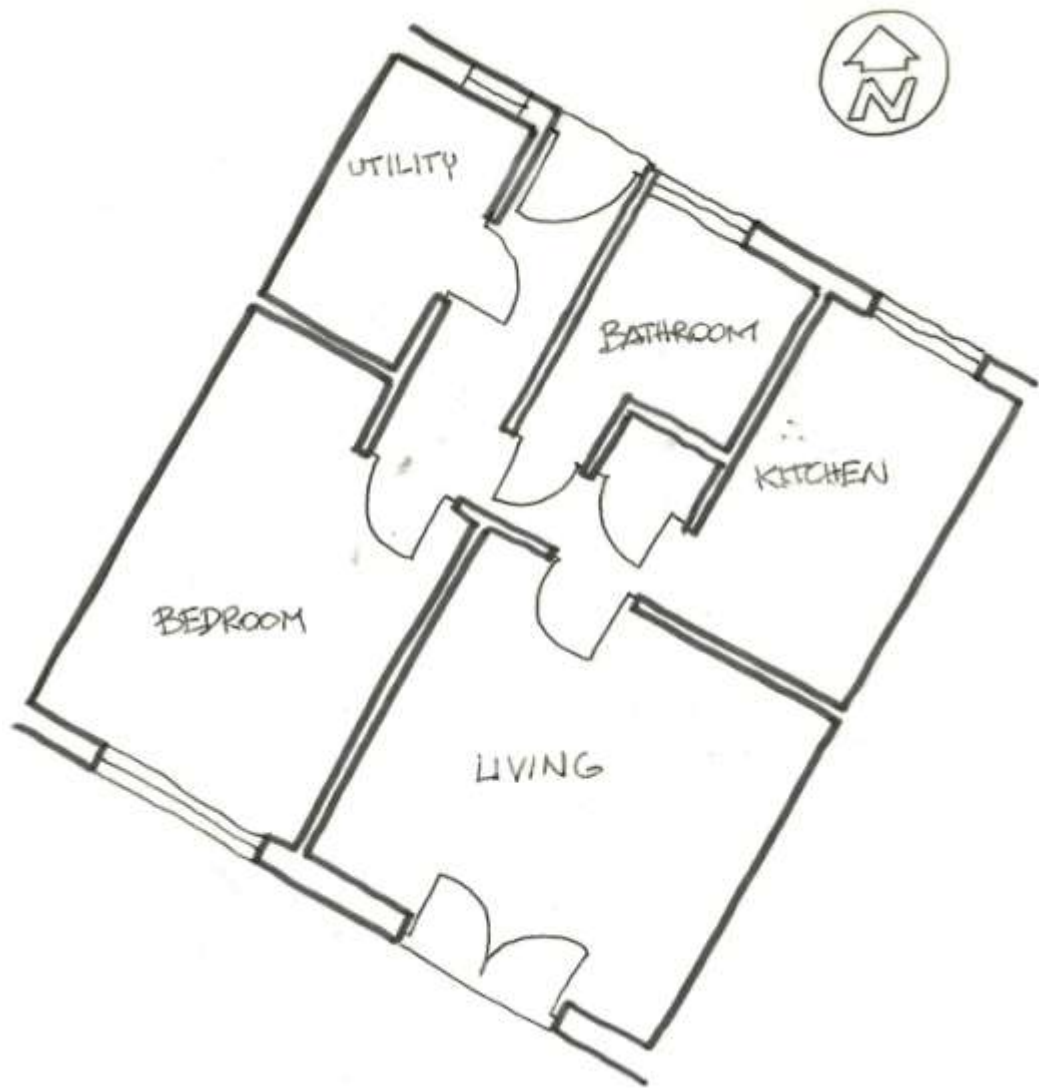
Figure 3.5: Plan with orientation of the single storey house type (type 2) in Rushenden

Figure 3.6: view of the single storey house (type 2)
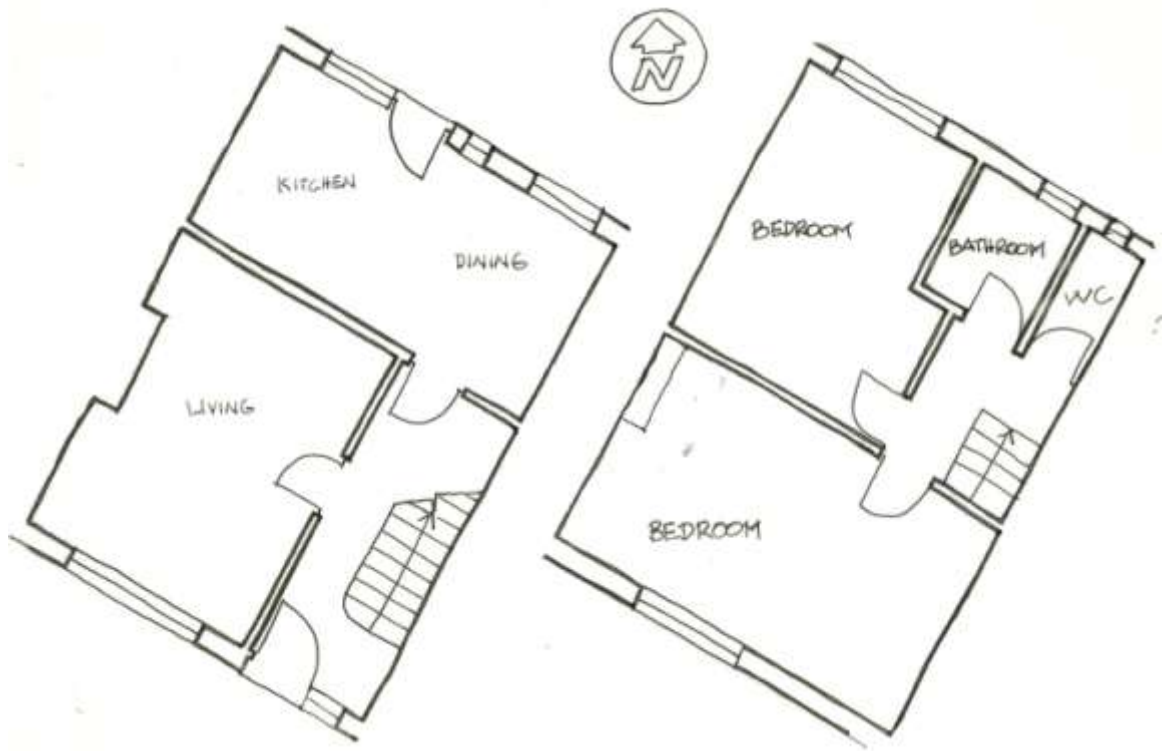
Figure 3.7: plan with orientation of the two storey house (type 4)

Figure 3.8: view of the two storey house (type4)

3.4.1 Weather files

The current weather files commonly used for designing buildings are Test Reference Years (TRY) and Design Summer Years (DSY). The Prometheus project (Eames *et al.,* 2010) has processed the UKCP09 data in order to generate files that can be used by building simulation software (Mavrogianni *et al.,* 2012). The author modelled the base-case single- and two-storey houses using the TRY and DSY for Dover, the closest location to Rushenden, downloaded from the Prometheus project website (University of Exeter, 2014).

In relation to future weather files the author has chosen to simulate using the Design Summer Years (DSY), high emission scenario (A1FI) with a probability of 90%. This means that it is very unlikely that the temperature increase will be above the one given by the projection. This complies with the current trend of designing for the worst-case scenario represented by the "Design for Future Climate" competition in 2011, where most competitors adopted the same approach. ESP-r was used to simulate cooling and heating loads and overheating hours using weather files for 1970s as well as high emissions scenario files for 2030s, 2050s and 2080s.

For the adaptation options concerned, the models were run using the high emission scenario for 2030s at 90% probability. This scenario corresponds to the medium emission scenario for 2050s with 50% probability and to the low emission scenario for 2080s with 50% probability. This roughly corresponds to an increase of +2 °C in the average global temperature. In the Design for Future Climate Conference, Bill Gething (2014) suggested this method of selection from the many weather files available on the Prometheus project website. To choose one scenario has the benefit of establishing a consistent representation of the future climate to 2080s (Figure 3.9).
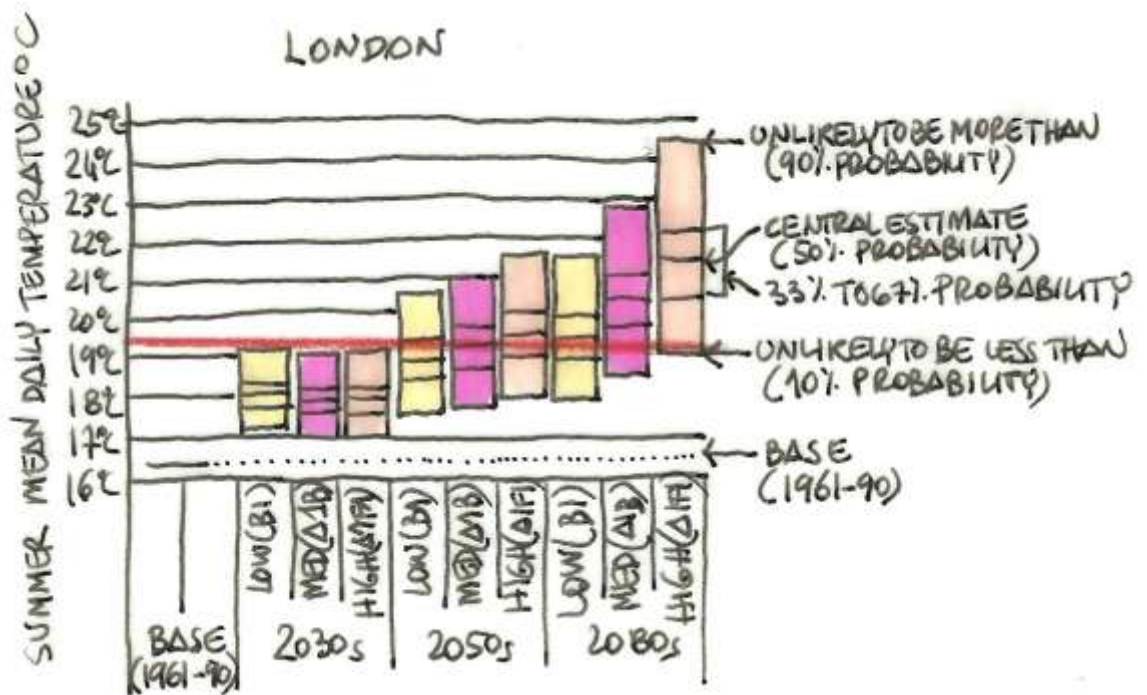
Figure 3.9: "What climate shall we design for?" Presentation to the Technology Strategy Board conference by Mark Wray (Source: Climate UK, no date)

Figure 3.10 represents the reference temperature used by the author in ESP-r to model the base case retrofitted houses. The weather file used contains the temperature averaged in the period between 1961 and 1990 and is called "the 1970s". The averaged maximum temperature is 25.7 °C in July and the minimum is 5.4 °C in February. The mean annual temperature is 9.6 °C. The mean relative humidity is 83.9% (Figure 3.11), the mean wind velocity is 5.2m/s (Figure 3.12) and the main wind direction measured as clockwise degrees from north is 193.2°, south westerly. The average direct normal solar radiation is 111 W/m² and the diffuse horizontal solar radiation is 65 W/m² (Figure 3.13).
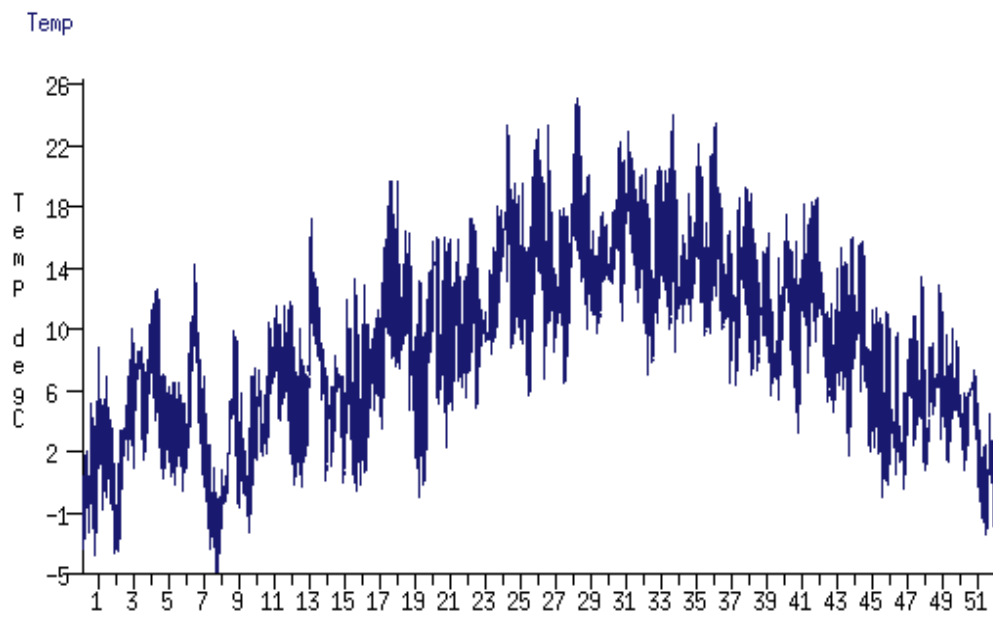
Temp

Figure 3.10: Temperature, Dover 1970s, ESP-r

RH
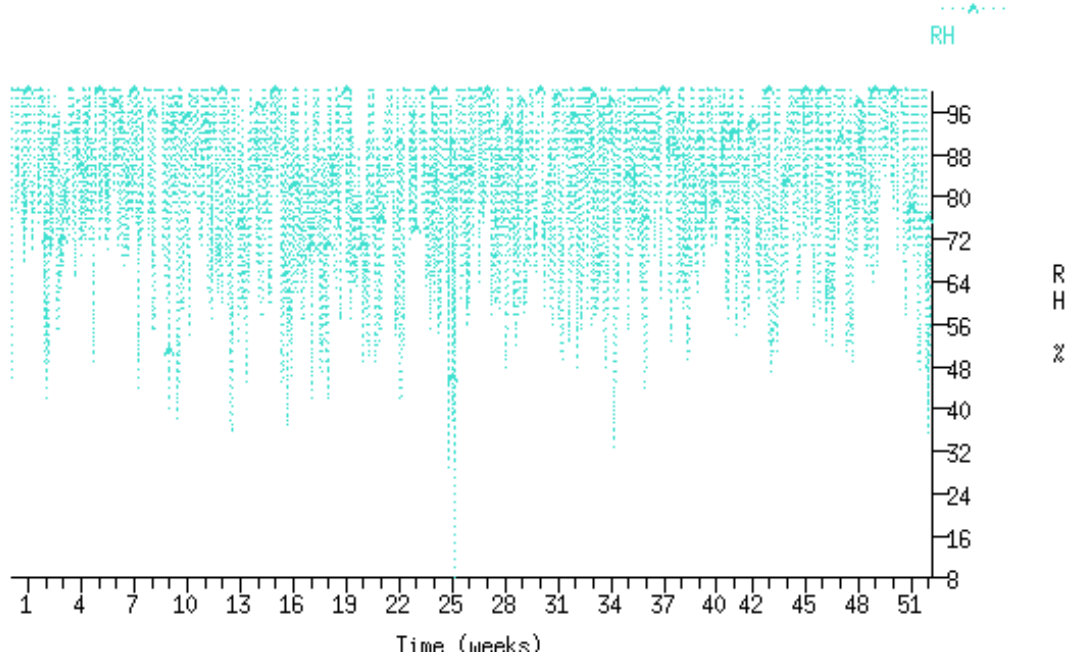
Figure 3.11: Relative humidity, Dover 1970s, ESP-r

Wnd sp
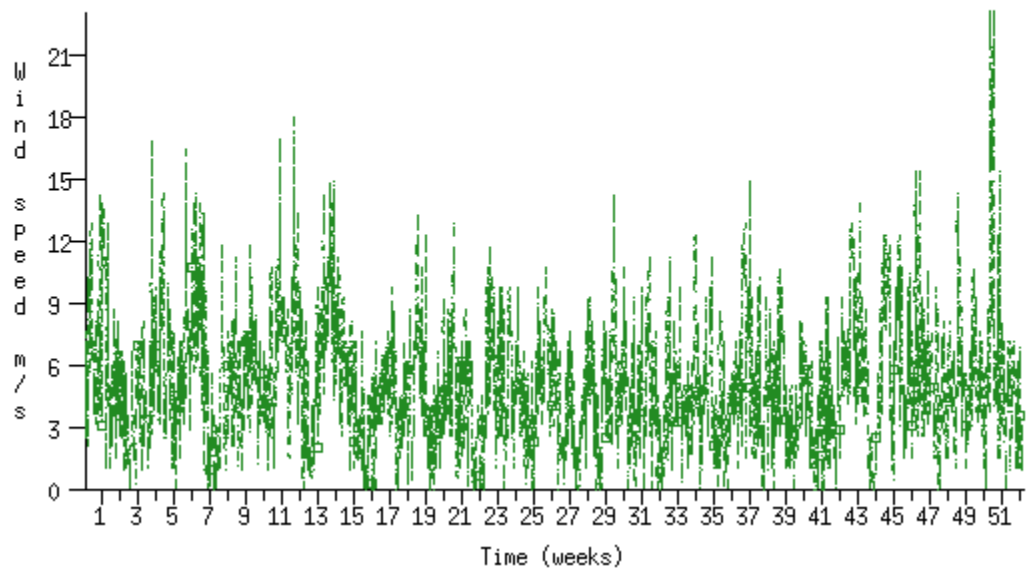
Figure 3.12: Wind speed, Dover 1970s, ESP-r
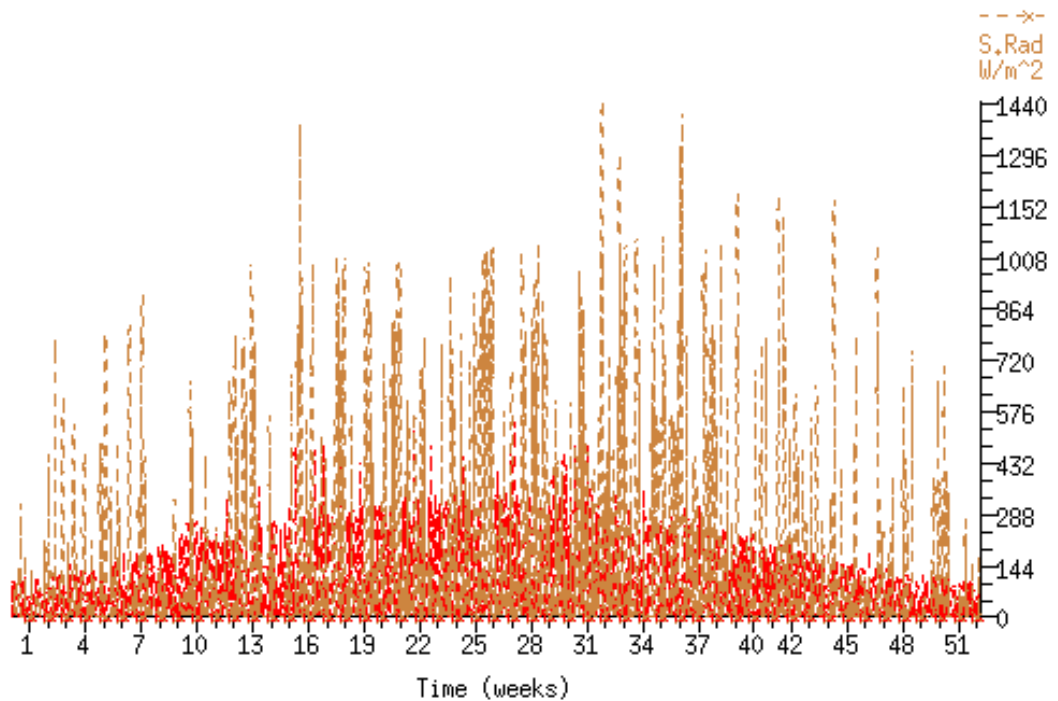
Figure 3.13: Direct and diffuse solar radiation, Dover 1970s, ESP-r

95

In 2030s, at the same latitude using the high emission scenarios probabilistic TRY (test reference year) climate file with 90% probability (see the literature review chapter for climate data) the maximum temperature increases to 31.7 °C in July and the minimum decreases to -3.7 °C in January; the annual mean temperature is 12.8 °C (Figure 3.14). The annual relative humidity decreases to 81.4% (figure 3.15) The wind speed is not predicted to change, while the wind direction changes only slightly, by 3 ° west (Figure 3.16). The direct and diffuse average yearly solar radiation increases to 130 W/m² and 65 W/m², respectively, as cloud cover is predicted to diminish considerably in the summer (Figure 3.17).
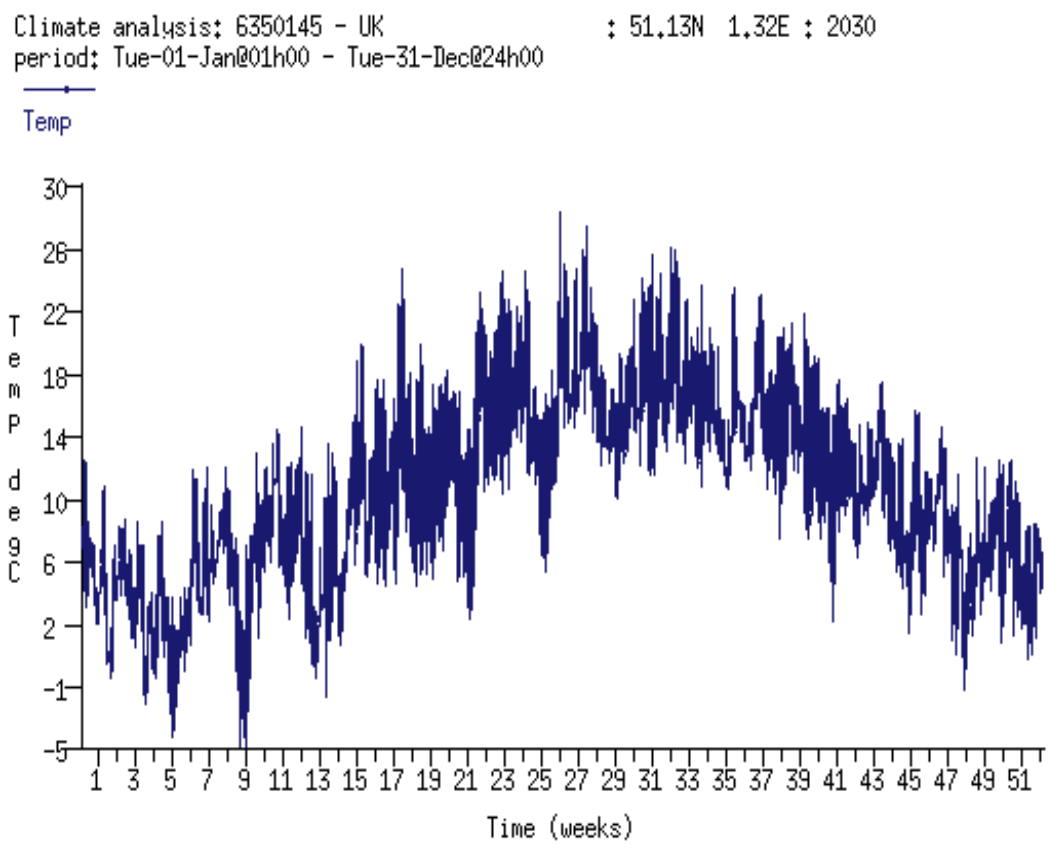
Figure 3.14: Temperature, Dover 2030s, ESP-r
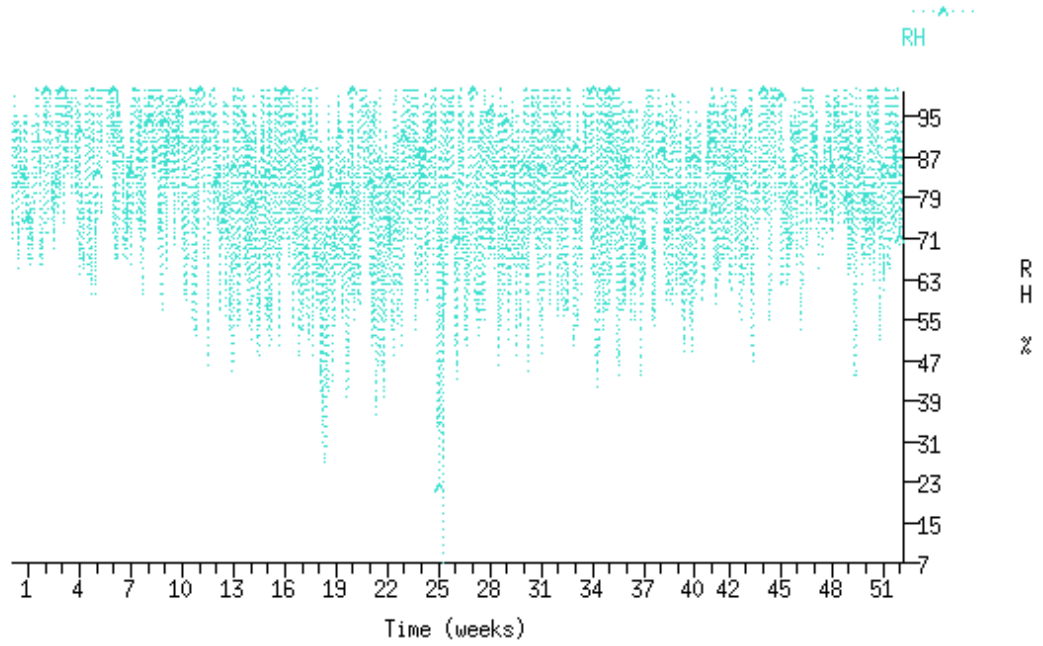
Figure 3.15: Relative humidity, Dover 2030s, ESP-r
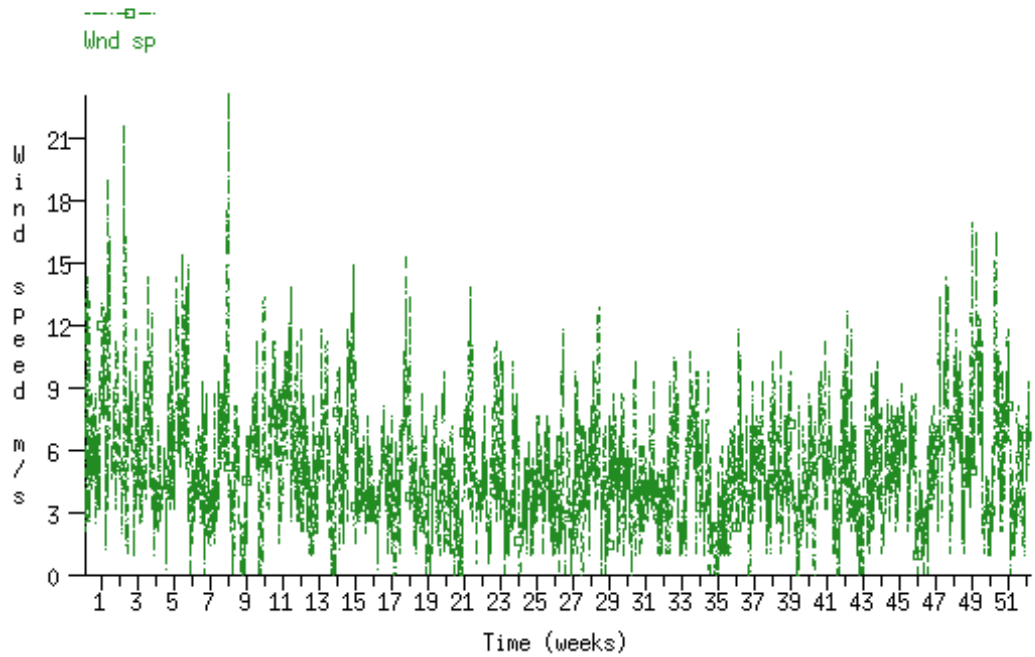
Figure 3.16: Wind speed, Dover 2030s, ESP-r
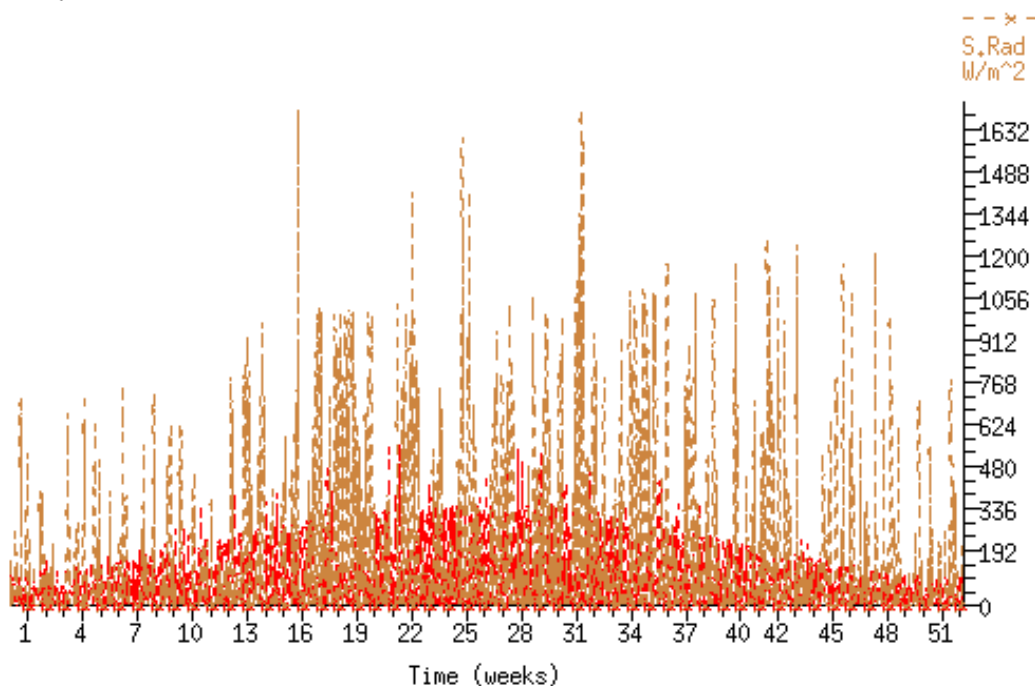
Figure 3.17: Direct and diffuse solar radiation, Dover 2030s, ESP-r

By 2050s, the average yearly temperature increases to 14.3 °C. The maximum is 31.4 °C in July and August. When compared to the temperature in 2030 this seems to be lower, however the monthly averages are higher in 2050, which means that higher temperatures will be protracted during the summer months. This increases the risk of health hazards and heat stroke especially in the case of the elderly. The minimum is -2.3 °C in January (Figure 3.18). In accord with the prediction that in the future we will see warmer and wetter winters and hotter and dryer summers the relative average annual humidity decreases to 80.6% (Figure 3.19). The wind speed and wind direction do not change considerably (Figure 3.20). The average direct solar radiation decreases to 122.6 W/m², while the diffuse solar radiation increases slightly to 66W/m² (Figure 3.21).

Figure 3.18: Temperature, Dover 2050s, ESP-r

Time (weeks)

Figure 3.19: Relative humidity, Dover 2050s, ESP-r

Figure 3.20: Wind speed, Dover 2050s, ESP-r

Figure 3.21: Direct and diffuse solar radiation, Dover 2050s, ESP-r

100

By 2080s, the average yearly temperature is predicted to increase to 16.5 °C, becoming 7 °C higher than the base case in 1970 (Figure 3.22). The maximum temperature is 35.4 °C in June and the minimum is -0.4 °C in January. If such high summer temperatures endure for a long period of time there is high risk to the population of heat stroke, as 35 °C is the threshold temperature for this type of risk. The average relative humidity decreases to 77.5% (Figure 3.23), the wind speed does not change substantially (Figure 3.24) and the direct solar radiation goes up to 134.1 W/m² and the diffuse decreases to 63W/m² (Figure 3.25). The increased temperature and global solar radiation are the causes of the overheating, moreover, the lower relative humidity in the summer will make the weather dryer. Evaporative cooling strategies, such as planting trees, are very appropriate in this type of climate.
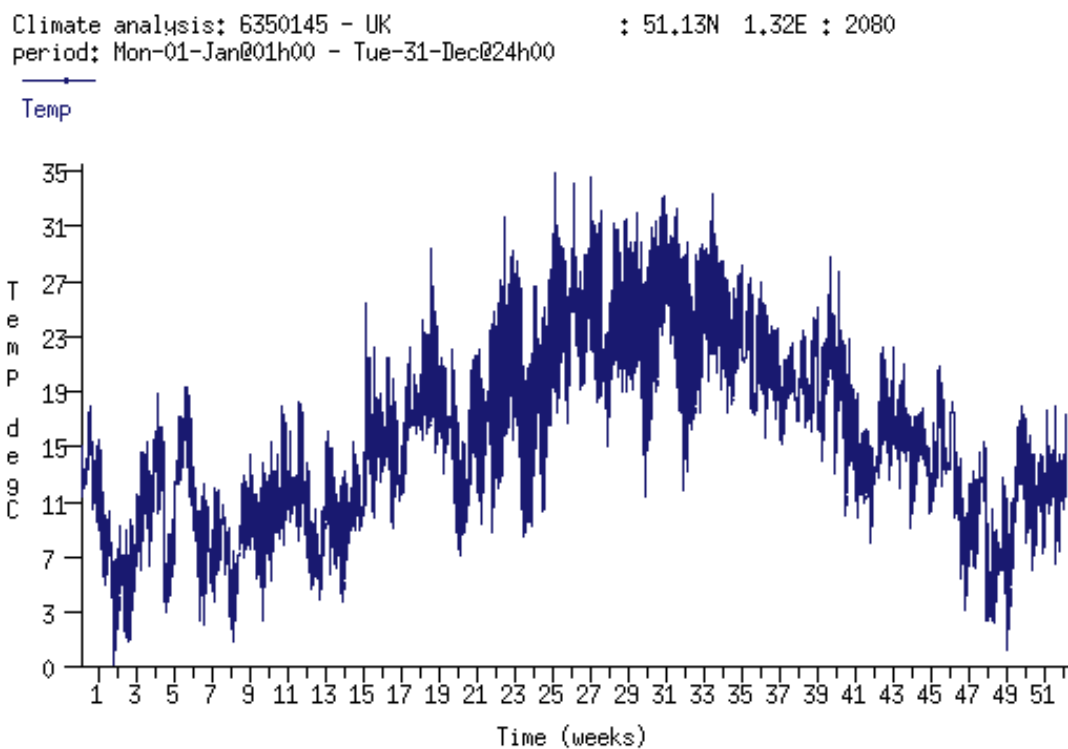
Figure 3.22: Temperature, Dover 2080s, ESP-r

Figure 3.23: Relative humidity, Dover 2080s, ESP-r

Figure 3.24: Wind speed, Dover 2080s, ESP-r

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Climate analysis: 6350145 - UK                  : 51.13N  1.32E : 2080
period: Mon-01-Jan@01h00 - Tue-31-Dec@24h00
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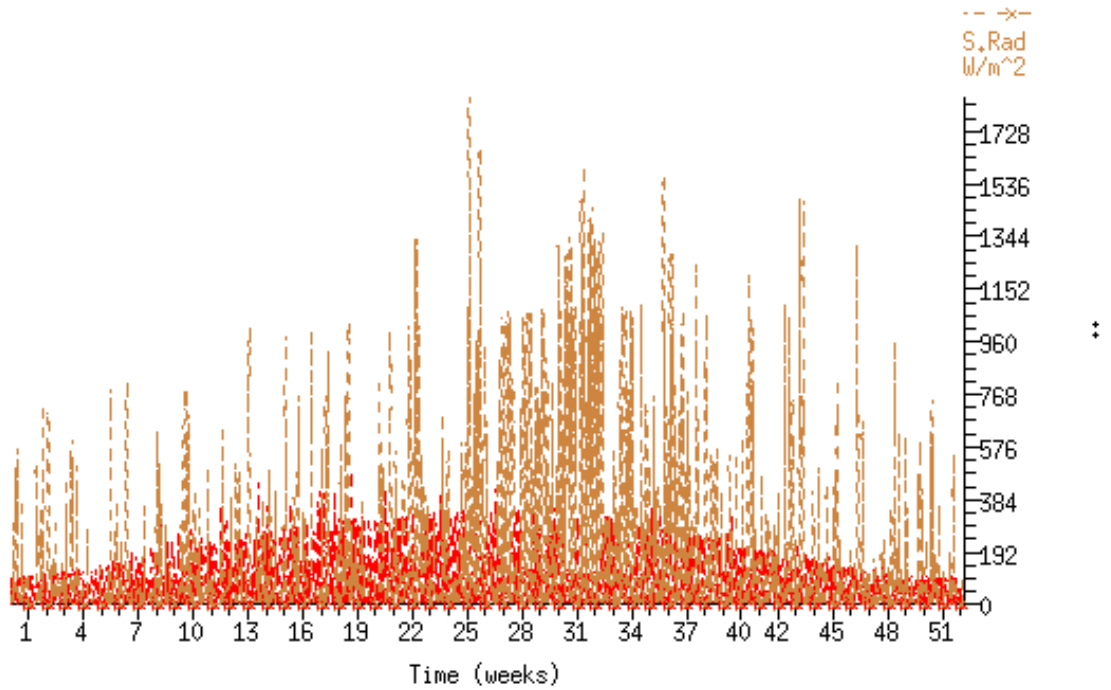
Figure 3.25: Direct and diffuse solar radiation, Dover 2080s, ESP-r

Cooling and heating loads determine present and future carbon emissions as they are associated with a running cost, both present and future. They were also used to determine the payback times of the adaptation options. A comparison of the overheating hours determined what adaptation option is more effective and at what point in the future will need to be implemented. A summary of the modelling process is simplified in the following flow chart (Figure 3.26).
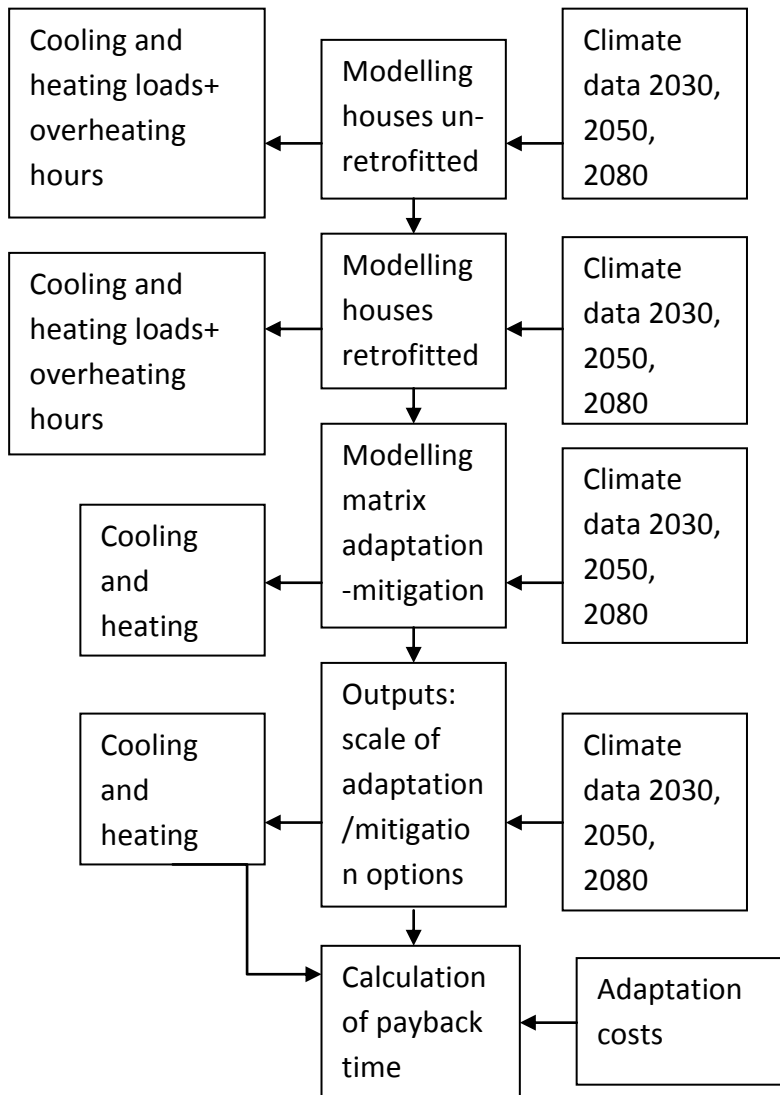
Figure 3.26: Flow chart summarizing the modelling process

3.4.2 Modelling assumptions and specification of the houses un-retrofitted and retrofitted

In order to answer the following four research questions:

- In the future, will the retrofitted social housing at Rushenden overheat to a greater extent than if the work had not been carried out?

- What type of retrofit, light retrofit or deep retrofit would tend to overheat more? For social housing (given limited financial resources) a reduced level of retrofit is the norm, how does that compare with deeper retrofit solutions (such as Enerphit) in terms of overheating risk?

- If retrofit might increase the overheating risk, which measures are likely to cause this increase - more insulation, air-tightness, or both?
- In which respects might the retrofit be helping to reduce the overheating risk, and which elements are the most beneficial?

The base-case models are first evaluated with no interventions. This first run of simulations gives an indication of the heating and cooling loads of the buildings before the low carbon retrofit measures are put in place and to what extent the houses would overheat in the future if they were not retrofitted. This represents a base for comparison for all other modifications.

The base-case models are then evaluated with the addition of the loft and the external insulation that were installed during IFORE. This assessment verifies if the insulation causes an increase or a reduction of the cooling load. The same assessment is carried out by modifying the air change rate of the base-case models to account for the air tightness improvements that were made during the retrofit. Finally the models retrofitted with insulation and air tightness are assessed and the heating and cooling loads compared with those of the un-retrofitted houses.

The simulations described above answer the first, third and fourth question. The second question is investigated by adding some of the Enerphit characteristics to the retrofitted models. Simulations are run by increasing further the thickness of the external insulation and improving the air tightness. The results clarify if deep retrofit increases or decreases the overeating risk and to what extent.

3.4.2.1 Building fabric

The construction details of all IFORE properties before the low carbon retrofit took place are the following. The U-values are shown in Table 3.3.

- Brick and block walls with a 50-75mm cavity.
- Cold roof with a minimum 100mm loft insulation at joist level
- Ground floor concrete slab-on-grade without insulation.
- First floor suspended timber.

Building component	Thickness mm	U-values W/m²K
External walls	266	1.382 (does not include cavity insulation)
Party walls	241	1.799
Ceiling	113	0.366
Roof	25	4.136
Ground Floor	140	3.611
First Floor	203	1.162
Windows	24	2.811

Table 3.3: U-values of the houses before retrofit

The houses retrofitted by IFORE have the following characteristics and U-values, shown in Table 3.4. The physical properties of the houses are represented herein as they were modelled by the author.

Building component	Thickness mm	U-values W/m²K
External walls	400	0.165
Party walls	241	1.799
Ceiling	283	0.143
Roof	25	4.136
Ground Floor	140	3.611
First Floor	203	1.162
Windows	24	1.713

Table 3.4: U-values of the houses after retrofit

This provides future predictions of energy use once the low carbon retrofit measures are in place. This assessment determines if low carbon retrofit increases the overheating risk and to what extent. A full list of retrofit measures is presented as follows:

(0) = base-case: building as it stands before retrofitting (cavity insulation uses the characteristics described below)

(1) = (0) + 270 mm of loft insulation (glass wool)

(2) = (1) + 80 mm of external insulation EPS with rendered plaster on the outside face

(3) = (2) + air tightness improvement

(4) = (3) + MVHR with 90% of the heat reclaimed (single storey terraces)

(5) = upgraded boiler (used in the calculation of the carbon emissions)

The ESP-r library does not include phenolic foam used with a thickness of 60mm in Rushenden for the external cladding. Therefore 80mm of EPS were used in the models instead. The thermal conductivity of the phenolic foam used in Rushenden ranges

between $\lambda = 0.2$ W/mK and $\lambda = 0.23$ W/mK (Kingspan, no date). The thermal conductivity of the EPS used in the models is 0.3 W/m²K. The thermal resistance, R = l/ λ (where l is the thickness of the insulation) is R = 2.6 m²K/W, the same for both EPS and phenolic foam. Surveys carried out by Amicus Horizon showed that the cavity wall insulation is of the type SUPAFIL, a glass fibre injected in loose form (Figure 3.27). The thermographic photos showed that there are gaps in the cavity insulation and the filling is generally uneven, so the conductivity and density of the fibre that is reported as being $\lambda = 0.04$ W/mK and $\delta =$ 18 kg/m³ from the British Board of Agreement (BBA) was adjusted to account for the age and gaps to $\lambda = 0.07$ W/mK and $\delta = 10$ kg/m³.

Thermal

Supafil® CarbonPlus Cavity Wall Insulation has a thermal conductivity of 0.034W/mK declared to lambda 90/90.

Fire

Supafil® CarbonPlus Cavity Wall Insulation is classified as

Euroclass A1 to BS EN 13501-1.

Figure 3.27: SUPAFIL cavity wall insulation (Source: Amicus Horizon)

3.4.2.2 Ventilation and infiltration

In the first instance, when assessing the heating and cooling loads of the models and answering the first four research questions, the infiltration rate was calculated using the following simplified formula (CIBSE Guide A, 2009):

$$ACH = q50/20$$

Where ACH is the air change rate to be used in the models and q50 is the air change rate at 50Pa from the pressure test results (Appendix B.1). These infiltration rates are 6 ACH

and 4.5 ACH for the single storey terrace and 9.5 ACH and 6 ACH for the two storey terrace un-retrofitted and retrofitted calculated with a pressure difference of 50Pa. A ventilation rate of 13 l/s for the single storey house and 25 l/s for the two storey house was added to the infiltration rate calculated using the above formula as prescribed by the UK building regulation Part F (HM Government, 2010). In addition to that, the un-retrofitted houses have intermittent mechanical extract in the kitchens and bathrooms. These were added to the ventilation rate using the indication given by SAP 2009 (Building Research Establishment, 2014) that prescribes 10 m³/h for each fan.

The final sum of infiltration and ventilation rates used in the models of the un-retrofitted single and two storey houses was therefore equal to 0.9 ACH and 1.26 ACH respectively. During the retrofit, mechanical ventilation heat recovery (MVHR) was installed in the single storey houses, while intermittent extract ventilation remained unchanged in the two storey houses. After the retrofit the sum of infiltration and ventilation rates used in the models of the single and two storey houses was 0.23 ACH and 1.06 ACH respectively. Since Airflow Duplexvent, the MVHR system installed in Rushenden, has a coefficient of performance of 90%, the fans in the kitchen and bathroom were sized to continuously extract only about 5 m³/h, split between the two, this flow rate being all the air that the boiler is required to heat. This calculation assumes that the rest of the required ventilation rate was recovered by the MVHR system. During the summer the MVHR in the single storey dwelling is normally switched off therefore the air flow rate is 0.645 ACH.

This technique of providing ventilation by using an MVHR in the winter and window opening in the summer is common practice in the single-storey houses in Rushenden. However, the difficulties associated with opening windows during the summer were highlighted during focus groups and one-to-one interviews, as some residents, in the two-storey houses, complained about the smell of the sewage system located towards the end of Manor Road. The summer was free-floating with no cooling in order to assess the overheating hours above the threshold.

3.4.2.3 Internal gains

The different occupancies, determined using survey data for Rushenden, are based on the recurrence of certain patterns of family composition. The occupancy profile for the modelling was assumed to be:

1. For the single-storey house: one elderly person at home all day
2. For the two-storey house: a family of four with two unemployed adults at home and two children at school during the day, and a family of three with a working parent out during the day and two children at school.

The family compositions chosen for the two storey houses were those most common in the type 4 terraces as determined by the author from the Green Doctor's surveys. This is in contrast with the national average of one child per household and with the outcomes from the questionnaires in Rushenden that showed that the majority of households have one child living at home. However this does not necessarily mean that the proportion of only children is increasing nationally (Office for National Statistics, 2012). "Women have been postponing childbearing to older ages in recent years, this could be temporarily increasing the number of families that had their first child but not yet had their second" (Office for National Statistics, 2012). Therefore the most common family composition in type 4 was analysed. The case of a lone parent was included since, as explained in the Social Housing context section of the Literature Review chapter, the vast majority of parents in this category live in social housing.

Internal gains for people and appliances were determined using CIBSE (CIBSE, 2006) and ASHRAE (ASHRAE, 2001) guideline values (Porrit *et al.,* 2010). Sensible gain values were set as follows: seated adults 65 W/person; seated child 50 W/person, sleeping adults 43 W/person and sleeping children 30 W/person (Porrit *et al*., 2010). Latent gains are set to be 30 W/person. Appliance gains of 150W for the living rooms (TV) and 100W for children's bedrooms (computers) were set to follow occupied hours (switched off when asleep) (Porrit *et al*., 2010). Low-energy lighting is assumed and 30W lighting heat gains are included for the living room and 10W for the bedroom (Porrit *et al.,* 2010). The fridge in the kitchen was set at 50W. The schedules of occupancy were set as follows for the single- and two-storey house types (Table 3.5).

Heating and cooling in the two-storey house were set following the schedules below (Table 3.6, 3.7) in the living room and in the bedrooms. The heating was set at 21 °C from 1st October to the 30th April. The cooling set point was set at 25 °C in the living room and 23 °C in the bedroom during the summer, from the 1st May to the 30th September in line with the CIBSE requirements (CIBSE A, 2006). The assumption was made that only the living room and the bedroom of the single- and two-storey houses would be air conditioned during occupied hours. The windows of these two rooms are close as a result. The other rooms, the kitchen, bathroom and the spare bedroom, remain naturally ventilated via opening the windows throughout the summer, but the doors to the living room and the bedrooms are kept closed day and night.

	Living room	Kitchen/diner	Bedroom
Elderly single	8.00-21.00		21.00 – 8.00
Family of 3 – employed	18.00-19.00/20.00-22.00	7.00-8.00/19.00-20.00	22.00 – 7.00
Family of 4 – unemployed	8.00-13.00/14.00-19.00/20.00-22.00	7.00-8.00/13.00-14.00/19.00-20.00	22.00 – 7.00

Table 3.5: Timetable of occupancy for the elderly single, the unemployed and the employed family

	Children: sensible heat	Children: latent heat	Adults: sensible heat	Adults: latent heat	Casual gains
Living room 8.00-13.00			130 W	60 W	150 W
14.00-19.00/20.00-22.00	100 W	60 W	130 W	60 W	150 W
Kitchen/diner 7.00-8.00/13.00-14.00/19.00-20.00	100W (morning and evening only)	60W (morning and evening only)	130 W	60 W	50 W+30 W (evening only)
Bedrooms 22.00-7.00	60 W	60 W	86 W	60 W	

Table 3.6: The family with unemployed parents has the above timetable and casual gains

	Children: sensible heat	Children: latent heat	Adults: sensible heat	Adults: latent heat	Casual gains
Living room 18.00-19.00/20-22.00	100 W	60 W	130 W	60 W	150 W (television) + 30 W (lights)
Kitchen/diner 7.00-8.00/19.00-20.00	100 W	60 W	130 W	60 W	50 W (fridge) + 30 W (lights)
Bedrooms 22.00-7.00	60 W	60 W	86 W	60 W	

Table 3.7: The family with the employed single parent follows the timetable above

3.5 Calculation of the overheating hours: the Adaptive comfort algorithm

Most of the guidelines on overheating were developed for offices and educational facilities because productivity is the key in these types of building (Barraclough, 2011). In housing, more than in offices and other building types, people can adapt to higher temperatures in their environment by changing their clothing, taking more showers or moving to a cooler room (Barraclough, 2011). That is why in housing is very important to ensure the occupants have the possibility to use the space flexibly, and to understand how people perceive comfort locally and search for it.

In the community of Rushenden, the residents are mostly single, elderly and retired or unemployed. These residents spend most of their time indoors and in the event of a heat wave they would be very vulnerable. In order to find the best adaptation strategy it is

therefore essential to determine what the particular comfort temperature is for this group of people.

ASHRAE defines thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (Fanger, 1970). Fanger's comfort theory (1970) explains that due to different physiologies, a group of people will never be satisfied at the same time, however, an optimum environment is created where the highest possible percentage of people will be satisfied (Fanger, 1970).

The indexes of PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) were developed using the equations for the skin secretion of the human body and a heat balance function utilising heat transfer theory. People's vote is expressed on a scale from -3 to +3 (ASHRAE), where 0 is the neutral point. However, this theory does not take into account the fact that humans tend to become accustomed to the environment they live in and over time they adapt to the thermal sensation of heat or cold within a certain range.

In order to explore this aspect of comfort, the adaptive comfort theory was developed by Nicol and Humphreys in the UK and Brager and de Deer in the USA. The comfort temperature is defined as "the indoor operative temperature at which an average subject will vote comfortable (or neutral) on the ASHRAE scale" (Nicol, 2002). It was found by Humphreys *et al.,* (2007) "in a survey of data from all over the world" that the average comfort temperature could be approximated in free running buildings to:

Equation 3.1: $T_c: 0.53T_o + 13.8$,

where T_o is the prevailing outdoor temperature (Nicol *et al*., 2012). The running mean temperature was found to be a much more reliable measure of the environmental conditions than the average outdoor temperature. The comfort temperature and the running mean temperature are shown to be in a linear relationship.

The SCATS project results (McCartney, 2002) and surveys were used to write the new European Standard on indoor environmental parameters for design and assessment of

energy performance of buildings EN 15251 (2007). Humphreys and Nicol published a paper in 2008 where the process of deriving the standard from the SCATs surveys is explained in great detail. The measurements were taken on 1449 free running buildings among the 4655 sets of surveys. The globe temperature (the temperature measured at the centre of a black or grey painted sphere, Nicol *et al.,* 2012) approximates the operative temperature and the comfort temperature (T_c) was derived by the following equation:

Equation 3.2: $$T_c = T_g - C/G,$$

where C is the comfort vote on the ASHRAE scale (from -3 to 3), G is the Griffiths constant that can be approximated to $G=0.5$ K^{-1} (Nicol *et al.*, 2008) and T_g is the globe temperature. G can be used to calculate the comfort temperature from a single vote or a group of votes, in that case T_g and C will be averaged (Nicol *et al.*, 2012). As "in most indoor conditions the operative temperature and the air temperature are not very different" (Nicol *et al.*, 2012); in this thesis the operative temperature or the globe temperature will be approximated by the indoor average air temperature (this minor approximation is due to the elimination of thermal mass from the calculation). The above equation will be used to calculate the summertime comfort temperature in Rushenden.

For naturally ventilated office buildings in Europe the relationship between the comfort temperature and running mean temperature was expressed as follows (Nicol, 2002) and is included in the European Standard EN15251 (2007). This relationship was found by plotting the values of the neutral (comfort) temperature against the outdoor running mean temperature for α=0.8. The formula below calculates the comfort temperature in free running offices in Europe plus or minus 3 °C (private conversation with Nicol, 14th November 2011).

Equation 3.3: $$T_c= 0.33\,(T_{rm}) + 18.8.$$

Specifically for housing in the South East of England there is not such a relationship since all the survey studies have been carried out to date for offices in Europe and for several other building types around the world. Using the summertime comfort questionnaire

carried out during the summer of 2012 the author determines what the current summertime comfort temperature is in Rushenden.

The number of overheating hours is assessed herein using the adaptive comfort set of equations that the CIBSE Technical Memorandum 52 (CIBSE, 2013) describes. TM52 is a transposition of the European Standard on adaptive comfort and was authored by Nicol *et al.* The equation was derived from hundreds of surveys that office employees were asked to complete by expressing their thermal sensations as well as clothing and activity levels. There is some interest in deriving a similar equation specifically for housing using surveys from housing residents. However TM52 is, to date, the only reference available on adaptive comfort in Europe and the algorithm can be used to assess adaptive comfort in all European buildings. The running mean temperature was calculated using the following equations 4.5 and 4.6 from TM52, where T_{rm} is the running mean temperature and T_{od} is the operative temperature that was approximated to the average outdoor temperature, and a=0.8 is a constant.

Equation 3.4

$$T_{rm} = (T_{od-1} + 0.8\, T_{od-2} + 0.6\, T_{od-3} + 0.5\, T_{od-4} + 0.4\, T_{od-5} + 0.3\, T_{od-6} + 0.2\, T_{od-7}) / 3.8$$

Equation 3.5 $$T_{rm} = (1 - a)\, T_{od-1} + a\, T_{rm-1}$$

CIBSE TM52 (2013) sets three criteria for comfort in the summer. "A room or building that fails any 2 of the 3 criteria is classed as overheating". The criteria are all defined in terms of ΔT, which is the difference between the indoor operative temperature T_o and the maximum temperature T_{max} (Equation 3.6). The first criterion sets a limit for the number of occupied hours that the operative temperature (approximated here to the indoor temperature) can exceed the maximum acceptable temperature T_{max}. "The number of hours, during which ΔT is greater or equal to one degree (K) during the period May to September inclusive shall not be more than 3% of occupied hours" (CIBSE, 2013). A lower threshold for the single storey dwelling, 1K (1K=1 °C) less than T_{max} was recommended for sensitive and fragile persons such as the elderly. The second criterion sets a daily limit for acceptability using equation 3.7. To allow for the severity of overheating the weighted

exceedance (*W*e) shall be less than or equal to 6 on any one day (Equation 3.7). The third criterion states that the maximum value of ΔT shall not exceed 4K.

Equation 3.6 $T_{max}= 0.33 (T_{rm}) + 21.8$.

Equation 3.7 $W_e = (\Sigma h_e) \times wf = (h_e0 \times 0) + (h_e1 \times 1) + (h_e2 \times 2) + (h_e3 \times 3)$,

where the weighting factor wf = 0 if $\Delta T \leq 0$, otherwise

wf = ΔT, and h_{ey} is the time (h) when wf = *y*.

3.6 Adaptations

The living room and bedroom windows have a south-west orientation and they are difficult to shade since the sun is low, even in summer. As an alternative, movable devices like roller blinds and awnings on the outside of the building, and roman or venetian blinds on the inside are more suitable for this orientation.

The implementation of the adaptation measures in the models answers the following research questions:
- How can these retrofitted houses be adapted to a warmer future climate?
- How can a specific adaptation strategy be established for these houses?

 The third run of simulations involves the use of adaptation measures. At this stage the adaptation measures are added to the retrofitted houses and the simulations run for each measure as was done in CREW and SNACC. Some of the adaptations applied to the retrofitted houses are selected from CREW and SNACC and are specified in Table 4.9 below. To advance beyond CREW and SNACC other measures such as trees, roller blinds and side fins were added to the list. A full list of adaptation measures is presented in Table 3.8, grouped into two categories of ventilation and solar shading.

Ventilation	Controlled daytime ventilation (CREW)
	Night ventilation (CREW)
Solar shading	External shutters (CREW)
	External overhangs and awnings (CREW, SNACC)
	External overhangs and awnings + side fins
	Roller blinds
	Venetian blinds (CREW)
	Drapes (CREW)
	Trees

Table 3.8: full list of adaptations

The author will start by testing night ventilation that when combined with thermal mass is described by CREW as a valid adaptation option, able to reduce the overheating hours and is also very cost effective. Thermal mass, however, has been proved (Dunster *et al*., 2005; Gupta, 2012) to increase the heating load in the winter. In the summer the option of night ventilation may generate security concerns and these will be explored in the Discussion Chapter.

Then the author testes a range of shading devices that have been proved to be the most effective adaptation measures as described by the majority of the documents referenced in the Literature Review. The first choice of shading is determined by the preferences indicated by the residents of Rushenden in the adaptation questionnaire. For example, net curtains and roman blinds were chosen as being the preferred options by most of the residents, followed by trees. Other types of shading such as venetian blinds, awnings and fixed overhangs were also preferred by a number of the residents interviewed. The modelling of these systems is described in the Results and Analysis Chapter.

Increasing the albedo of external surfaces (painting the external surfaces white) is said to reduce the cooling load, while slightly increasing the heating load in the winter. It was adopted by both CREW and SNACC. The IFORE retrofit changed the albedo of the external walls by applying a light coloured layer of render over the plaster covering the external insulation. The effects of external insulation proved to reduce the overheating hours (Shao *et al.*, 2012) when coupled with an adequate ventilation strategy. This will be discussed in more detail in the Results and Analysis Chapter.

3.6.1 Complex Fenestration Components (CFC)

Complex fenestration components (Lomanowski, 2008) were used for the simulations of the different types of shading currently existing in Rushenden and for those that potentially could be installed as part of a future retrofit. The CFC database supplies a large number of shading devices, insect screens and a large library of glazing types and manufacturers. Venetian and roller blinds as well as other types of curtain can be inserted into the construction of the existing windows in ESP-r.

Pilkington float glass of 6mm with an air gap of 12mm between the panes was selected from the CFC database. Between the glazing and the shading device, an air gap of 40mm was specified for both internal and external shading. Venetian blinds were modelled in ESP-r as they are already used by the residents in Rushenden. No control was applied to the blinds during the simulations.

3.7 Monitoring, questionnaires and focus groups

3.7.1 Monitoring

The author did not have direct access to the residents' homes and had to rely on the Housing association to install the monitoring equipment. The choices of which household to monitor and for how long, and the method used, were made by the Housing Association. During IFORE several types of monitoring equipment were installed in the houses. Monitoring the indoor temperature and the energy consumption after the retrofit measures were installed was an integral part of the project. Wattbox, an

intelligent heating control, was installed in a small sample of houses in November 2011. At the same time, temperature and relative humidity data loggers were installed within 100 properties for a period of six months. In 2012, AlertMe, a simpler smart meter, was installed in the rest on the houses. Wattbox monitored the internal temperature as well as the gas consumption. Some tinytags, temperature data loggers, were also installed in the houses at the end of the project between November and May 2013 with the aim to validate the modelling results and to offer some comparison in relation to the data that Wattbox had produced.

Comparison between the data from Wattbox and the data loggers showed that the Wattbox temperature was generally lower than the temperature recorded by the tinytags. Moreover the Wattbox recordings were not always reliable, because the raw data was very rough. The readings often showed the same value throughout the day, several hours with values too low to be trusted, or days and weeks with missing data. However, some surveys were carried out by the author with the aim to fill the gap and create a better understanding of the summertime thermal sensations that the residents are currently experiencing. To carry out the comfort study the author uses the summertime indoor and outdoor temperature monitored by IFORE and compares it with the results of the questionnaires. The only temperature data during the time of the comfort study was recorded by Wattbox. This data is used together with the comfort questionnaires to compare occupants' answers with real-time data.

3.7.2 Qualitative research

Qualitative research is often seen to be opposed to quantitative research, while in fact these two research methods can complement each other (Pope and Mays, 2006). One simple way to use qualitative research is to use it as a preliminary to quantitative research (Pope and Mays, 2006). Qualitative research has also a role in validating the findings of quantitative research. Questionnaires and focus groups were used by the author to answer the following research questions presented in the introduction.

-How can a specific adaptation strategy be established for these houses?
-What else can the community do to adapt to a warmer climate?

-Which behavioural aspects adopted in other countries might be applicable to the south-east of England - offering extra comfort in the event of a heat wave?

The first question was explored from a technical and behavioural point of view. The last two were explored from a behavioural point of view only through questionnaires and focus groups. There are three types of qualitative interviews: Structured, semi structured and depth. Structured interviews consist of asking questions with a fixed choice of responses. Semi-structured interviews are conducted on a basis of open-ended questions, and depth interviews may cover only one or two issues in much greater detail. The one-to-one questionnaires and focus groups in Rushenden were a mix of these three types. During the questionnaires, the author (or the Green Doctor) noted down, on the questionnaire sheet, the answers to multiple choice questions and the comments given by the residents to open-ended questions. When the questionnaires were all completed the author carried out the analysis by counting the number of residents that answer the questions in a similar way.

3.7.3 IFORE questionnaires

During the timescale of the IFORE project three sets of questionnaires were submitted to the residents in Rushenden in order to assess their level of energy awareness before, during and after the low carbon retrofit measures were installed. The first questionnaire was done in 2011, the second in 2012 and the third in 2013. The IFORE questionnaires were prepared by Groundwork, a national charity that trains Green Doctors and modified by the IFORE teams during project's meetings.

During the IFORE project the Green Doctor made a series of visits to residents to advise on energy and water usage reduction techniques, providing a 'prescription' of measures each household could take to ensure a reduction in household energy consumption (Hanna *et al*., 2014). At the same time as giving advice the Green Doctor asked the residents the questions of the IFORE questionnaires as presented in Appendix A.1. This enables the community engagement group to establish a personal relationship with the residents who, in turn, open up and are willing to collaborate with the project.

The housing association, Amicus Horizon, played a vital role in ensuring participation. Their existing community activities and network enabled the behaviour change that has taken place in Rushenden. The sociologist, Laura Banks, and the author accompanied the Green Doctor during the first visits and observed the resident interviews.

The questions listed below were written into the IFORE questionnaires by the author, were checked and modified by Professor Fergus Nicol who is Deputy Director of the Low Energy Architectural Research Unit at London Metropolitan University and provided verbal advice, with Laura Banks, before being submitted to the residents. These questions concerned overheating and they were targeted at understanding the residents' perceptions about these topics before and after the retrofit. The aim was to comprehend whether their perception had changed as a result of the occupants' engagement activities.

1. Do any of the rooms in your home become too hot in the summer? yes/no
2. If so which one(s)?
3. How often? just occasionally, about once a week or every day (underline as appropriate)
4. Do you use an electric fan or other cooling device during summer? yes/no
5. If so, what kind of device and in which room(s)?
6. Do you use it just occasionally, about once a week or every day (underline as appropriate)
7. During very hot summer days, how would you rate the overall comfort of your home (underline as appropriate?

Very comfortable moderately comfortable   slightly comfortable

slightly uncomfortable   moderately uncomfortable   very uncomfortable

3.7.4 Adaptations questionnaire

In the summer of 2012, when the IFORE low carbon retrofit work had just started, a summertime questionnaire specifically targeting overheating and adaptation options was

presented to a sample of residents. The aim of this questionnaire was to answer the above research questions and to understand how the residents perceive warming and overheating, what strategies they put in place before retrofit and what measures they are willing to use in the event of a future warmer climate. A draft questionnaire was prepared by the author and checked through by Laura Banks, the University of Brighton sociologist working on IFORE.

The author asked 16 residents living in 16 households, two living in the single-storey houses and 14 living in the two-storey houses, a maximum of 19 questions regarding their preferred shading devices, the potential use of air conditioning, concerns about windows opening and the willingness to pay for some adaptation options. At the end of the questionnaire the residents were asked to rate in a scale from 1 to 5 the practicality, cost, appearance, security and the need for financial help of the shading devices. A copy of the questionnaire is presented in Appendix A.2.

3.7.5 Focus groups

"Focus groups are a form of group interview that capitalizes on communication between research participants to generate data" (Pope and Mays, 2006). Rather than the researcher asking each person to respond to a question in turn, during focus groups participants are encouraged to talk to one another, ask questions, exchange opinions, experiences and points of views (Pope and Mays, 2006). When groups' dynamic work and the people participating act as co-researchers they can open new paths and take the research in new and often unexpected directions (Pope and Mays, 2006). This is what happened in Rushenden.

In Rushenden, the focus groups were recorded on videos using a laptop and the author acted as a moderator. The analysis of the results was carried out using the research questions as a guide. As suggested by Stewart and Shamdasani, (2015) the author watched the videos of the focus groups several times in order to identify the most relevant passages that elucidated the opinion of the participants on the topics proposed by the author. These passages were then summarized and reported in chronological order in the Field Study Chapter. There were some instances when the discussion naturally

evolved taking different directions including topics that were not initially planned by the author. Some of these instances are reported by the author herein for completeness.

The contemporary focus group interview generally involves 8 to 12 participants. Experience showed that smaller groups may be dominated by few individuals while in bigger groups it may be difficult to hear the opinion of all (Stewart and Shamdasani, 2015). A typical session will last about 1.5-2.5 hours and the groups discussions can be conducted in a variety of sites, from home to offices, by conference telephone and even in virtual worlds (Stewart and Shamdasani, 2015). The role of the moderator is to guide the discussion without interfering too much as long as it remains within the topic of interest (Stewart and Shamdasani, 2015). In Rushenden it was not always possible to achieve the ideal number but the length of the discussion generally complied with the above guidance. The author tried to facilitate the discussion without bias. A list of the focus group's open ended questions is presented in Appendix A.4.

3.7.6 Summertime comfort questionnaire

In 2012, a comfort survey was used to determine the current summertime comfort level and temperature in Rushenden. A sample of residents answered a summertime comfort questionnaire. On an ASHRAE scale from -3 (cold) to +3 (hot) the residents were asked to rate, on a daily basis, the overall comfort of their dwellings over a period of about 60 days during July, August and September. Questions about clothing, activity levels and environmental control were also included in the questionnaire. The first questionnaire was discussed by the author during an interview with each resident, accompanied in some cases by the Green Doctor. During this first visit an envelope containing a copy several copies of the questionnaire were left for the residents to complete.

The occupants were free to choose where and when to carry out their daily task. They were asked to complete the comfort questionnaire in whichever room of the house they were at the time. On each sheet they indicated the date and time and the room they were in. They were asked to express their thermal sensations, their preferences, their clothing and activity levels, and the level of environmental control in place. A copy of the longitudinal questionnaire is presented in Appendix A.4.

Indoor and outdoor temperature and relative humidity are recorded in the houses by Wattbox. Using the summertime comfort study, the recordings were used to draw preliminary graphs of temperature versus comfort vote and trace a correspondence between the thermal sensation and the indoor temperature for the housing sample. The comfort temperature was then related to the outdoor temperature and to the running mean. Wattbox recorded, for each house, only the temperature in a control room and both temperature and relative humidity in the lounge. Data was recorded every minute. This data was also used during IFORE to validate the results of the models of the houses (Appendix B.3). It was averaged to hourly temperature in order to calculate the number of overheating hours.

There are several preliminary analyses that can be carried out to find the relationship between the comfort vote and environmental variables before establishing numerical equations. Empirically, a plot of the comfort vote on the ASHRAE scale against the summertime indoor and outdoor temperatures will give an idea of what the current summertime comfort temperature range is in Rushenden (Nicol *at al.*, 2012). This can be used to validate the results from the numerical analyses. The comfort temperature can also be identified by performing some simple statistical analysis using SPSS and the questionnaires that will be presented in the Field Study Chapter.

3.8 Calculation of payback times

The calculation of the payback times of the adaptation measures and of adaptation packages contributes to answer the following research question: "How can a specific adaptation strategy be established for these houses?". An assessment of the economic impact of adaptation can help Housing Associations in the decision making process. The author therefore proceeded with a calculation of the payback times of the adaptations and clusters of measures. The evaluation of payback times is carried out by calculating cooling loads for each model variation, each future weather year, and with and without adaptation measures. The different models described above and used to evaluate the overheating hours and the percentage reduction that each adaptation allows are re-run to evaluate the relative cooling loads. The cooling loads in kWh/year are then multiplied by a cost for electricity per kWh, assuming that the occupants, in the absence of any

adaptation, buy an air conditioning unit to provide comfort. There are many unknown variables in the calculation. When the author carried out the calculation of payback times for IFORE interest rates were not used. In this thesis as well, interest rates were not used for simplicity. However, for completeness an explanation of the time value of money and its possible implications in the assessment is given below.

The time value of money calculates future cash flows at different points in time. It is based on the principle that a pound today is not worth a pound tomorrow or in a year's time (Peterson Drake and Fabozzi 2009). Moving money through time that is, finding the equivalent value of money at different points in time, involves translating values from one period to another. This process involves interest, which is how the time value of money and risk enter into the process. Compounding is translating a present value into the future. The future value is the sum of the present value and interest. Interest can be both, simple and compound (Peterson Drake and Fabozzi 2009). The formula below (Equation 3.8) explains how to calculate the future value (FV) using the present value (PV) and the interest rate *i* over a number of years n. The interest rate used below is simple.

Equation 3.8 $FV = PV (1+i)^n$

Payback times are calculated as the ratio of the cost of the adaptation options and the cost of an air conditioning unit plus the cost of electricity per year. The result is the number of years that are necessary to pay back the adaptation measures. If the adaptations are implemented by the Housing Association at the present time then the interest rate will be only applied in the calculation to the price of electricity that is projected into the future and increases each year. In this case the number of years to payback the initial investment is likely to be less that that indicated in the Discussion Chapter because the interest rate will increase the future market price of electricity. If however the adaptations are implemented in say, 10 years time, then the interest rate will be applied to the price of the adaptations as well as to the price of electricity. In this case the actual payback times are likely to be closer to those indicated in the Discussion Chapter.

The future price of electricity however has another element of uncertainty. Gaterell and McEvoy (2005) assert that the market price of energy does not reflect the actual cost of its generation and consumption. Externalities represent the environmental cost associated with energy generation and consumption. The share of electricity production and the consequent externalities can have a big impact in the price's fluctuation. Externalities are not included in the calculation presented herein because it was illustrated by Gaterell and McEvoy that in the presence of climate change the value of externalities does not affect the ranking of energy saving measures in terms of their cost-effectiveness.

The asset life of the adaptations is indicated in the table below to account for the expected lifetime of a given investment in the calculation of payback times. The corresponding price of air conditioning is compared with the price of each adaptation and cluster of measures. A scale of adaptation measures is established and relative payback times added to each adaptation. The costs of the measures have been taken from current catalogues and include the price for installation. The price for maintenance and the asset life of each option were recommended by manufacturers. The basic rates of wages for a general building operative (Laxton's, 2013) were associated with the maintenance times given by the manufacturers. An example is shown in Table 3.9 below (see Appendix B4 for details on the derivation of prices).

Adaptation strategy	Price for installation	Nominal price	O&P and sundries	total	Asset life	maintenance
Acer campestre	£ 15	£ 17.42	£ 4.86	£ 37.28	At least 50 years	£ 11.77/year
External overhang/fins	included	included	included	£ 114 /m²	Building's lifetime	£ 4.8/year
Roller blinds	£ 27.67	£ 71.23	£ 10.3	£ 109.2	10 years	n/a
Venetian blinds	£ 27.67	£ 57.19	£ 8.89	£ 93.75	10 years	n/a
External roller blinds	included	included	included	£ 602.3	20-25 years	£ 6.50/year
Awnings	included	included	included	£ 862.37	10-15 years	£ 6.50/year
External shutters	included	included	included	£ 100/m²	10 years	£ 4.8/year

Table 3.9: Examples of costs of adaptation measures

Once the adaptation measures are tested and evaluated, scales of adaptations can be established for a reduction in overheating hours and calculation of the payback times. This enables an assessment of the best packages of adaptation measures for Rushenden. These examples can then be transposed to other social housing with similar building fabric. The assessment is intended for the Housing Association and therefore is inclusive of the cost of installation and when possible the cost of maintenance. In the case of private housing the prices given may be different.

3.9 Conclusion to the methodology chapter, summary of the analysis

The houses retrofitted by IFORE are assessed and their overheating risk identified at the present time and in 2030s, 2050s and 2080s. Cooling loads are presented for the future climate change scenarios in the single and the two storey houses with and without the retrofit measures. The overheating hours are calculated for the single and two storey house types with and without the retrofit measures using the latest CIBSE TM52 (2013)

that establishes a definition for overheating thresholds based on the adaptive comfort algorithm. The properties are therefore evaluated using both methods, the calculation of cooling load and the adaptive comfort method. Comfort is a subjective matter; adaptive comfort theory links the outdoor temperature to the comfort temperature in a given place. It is based on the finding that people make adjustments themselves to create a condition of comfort.

The field study is used to investigate what adaptation measures are more suitable for the case study, what are the obstacles to adapt and how to overcome them. Questionnaires and focus groups are carried out by the author and are analysed using qualitative and quantitative research methods. The summertime comfort survey assessed what the comfort temperature is for Rushenden and what the lower and higher temperature thresholds are for this group of residents.

A rank of single shading devices is established for the single and the two storey house types. A calculation of the overheating hours is carried out to assess the overheating reduction of night ventilation in the single and two storey houses. The indoor temperature and cooling load reductions are assessed for clusters of adaptations in the single and the two storey houses using the higher temperature threshold for this group of residents derived from the questionnaires in order to identify specific adaptation strategies for both house types analysed.

Cost-benefit analysis is applied to the adaptation measures to identify what is the payback time of each option and cluster of adaptations is. This helps the Housing Association in the decision making process. The same packages can be applied to other social housing in the South-East with similar building fabric.

Chapter 4. Field study

"The noble human qualities of compassion, goodwill, friendship, kindness, earnestness and simplicity cannot be fostered outside the context of the local community."

Tsunesaburo Makiguchi, "The Geography of Human Life" (1903).

4.1 Introduction

Although the modelling presented in the Results and Analysis Chapter was carried out at the same time as the monitoring and the survey, the author presents the results of the Field Study first because some of the outcomes from surveys and focus groups were used to determine some of the variables during the modelling process. The analyses that follow start by presenting the preliminary findings related to the resident's perception of indoor thermal comfort before, during and after the implementation of the low carbon retrofit measures. The questions were asked to most of the residents of the 100 dwellings participating in the IFORE project, during its timescale, over a period of three years. The questions were used to validate some of the findings from the modelling, for instance what the extent of the overheating that the residents experience at present is. The surveys were used to inform the choices made in relation to the adaptation measures to be modelled.

A summertime longitudinal comfort survey was carried out in the summer of 2012 when the implementation of the retrofit measures had just started in Rushenden and is presented herein. The aim was to investigate what the summertime comfort temperature is for the residents of Rushenden to be later used in the modelling process to assess the overheating risk. A sample of residents was chosen within the community of Rushenden and the questions were answered by the selected sample over a period of about 2 months during the summer of 2012.

The results from one-to-one questionnaires and focus groups are presented in the last part of this chapter and highlight aspects of the discussions that help answer the following research questions presented in the introduction:

-How can a specific adaptation strategy be established for these houses?

-What else the community can do to adapt to a warmer climate?

-Which behavioural aspects adopted in other countries might be applicable to the south-east of England - offering extra comfort in the event of a heat wave?

The surveys were also used to understand how the residents think they can cope with a future increase in temperature. Finally, in the conclusions to this chapter all findings are summarized and the more relevant outcomes are then used to define the parameters of the modelling exercise presented in the Results and Analysis Chapter.

4.2 Results from the analysis of the IFORE questionnaires[3]

The author analysed the results to the questions that were presented to the residents by the Green Doctor during the first set of questionnaires. The author used SPSS (IBM, 2012), a software used widely for statistical analysis. The survey carried out in 2011, before the IFORE retrofit measures were installed, shows that over 60% of the residents own an electric fan (Figure 4.1). Almost 40% of the residents were finding at least one of their rooms too hot during some summer days (Figure 4.2), and most of the residents found their bedroom(s) and lounge too hot during some days in the summer (Figure 4.3, Figure 4.4).

To the question: "how would you rate the overall comfort of your home in the summer?" asked before the houses were retrofitted, 50% of the residents voted reasonably comfortable, 35% voted slightly uncomfortable, 10% very comfortable and 5% very uncomfortable. This result seems to imply that the residents are quite comfortable in the summer, however when the residents, during the focus groups that are presented in the following sections, were discussing what their habits are during hot summer days the picture changed quite radically. They said that they use several fans in the house to ensure comfort day and night as it will be discussed below.

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[3] This section contains the results of the questions written by the author into the IFORE questionnaires and analysed by Hanna *et al.*, (2014). Citation is made explicit throughout the text
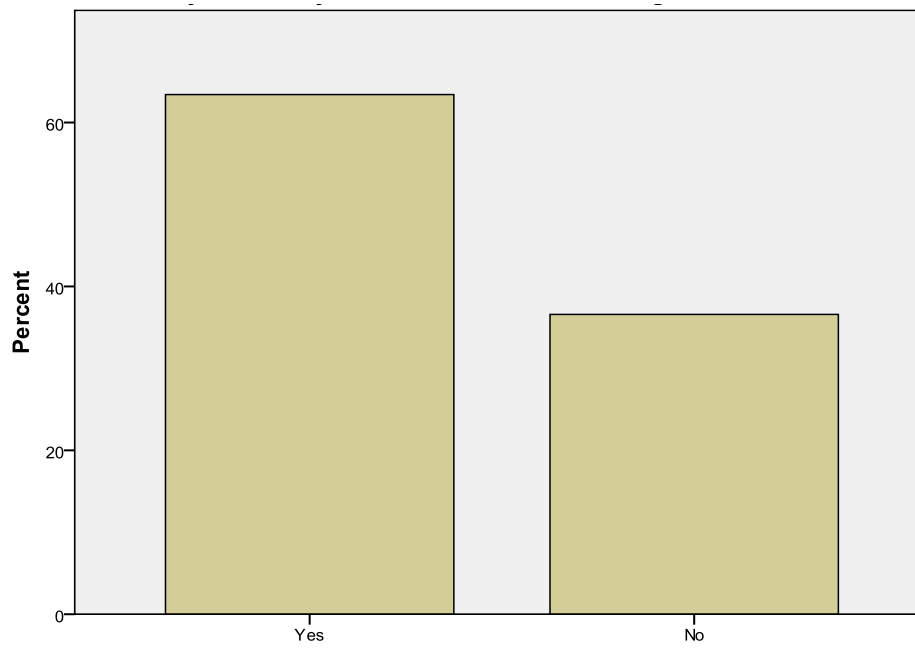
Figure 4.1: Do you use any electric fans or other cooling devices? (Source: IFORE questionnaire)
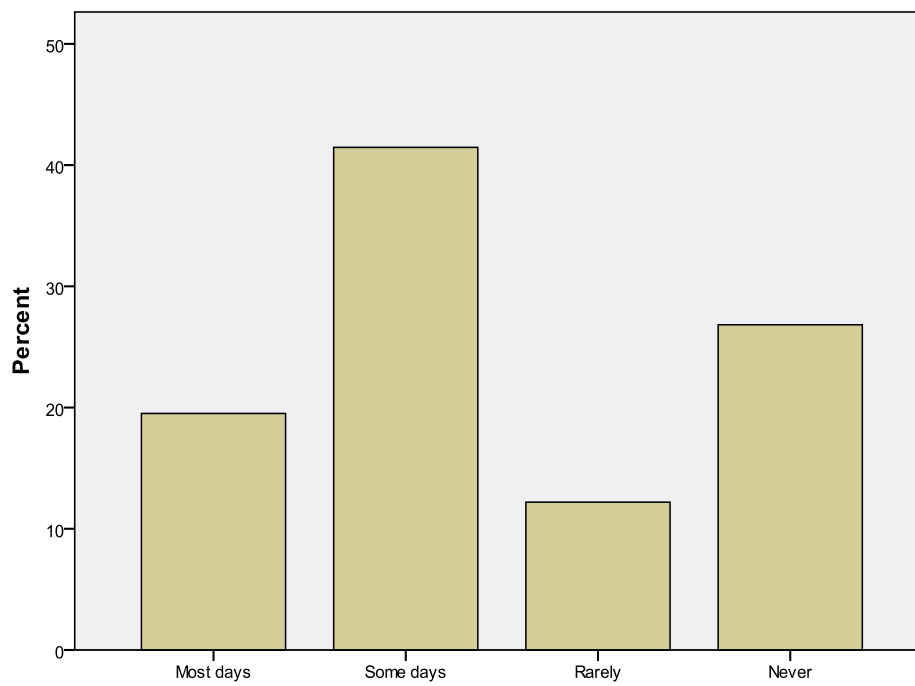
Figure 4.2: How often do you tend to find any of your rooms too hot in summer? (Source: IFORE questionnaire)
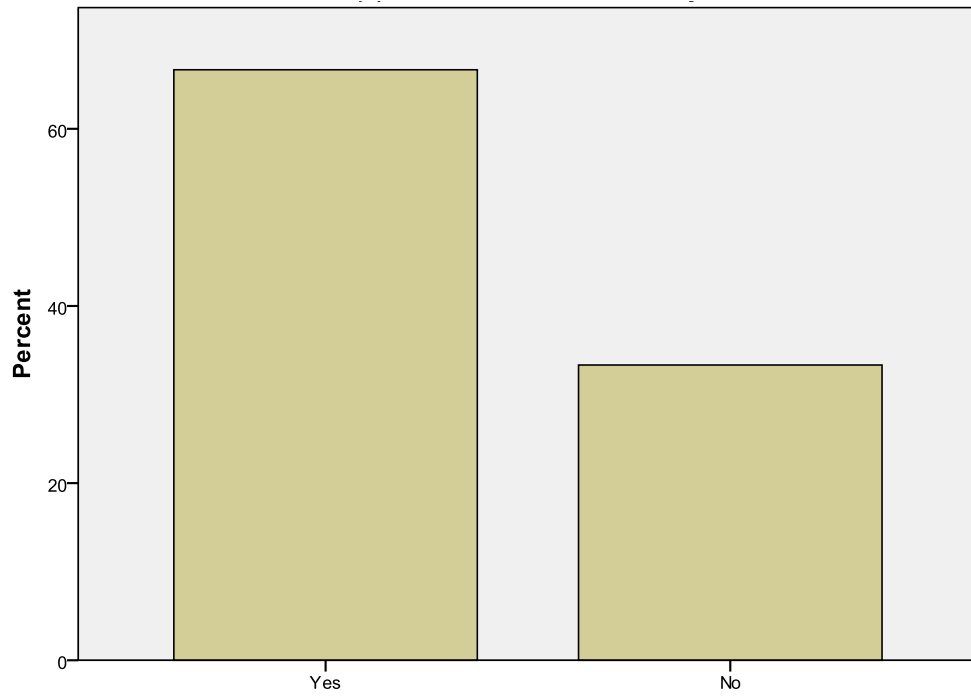
Figure 4.3: Bedrooms too hot some or most days (Source: IFORE questionnaire)
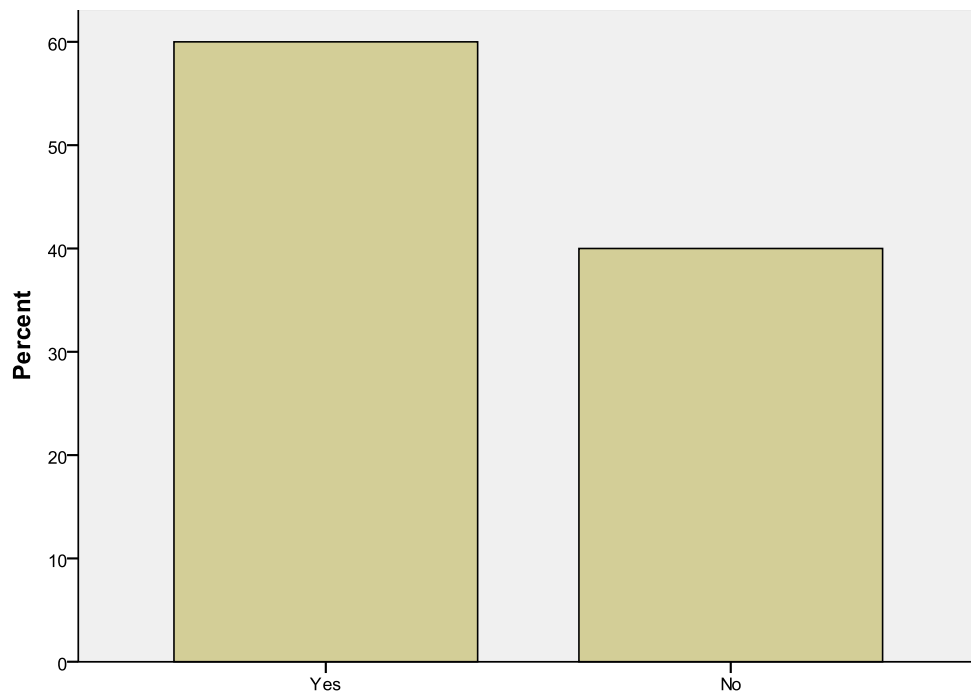
Figure 4.4: Lounge too hot some or most days (Source: IFORE questionnaire)

This view was confirmed by the focus group discussions with regard to the limited opening of doors and windows in the summer months, especially at night. The reasons for that are various and are discussed later, and an understanding of the current behaviour of the occupants in the summer is necessary.

This enables one to find the right solutions for the specific case of Rushenden and to reflect on those habits that can be shifted without radically changing the architecture. What can be changed will be taken into consideration when applying certain measures to the houses and analysed through thermal modelling. Current human behaviours in the summer, such as the resistance to opening windows at night, are quite common to residents living in urban environment as well. Therefore the solutions suggested below are also of a general nature and can be applied to other house types and to different built environments.

The sociologist, Dr Paul Hanna, was employed by IFORE in 2012 to analyse the questionnaires (Appendix A1). Dr Paul Hanna analysed the second and third sets of questionnaires only and discarded the first set. Some of the findings from the questionnaires are presented below. Generally there was good acceptance from the residents of the new technologies that were installed during IFORE and the training that was given to accompany them. The work of the Green Doctor was also praised by the residents and the perception about their ability to reduce their energy consumption was increased. General practices such as using the power-off button on the television and reducing washing machine use became more common after the Green Doctor's visits (Hanna *et al.*, 2014).

Among the technological installations, ground source heat pumps and photovoltaic panels were the most successful in terms of usefulness and ease of use. Wattbox and Alert Me (a second energy monitoring system used in Rushenden), on the other hand, were not very popular. Although for these two technologies the residents have declared that they are quite satisfied with the technical support received from Amicus Horizon (Hanna *et al.*, 2014).

The following analysis was carried out by Dr Hanna and compares the answers to the second and third questionnaires to the question "During hot summer days, how would you rate the comfort of your home?" (Figure 4.5). There was a remarkable increase in those who rated the houses as being very comfortable in the summer after the retrofit, at data point 3 (Hanna *et al*., 2014). The votes increased from 5.1% to 27.8%. Those who rated the houses slightly uncomfortable decreased accordingly, from 32.9% to 18.1%. The very uncomfortable vote also decreased from 6.3% to 2.8%. This result is statistically significant and implies an increase in summertime comfort after the retrofit (Hanna *et al*., 2014).

It was not possible to compare these answers with the instant measures of indoor temperature because the questions were asked to the residents by the Green Doctor who was not carrying any monitoring equipment with her at the time of the survey. The monitoring equipment used to measure the indoor temperature was not installed in all the terraces but only in a small sample. In IFORE, the schedule that the monitoring task followed was different from the schedule of the Green Doctor's interviews. It was not possible for the author to match the answers with the indoor temperature because of the difficulty to gather reliable data. However the answers to these questions clarify that the perception of the residents in relation to the indoor comfort in summer has improved after the retrofit. The comfort temperature in Rushenden is analysed in more detail in a following section of this chapter.

During hot summers days, how would you rate the comfort of your home?
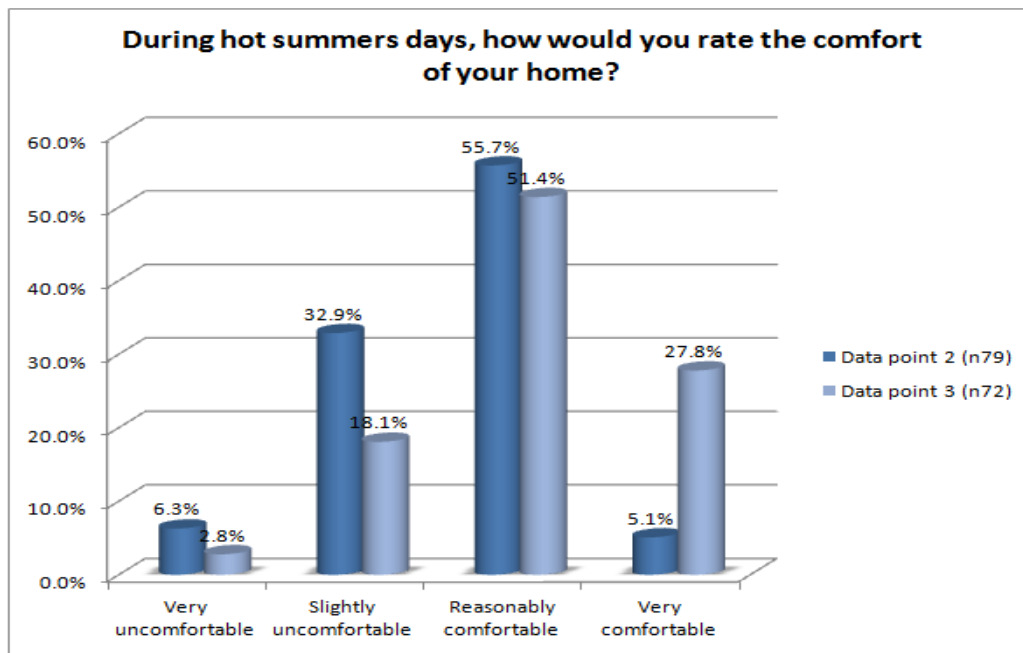
Figure 4.5: change in the perception of comfort in summer in Rushenden after the retrofit
(Source: Hanna *et al*., 2014)

4.3 Community engagement and climate change adaptation

Just as the IFORE low carbon retrofit measures in Rushenden and the occupants' behavioural change go hand-in-hand in the community's efforts to reduce carbon emissions, occupant participation can have a big impact in future climate change adaptation. This PhD unusually looks at both the technical and social aspects of climate change adaptation. In the case of the adoption of new technologies, research by Darby (2006) has proved that the combination of technical, social, educational and infrastructural factors can shift communities' behaviour.

The author in this thesis is advocating a cultural change in the case of global warming, towards a different lifestyle that sees people spending more time outdoors in communal areas and sharing time together during the summer. Even if these behaviours do not belong to the English tradition at present, they can be integrated into the current habits. Similar gatherings are already happening in indoor or semi indoor spaces like the pub, parks and gardens that are integral part of English culture. More references of this aspect are given in the Discussion Chapter.

In addition to the questions written into the IFORE questionnaires, the author carried out, independently from IFORE, two extra questionnaires during the summer of 2012. The first questionnaire is the summertime comfort questionnaire that will be presented in the following section. The second is the adaptations questionnaire. It contains questions about different shading devices, night ventilation and behavioural adaptation i.e. switching off the lights and appliances when too hot in the summer. To complete the picture, three focus groups were carried out by the author and some of the residents in the summer of 2013. This discussion about the adaptation measures highlighted what the problems are in implementing them and how these problems can be overcome.

The measures discussed with the residents in the adaptations questionnaire were selected by the author from the lists within CREW and SNACC and some more measures were added to the list. The author chose the adaptations that are more affordable and easier to use such as curtains, external and internal blinds, awnings, shutters, day-time and night-time ventilation. All these measures require some kind of occupant interaction. To the measures adopted from CREW and SNACC the author added some questions on trees. Questions regarding the colour of external walls were not included in the questionnaire because the appearance of walls was made lighter by the installation of the external insulation.

4.3.1 Summertime comfort questionnaire

In the summer of 2012 the author presented 17 households with a pre-retrofit summertime comfort survey. The households surveyed had a Wattbox monitoring system installed in their houses by Amicus Horizon on behalf of IFORE. The households were selected by Amicus Horizon in relation to their willingness to participate in the project and their openness towards the installation of new technological devices. The author surveyed these particular households because the temperature was available from the monitoring of their particular house type. There was therefore no control from the author over the composition of the households and the split between elderly and family occupancy.

In Rushenden the author used the same longitudinal survey that Nicol and Humphreys designed to derive the comfort equation for the European Standard on adaptive comfort (CIBSE, 2013). Some of the questions were adjusted to be relevant to Rushenden by Fergus Nicol and some general advice was given by him to the author about how to interview the residents. Nicol advised the author to make sure that the residents understood that they were supposed to answer "how warm they feel" and not "how warm the room is".

Among all the occupants interviewed only eight returned their surveys to the author or the Green Doctor for analysis. Of these eight participants, only seven occupants gave plausible answers. One set of questionnaires was excluded from the final analysis. The comfort votes collected from this resident were all zeros, equal to a condition of comfort throughout the summer. This result was omitted from the final synthesis, because it is probably the result of a misunderstanding by the resident of the purpose of the comfort questionnaire.

Only 11 questionnaires were collected from the two elderly occupants living in the single-storey houses in Manor Close. These questionnaires were all completed by one of the two residents, while the other completed only four questionnaires and it was not possible to match any of her votes with the available Wattbox temperature recordings. The majority of the comfort votes were therefore collected in the two-storey houses where families live.

A comfort vote varies greatly from resident to resident. Most votes are normally above zero, in the range from 0 to 3. This is equal to a thermal sensation that ranges from neutral to very hot. One resident is an exception because he gave a majority of votes below zero, equal to a thermal sensation of cold. He also declared he had a fan on most of the summer, so it is uncertain whether this resident completely understood the questionnaire.

Six sets of questionnaires remained from which to derive an equation targeted at housing design to be used throughout the South East of England. This is already a very small sample and other problems arose when the sample of comfort votes was analysed using

Wattbox data. The data appeared to be very patchy and not every comfort vote could find a corresponding indoor temperature from Wattbox.

Two summary plots were presented by the author as suggested in Nicol *et al*., (2012). A frequency plot of the comfort votes collected in Rushenden can be seen in the following histogram (Figure 4.6), which shows that most votes are above zero, as described earlier. Another useful plot is the scatter of comfort votes and indoor temperature (Figure 4.7), which clearly shows that, at present, for a temperature of 20 °C – 27 °C the prevalent thermal sensation ranges from neutral to very hot. If we consider the thermal sensations of slightly warm, neutral and slightly cool (-1, 0, 1), we can see that the comfort temperature ranges from the minimum of 18.9 °C to the maximum of 27.6 °C for this group of residents (Figure 4.7).
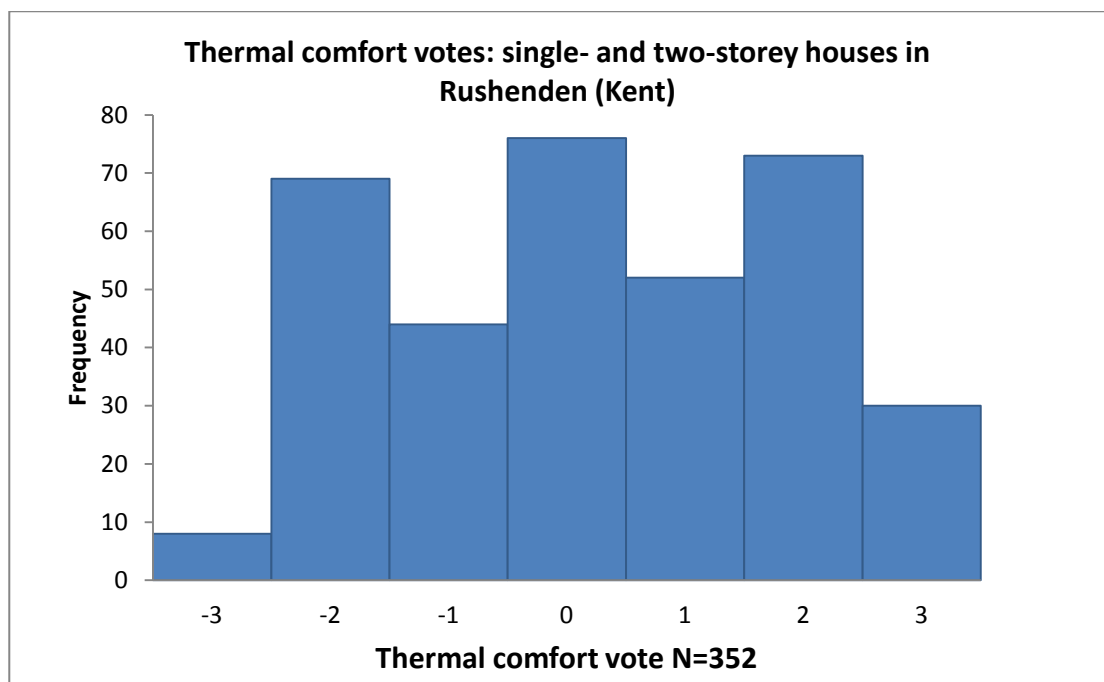
Figure 4.6: histogram of comfort votes
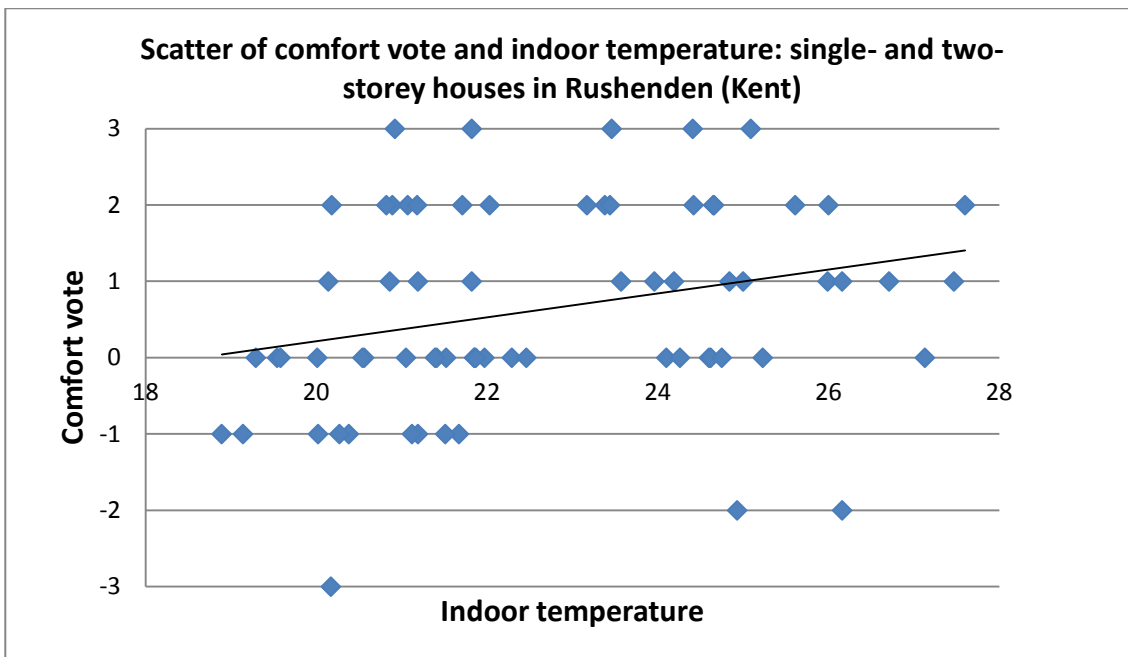
Figure 4.7: Plot of comfort votes against indoor temperature with trend line

The data available from Wattbox was compared with the indoor temperature recordings from the data loggers. The Wattbox data appeared to be generally lower by 2-3 °C compared with the loggers' data. This uncertainty about the validity of the Wattbox data was confirmed by previous measurements that were carried out in the context of the "Retrofit for the Future competition" (Barraclough, 2011). There is also a great diversity among the measurements of external temperature that the different Wattboxes recorded.

The author had the opportunity to show the results to Fergus Nicol for review. He confirmed that the data did not look too unusual (personal communication, 2014). Nicol thinks that there is probably a very low regression slope, as is shown in the figure, and with the comfort votes mainly on the warm side this will result in a low predicted comfort temperature. The equation for the regression slope is:

Equation 4.1 $C = a + b * T_{op}$,

where C is the comfort vote, a is the intercept on the vertical axis, b is the gradient of the line (the regression coefficient) and T_{op} is the independent variable (temperature in this

case) (Nicol *et al.,* 2012). The indoor temperature from Wattbox was used instead of the operative temperature because of the close similarity between the two. When the regression coefficient b is low and the comfort vote is neutral or close to neutral then the comfort temperature will also be low (Equation 4.2). The comfort temperature is linked to the indoor average temperature and if that is low, as it was in the summer of 2012, then the predicted comfort vote will be low as a result (Equation 4.2).

Nicol suggested using the Griffiths method to calculate the comfort temperature. If T_m is the mean temperature and C_m is the mean comfort vote then the comfort temperature T_c can be derived from:

Equation 4.2 $T_c = T_m - 2 * C_m.$

Nicol suggested that by using this equation the comfort temperature will be similar to other case studies in Europe. The mean temperature is 23 °C and the average comfort vote is 0.64. Therefore the comfort temperature is 21.7 °C, which is quite low. Nicol pointed out that in this case the low regression slope is because people are a) different from each other and b) are adapting so the change in comfort vote by the temperature is being changed by their adaptive actions.

4.3.2 Adaptations questionnaire

To the question: "would you consider buying an air conditioning unit?" nine people said that they would if the average indoor temperature increased by 3° - 4 °C. An increase of 3° - 4 °C would result in a summer temperature which was described by the author to the residents as very hot, as hot as Southern Europe or Central America. The majority of them said that they would pay a maximum of £200 and one resident would require some financial support. Six residents said that they use fans day and night during the summer and one of them has three fans, one for the lounge, one for the bedroom and one in the study.

All the residents interviewed open the windows to ventilate in the summer. The residents in the single-storey terraces expressed concerns when opening the windows at the front

of their houses and said they would only open them at the back. At night, they would not open the windows at the front and one resident would not open the bedroom window at the back in the summer because of fear of someone breaking in. In the two-storey houses most of the residents keep the windows in the bedrooms open on the first floor day and night. Six households in the two-storey houses open the windows throughout the year, in both summer and winter.

Most residents interviewed showed an interest in the adaptation measures presented. They reacted by saying: "*this is a good idea*" when asked about the potential installation of an overhang and "*I have heard of that*" when external shutters were discussed. When asked if they would pay for any of the measures they all said that they would need some help from the housing association. This is understandable, because of the nature of social housing most of the technological upgrades, such as the new boilers, were provided by the housing association at no cost to the residents. This means that social housing residents (in the UK) may be more open to climate change adaptation options when compared to private residents that have to pay for their own retrofit measures.

Several types of shading including awnings, external and internal shutters, blinds and overhangs were presented to the residents using images for an immediate visual understanding of the device. The residents prefer roller blinds above all other shading and in fact they already use them in their living rooms and bedrooms. Venetian blinds are more widely used in kitchens and are generally appreciated more for their affordability than for their appearance. Among the elderly, net curtains are widely used because they prevent the interior of the home being seen from the outside. This is true for the residents of the bungalows as well as the two storey-terraces, which have kitchens, living and dining rooms on the ground floor (Figure 4.8).

External louvers and shutters were not viewed positively by the residents and none of the interviewees expressed a preference for these types of external shading (Figure 4.8). Although rated as highly practical in some cases their cost, also presented to the residents, put the residents off buying them. Among all trees, fruit trees are generally preferred, although a couple of residents expressed concerns about trees blocking the daylight coming into the home. Awnings are also a shading device that some residents

find is "*a good idea*" especially for houses with patio doors. These answers have been used to inform the computer models so they can be programmed with the residents and their needs in mind.
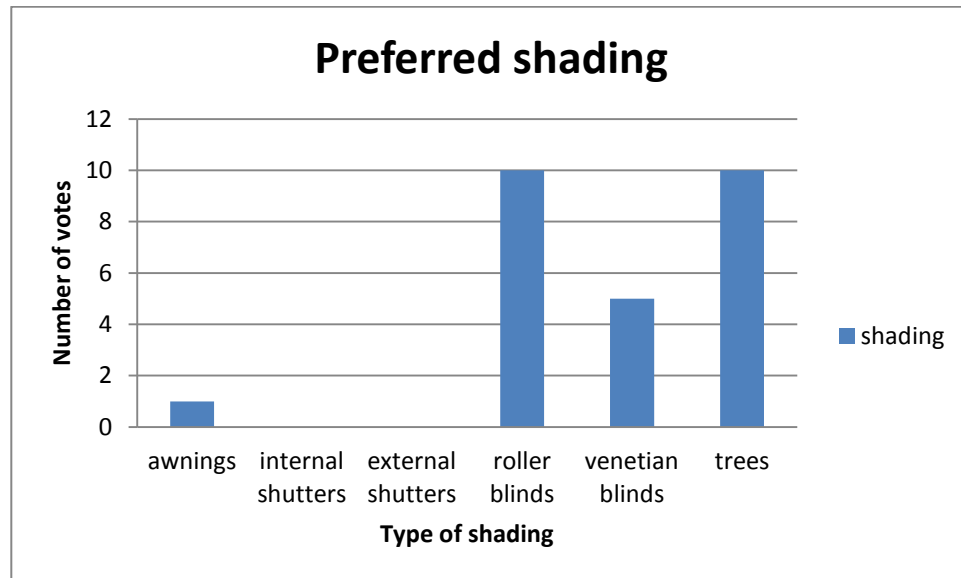
Figure 4.8: Preferred shading by the occupants interviewed in Rushenden

4.3.3 Focus groups

In 2013, a survey on summertime behavioural changes and outdoor space facilities was conducted with the residents. The author adopted the same technique of showing images of outdoor spaces such as patios, outdoor cinemas, beaches and pergolas taken from Southern European countries. Three focus groups were held in the community house in July and supported by Tina Miles, the community officer working on IFORE. In August, the author attended a community event where five children who participated in the "energy champions" initiative were interviewed using the questions in Appendix A.3. What follows is a record of the three focus groups and the one-to-one questionnaires with the children. The author prepared the open ended questions presented in Appendix A.5 to be discussed with the residents during the first focus group. Some of the images used during the questionnaires were also used during the focus groups. Some images depicting outdoor living, such as open air cinemas, patios, pergolas and beaches were included in the set.

The first focus group was held in the Rushenden community house on the 4th July 2013 (Figure 4.9). The residents present were A., K., L., D., R. (teenager), R. (teenager), J. (teenager) and P. P. is the only resident of the bungalows in Manor Close. During this meeting the author introduced the topic of climate change. However the discussion was soon directed towards the IFORE retrofit work by Tina Miles, the community officer present during the discussion. This was useful to ease up the conversation and to gain a general understanding of the main problems faced during and after the IFORE retrofitting measures were installed, and some awareness of possible topics to focus on during future meetings. P. complained about the MVHR system in her bungalow. Some of the teenagers discussed the solar thermal panels, which they said were not very efficient when compared with the photovoltaic panels that seem to save a lot of electricity. The group discussed the problems with the installation of new boilers in Manor Close and the lack of adequately hot water in the residents' kitchens.

Possible behavioural adaptations were also discussed such as going to the nearby beach or organising night-time open-air cinemas. The residents remarked that transport around the island, to go to a sandy beach in Leysdown, is too expensive. There is a beach in Queenborough and one in Rushenden but they require maintenance work. The group discussed trees and the fact that the salty soil on the island does not allow many species to thrive. There is a certain degree of scepticism about climate change and global warming. K. does not think that global warming is happening because she cannot see its immediate effects. A. thinks that if the climate becomes much warmer, air conditioning will become widely spread as it is in the South of the United States.

Figure 4.9: These round table discussions were held in the Rushenden community house

(Photo: Tina Miles)

The second focus group was held on the 18th July 2013. The residents present were P., S. (teenager), S., L. and K., who all live in two-storey family houses. Tina Miles, the community officer was also present, and the topics of shading and ventilation were discussed in detail. This was based on a depth interview that covered only two issues in greater detail as was explained in the Methodology Chapter. The topic of behavioural adaptation and outdoor living was touched only briefly.

The residents find that their houses get very hot upstairs. During the day they close the curtains and open the windows to allow for some ventilation. The topic of going to the beach when the temperature is very high was discussed again. K. goes regularly with her children to the beach in Sheerness which is more organised than the local beaches. However, she cannot go as much as she likes because of money concerns; the train is very expensive. There are a few beaches near Rushenden but they are not very welcoming for

local residents; the nearest beach in Rushenden has no sand and is very unattractive (Figure 4.10). The beach in Queenborough, however, has a blue flag for cleanliness.

Figure 4.10: The "beach" in Rushenden

The residents currently sleep with a fan on all night, one in each bedroom. Both families run a fan in all the bedrooms at night, even after the insulation was installed in the loft space. They suggested that the loft insulation has not made the house any cooler in the summer, and without a fan running they cannot sleep. They do not open the windows at night because of the presence of insects, especially spiders. They have become used to the noise of a fan at night.

The author introduced the topic of external roller blinds and the group discussed the role of patio doors. The residents suggested the use of white internal venetian blinds and shutters that reflect a bit of the light. The residents suggested the use of sliding windows, which are a good solution to overcome the problem of the windows opening outwards when installing external roller blinds and other types of external shading.

Usually all internal doors are closed at night for privacy. The doors are comprised of the main opening part and a small pane of glass on top of it. At night it may be possible to open the glass pane at the top in order to ventilate throughout. The residents would not consider security bars on windows and they would not need them because their bedrooms are on the first floor.

The colour of the insulated cladding installed by IFORE is generally slightly more reflective than the original brick. The tenants discussed the possibility of painting the brickwork of the houses, that have not been externally insulated, with a white paint. As a result of the insulation the tenants reported that the indoor temperature was higher but more stable this summer. The group discussed the possibility of having a flap on the roof that could be opened at night; the tenants think that this would be a good solution. They also seemed keen to buy an air conditioning unit if they could afford it.

The third focus group was held on the 25th July 2013. The residents present were M., O., P., K., A., and D. The subject of this meeting was open spaces. The author talked to O., a 10 year old, who would like to have a big swimming pool if it gets very hot, in order to go swimming with friends in the summer; O. would also like to go to open-air cinemas and to the beach. The other residents talked about the Queenborough and Rushenden regeneration plan and their experience with Planning For Real. They said that their advice was not listened to fully, as there is not going to be a Rushenden Square, as was promised; they also suggested regenerating the beach as part of the new plan but that has not been done either. Instead, there is a big new supermarket and local restaurant.

4.3.4 Children's questionnaire

As part of the IFORE project, the "energy champions" program was run by the education officer involving local schoolchildren in an energy reduction programme with the aim of influencing adults at home. The children were given lessons on energy saving, learning through games, sports and community events. They participated in local activities targeted at educating them and their parents to reduce energy use. It is believed that the influence of children can be very significant on adults in the same household and educating the children ensures that the project leaves a legacy for the future. The author

participated in one of these community events and interviewed some of the children that were part of the programme to understand their level of knowledge of climate change and the differences and similarities between theirs and their parents' points of view.

On the occasion of a community event run by the IFORE community engagement team on 21st August 2013, the author interviewed five energy champions at different stages of their training: L., O., J., L. and S. They are not fully aware of climate change, although they are aware of the warming of the planet. They all said that the purpose of energy saving measures is to save the planet and to avoid wasting energy. Most of them would like to see more trees in Rushenden, their preferred species being oak and willow. The children showed a very open and enthusiastic attitude towards the planet and the environment that reflects their empathy with nature.

4.4 Conclusions to the field study

In order to answer the research questions presented at the beginning of this chapter the author carried out a series of surveys, including questionnaires and focus groups during the timescale of the IFORE project. A change in the perception of the summertime internal temperature, after the retrofit measures were installed, was revealed by the results of the questions that the author wrote into the IFORE questionnaires and the sociologist, Dr. Paul Hanna, analysed during the project. The outcomes from the surveys showed that overheating was already a problem before the retrofit measures were installed and, after the retrofit, the perception of summertime thermal comfort improved. The residents feel that they are more comfortable during hot summer days after the IFORE low carbon retrofit measures were installed and this is a statistically valid result.

A survey of the summertime comfort temperature for the residents in Rushenden using the adaptive comfort theory showed that this is not very dissimilar from other case studies carried out by Nicol and Humphreys (2010) in Europe to derive the adaptive comfort algorithm. It was not possible to derive a specific algorithm to be used to assess overheating in housing using the surveys carried out in Rushenden for 2 reasons:

1. The sample used for the analysis was too small

2. The monitoring data that measured indoor and outdoor temperatures was not always reliable.

That is why in the following chapter, the Results and Analysis, the author uses that same algorithm presented in TM52 (CIBSE, 2013) to assess the overheating risk in Rushenden. From the surveys, it was possible to identify the minimum and maximum comfort temperature thresholds for this particular group of people. The maximum comfort temperature threshold of 27.6 °C was used in the models to assess the reduction in cooling load that the adaptation measures generated.

Focus groups and questionnaires helped the author to understand how a specific adaptation strategy can be established for Rushenden and what actions and measures to implement in the models as a result of the discussion. Behavioural aspects that are taken from warmer countries were also discussed during focus groups. From the focus groups, external roller blinds seem to be the preferred external shading device. External overhangs and trees have also received a good number of votes during questionnaires. Internal roller and venetian blinds are very popular in Rushenden and are widely used, however, these simple devices are not very effective at blocking solar radiation because the radiation has already entered the building (Wienold *et al.,* 2011).

Focus groups and questionnaires were completed to make the adaptations more specifically targeted at the residents of the Rushenden community and to gain feedback on what may be suitable for them. What is possible for them to implement in terms of technical solutions and behavioural change was widely discussed with groups of residents. The IFORE community engagement team created the existing network that was used by the author to establish this relationship with the residents. Similar methods of community engagement can be extended to other social housing communities throughout the South East and to the rest of the UK.

This change in attitude was reflected in the way the residents responded to the themes of climate change and overheating during the one-to-one interviews and focus groups. They were generally very helpful when discussing types of shading and different behavioural adaptations. There was a certain degree of scepticism about global warming and climate change and greater attention was paid to the financial savings rather than the

environmental benefits that these measures could bring. This was more evident among the elderly, adults and teenagers than among the children, who have a more open attitude towards the environment and the planet.

However, there was generally a great openness when discussing the topics of energy saving measures, behavioural change and adaptation measures, such as shading devices. The author and the residents discussed these subjects, together with the problems that arose after the IFORE measures were installed, in a very informal and relaxed manner. The residents seem to be very aware of the options available to them and are satisfied with the improvements that were made to their houses by the housing association.

During the discussion on adaptation options the residents included, for example, their preference for internal roller blinds (questionnaires) and the suggestion to use white venetian blinds and shutters to reflect the light (focus groups). It was suggested that the difficulty in integrating external blinds with windows which open outwards could be overcome by installing patio doors on the ground floor and different windows opening types such as inward opening or sash (focus groups). The ventilation at night, limited on the second floor of the two-storey houses because of privacy can be overcome by opening the top pane of the internal doors or by installing vents and by putting insect screens on windows.

A thorough discussion was stimulated by the author on the subject of the quality of the outdoor space during focus groups. Creating more shaded areas with trees or maintaining the local beach can offer even greater relief when the temperature outdoors is very high. These initiatives can be driven by the people living in the community, as they have a voice and can ask for improvements to be made to where they live.

The largest single group of residents in Rushenden are the elderly retired. This poses concerns for their health in the case of a heat wave. Reduced mobility due to old age and illness can increase the risk of mortality. Support networks such as families, housing associations and the local council can help to act fast when heat waves occur. Services offered to the most vulnerable by charities on a regular basis, for example buses to the local beach, will take the pressure off families and increase the resilience of the

community. The housing association that is in direct contact with the residents needs to establish fast and effective support for the most vulnerable. This can be done through smart metering or other forms of monitoring.

In this process the housing association has a crucial role for two main reasons. First, informing the key players, stakeholders, council and government organisations of what is needed to make the buildings more resilient. The housing association will also fund the measures applied to the houses and because of that will have an interest in making other organisations aware of what is needed to ensure the occupants are safe and comfortable. Second, as a result of the existing networks, resident associations and local authorities, they can positively influence the necessary change in policy that enables the residents to benefit. This second aspect concerns the development of new activities within the community and new areas within Rushenden; this encourages the participants to get together and stimulates community resilience.

Chapter 5. Results Analysis

"We are all caught in an inescapable network of mutuality, tied into a single garment of destiny...We are made to live together..."

Dr Martin Luther King Jr.

In order to answer the following research questions:

- In the future, will the retrofitted social housing at Rushenden overheat to a greater extent than if the work had not been carried out?

- If so, what type of retrofit, light retrofit or deep retrofit would tend to overheat more? For social housing (given limited financial resources) a reduced level of retrofit is the norm, how does that compare with deeper retrofit solutions (such as Enerphit) in terms of overheating risk?

- If retrofit might increase the overheating risk, which measures are likely to cause this increase - more insulation, air-tightness, or both?

- In which respects might the retrofit be helping to reduce the overheating risk, and which elements are the most beneficial?

The author started by running some simulations using the models for the single and the two storey house types as if the retrofit in Rushenden had not taken place. The purpose of this run of simulations was to find out what the thermal performance of the houses was before the retrofit measures were installed. The simulations were then run for the models with the retrofit measures installed to compare them with the previous result. In order to answer the first research question, for completeness, the corresponding carbon emissions for heating and cooling were also assessed. The cost associated with the electricity used to cool down the house is compared in the Discussion Chapter with the price of the adaptation options.

In order to answer the second research question, the heating and cooling loads are assessed for house type 2 with some of the Passivhaus characteristics applied to it. This exercise clarifies if an increase in insulation and air tightness will increase the overheating risk. First of all, simulations are run by applying some extra insulation on the external

walls of the model. A second run of simulations calculates heating and cooling loads with reduced air-tightness. The extra insulation and air-tightness are then applied together.

5.1 Heating and cooling loads of the single-storey house, type 2, un-retrofitted and retrofitted

The terms un-retrofitted and retrofitted refer to the IFORE specification described in the methodology chapter. Simulations were run for the models of a single-storey house type before and after the retrofit measures were installed by the IFORE project. Therefore, the first run of simulations (Table 5.1, Figure 5.1) shows the results of the annual heating and cooling loads for type 2 as if the IFORE low carbon retrofitting had not taken place. The second run of simulations (Table 5.2, Figure 5.2) shows the results of the heating and cooling loads after the external and the loft insulation were installed. The third run of simulations (Table 5.3, Figure 5.3) assessed the heating and cooling loads of the retrofitted house if the air-tightness improvement only was in place. The fourth run of simulations shows the heating and cooling loads when both, the insulation and the air-tightness were in place (Table 5.4, Figure 5.4)

The external and loft insulation reduce the heating and cooling loads up to 2080s. (Table 5.1, 5.2; Figure 5.1, 5.2). The air-tightness, on the other hand, while substantially reducing the heating load, increases slightly the cooling load (Table 5.3). As it gets warmer, however, by 2080s for instance, the air tightness causes a slight decrease of the cooling load. This is because, as the ambient temperature rises, the air-tightness helps to keep the warm air outside. The combination of insulation and air tightness reduces the cooling load (Table 5.4, Figure 5.4). This result is very encouraging because it proves the validity of the low carbon retrofit in terms of reduction of both, the heating and the cooling loads. The air-flow rate was modelled as constant at 0.23 ACH in the winter from October to April. From May to September the simulations were run using an air-flow rate of 0.645 ACH because the MVHR is switched off or in summer mode and occupants open windows to ventilate (Methodology Chapter). This aspect and the indoor temperature by 2030s will be explored in detail later on in the chapter during the assessment of the internal temperature.

The increase in cooling load and reduction in heating load by 2030s is calculated in relation to "the 1970s". The 1970s base case is modelled un-retrofitted using the specification in the Methodology Chapter. For comparison, simulations were also run using the weather file called the 1970s (averaged between 1961-1990) with the specification for insulation and air-tightness used during IFORE even if in reality the houses were retrofitted in 2012. The Prometheus future files used in this thesis were developed using the 1970s as a base case.

When comparing heating and cooling loads using past and future weather data, it is clear that as the heating load decreases in the future, the cooling load increases. The heating load decreases between 1970s-2080s generally more as a percentage for the retrofitted house than for the un-retrofitted house. The cooling load increases less as a percentage for the retrofitted house than for the un-retrofitted house. This indicates that the retrofit measures installed, including insulation and air tightness, make the indoor temperature more stable.

type 2 un-retrofitted	1970	2030	2050	2080
Heating load (kWh/m²·year)	179	144	137	122
Cooling load (kWh/m²·year)	1	4.6	7	13.3
Total	180	149	144	135
Cooling load living room kWh/year	28	124	181	316
Cooling load bedroom kWh/year	0.05	6	20	57

Table 5.1: Heating and cooling loads of the single storey house, type 2, un-retrofitted
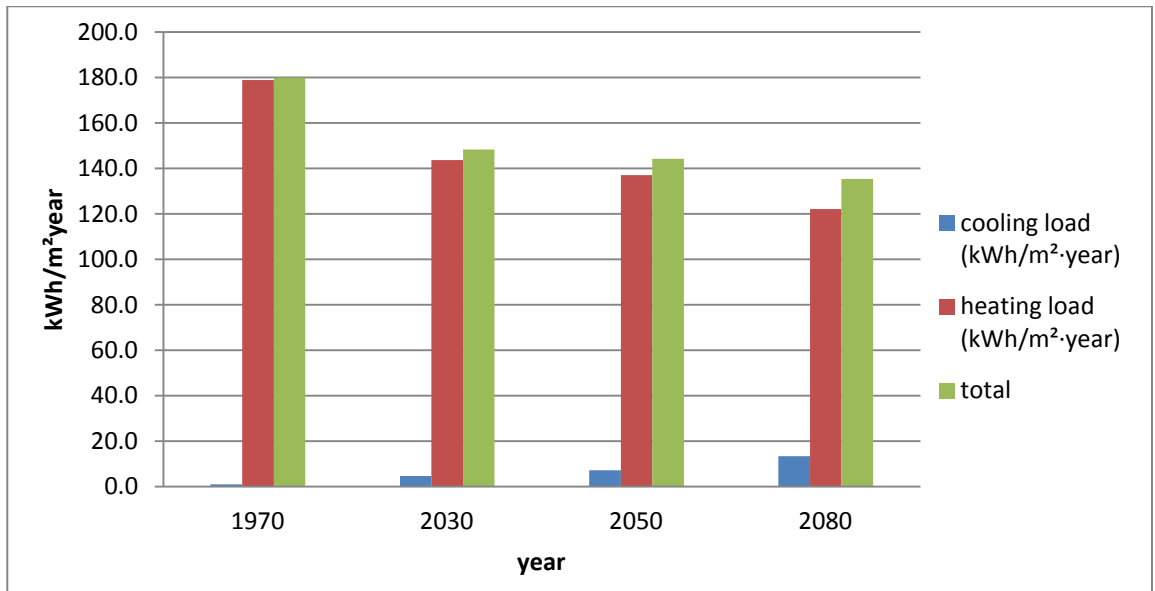
Figure 5.1: Heating and cooling loads of the single storey house, type 2, un-retrofitted, kWh/(m²·year)

Type 2 retrofitted, insulation only	1970	2030	2050	2080
Heating load (kWh/m²·year)	161	132	127	115
Cooling load (kWh/m²·year)	0.7	3.5	5.36	9.8
Total	162	136	132	125
Cooling load living room kWh/year	20	96	143	251
Cooling load bedroom kWh/year	0	1.5	8	23

Table 5.2: Heating and cooling loads of the single storey house, type 2, retrofitted with insulation only
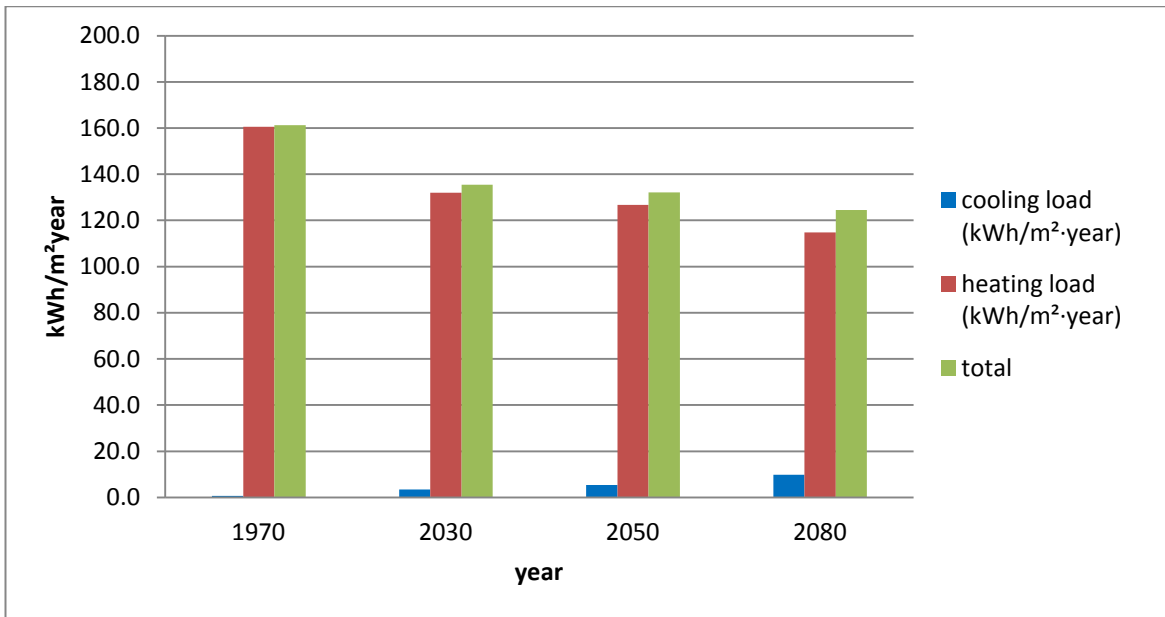
Figure 5.2: Heating and cooling loads of the single storey house, type 2, retrofitted with insulation only, kWh/(m²·year)

Type 2 retrofitted, air-tightness only	1970	2030	2050	2080
Heating load (kWh/m²·year)	142	117	113	103
Cooling load (kWh/m²·year)	1.2	5.0	7.3	13
Total	143	122	120	116
Cooling load living room kWh/year	34	133	184	308
Cooling load bedroom kWh/year	0.7	7	20	56

Table 5.3 Heating and cooling loads of the single storey house type 2, retrofitted with air-tightness only
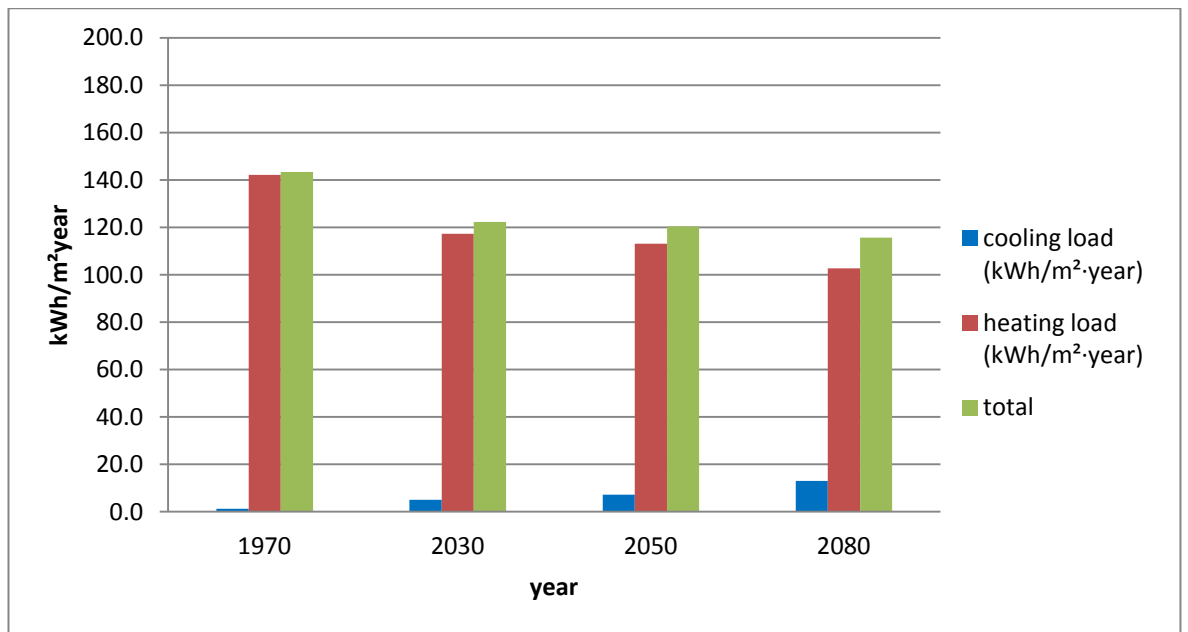
Figure 5.3: Heating and cooling loads of the single storey house, type 2, retrofitted with air-tightness only, kWh/(m²·year)

type 2 insulation and air-tightness	1970	2030	2050	2080
Heating load (kWh/m²·year)	124	106	103	95
Cooling load (kWh/m²·year)	0.9	3.8	5.4	9.4
Total	125	110	108	104
Cooling load living room kWh/year	25	103	144	241
Cooling load bedroom kWh/year	0.00	1.5	7	21

Table 5.4 Heating and cooling loads of the single storey house type 2, retrofitted with insulation and air-tightness
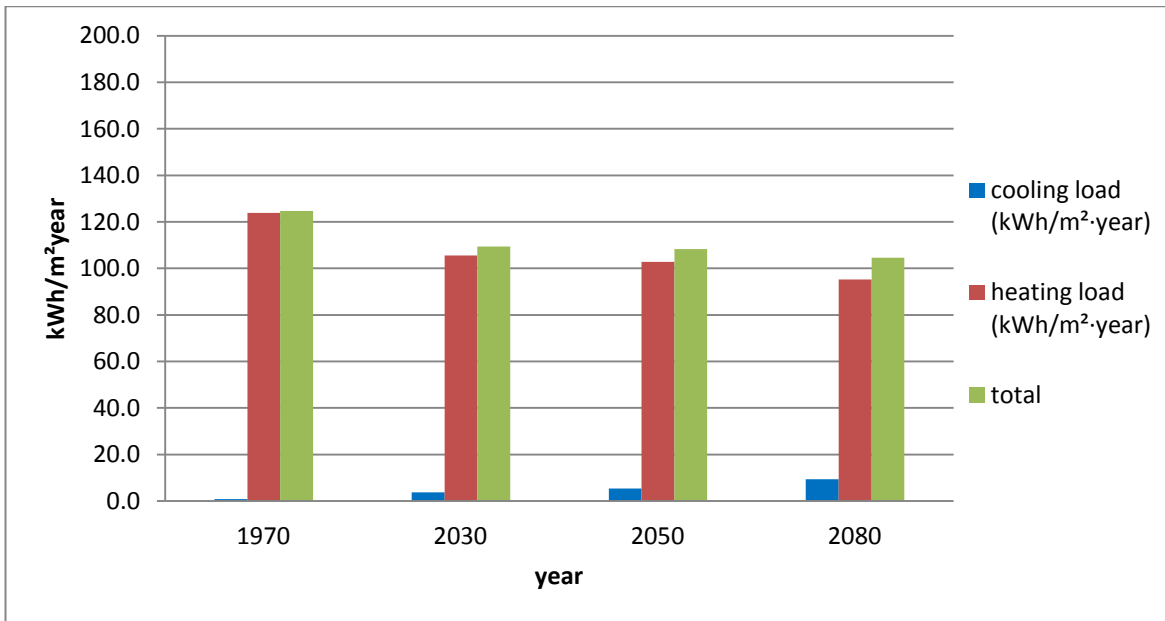
Figure 5.4: Heating and cooling loads of the single storey house, type 2, retrofitted with insulation and air-tightness, kWh/(m²·year)

There is in both, the un-retrofitted and the retrofitted models a big reduction in heating load between 1970s and 2030s (Figure 5.5, 5.6). Looking at the cooling loads in more detail the results show that the cooling load of the un-retrofitted house by 2080s is thirteen times what it would have been in the 1970s. A less dramatic increase is found after the low carbon retrofit measures are installed (Figure 5.5, 5.6, 5.7). A comparison of the cooling loads of the un-retrofitted and retrofitted house shows that the retrofitted house performs better in that the cooling load decreases by 11% for the 1970s base-case, 19% in 2030s and as it gets warmer the cooling load decreases by 24% in 2050s and by 30% in 2080s (Figure 5.7).
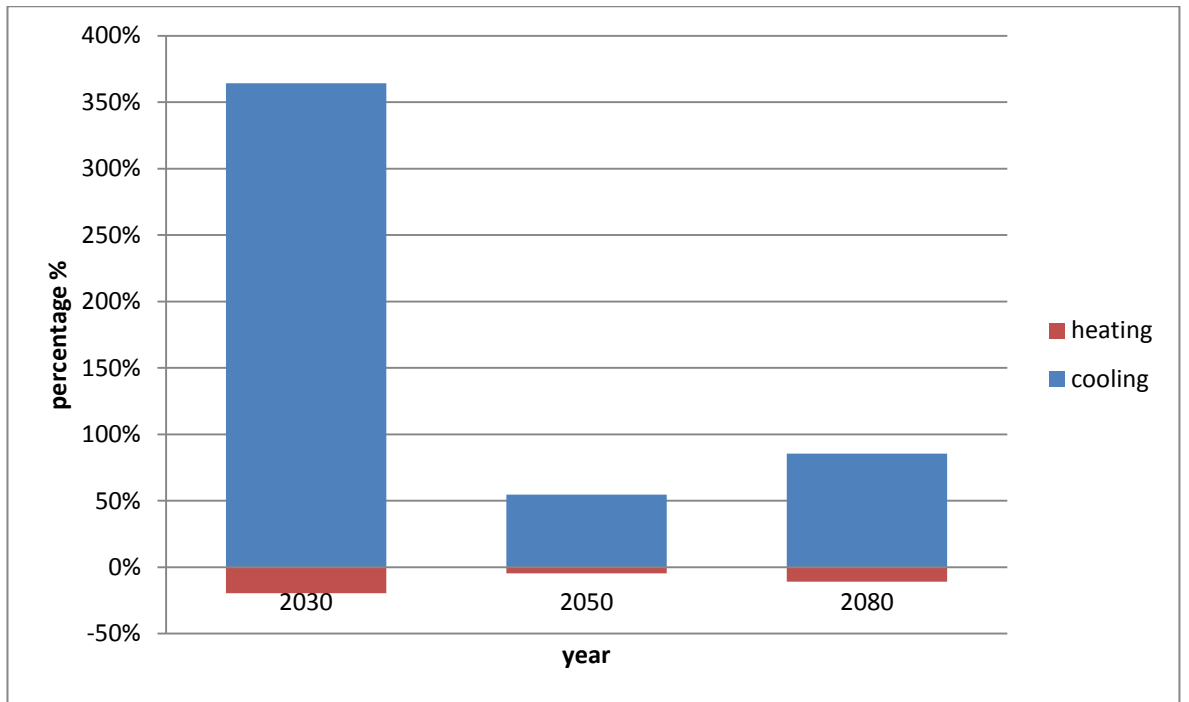
Figure 5.5: Heating load reduction and cooling load increase of the single storey house, type 2, un-retrofitted, percentages
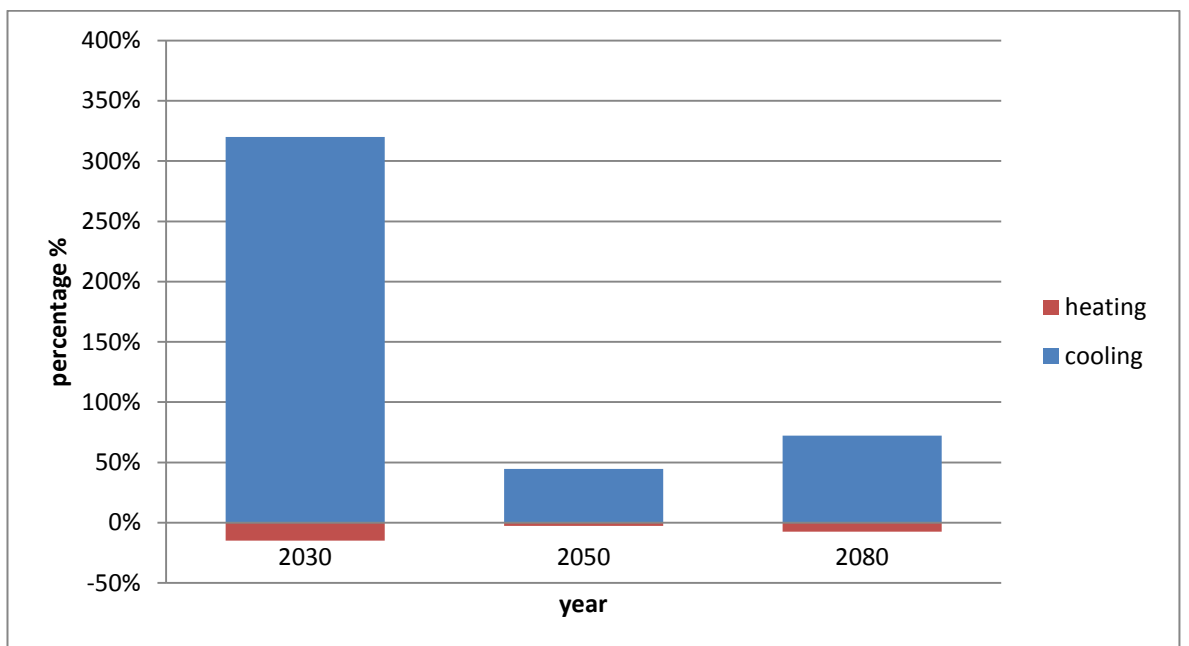
Figure 5.6: Heating load reduction and cooling load increase of the single storey house, type 2, retrofitted, percentage
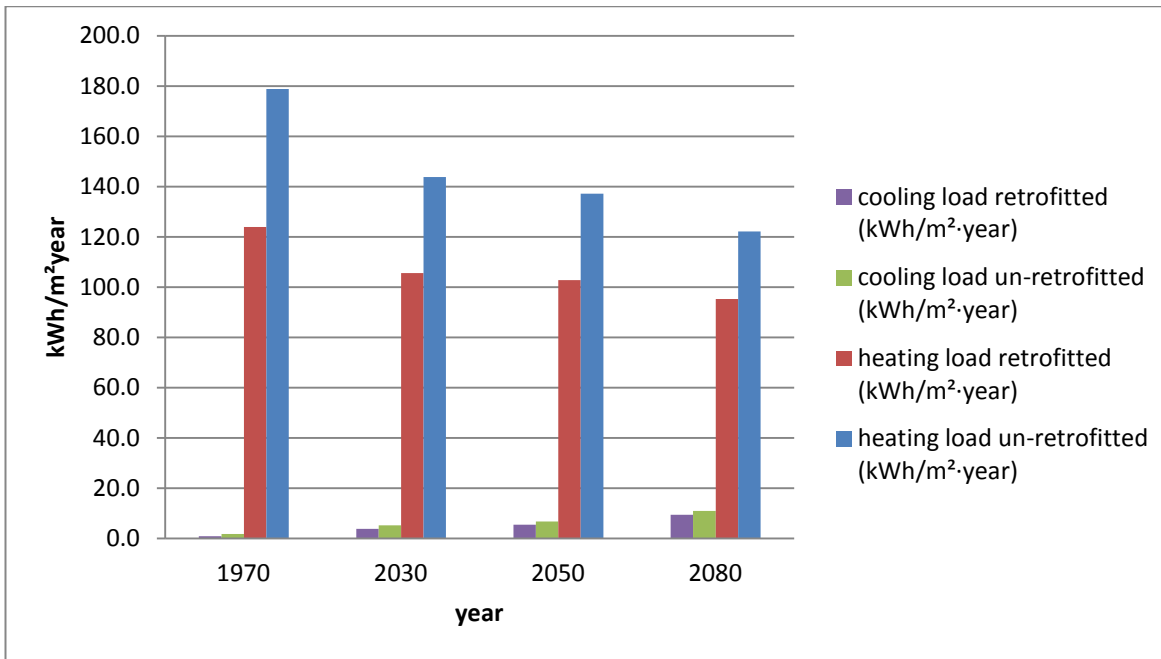
Figure 5.7: Summary of heating and cooling loads of the single storey house, type 2, un-retrofitted and retrofitted, kWh/(m²·year)

5.2 Heating and cooling loads of the two-storey house, type 4, un-retrofitted and retrofitted

These houses are located on both sides of Manor Road. Living rooms therefore face the orientations south-west and north-east and the houses have the same orientation as type 2 houses, where the living room faces south. On the first floor the main bedroom faces the front and the second bedroom faces the back, so the bedrooms are facing both orientations, south-west and north-east.

The model was built in ESP-r and the operation file was set for the two occupancy types, the family in employment and the unemployed (the parameters tabled in the Methodology Chapter). The relation between these family compositions and the wider national context is clarified in section 3.3 of the Methodology Chapter. As it was done for the single storey house type, the first run of simulations assumed that the low carbon retrofit measures have not been installed (Table 5.5, Figure 5.8). This used the operation files for the house being unoccupied during the day. The simulations that follow are of the same type as those run for the single storey terrace (Table 5.6, 5.7, 5.8; Figure 5.9,

5.10, 5.11). Finally, simulations were run for the retrofitted two storey terrace with the employed family (Table 5.9, Figure 5.12). For simplicity and comparison with the single storey house type the heating was set to be on a thermostat at all time between the 1st of October and the 1st of May using a set point temperature of 21 °C. The cooling was set to be on between 1st of May and 30th of September between 7am and 10pm in the living room using a set point temperature of 25 °C. In the bedrooms cooling was on between 10pm and 7am using a set point temperature of 23 °C.

First of all, the heating load is lower per m² in the two storey house than in the single storey house because of the higher volume/floor area ratio in the bungalow. This result remains constant up to the end of the century. The cooling load is also lower per m² in the two storey house but it increases more as a percentage in 2030s, 2050s and 2080s than in the single storey. This is true when the houses are un-retrofitted and retrofitted and is due to the different configurations of the two house types (Table 5.5, 5.9; Figure 5.8, 5.11).

In the retrofitted two-storey houses the cooling load increases more dramatically than in the single-storey houses. It increases from the very low 0.1 kWh/(m²·year) in 1970s to 4 kWh/(m²·year) by 2030s. It quadruplicates from 2030s to 2080s becoming 16 kWh/(m²·year). The cooling load is higher in the bedrooms on the first floor than in the living room on the ground floor. As the cooling load increases around the middle and then again towards the end of the century, the difference between the cooling needed on the ground floor and that on the first floor also becomes more substantial. Both bedrooms have a high cooling need and will overheat greatly if the outdoor temperature increases as projected (Table 5.8, Figure 5.11).

In terms of insulation and air-tightness, the results from the simulations of the two storey house are very similar to those previously discussed for the single storey dwelling. The external and loft insulation generally reduces the cooling requirements (Table 5.6, Figure 5.9). The air tightness however, causes an increase of the cooling load up to 2050s and then reduces it slightly towards the end of the century as the outside temperature becomes higher (Table 5.7, Figure 5.10). In the two storey house Insulation and air

tightness cause a reduction of the cooling load from 2030s onwards (Table 5.8, Figure 5.11).

type 4, unemployed, un-retrofitted	1970	2030	2050	2080
heating load (kWh/m²·year)	141	104	96	81
cooling load (kWh/m²·year)	0.1	5	8.5	19
total	141	109	105	100
Cooling load living room kWh/year	2	88	151	327
Cooling load bedroom 1 kWh/year	1	75	144	330
Cooling load bedroom 2 kWh/year	1	63	128	279

Table 5.5 Heating and cooling loads, two storey house, type 4, unemployed family, un-retrofitted
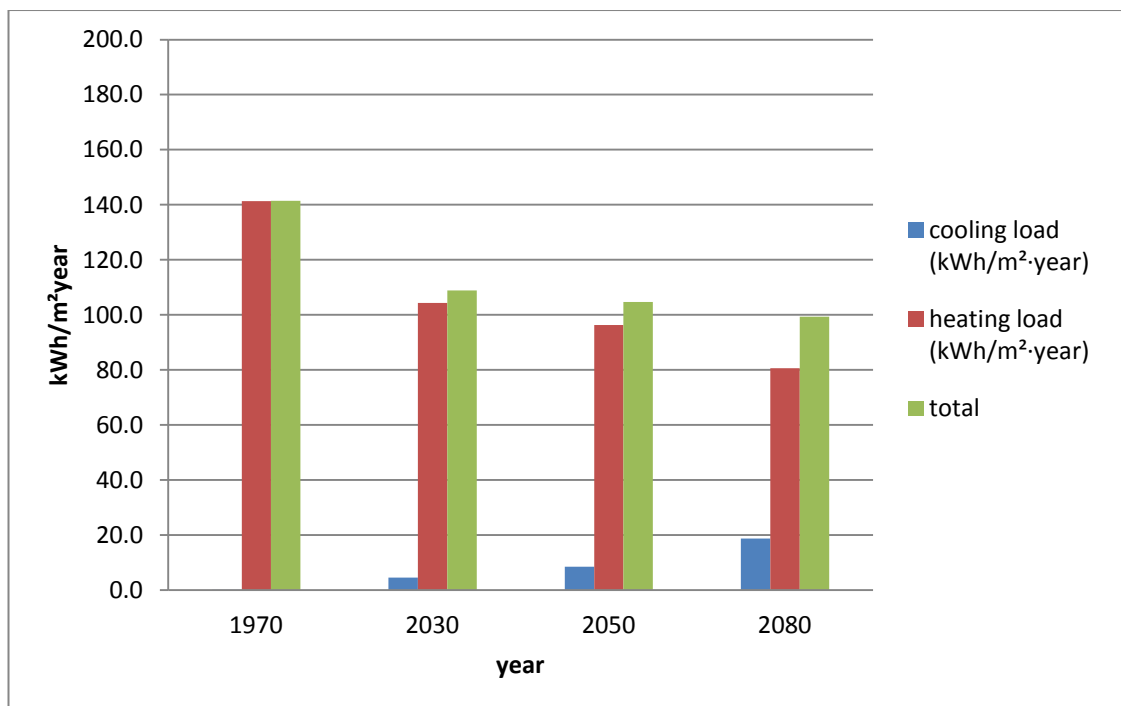
Figure 5.8: Heating and cooling loads, two storey house, type 4, un-retrofitted, unemployed family

type 4 unemployed, retrofitted, insulation only	1970	2030	2050	2080
heating load (kWh/m²·year)	124	93	86	74
cooling load (kWh/m²·year)	0.05	4	7	15
total	124	97	93	89
Cooling load living room kWh/year	2	63	114	256
Cooling load bedroom 1 kWh/year	0.4	64	123	274
Cooling load bedroom 2 kWh/year	0.7	56	110	238

Table 5.6: Heating and cooling loads, two storey house, type 4, unemployed family, retrofitted, insulation only
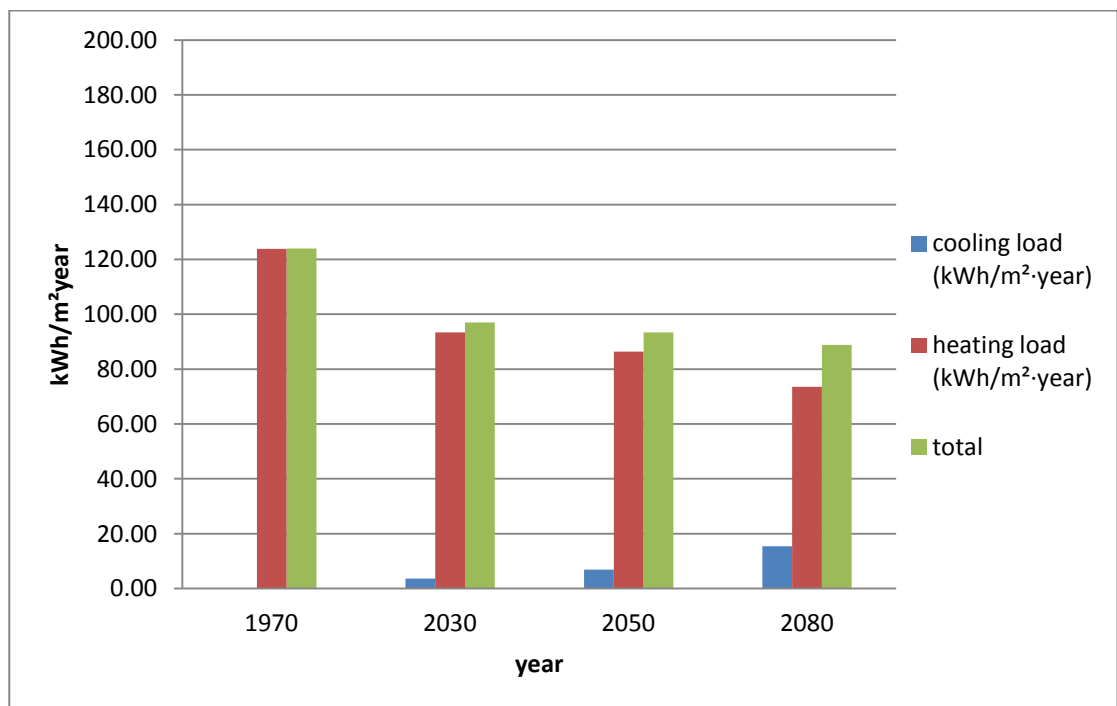
Figure 5.9: Heating and cooling loads, two storey house, type 4, unemployed family, retrofitted, insulation only

type 4 unemployed, retrofitted, air-tightness only	1970	2030	2050	2080
heating load (kWh/m²·year)	131	97	89	75
cooling load (kWh/m²·year)	0.2	5	9	19
total	131	102	98	94
Cooling load living room kWh/year	4	96	156	322
Cooling load bedroom 1 kWh/year	3	88	157	341
Cooling load bedroom 2 kWh/year	2	74	137	287

Table 5.7: Heating and cooling loads, two storey house, type 4, unemployed family, retrofitted, air-tightness only
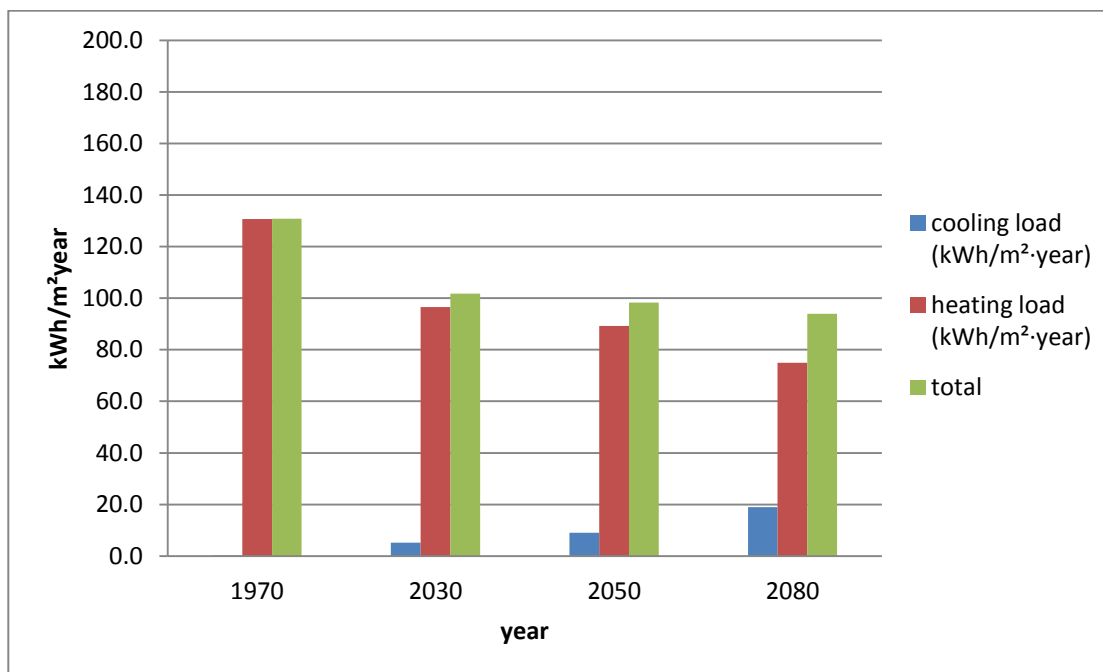
Figure 5.10: Heating and cooling loads, two storey house, type 4, unemployed family, retrofitted, air-tightness only

type 4 unemployed, retrofitted, insulation + air-tightness	1970	2030	2050	2080
heating load (kWh/m²·year)	113	85	79	68
cooling load (kWh/m²·year)	0.1	4	7	16
total	113	89	86	84
Cooling load living room kWh/year	3	68	116	249
Cooling load bedroom 1 kWh/year	1	78	136	285
Cooling load bedroom 2 kWh/year	2	69	121	246

Table 5.8: Heating and cooling loads, two storey house, type 4, unemployed family, retrofitted, insulation and air-tightness
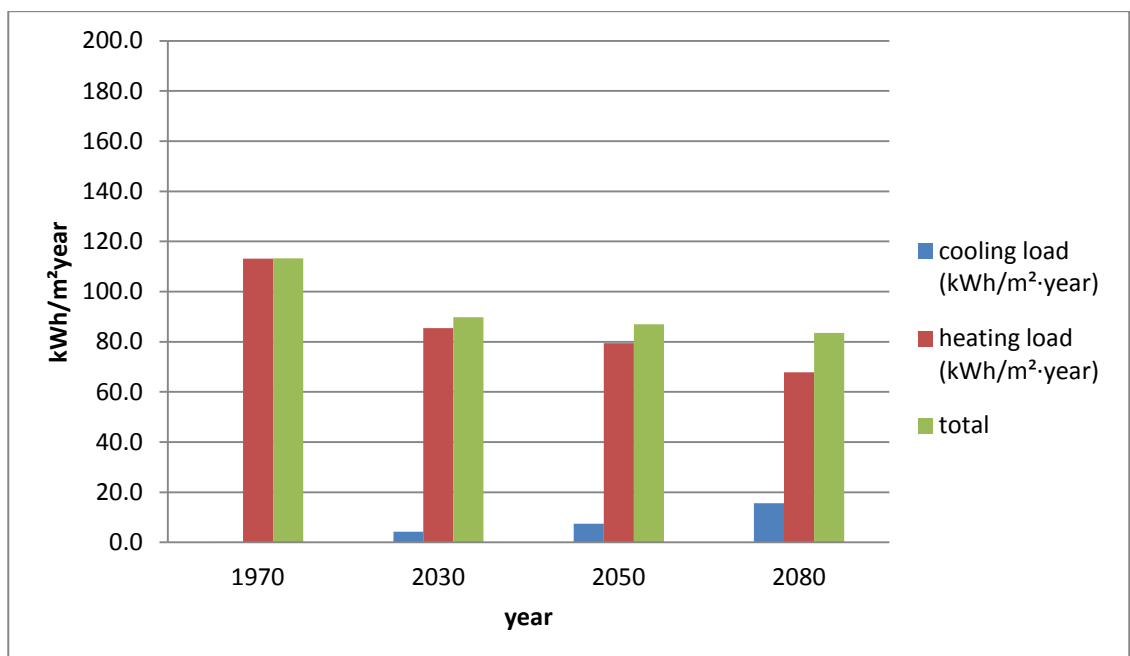
Figure 5.11: Heating and cooling loads, two storey house, type 4, unemployed family, retrofitted, insulation and air-tightness

The family with employed parents has a far lower cooling load than the family at home all day. This is a result of the casual gains, which are higher if there are people at home with appliances switched on. The heating load however is only slightly lower for the working family. This seems to suggest that a medium-weight envelope responds slowly to temperature changes and in some cases it is more convenient to keep the heating on all day rather than switching it on and off. This seems to be the case as the outside

temperature increases, by 2080s for instance and the house is occupied increasing the internal gains from people during the day. The sum of heating and cooling requirements is much lower in the house where the parents work than in the house where the parents are unemployed because of the lower cooling load (Table 5.9, Figure 5.12).

There are obvious social and financial benefits to keeping residents in work. The simulations show that there are also energy and environmental benefits (Figure 5.15). It is true that social housing residents tend to be in need and are often unemployed, are elderly and may also have a disability. This is why it is important in this research to analyse the case of elderly or unemployed residents spending more time at home that are more vulnerable to heat waves.

Amicus Horizon, during IFORE, has made efforts to employ some of the residents through the project. This is understandable because their aim is to try to improve people's lives within the community by empowering the residents to feel more socially and financially secure. Saving energy can be an extra incentive to get residents into employment.

For this research the important point is that staying at home during the day in the summer implies an increase in the cooling load. The residents at home not only experience higher temperatures but also for a longer time. On the other hand, the employed parents, being away all day, can benefit from spending time outdoors and in different environments. From a broader prospective this result verifies the theory that spending time away from home, outdoors for example, is a way to adapt to an increase in temperature.

type 4, working parent	1970	2030	2050	2080
heating load (kWh/m²·year)	106	83	78	68
cooling load (kWh/m²·year)	0.02	2	4	10
total	106	85	82	78
Cooling load living room kWh/year	0	2	6	31
Cooling load bedroom 1 kWh/year	0.02	42	91	228
Cooling load bedroom 2 kWh/year	0.6	55	108	233

Table 5.9: Heating and cooling loads, two storey house, type 4, employed family, retrofitted, insulation and air-tightness
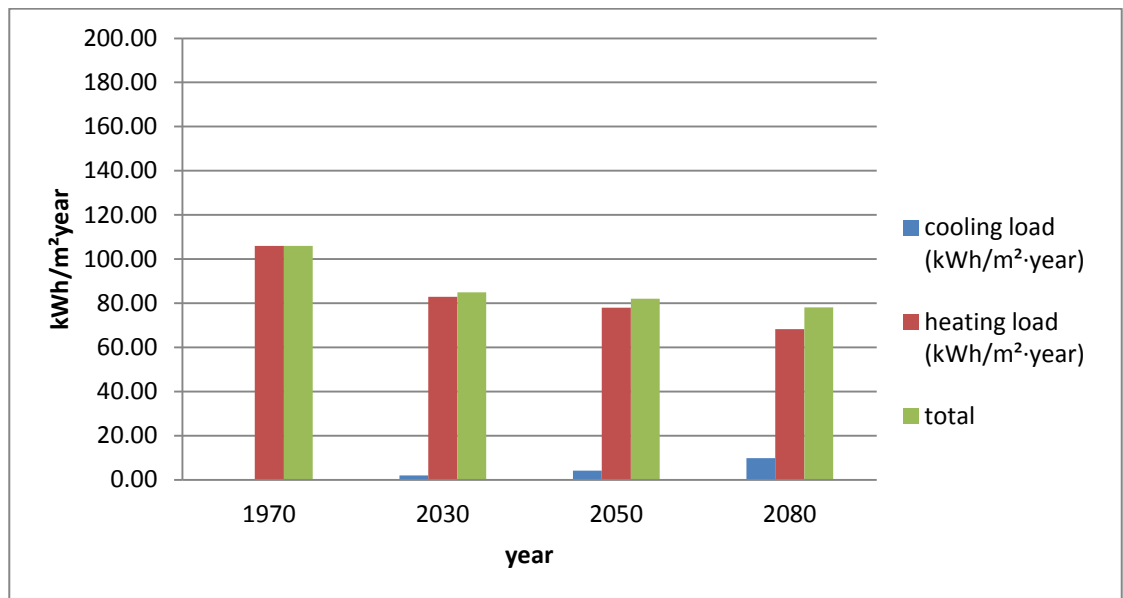
Figure 5.12: Heating and cooling loads, two storey house, type 4, employed family, retrofitted, insulation and air-tightness
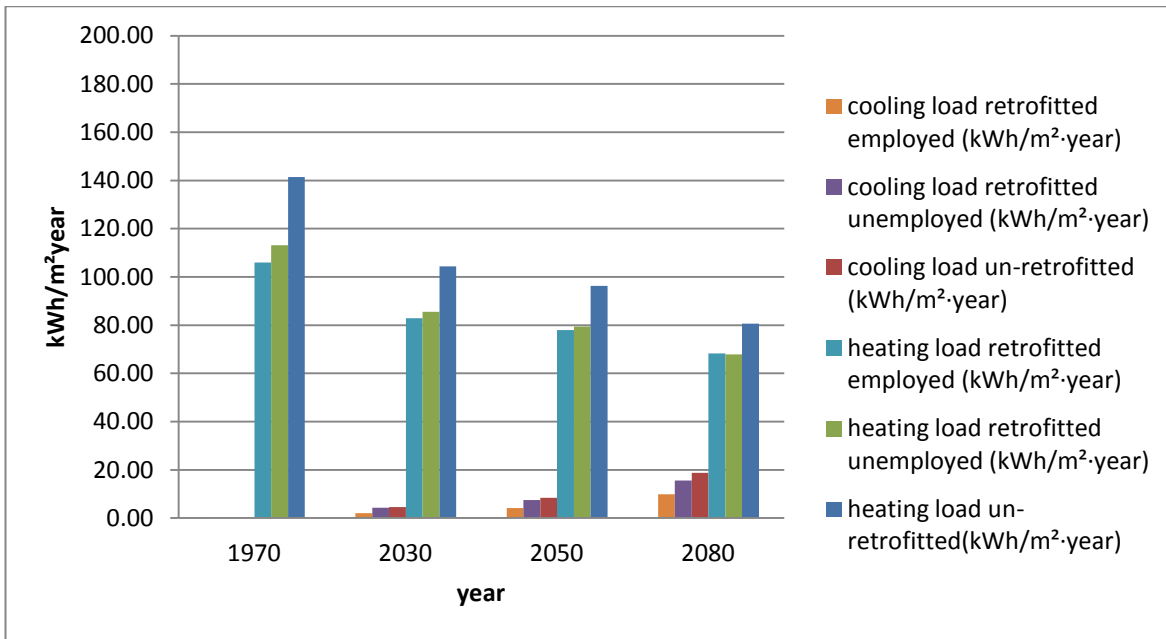
Figure 5.13: Summary of heating and cooling loads of the single storey house, type 2, un-retrofitted and retrofitted, kWh/(m²·year)

5.2.1 Carbon emissions, single storey house, type 2

A global assessment of the delivered energy allows one to decide whether the retrofit was worthwhile in terms of global carbon emissions. It was found by C. Diaz from WSP, (an engineering consulting firm) in his research on global future energy use that the sum of heating and cooling loads remains constant throughout the century. He carried out research on a simple building type situated in different parts of the world. The result shows that in temperate climates like the one experienced in London, New York and Johannesburg, the sum of heating and cooling does not change considerably in the future (Camilo Diaz, private email).

Figure 5.14 shows that for both the un-retrofitted and retrofitted case studies the sum of heating and cooling loads will decrease slightly in the future. The sum will decrease more in the un-retrofitted house than in the retrofitted one. In order to compare the impact of heating and cooling loads for the retrofitted house on the environment a calculation of the carbon emissions is necessary. The carbon emission factors used to perform the conversion of heating and cooling loads were taken from SAP 2009 (Building Research Establishment, 2014). For each kWh of energy delivered the emissions are equal to 0.517

kgCO$_2$/year for electricity and 0.198 kgCO$_2$/year for gas consumption. The result of the energy delivered for heating derived from ESP-r was multiplied by the efficiency of the boiler (72% and 90%)[4] for both the un-retrofitted and retrofitted house. The calculation of the carbon emissions from cooling devices follows a more complex procedure illustrated below.
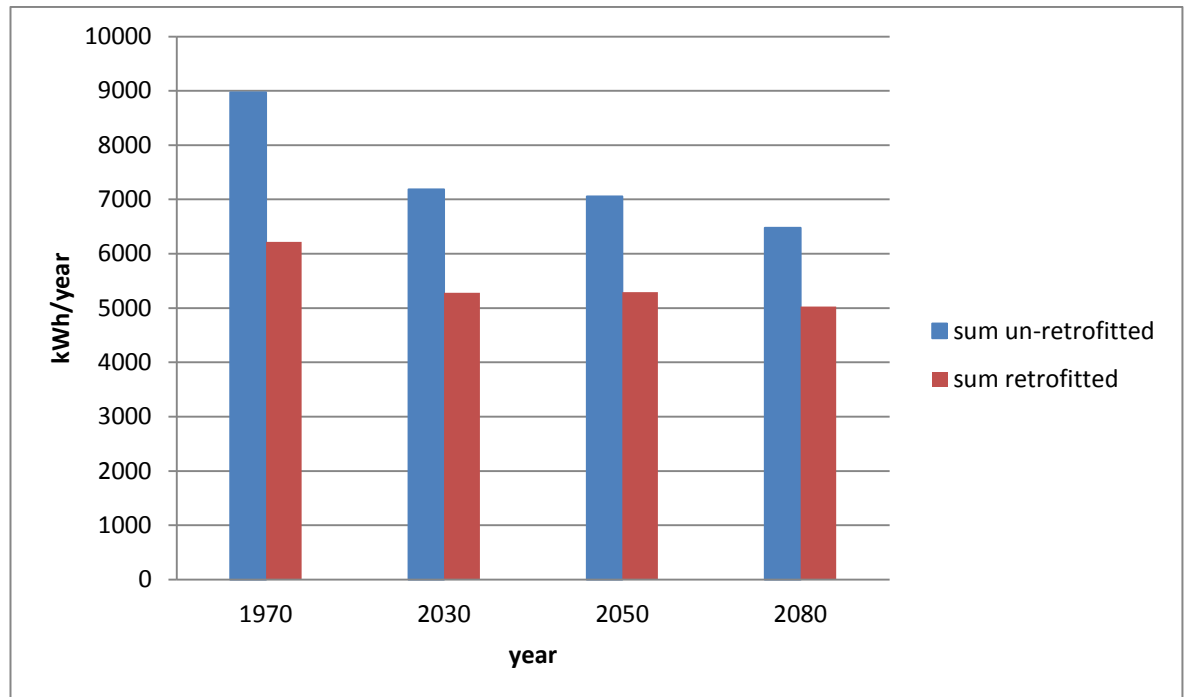
Figure 5.14: Sum of heating and cooling loads, single storey house, type 2, kWh/year

The following calculation assumes that room air conditioning units are installed in the living room and the bedroom of the single storey house. The efficiency of a room air conditioning unit can vary greatly. The efficiency of central air conditioning units is measured by the Seasonal Energy Efficiency Rate (SEER). SEER is defined as the number of kWh of cooling delivered during the season divided by the electrical consumption in kWh (Building Research Establishment, 2012). The European regulation recommends a SEER of at least 3.6 for room air-conditioners with an output power equal or inferior to 12kW (Building Research Establishment, 2012).

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[4] This data was taken from the survey carried out by Amicus Horizon in Rushenden and used by author during IFORE

The amount of power used by the air conditioning unit in the retrofitted house is not very high. On the other hand, if emissions continue to rise and mitigation options are not fully implemented, then by 2080s the amount of kWh/year of electricity used to run the air conditioning system could become over ten times more relative to the 1970s basecase. Since overheating is already experienced as a problem, as expressed by the residents during questionnaires and focus groups, the results on Table 5.10 show that air conditioning would be a relative inexpensive and attractive option in the very near future.

year	1970	2030	2050	2080
living room	7	29	40	67
bedroom	0	0	2	6
total	7	29	42	73

Table 5.10: Electricity consumption of air conditioning, single storey house, type 2, retrofitted, kWh/year

However, if the mitigation and adaptation efforts meet the targets set by the international community and national policy, climate change may represent an opportunity. In fact, if global carbon emissions reduce as planned and adaptations are put in place rapidly, then the reduction in the heating load in the South East of England could be a benefit. The amount of carbon emissions from the air conditioning unit may seem quite small in comparison to that from the boiler (Table 5.11, Figure 5.15). However if air conditioning becomes the strategy to combat overheating it will exacerbate further the problem of global warming. It is evident from Figure 5.16 that it was worth retrofitting the single storey terrace from a carbon point of view.

Year	1970	2030	2050	2080
Retrofitted heating	1349	1150	1119	1038
Retrofitted cooling	4	15	22	38
Un-retrofitted heating	2266	1821	1738	1548
Un-retrofitted cooling	4	19	29	54

Table 5.11: Carbon emissions from heating and cooling, $kgCO_2$/year, un-retrofitted and retrofitted single storey house, type2
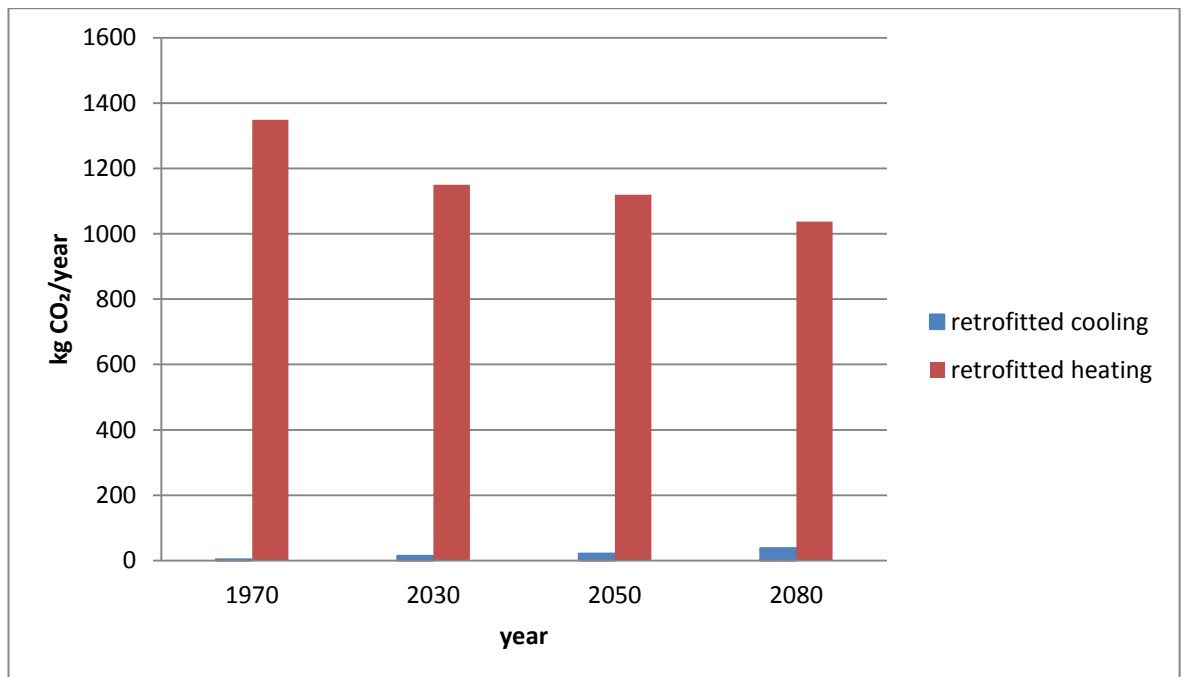
Figure 5.15: Carbon emissions from heating and cooling, single storey house, type 2, retrofitted, kg CO_2/year
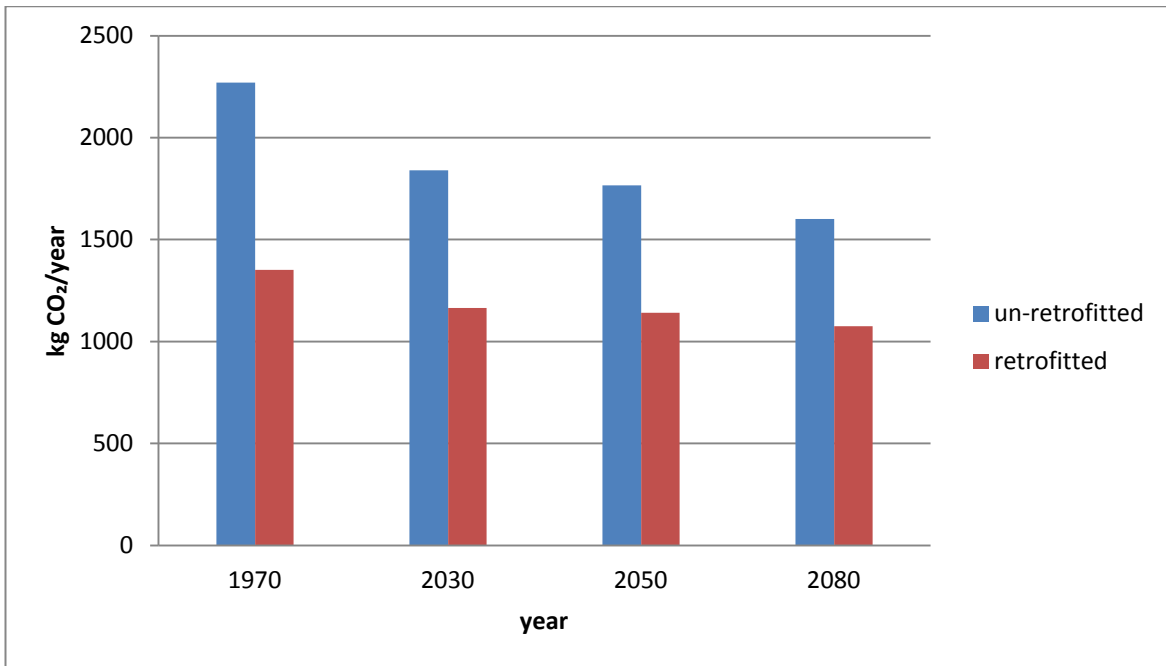
Figure 5.16: Global carbon emissions (heating and cooling), single storey house, type 2, un-retrofitted and retrofitted, kg CO_2/year

5.2.2 Price weighted heating and cooling loads, single storey house, type 2

In order to calculate the price that the residents will pay for the heating and cooling they need to remain comfortable in their homes the weighting factors of 12.5p/kWh for electricity (LCCP, 2013) and 5p/kWh for gas (IFORE, 2012) were used. These tariffs are current and include annual standing charges. They were averaged over the many different energy suppliers (UK Power, 2014) as for the 26th September 2014. They are representative averages and are not intended to give a precise value but an idea of the trend we face this century.

The following calculation is static and it assumes that the cost of gas and electricity will remain constant for the rest of the 21st century. This may not be the case but at present there is a high level of uncertainty regarding future energy prices. There are no available and reliable projections for the future cost of gas and electricity.

Several possible pathways remit from the Department of Energy and Climate Change (GOV.UK, 2013) report commissioned from Professor David MacKay, who subsequently

developed the 2050 pathway calculator of possible future energy mixes. The cost of energy will vary greatly depending on the different mix of fuels and renewable energy. For this reason, it is assumed for simplicity that the cost of electricity and gas remains constant.

Table 5.12 and Figure 5.17 show that as the total price for heating decreases, the price for cooling increases towards the 2080s. The price of heating remains much higher than the price of cooling up to the 2080s. The total price for heating and cooling the house will decrease towards the end of the century as a result of the temperature rise.

This is a highly hypothetical picture, as in reality the price of gas and electricity depends on socio, political and economic factors involving all countries worldwide. This graph elucidates the fact that cooling may soon become a proportion of the price that elderly residents in fuel poverty have to pay for their energy in order to remain comfortable and healthy. This calculation makes the case for installing climate change adaptation measures especially for social housing residents.

Un-retrofitted	1970	2030	2050	2080
heating	492	395	377	336
Cooling	1	5	7	13
Total	493	400	384	349
retrofitted	1970	2030	2050	2080
heating	341	290	283	262
cooling	1	4	5	9
total	342	294	288	271

Table 5.12: running cost, £/year, single storey house, type 2, un-retrofitted and retrofitted
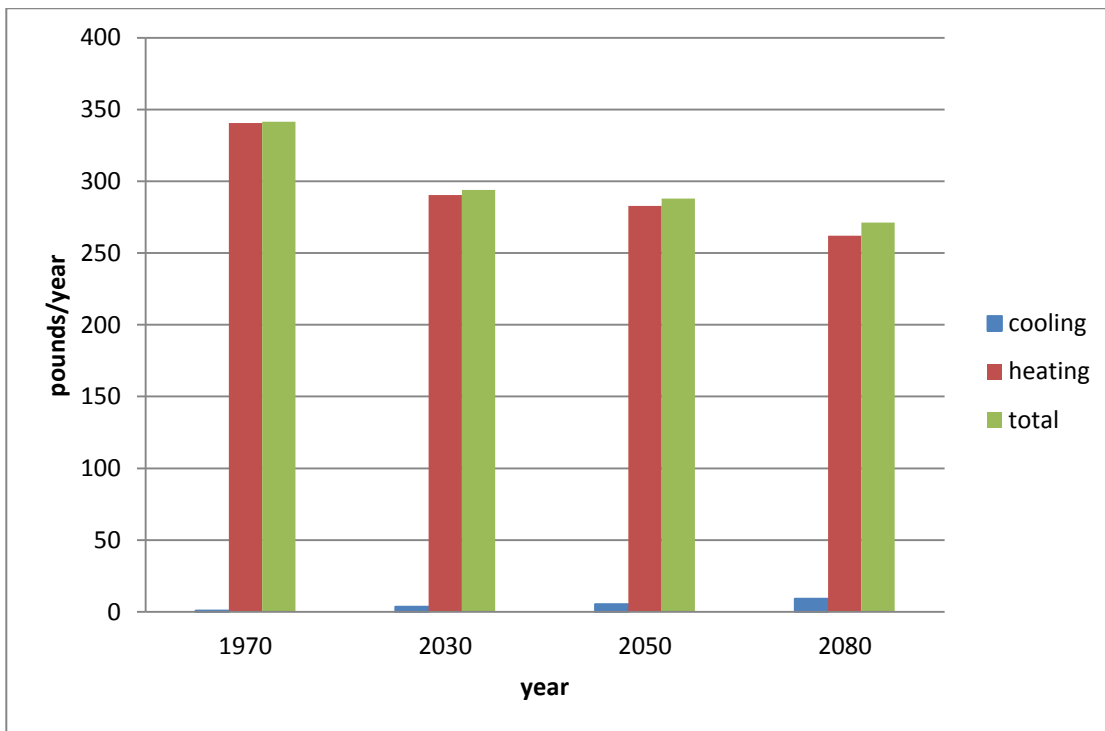
Figure 5.17: running cost, single storey house, type 2, retrofitted, pounds/year

5.2.3 Carbon emissions, two storey house, type 4

The calculation for the electricity consumption of the single-storey house presented previously was also run for the two-storey house, occupied and unoccupied. A SEER of 3.6 was used in the calculation. Compared with the single storey house there is less difference between the sums of heating and cooling loads in the un-retrofitted and retrofitted house (Figure 5.18).

The cooling load of air conditioning is higher in the two storey house than in the single storey house (Figure 5.19). As the cooling load increases in the future especially in the two bedrooms on the first floor, the carbon emissions to run the hypothetical air conditioning system increase as well. As for the single storey terrace, in the two-storey, energy will mainly be used for space heating up to the end of the century. However, from 2030s onwards, the amount of energy required for cooling the space becomes significant.

174
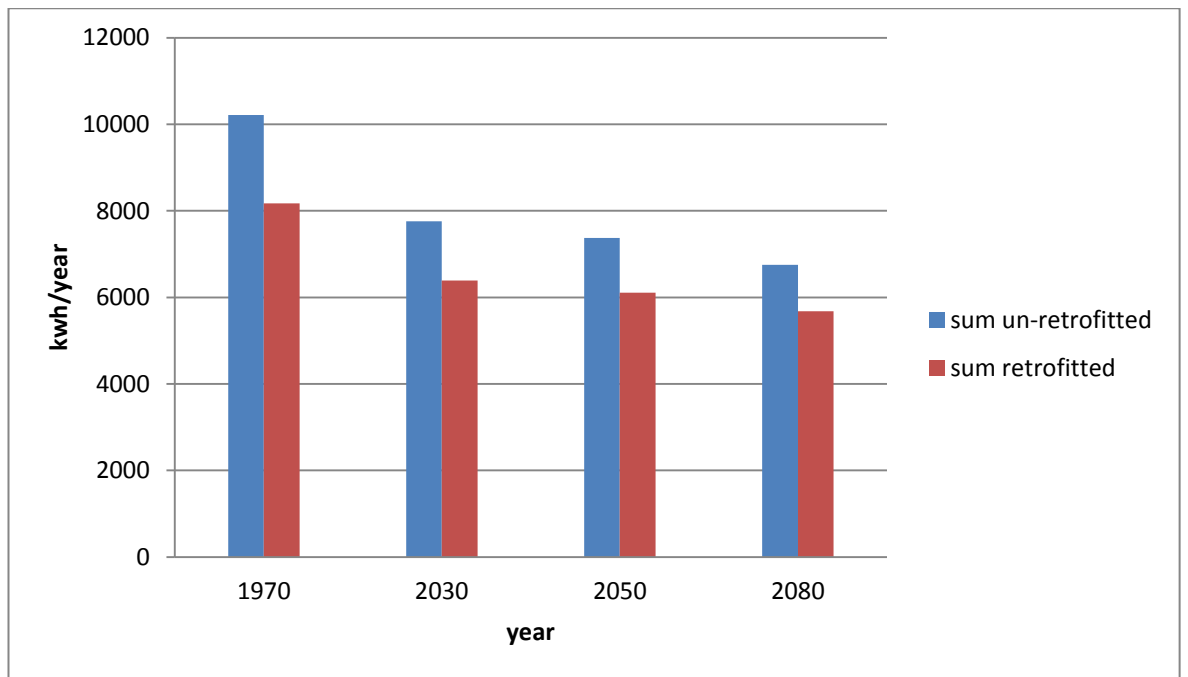
Figure 5.18: sum of heating and cooling loads, two storey house, type 4, unemployed family, kWh/year

year	1970	2030	2050	2080
living room	1	19	32	69
bedroom 1	0	22	38	79
bedroom 2	1	19	34	68
total	2	60	104	216

Table 5.13: Electricity consumption of air conditioning, two storey house, type 4, unemployed, retrofitted, kWh/year

Year	1970	2030	2050	2080
Retrofitted heating	1779	1344	1249	1067
Retrofitted cooling	1	31	54	112
Un-retrofitted heating	2223	1640	1514	1267
Un-retrofitted cooling	1	32	61	134

Table 5.14: Total carbon emissions, two storey house, type 4, unemployed, retrofitted and un-retrofitted, kgCO$_2$/year
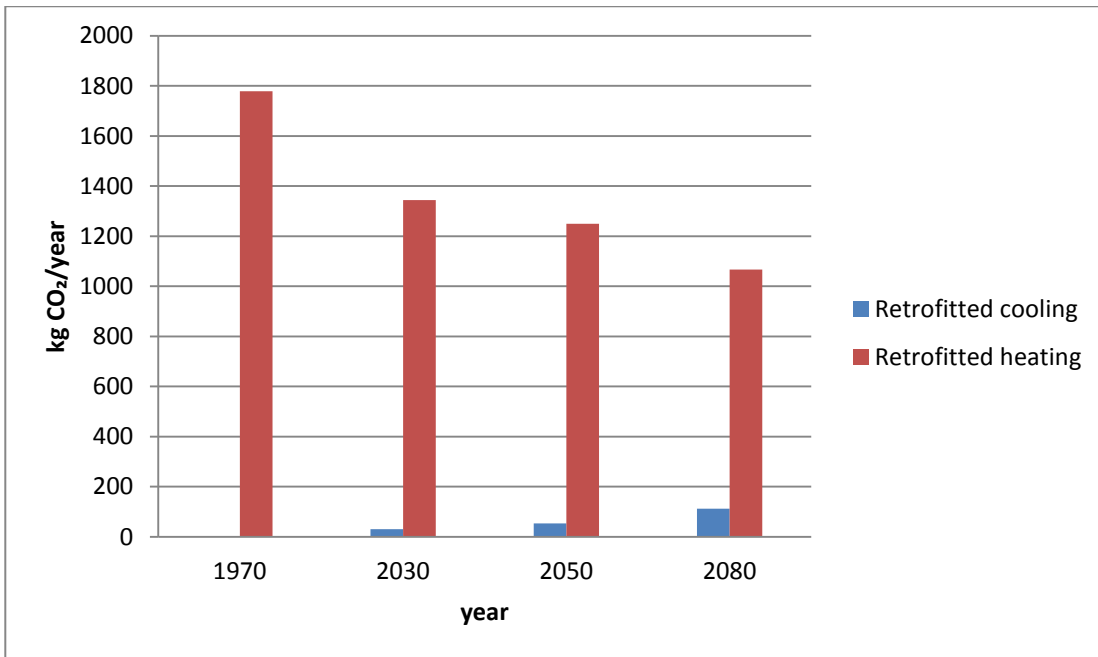
Figure 5.19: Carbon emissions from heating and cooling, two storey house, type 4, unemployed, retrofitted, kg CO_2/year
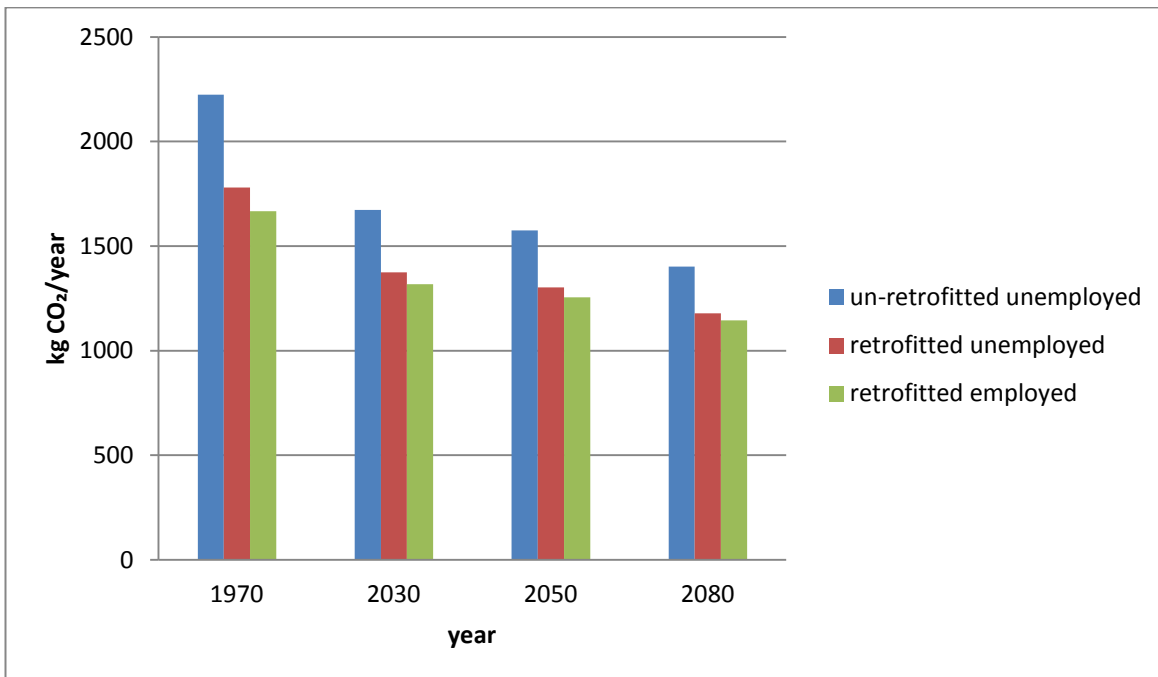
Figure 5.20: Global carbon emissions (heating and cooling), two storey house, type 4, un-retrofitted: unemployed and retrofitted: unemployed and employed, kg CO_2/year

5.2.4 Price weighted heating and cooling loads, two storey house, type 4

The same assumptions used for the single storey are also applied to the two storey terrace. The price of heating remains higher than the price of cooling up to the 2080s (Table 5.15, Figure 5.21). The price of cooling the two storey house occupied by the unemployed family will be higher than in the single storey house from 2050s onwards. This is because the surface to be cooled down is larger in the two storey house than in the single storey house. In the case of the family in employment the cooling price will be very low, lower than in the single storey highlighting again the benefits of keeping residents in work.

running cost un-retrofitted unemployed	1970	2030	2050	2080
heating	561	414	382	320
cooling	0.2	8	15	33
total	561	422	397	353
running cost retrofitted unemployed	1970	2030	2050	2080
heating	449	339	315	269
cooling	0	7	13	27
total	449	346	328	296
running cost retrofitted employed	1970	2030	2050	2080
heating	421	329	309	271
cooling	0	3	7	17
total	421	332	316	288

Table 5.15: Running cost, two storey house, type 4, un-retrofitted and retrofitted:

employed and unemployed families, £/year
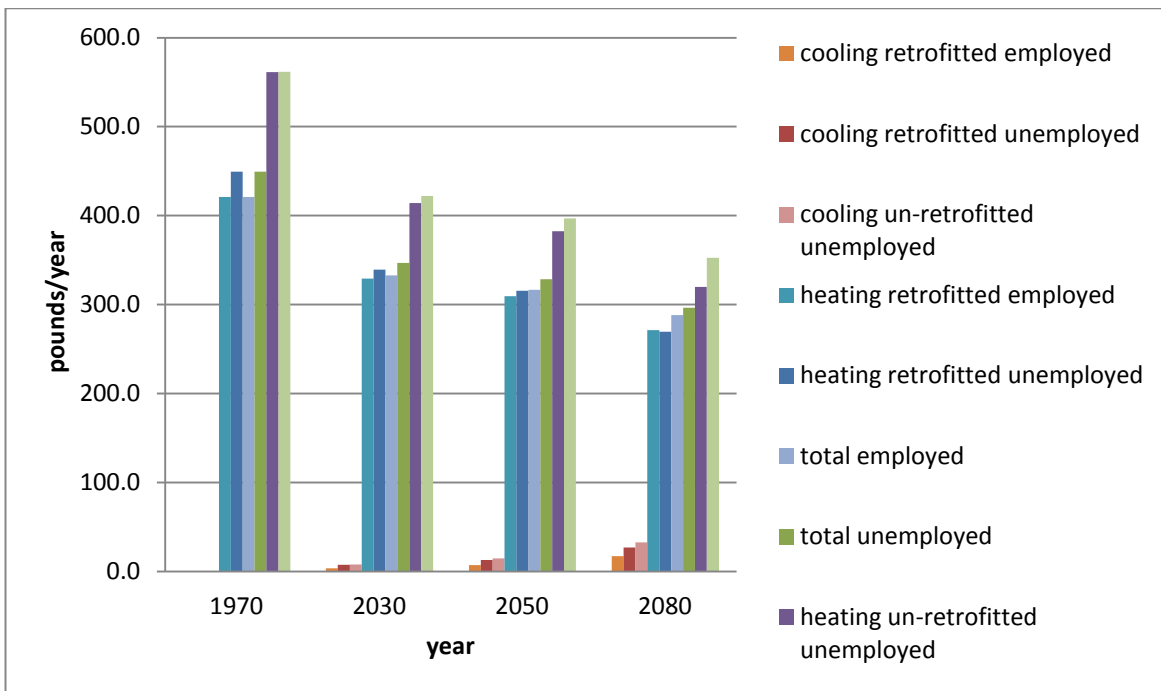
Figure 5.21: running cost, two storey house, type 4, un-retrofitted and retrofitted: employed and unemployed families, pounds/year

5.3 Heating and cooling loads when increasing the insulation thickness and improving the air tightness

These results will change if the thickness of the insulation is increased and the houses are made more air tight to comply with, for example, the Passivhaus standard. With UK housing needing to be virtually zero carbon by 2050 in order to meet the Climate Change Act commitment (Anderson, 2011) this type of deep retrofit may be more sought after. It was shown in the previous sections of this chapter that insulation and air tightness can reduce the cooling load in the future, when the outside temperature becomes higher.

Passivhaus uses mechanical ventilation heat recovery (MVHR). This system was installed during the retrofit in Rushenden in the single storey terraces because they were more air-tight than the two storey dwellings. Therefore the following assessment will be verified for the single storey house model. Simulations were run to assess heating and cooling loads for the model using Passivhaus standards, relative to the external walls only and the air-tightness improvement and the version of the specification called EnerPHit, which is especially targeted at retrofit. The EnerPHit component criteria are the following (Table

5.17, 5.18). The intention is to show the effect of Passivhaus levels of insulation but not to get the houses to the EnerPHit standard – for that the floor will need to be insulated and the windows replaced.

First of all, in the first run of simulations, the thickness of external wall insulation used to comply with the standard was improved from 80mm by up to 200mm of EPS and the cavity wall insulation was also improved. The U-value of the walls then becomes 0.117 W/m²K; other elements such as the ceiling and windows remained unchanged (Table 5.16). The air tightness of the retrofitted two storey terrace used above was not modified (Table 5.16, 5.19, Figure 5.22). In order to test the effects of the improved air tightness only, the second run of simulations used the air tightness of 1 ACH at 50 Pa to comply with Passivhaus standard (Table 5.20; Figure 5.23). The ventilation rate provided by the MVHR was added to the infiltration and the final rate used in the models was 0.0545 ACH. In the summer, the sum of infiltration and ventilation rates is 0.47 ACH assuming that the MVHR is switched off or in summer mode and/or windows are open to ventilate. The insulation was the same as that of the retrofitted single storey terrace previously analysed. Finally the third run of simulations represents the two storey terrace retrofitted with the extra wall insulation and the improved air tightness to comply with Passivhaus standards (Table 5.21, Figure 5.24).

| U walls: 0.117 W/m²K |
| U ceiling: 0.143 W/m²K |
| U windows: 2.811 W/m²K (windows assumed not replaced) |
| Infiltration + ventilation rate: 0.23 ACH |

Table 5.16: U-values used when the insulation was increased to comply with Passivhaus criteria

Criteria	Passivhaus	EnerPHit
Specific Heat Demand	≤ 15 kWh/m².yr	≤ 25 kWh/m².yr
Primary Energy Demand	≤ 120 kWh/m².yr	≤ 120 kWh/m².yr
Limiting Value air tightness ACH	$n_{50} \leq 0.6^{-1}$	$n_{50} \leq 1.0^{-1}$

Table 5.17: Passivhaus and Enerphit criteria (Source: Taylor, M. 2012)

Building component	Retrofit criteria
External wall insulation	U≤ 0.150W/(m²K)
Internal insulation	U≤ 0.300W/(m²K)
Roof or top floor ceiling	U ≤ 0.120W/(m²K)
Windows UW installed	≤ 0.85W/(m²K) *g -1,6W/(m2K) ≤Ug*
External door UD	installed ≤ 0.80W/(m²K)
Thermal bridges	No linear thermal bridges with > + 0.01W/(m²K) or
Punctiform thermal bridges	> + 0.04W/(m²K)
Ventilation	HR,eff ≥ 75%
Electrical efficiency of ventilation system	≤ 0.45Wh/m³

Table 5.18: Passivhaus criteria (Source: Passivhaus, 2011)

Similar results to those found previously were also found when the thickness of the insulation was increased further and the air-tightness was improved. Increasing the thickness of the external insulation reduces the heating load. It does not make any difference to the cooling load. This shows that when the external envelope is already insulated, adding an extra layer of external insulation does not help further reduce the overheating risk (Table 5.19, Figure 5.22). The air tightness, reduces the heating load and increases slightly the cooling load (Table 5.20, Figure 5.23). When both, insulation and air tightness are improved the heating load reduces and the cooling load increases slightly

compared to the house lightly retrofitted during IFORE (Table 5.21, Figure 5.24). In 2080s however, the cooling load of the house retrofitted using Passivhaus specification decreases compared with the light retrofit. A possible explanation to this can be that as the outside temperature increases, the extra insulation and air-tightness help keeping the ambient air outside of the building. It seems however, when comparing these with previous results, that as the building becomes more insulated and air tight, these become less effective at reducing the heating load whilst the cooling load still increases (Figure 5.25, 5.26).

The fabric and design of the retrofitted houses in Rushenden is typical of social housing of the 1940s, 1950s and 1960s and it is similar to many social housing developments built in that period throughout the country as it was explained in the Social Housing Context of the Literature Review Chapter. The floor to ceiling height is little more than two metres; there are small windows and small rooms. The Passivhaus approach increases at first the cooling load compared with light retrofit and it slightly reduces it by the end of the century. By then the houses may have been demolished or replaced. That is why, in the case of similar housing it may be more cost effective to adopt a light retrofit approach coupled with community engagement. The current IFORE low carbon retrofit measures are dictated by the tight budget that Amicus Horizon, the social housing provider, made available for each house (about £15,000 per house). This reflects the economic reality of social housing in Rushenden and other communities in the UK. The above results, although encouraging, assume the use of air conditioning to handle the cooling loads (though ideally avoided for environmental and socio-economic reasons). That is why an assessment of the overheating hours, representing actual comfort conditions, assuming that the buildings are naturally ventilated, is essential to finding sustainable solutions to overheating.

Passivhaus insulation-walls-type2	1970	2030	2050	2080
heating load (kWh/m²·year)	122	104	101	94
cooling load (kWh/m²·year)	0.9	3.8	5.4	9.3
tot	123	108	106	103
living room kWh/year	26	104	144	240
bedroom kWh/year	0	1.4	7	20

Table 5.19: Heating and cooling loads of the retrofitted single storey house, type 2, with Passivhaus wall U-Values
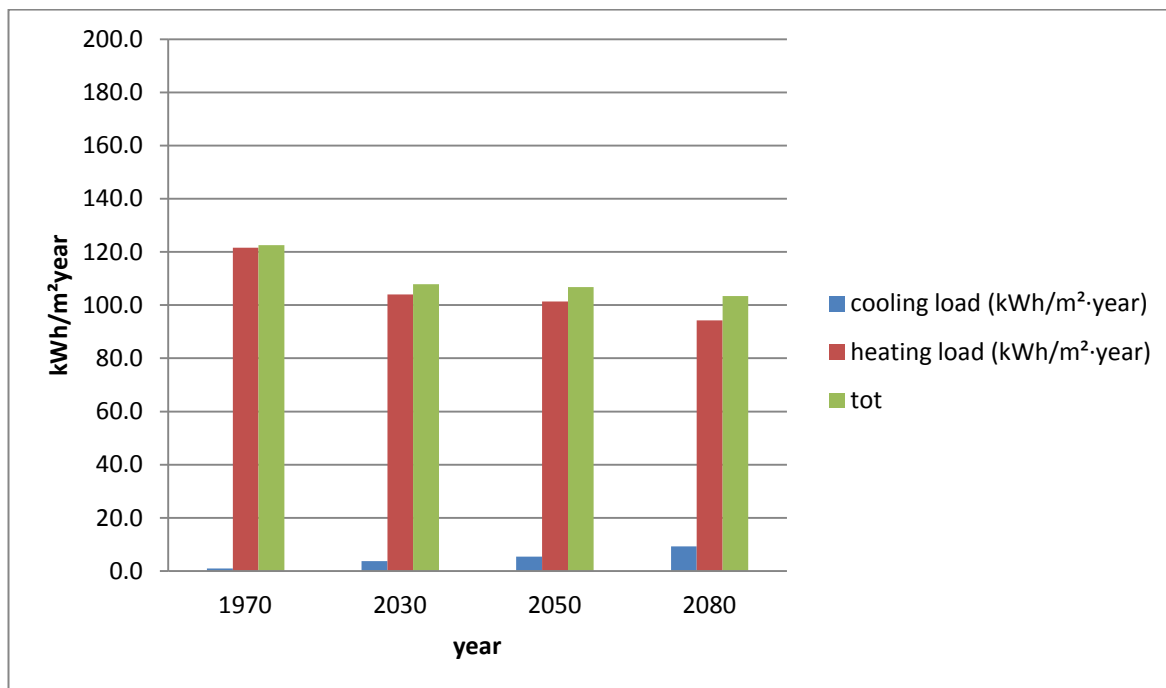
Figure 5.22: Heating and cooling loads of the retrofitted single storey house, type 2, with Passivhaus wall U-Values

Passivhaus air-tightness type2	1970	2030	2050	2080
heating load (kWh/m²·year)	114	98	96	90
cooling load (kWh/m²·year)	1	4	6	9
tot	115	102	102	99
living room kWh/year	31	110	146	234
bedroom kWh/year	0	2	7	19

Table 5.20: Heating and cooling loads of the retrofitted single storey house, type 2, with Passivhaus air-tightness
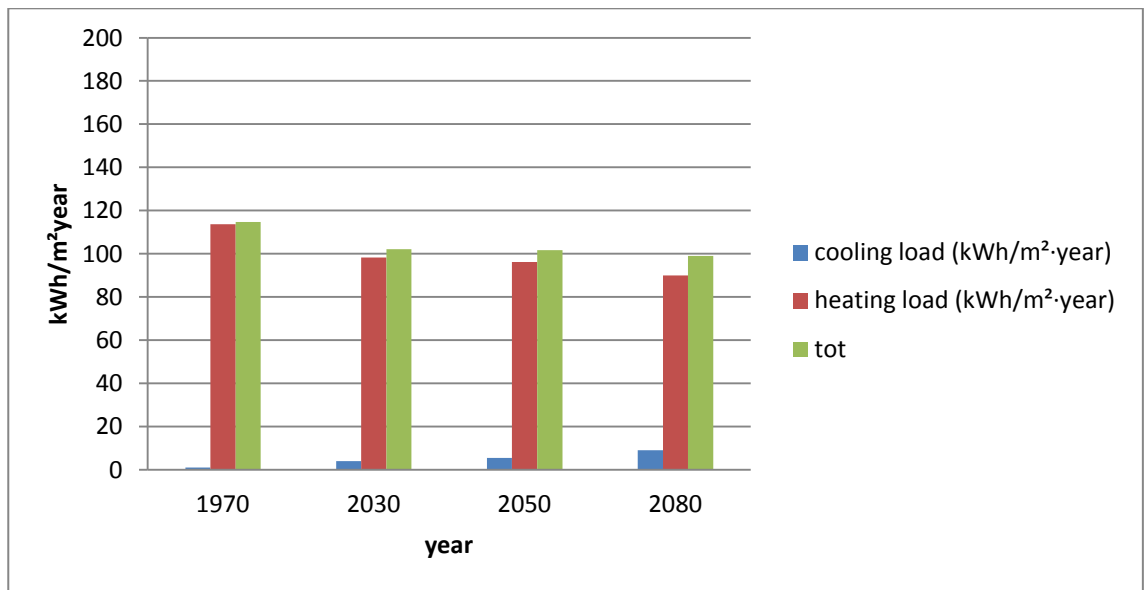
Figure 5.23: Heating and cooling loads of the retrofitted single storey house, type 2, with Passivhaus air-tightness

Passivhaus insulation and air-tightness type2	1970	2030	2050	2080
heating load (kWh/m²·year)	112	97	95	89
cooling load (kWh/m²·year)	1	4	6	9
tot	113	101	101	98
living room kWh/year	0	2.91	9	23
bedroom kWh/year	141	280	309	403

Table 5.21: Heating and cooling loads of the retrofitted single storey house, type 2, with Passivhaus walls U-Value and air-tightness
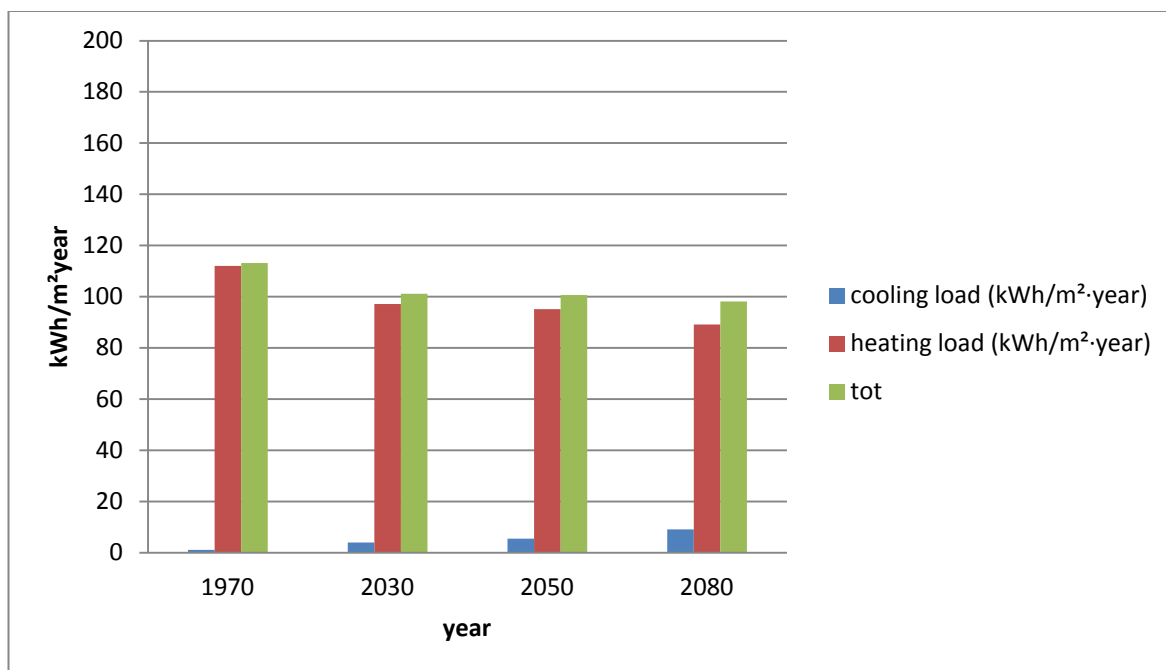
Figure 5.24: Heating and cooling loads of the retrofitted single storey house, type 2, with Passivhaus walls u-values and air-tightness
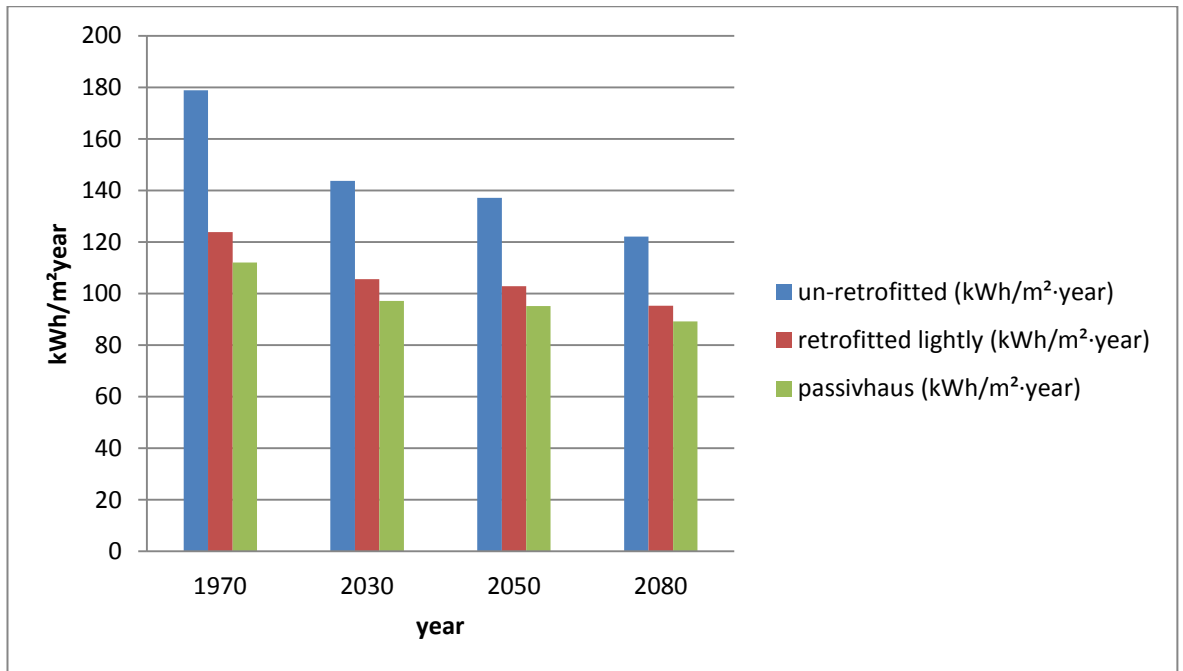
Figure 5.25: Summary of heating loads of the single storey house with different fabrics
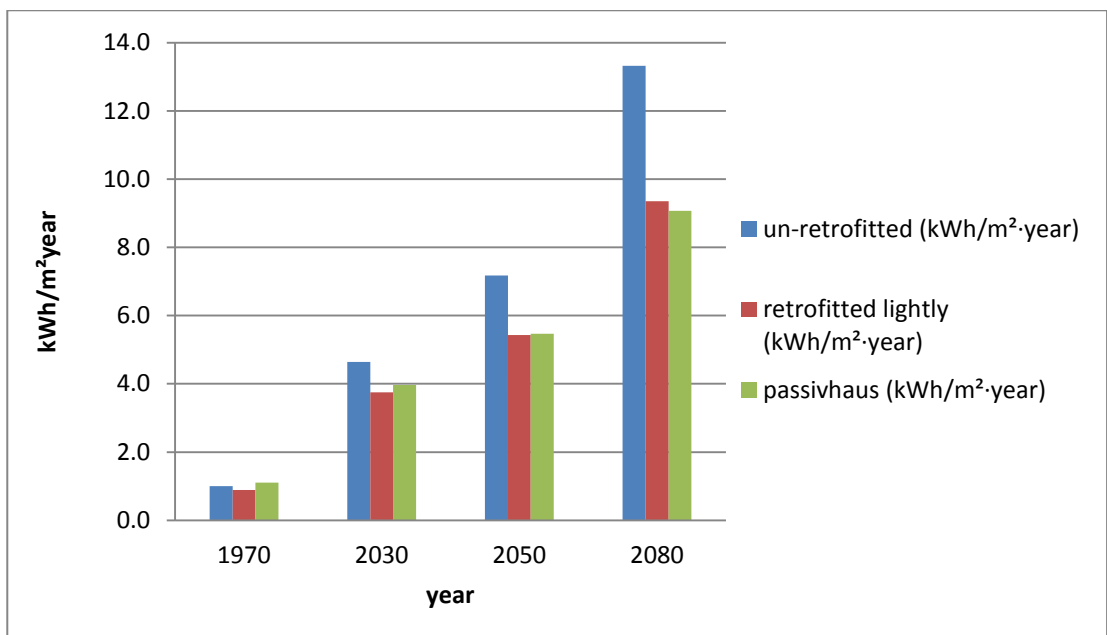
Figure 5.26: Summary of cooling loads of the single storey house with different fabrics

5.4 Assessment of the overheating risk using the adaptive comfort set of criteria

The simulations above show that by 2030s, the overheating risk measured as cooling load in the houses retrofitted by IFORE, reduces in the single and two storey in the terraces when compared with the un-retrofitted models. In reality the residents adapt to the higher summer temperature and ventilate naturally by opening the windows. As explained in the Field Study Chapter, it is common behaviour in Rushenden to open the windows during the day in summer. In the two storey dwellings, windows are usually open in the bedrooms on the first floor and when occupied on the ground floor. In the single storey terraces, windows are open mainly in the living room and bedroom at the back. At night some residents expressed concerns when opening their windows in both the single and two storey houses.

In the retrofitted houses the residents will adapt to the new temperature, which they find higher but more stable (as discussed during the focus groups) The cooling set point of 25 °C in the living room and 23 °C in the bedrooms (CIBSE A, 2006) used in the simulations to calculate the cooling load may seem inflexible, but in a naturally ventilated environment the occupants adapt to their houses and at present they are not using any form of air conditioning. This is why an assessment of the overheating hours above the comfort threshold and the likelihood of air conditioning being installed is more accurate representation of what the comfort levels are.

The adaptation survey was carried out in the summer of 2012 using a sample of 16 households as discussed in the Field Study chapter. The majority of the residents expressed no concerns about opening windows during the daytime. On the contrary, they declared that they ventilate their houses regularly by opening windows all year round.

Mrs J.B. of Manor Close said: *"I open all windows during the day in the summer, I shut them all up at night apart from the window of the small bedroom (utility) that is on a night draught all year round"*

The difference between a static measure of the overheating hours or cooling load and the adaptive comfort equation is that the equation accounts for adaptation by the residents.

This is why the running mean temperature is used as a measure of the overheating. The running mean is calculated using the seven days preceding the actual day that the measurement of comfort is taken. This means that it takes into account the capacity of the residents to adapt over a week to a higher temperature. In this way it can be called a dynamic measure.

5.4.1 Single storey terrace, un-retrofitted and retrofitted, elderly occupants

The simulations were run for the month of July using future files for 2030s, high emission, 90 percentile. The following graphs (Figures 5.27, 5.28) show the indoor temperature during July 2030s. Figure 5.27 shows how the indoor temperature would be if the windows were kept closed during the summer in the retrofitted dwelling and the sum of infiltration and ventilation rates was constant at 0.23 ACH. The living room would overheat considerably because of the very low air-flow rate. If the air-flow rate becomes 0.645 (Figure 5.28), the minimum prescribed by Part F of the UK building regulations for this house type (HM Government, 2010), and calculated in the Methodology Chapter, assuming that the MVHR is switched off, then the temperature lowers considerably.

The air-flow rate was then increased up to 1 ACH and 1.5 ACH and decreased to 0.5 ACH. The indoor temperature profiles in the living room and in the bedroom do not differ substantially from those presented in figure 5.28. Simulations showed that when the sum of infiltration and ventilation rates is increased to 3 and 6 ACH however, the temperature increases considerably during the hottest day of the month, the 12th of July, and reduces when the outdoor temperature decreases. In the retrofitted single storey dwelling therefore it would be better, during heat waves, to reduce to a minimum the extra ventilation provided by opening the windows. That will keep the indoor temperature more stable and below the outdoor peaks.

Figure 5.29 shows a plot of the temperatures in the bedroom and living room of the un-retrofitted and retrofitted single storey dwelling during the heat wave in July 2030s. In the un-retrofitted model the sum of ventilation and infiltration rates is 0.9 ACH (Methodology Chapter, Section 3.4.2.2). In the living room and in the bedroom, the indoor temperature is consistently lower after the retrofit measures were installed. In the

retrofitted dwelling, the loft and the external wall insulation cause this reduction. As it was discussed earlier, the air-tightness improvement does not make any substantial difference in this case.

When assessing the risk of overheating using the adaptive comfort set of criteria (Methodology Chapter, Section 3.5) one can see from Figure 5.29 that:

- The living room of the un-retrofitted single storey house fails the third criterion because the indoor temperature exceeds the upper limit temperature T_{upp} set by TM52 (CIBSE, 2013).

- In the retrofitted living room, the third criterion is met and the upper temperature is not exceeded.

- In both cases, the un-retrofitted and retrofitted living room, fail the second criterion on three consecutive days in July.

The un-retrofitted living room therefore fails 2 out of three criteria and can be classed as overheating. Even if the retrofitted living room passes the third criterion the number of occupied hours above the threshold T_{max} over the period from May to September is 171, equal to 9% (Figure 5.30). The first and third criteria are therefore failed and the retrofitted living room will be classed as overheating according to TM52. Some necessary adaptation measures will be applied later to the model and explored in detail. The bedroom is not overheating, the indoor temperature is generally below T_{max} and the three criteria are met.
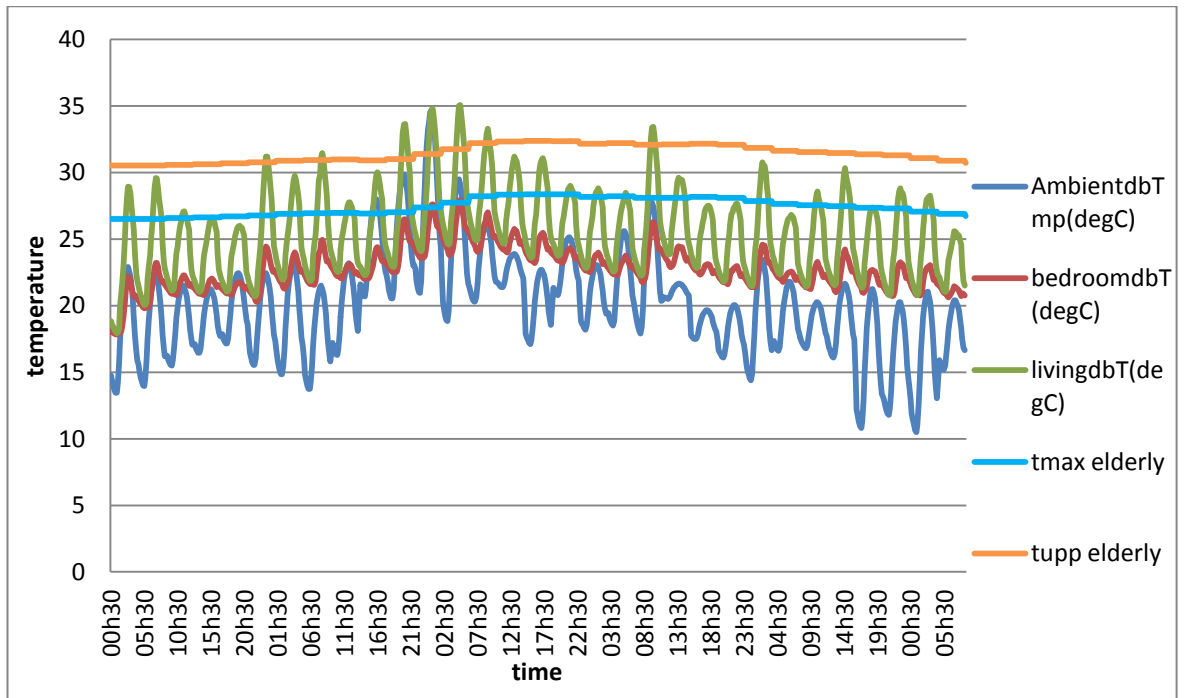
Figure 5.27: Temperature in July 2030s, single storey house, type 2, retrofitted with constant air-tightness of 0.23 ACH showing Tmax and Tupp the using adaptive comfort equations (CIBSE, 2013)
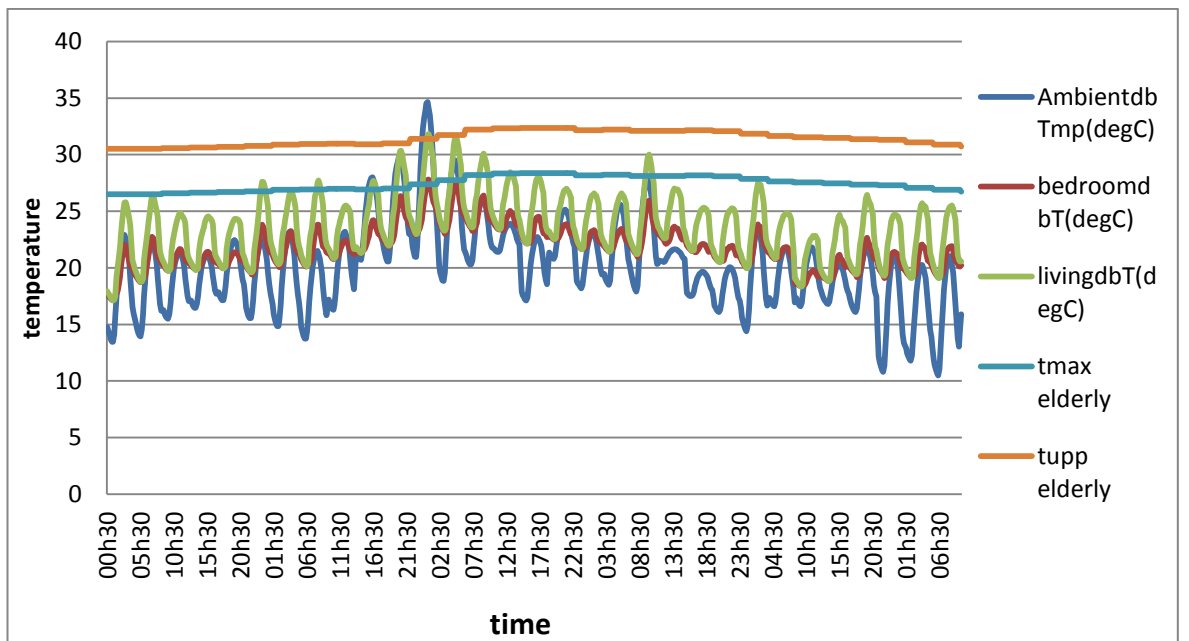
Figure 5.28: Temperature in July 2030s, single storey house, type 2, retrofitted with constant air-tightness of 0.645 ACH, showing Tmax and Tupp the using adaptive comfort equations (CIBSE, 2013)

189
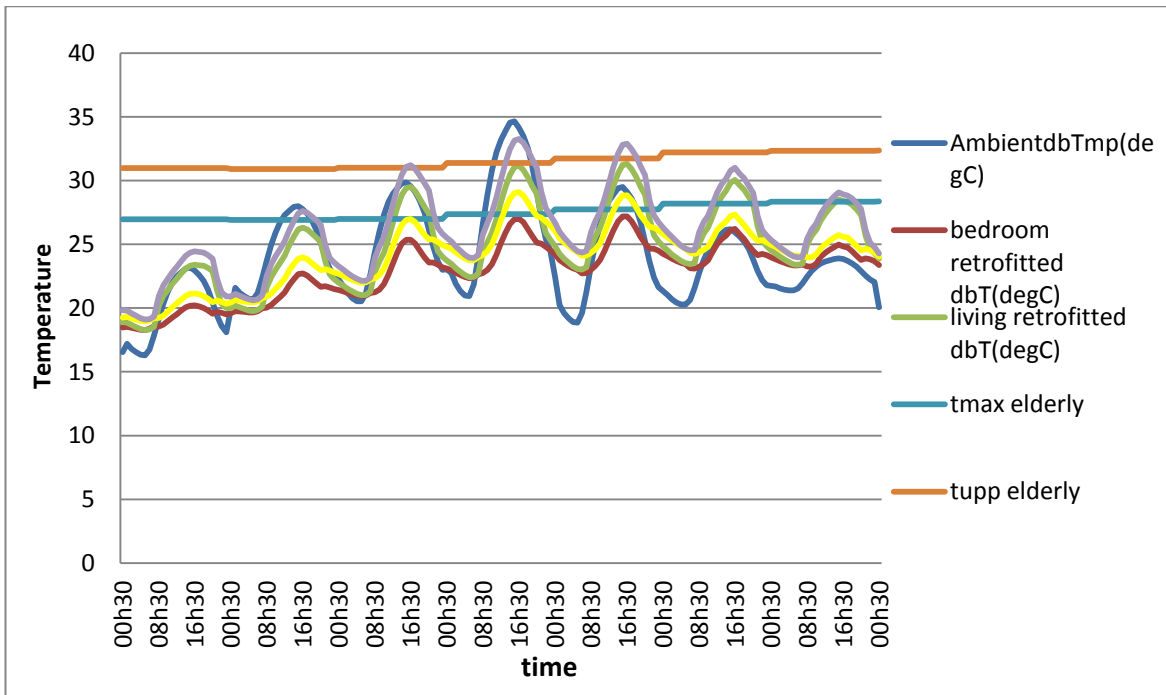
Figure 5.29: Comparison of the indoor temperature from 9th to 15th of July 2030s, single storey house, type 2, un-retrofitted and retrofitted, showing Tmax and Tupp using adaptive comfort equations (CIBSE, 2013)
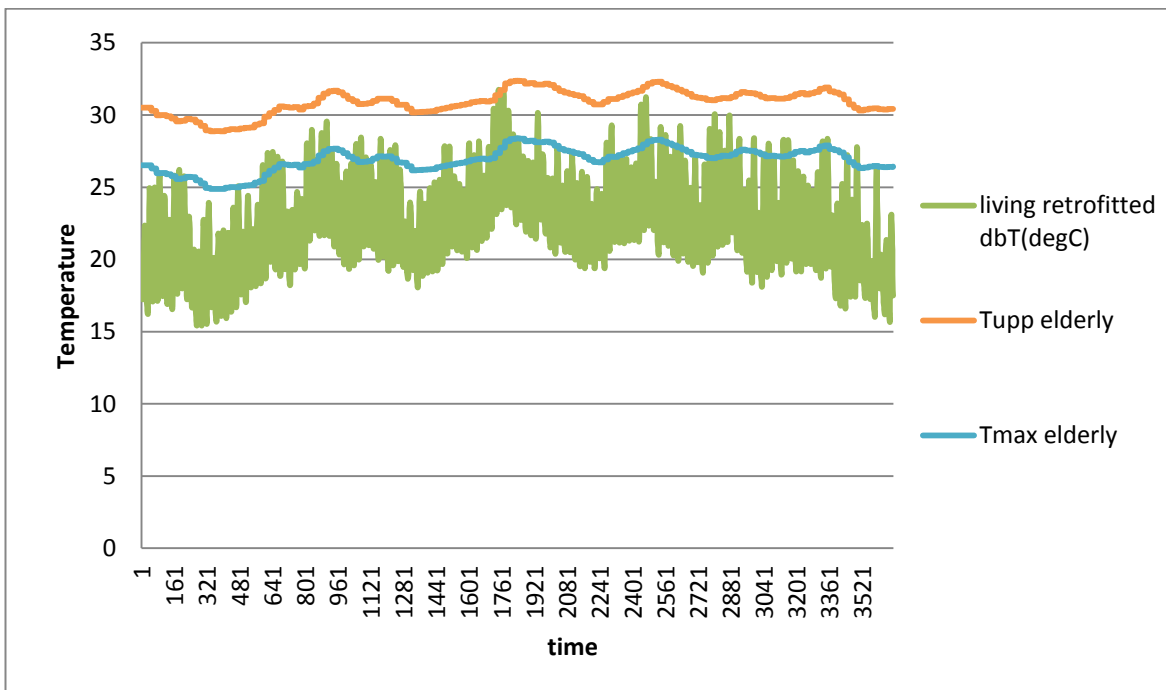
Figure 5.30: Temperature in the living room of the single storey house, type 2, retrofitted, from May to September 2030s, showing Tmax and Tupp the using adaptive comfort equations (CIBSE, 2013)

190

5.4.2 Two storey terrace, un-retrofitted and retrofitted, unemployed occupants

Similarly to what was found previously for the single storey dwelling, when the ventilation rate in the living room and bedrooms of the two storey terrace increases, to 3 and 6 ACH, by opening windows for instance, the indoor daily temperature increases as well. The two storey dwelling, that is leakier after the retrofit with an air-change rate of 1.06 ACH, benefits from keeping the windows closed during heat waves or open by a small amount (Figure 5.31). An air-change rate between 0.5 and 1.5 ACH does not change substantially the temperature profile shown in Figure 5.31.

When we compare the indoor temperature during the hottest week of July 2030s in the two-storey terrace we see that it is lower in the living room after the retrofit measures are installed (Figure 5.32). In the two bedrooms on the first floor there is almost no difference between the temperature of the un-retrofitted and retrofitted models (Figure 5.33). The south-east facing bedroom 1 at the front benefits from the effects of the increased insulation especially in the afternoon, while the south-west facing bedroom 2 benefits from it more in the morning.

The temperature threshold set up by TM52 is 1 °C higher for the two storey terrace that is occupied by the unemployed family than it is for the bungalow occupied by elderly and therefore the temperature difference ΔT is less stringent.

- Figure 5.34, 5.35 show that the third criterion is met in both the retrofitted bedrooms and in the living room and the indoor temperature does not exceed the absolute maximum value T_{upp}.
- The retrofitted living room fails the second criterion one day in July.
- The bedrooms become very hot during the day when unoccupied but at night the temperature drops below T_{max}.

The first criterion is met in both bedrooms and living room, the retrofitted two storey dwelling therefore will not be classed as overheating by 2030s because it meets the criteria of TM52.
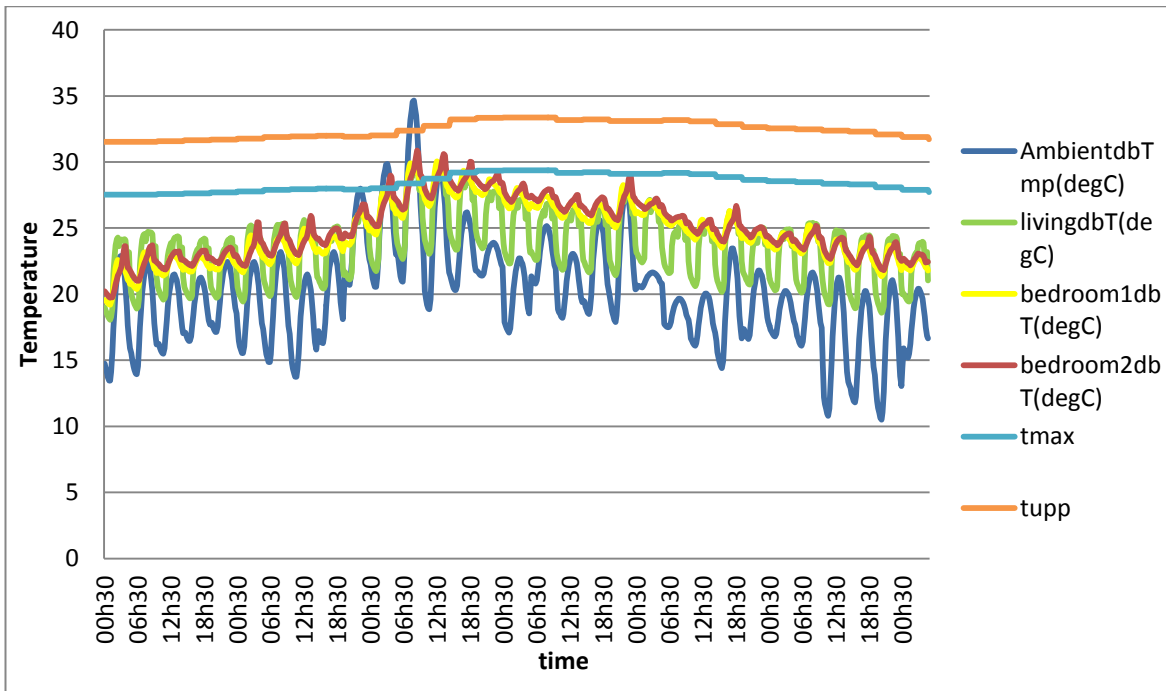
Figure 5.31: Temperature in July 2030s, two storey house, type 4, retrofitted with constant air-tightness of 1.06 ACH, showing Tmax and Tupp the using adaptive comfort equations (CIBSE, 2013)
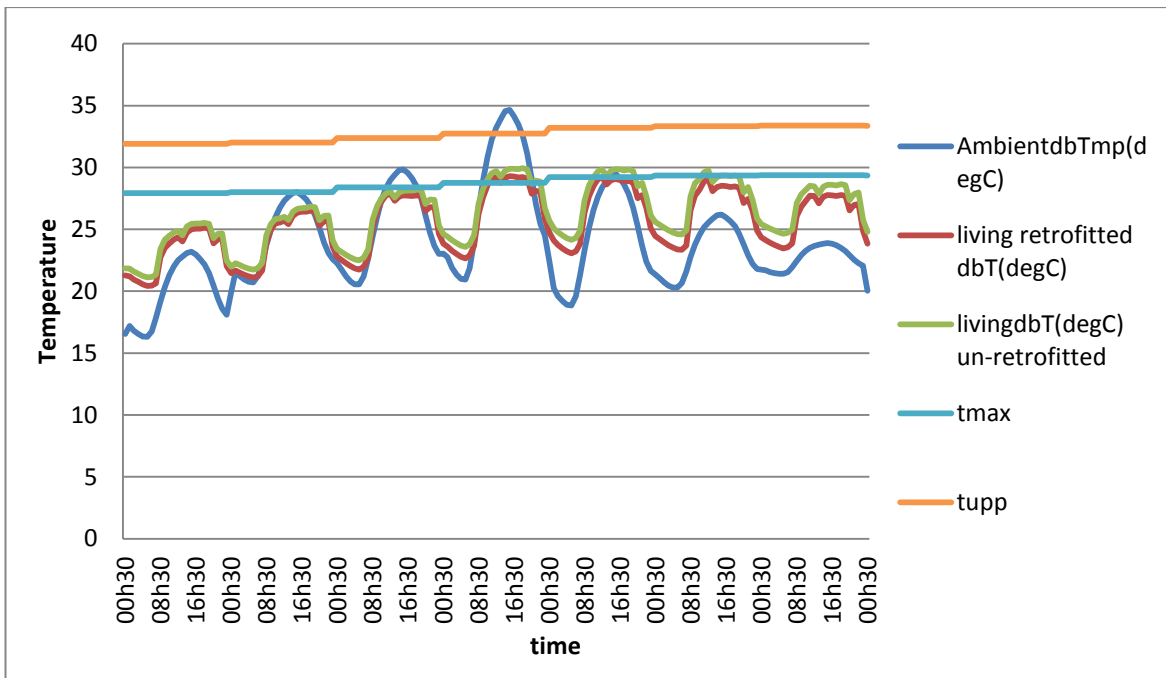
Figure 5.32: Comparison of living room's temperatures from the 9th to the 15th of July 2030s, two-storey house, type 4, un-retrofitted and retrofitted
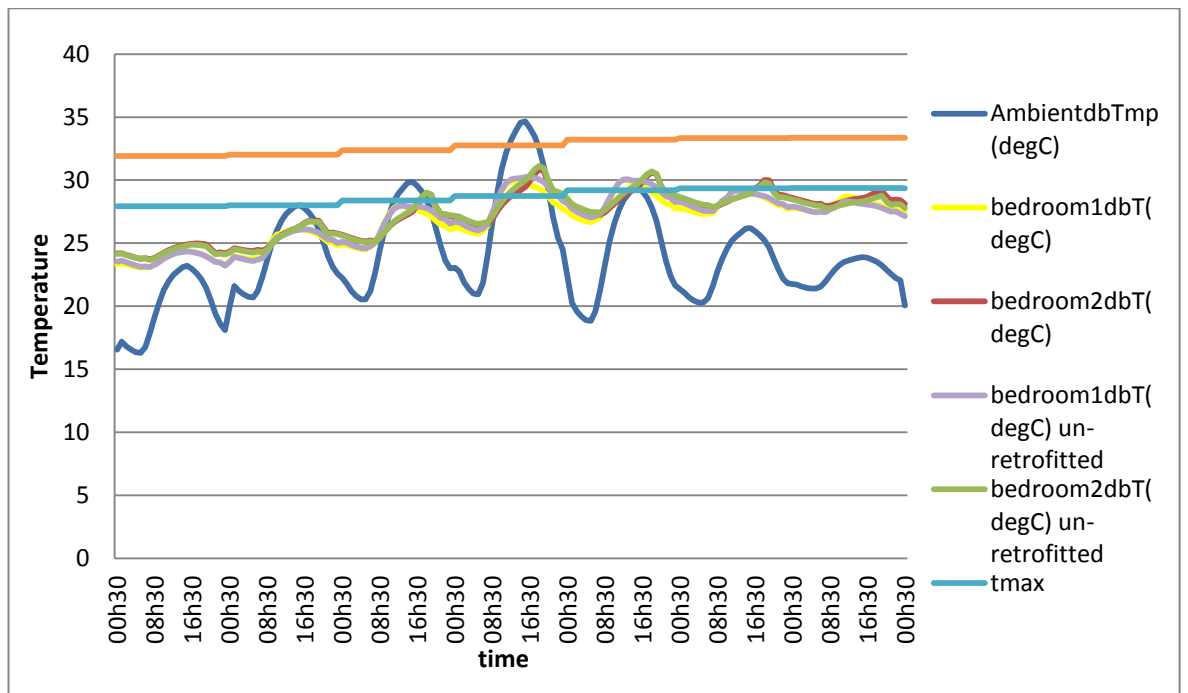
Figure 5.33: Comparison of the temperature in the bedrooms from the 9th to the 15th of July 2030s, two-storey house, type 4, un-retrofitted and retrofitted

Some of the two storey dwellings however are occupied by elderly couples. In this case, when using the 1 °C lower threshold, the bedrooms and living room will still meet the third criterion. The time the indoor temperature in the retrofitted living room is above the lower threshold is equal to 2.6% of the total occupied hours, therefore it will meet the first criterion. Even if the second criterion is failed, the living room will not be classed as overheating because two out of three criteria are met. The bedrooms meet the three criteria during the occupied hours even when using the lower threshold for elderly occupancy and will not overheat according to TM52.

In the case of the family in employment the indoor temperature in the living room will be lower during the day when unoccupied because of the lower casual gains and in the bedrooms it will be similar to the case discussed above. Therefore it will not be classed as overheating. A more in-depth study was not carried out in this case because it presents a lower risk of overheating.
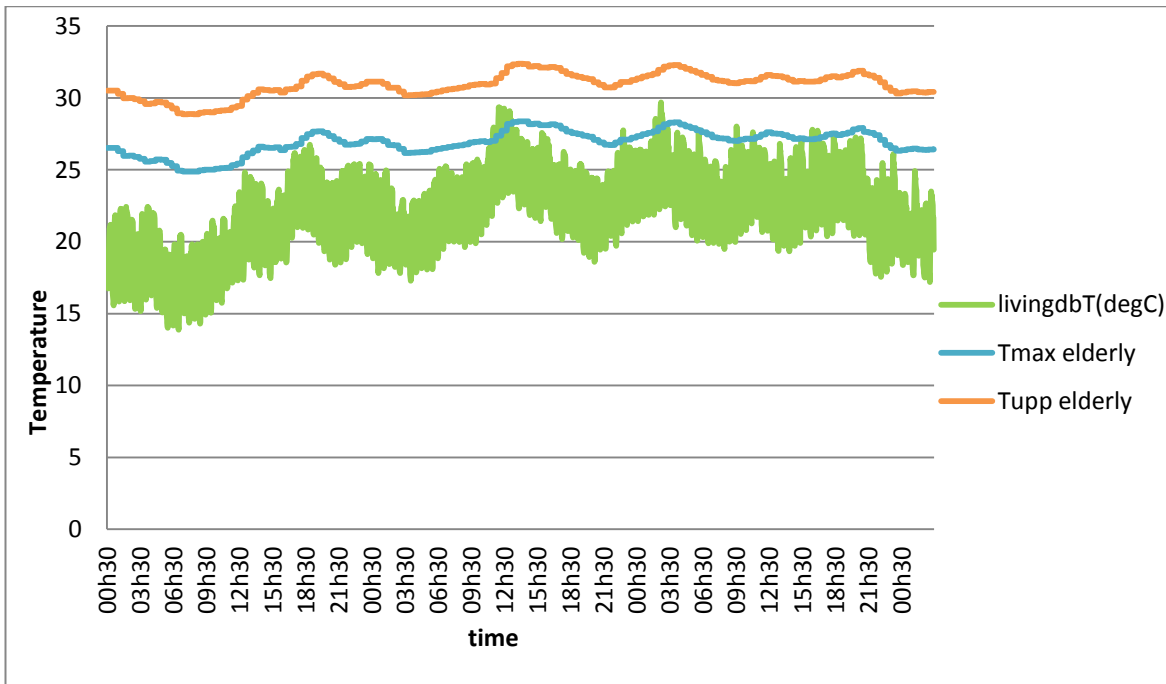
Figure 5.34: Temperature in the living room of the two storey house, type 4, retrofitted, from May to September 2030s, showing Tmax and Tupp (elderly) using the adaptive comfort equations (CIBSE, 2013)
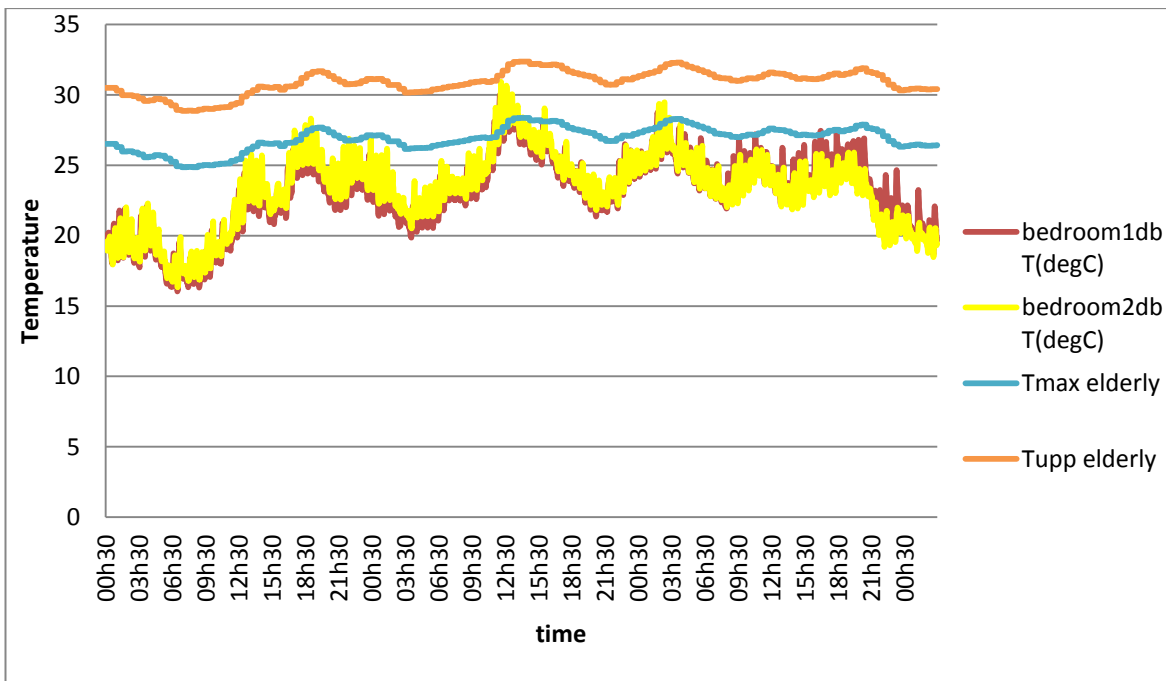
Figure 5.35: Temperature in the bedrooms of the two storey house, type 4, retrofitted, from May to September 2030s, showing Tmax and Tupp (elderly) using the adaptive comfort equations (CIBSE, 2013)

5.4.3 Monitoring results and summary of the overheating risk assessment

Modelling shows that summertime indoor temperatures are lower and more stable in the retrofitted houses. The author has verified this result by analysing the indoor temperatures monitored hourly by data loggers over the month of February in winter 2012 and 2014, during the IFORE project (Figures 5.36, 5.37). The residents, during some of the interviews carried out by Professor Mike McEvoy at the end of 2013, confirmed that they feel more comfortable in the summer and that the indoor temperature is more stable after the low carbon retrofit measures were installed.

The models show that in the living rooms the temperature will reach peaks of 32 °C in the single storey house and 30 °C in the two storey house by July 2030s. A recording of the monitored internal temperature in July 2014 in the single and the two storey dwellings is plotted in Figures 5.38 and 5.39. There are similarities between the monitored temperature and the results from the simulations. From the graphs it is possible to identify similar patterns. In July 2014 the temperature peaked to 29 °C in the living room of the single and two storey dwellings showing a similar evolution to that shown previously by the models. It is very likely that in the future, with an increase of the external temperature, the indoor temperature will also increase in a similar way that the models have demonstrated. Unfortunately it was not possible to find a record over the same time period of the external temperature from the weather station installed in Rushenden.

Table 5.22 shows a summary of the overheating risk assessment carried out in the single and two storey dwellings using the adaptive comfort set of criteria. Although this shows that only the living room of the single storey house will be classed as overheating by 2030s, the preliminary analysis, the questionnaires and the focus groups however suggest that the households in Rushenden are already experiencing overheating. In order to re-establish a comfortable indoor environment in type 2 and avoid the use of air conditioning it will be necessary to introduce some kind of passive cooling technique, such as shading and/or night ventilation.

Although levels of comfort will have increased after the retrofit, the use of fans is still widespread. This may be the result of several factors. The residents' behaviour may not help them in achieving optimal ventilation. During focus groups it became evident that for privacy, security and other personal reasons the residents do not always open the windows and doors at night. TM52 may underestimate the overheating risk in housing since it was derived from surveys of office buildings and the equations are targeted at naturally ventilated offices. The solution to this problem proposed by the author is the adoption of a lower threshold representing the maximum comfort temperature for this particular group of residents derived from the comfort survey run in 2012 and presented in the Field Study Chapter.
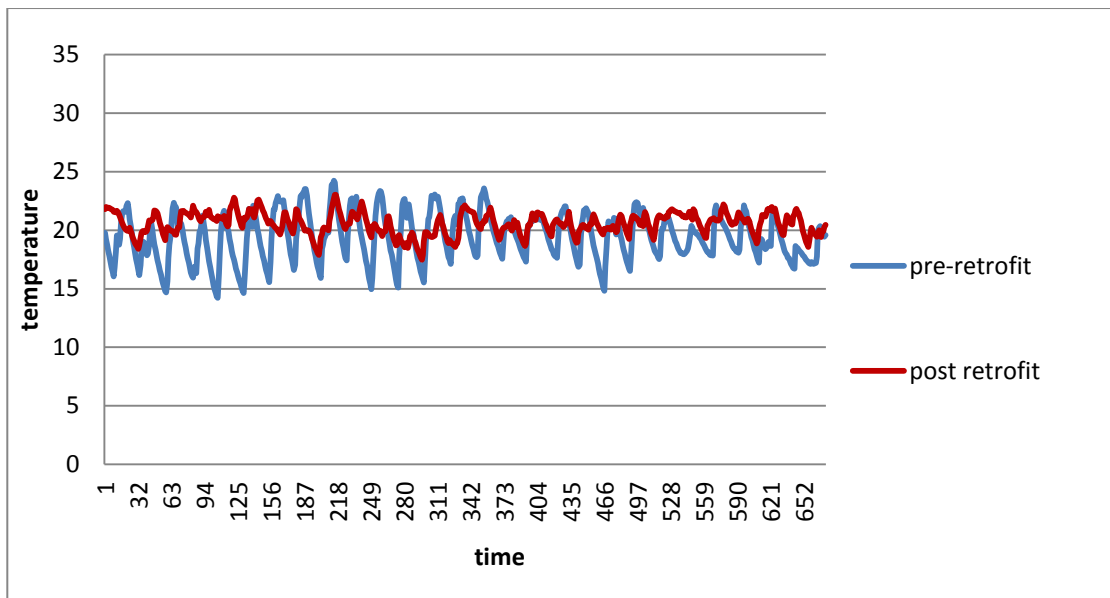
Figure 5.36: Monitored indoor winter temperature in the single storey terraced house un-retrofitted and retrofitted, type 2, February 2012 and 2014
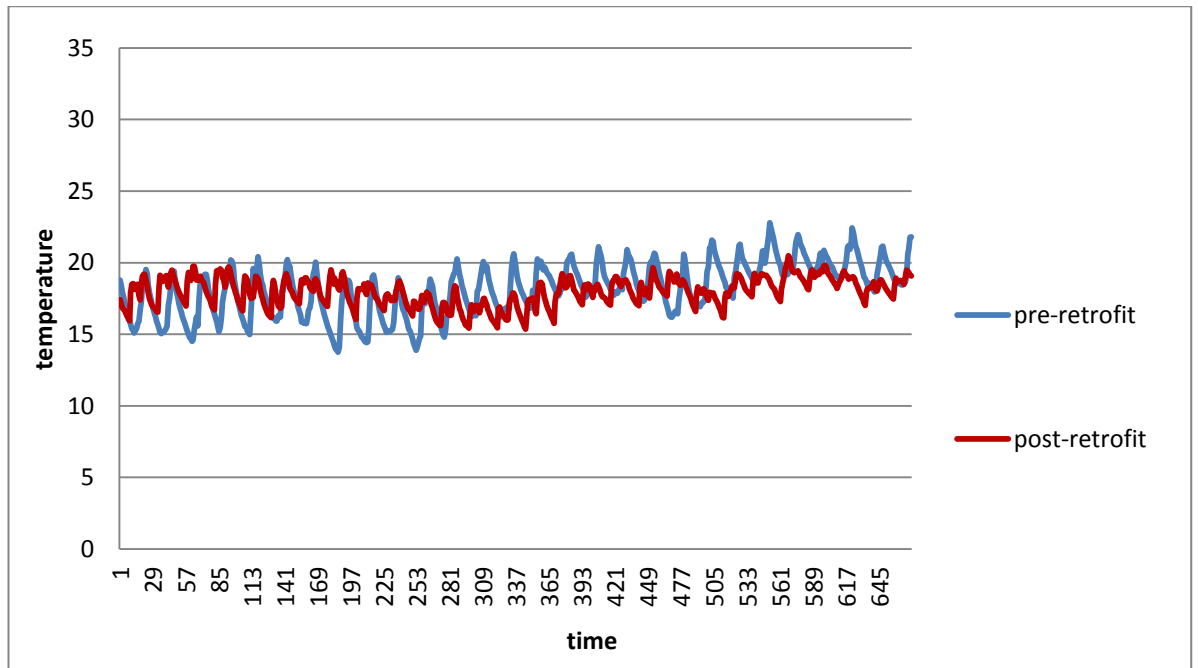
Figure 5.37: Monitored indoor winter temperature in the two storey terraced house un-retrofitted and retrofitted, type 4, February 2012 and 2014
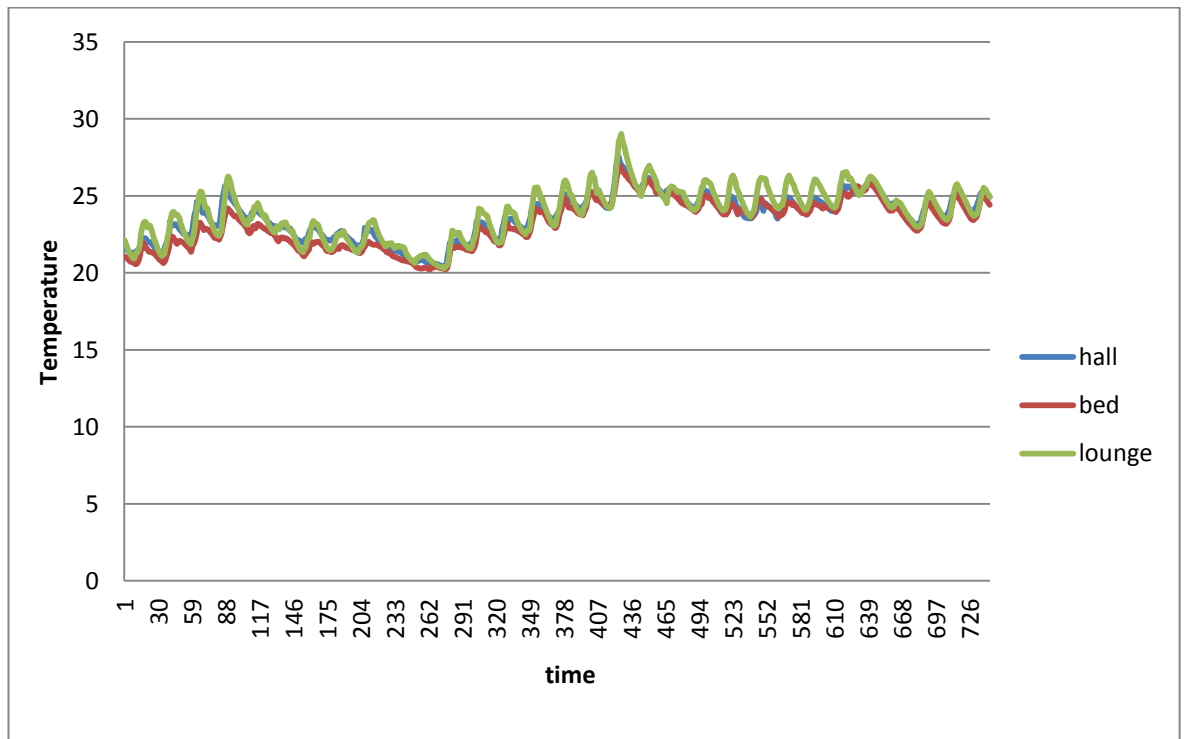
Figure 5.38: Monitored temperature in July 2014, single-storey terraced house, type 2 (14 Manor close), retrofitted
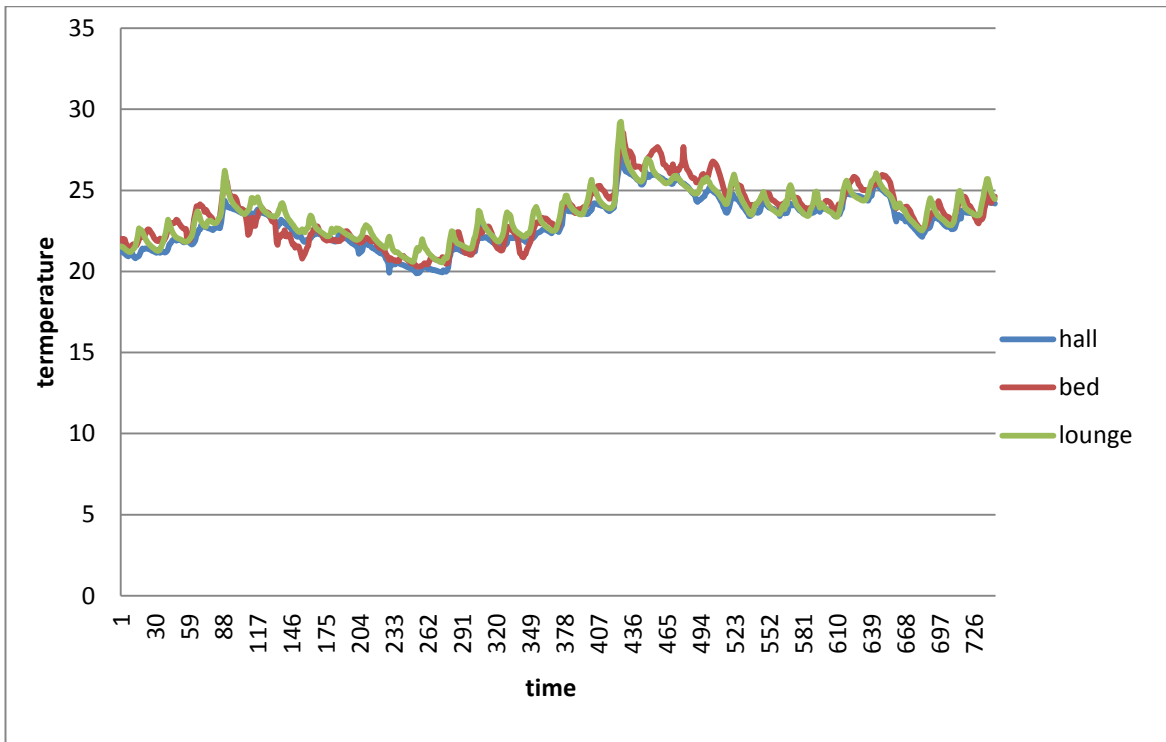
Figure 5.39: Monitored temperature in July 2014, two-storey terraced house, type 4 (1 Manor road) retrofitted

Retrofitted	Living room	Bedroom 1	Bedroom 2
Single storey house	fail	pass	
Two storey house	pass	Pass	pass

Table 5.22: Summary of the results of the analysis of the overheating hours by 2030s using the adaptive comfort criteria, TM52 (CIBSE, 2013)

5.5 Adaptations

The simulations above show that although the low carbon retrofit measures reduced the indoor temperature, by 2030s the living room of the single storey house will still fail the criteria of TM52 (CIBSE, 2013) and be classed as overheating. Some adaptation measures need to be put in place to re-establish a comfortable environment. The following section explains the process followed by the author to adapt the houses to a warming climate and reduce the indoor temperature. Although the two storey house type meets the

criteria of TM52 (CIBSE, 2013) and will not be classed as overheating, the residents still experience discomfort during heat waves.

In order to answer the following research questions:

- How can these retrofitted houses be adapted to a warmer future climate?
- How can a specific adaptation strategy be established for these houses?

The author applied the adaptation measures listed in the Methodology Chapter, Table 3.8, to the retrofitted models previously equipped with the low carbon measures installed by IFORE in Rushenden with the aim to reduce the indoor temperature. Simulations were run using the high emissions scenario weather files for 2030s at 90% probability (Figure 3.9, Methodology Chapter) with the purpose to eliminate people's perception of overheating. As well as assessing the comfort criteria of TM52 (CIBSE, 2013) in the living room of the single storey house, the results showed the cooling load when using the maximum comfort temperature of 27.6° derived from the comfort survey. In the bedrooms the lower threshold of 25.6° was used to account for the fact that occupants are comfortable with a lower temperature when asleep. The two storey house occupied by the family in employment has a very low cooling load up to the end of the century and therefore has a very little overheating risk and that is why only the case of the unemployed family will be analysed in more details in this section.

When needed, a plot of the temperature from May to September in the 2030s is also presented for each adaptation measure. This shows how much the adaptations reduce the indoor temperature in the event of a heat wave and enable the community to become more resilient. This is a way to make the houses climate proof in the immediate future. Best practice solutions are then be suggested with pros and cons for each measure. First of all, night ventilation will be assessed in both, the single and two storey dwellings. External shutters or roller blinds were ranked as the single most effective adaptation measure by CREW (Shao, 2012). Other shading types will also be analysed and the benefits measured in terms of reduction of indoor temperature and cooling needs.

5.5.1 Single storey house, type2

With regard to the case of the single storey terrace, the temperature in the bedroom does not pose any problem when using the adaptive comfort criteria and was not classed as overheating. However, ceiling fans have been installed in the bedrooms of several of the bungalows during IFORE which signifies that residents are experiencing discomfort some nights during the summer. The criteria explained in TM52 (CIBSE, 2013) were defined for office buildings that are only occupied during the day and do not take into account the fact that people prefer a lower temperature at night.

Simulations were run using the cooling set point temperatures of 27.6 °C in the living room and 25.6 °C in the bedroom. In the bedroom the indoor temperature does not surpass the threshold of 25.6 °C from May to September in the 2030s during the occupied hours. The cooling needed in the living room is 18.3 kWh/year (Table 5.23). There may be residents that will still experience some discomfort, in this case the bedroom window can be open to supply 3ACH (sum of infiltration and ventilation). Night ventilation is the easiest, more cost effective way to lower the indoor temperature (Figure 5.40). It may be enough to open the top part of the window in the bedroom to achieve that. Rushenden is a windy place so when the internal doors of the bungalow are open cross ventilation is possible.

Cooling load 2030s	kWh/year
Living room	18.3
bedroom	0

Table 5.23: Cooling loads, single storey house, type 2, May to September in the 2030s using the maximum comfort temperature of 27.6 °C in the living room and 25.6 °C in the bedroom, kWh/year.

When the bedroom is ventilated at night, and the doors are open, the temperature in the living room will also drop slightly. However, that will not be enough to meet the criteria of TM52 (CIBSE, 2013) and the living room temperature will not be below the threshold of

27.6 °C. Another way to ensure a drop in the daytime temperature in the living room needs to be sought, and shading is an appropriate technique to be applied during the day.
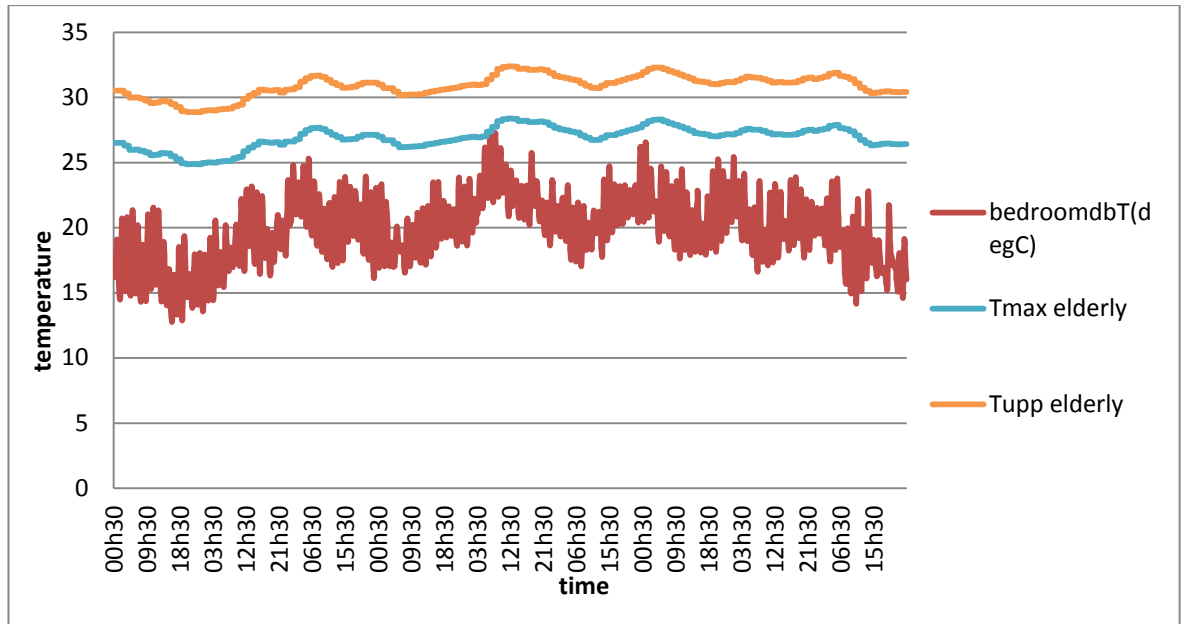
Figure 5.40: Bedroom temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with night ventilation

5.5.1.1 External shading (pros and cons)

In the first instance, the shading and insulation analysis in ESP-r was used to determine the depths required for the shading devices. Fixed shading was designed to block the direct sun during the three hottest months of the year, June, July and August, while allowing some solar radiation into the buildings when most needed during the winter. However, fixed shading has the disadvantage that whilst blocking direct solar radiation in the summer, it also reduces the amount of solar radiation entering the house during the heating season.

This is true even if the fixed shading has been designed to take into account the angle of the sun in summer and winter. If the aim is to block completely the sun entering the room the all summer, in order to account for the lowest sun angle we need to design for the equinoxes of the 21st March and 21st September (Szokolay, 2007), which slightly increases the heating load. It also requires an extremely deep canopy that is impractical. However,

201

if we design for the winter and summer solstices then only the highest sun angle on 21st of July will be blocked. But, when the sun angle is lower in the summer it will still enter into the room. Moreover, some of the indirect component of the solar radiation will enter into the room in the case of fixed shading.

The orientation of this house type is fairly difficult to shade with fixed shading because the living room and the bedroom of the single-storey house modelled face south-west with a rotation angle of 30° from the south. Unless the houses were designed to be passive solar, the orientation of living rooms is rarely due south. The sun angle is quite low in relation to south-west facing windows so some vertical elements are necessary to completely block the direct sun (Givoni, 1994).

In summer and winter, daylight coming into the rooms will be reduced as a result of shading and, as a consequence, the occupants may use artificial lighting indoors. This will increase the electricity load and summertime overheating will increase unless LED lighting is used. To avoid this possibility movable shading like awnings, external venetian blinds and roller blinds may be a better option.

However, there is a problem in Rushenden when using movable shading (which is commonly used in Southern Europe). External movable shading in the UK is difficult to install on windows which open outwards. It would be necessary to change the windows to inward opening to allow the use of external roller blinds or shutters.

Fixed shading is, for this reason, an option that can be easily applied to the existing windows. Some residents during the survey expressed their preference for an external overhang saying that "it is a good idea". An added advantage is in creating an external intermediate shaded area between the house and the garden that can be used during hot and sunny days.

In ESP-r it is not possible to establish a control function to retract fixed shading e.g. awnings. What will follow it is an account of the trials carried out by the author to assess how much the cooling load and the overheating hours can be reduced when using external shading. First of all, external shutters or external roller blinds were assessed.

5.5.1.2 External shutters or roller blinds

A copy of the single-storey house model was made in ESP-r. Some external shading was applied to the new model to assess the reduction that the shading elements produce on the cooling load when compared with the retrofitted base case. One solar obstruction was created and positioned to completely shade the window of the living room facing south-west and block all solar radiation.

A simulation was run using the weather file for the 2030s high emissions scenario with the obstructions in place from 1st May to 30th September, during the cooling season. First of all, the simulation was run using a free-floating set up assuming that no mechanical cooling is in place. Now the living room met all of the comfort criteria from TM52 and therefore is not classed as overheating (Figure 5.41).

Then the cooling load was assessed using the comfort temperatures for this particular group of residents. The control file was set up with the cooling energy switched on to keep the temperature down to 27.6 °C in the living room. The cooling load was found to have a dramatic reduction with the shading in place. In the living room no extra cooling was needed.
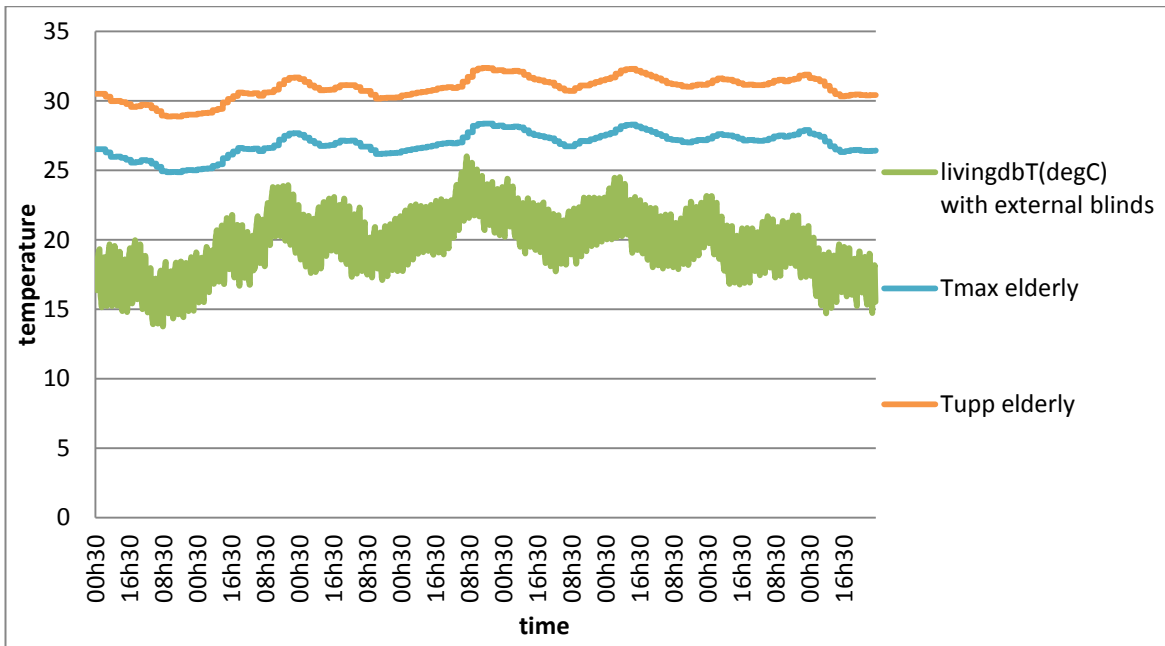
Figure 5.41: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with external shutters or roller blinds

The problem with this very schematic type of shading, similar to external shutters or blinds, is that by (almost) completely obscuring the window of the living room, the occupant may be tempted to switch on the light indoors to keep the illuminance to a higher level during the day in summer. This is true if the house is continuously occupied, which is often the case for Type 2. That is why education is important to insure that people understand how to minimize the risk of overheating and keep cool as it will be explained in the Discussion Chapter. Living more outdoors in shaded and ventilated areas, in private gardens or in public spaces prepared to shelter residents in the event of a heat wave is an alternative way to adapt to a warmer climate.

5.5.1.3 External overhangs or awnings

A model of the south-west wall containing the living room window was built with Autodesk Ecotect Analysis (2011). Using a sun-path diagram for the site of London Heathrow, the closest location to Rushenden to design the external shading overhang the author identified the Vertical and Horizontal Shading angles (VSA , HSA) plotted at half-

hour intervals, for several dates including 21st of June the summer solstice, and 21st of March the spring equinox. The latitude and longitude of Heathrow are 51.4° and -0.8°.

Since the living room of the two storey house has a south-west orientation, the sun will mainly penetrate in the afternoon. With this orientation, in the morning, the Horizontal Shading Angle will generally be very high in the summer. The Vertical Shading Angle was chosen on the 1st of June at 4pm to be VSA= 50°. The external overhangs extend outside the dwelling by 1.80m over the living room window (Figure 5.42). These dimensions, especially outside the living room, make the overhang large enough to form an intermediate external space. The simulation was run in ESP-r to assess the reduction in cooling load when compared with the base case.

This illustrates how useful overhangs are; if the opening was to be shaded completely, the overhang would be over three metres. The use of several horizontal elements will reduce the necessary depth of the overhang but this solution may be more appropriate for a new build project where it is easier to integrate design elements into the building fabric. If a different design method is used, as is illustrated by Reinhart (2014) and the overhangs are designed for the 21st June, the summer solstice, at 12noon, when the sun is at its highest point, then the VSA= 66° and the depth of the overhang is 0.9 m (Figure 5.42).

When using the overhang 1.8 m deep, the three criteria from TM52 are passed and the cooling load using the 27.6 °C temperature threshold in the living room is 0.9 kWh/year, almost eliminated (Figure 5.43). When the overhang is 0.9 m deep the second criterion of TM52 is failed but the first and third criteria are passed (Figure 5.44). The cooling load is 1.8 kWh/year. Considering the indoor temperature however there is not much difference between the two configurations.
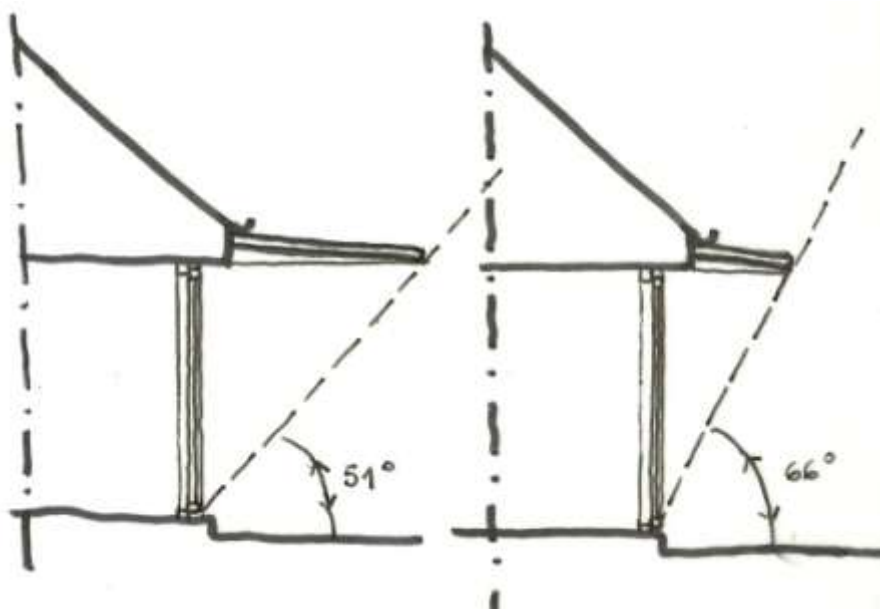
Figure 5.42: Horizontal overhangs 1.8 m (left) and 0.9 cm (right) deep showing vertical shading angles on 1st June at 4pm, 51° (left) and on 21st of June at 12 noon, 66° (right)
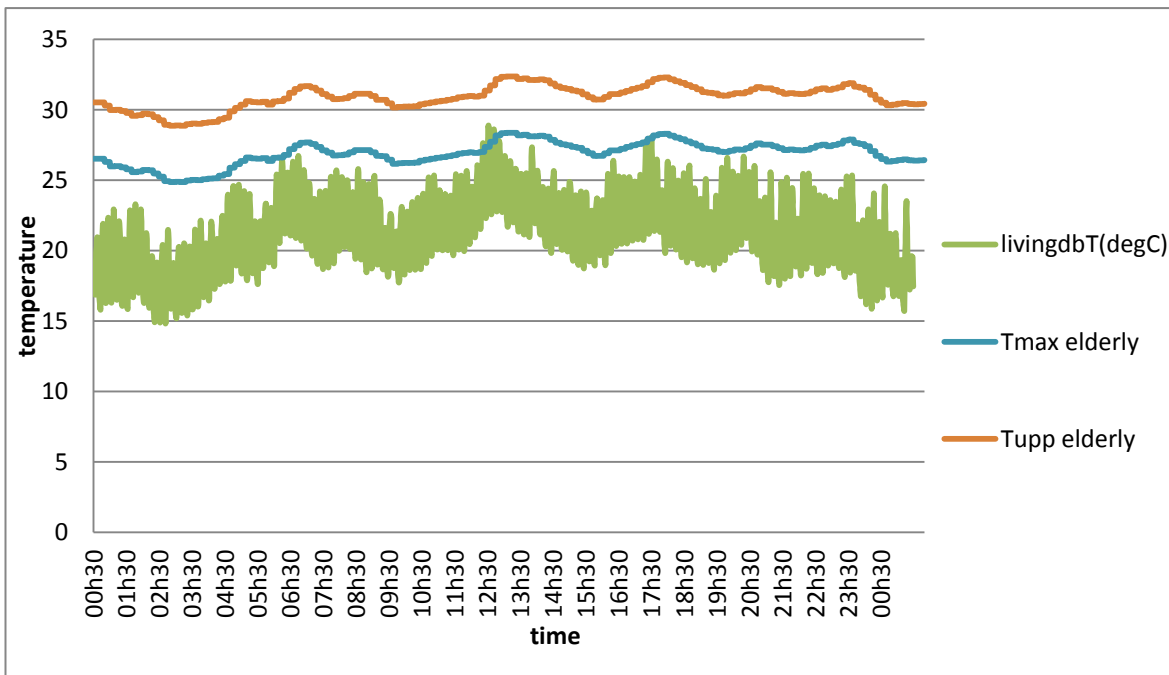
Figure 5.43: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with external overhang 1.8 m deep
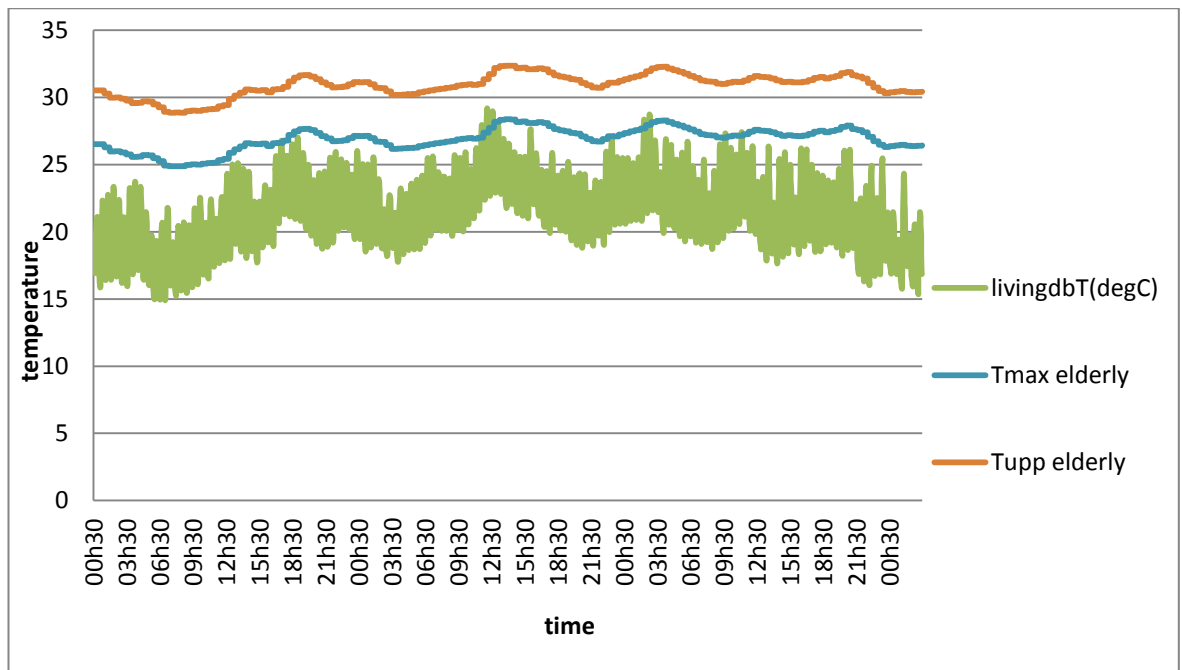
Figure 5.44: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with external overhang 0.9 m deep

This is a good result for a measure that can be installed right away to the existing windows. However, fixed shading has the inconvenience that it reduces the daylight entering the room in winter and some electric light may be necessary indoors. This problem may be resolved when using awnings, which are fabric elements on a lightweight metal structure.

5.5.1.4 Side fins plus overhangs or awnings

Awnings and retractable or foldable shading could usefully be applied if employing the right geometry, although that will have to be considered carefully for this type of social housing. Since there is little space between the windows and the roof eaves on the outside wall it will be difficult to install the folding mechanism. The awnings were modelled by adding some side fins to the external overhang or outside canopy.

As mentioned previously, it was not possible to establish a control function for the shading elements within ESP-r. As a result the author added some vertical elements to the 0.9 m deep external overhang analysed above and re-ran the shading and insolation

analysis within the software. The Horizontal Shading Angle on 1st and 21st of June at 4 pm is 51°. The depth of the fins is 1.3m (Figure 5.45). This option eliminates the need for cooling when using a set point of 27.6 °C and the TM52 criteria are all fulfilled (Figure 5.46).
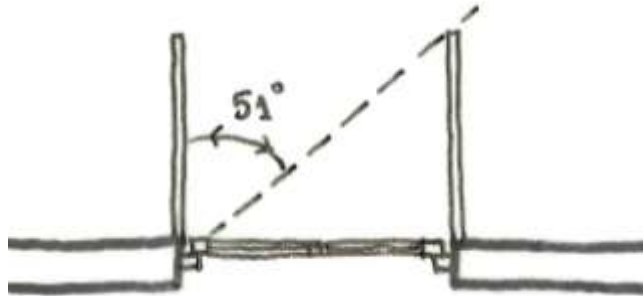
Figure 5.45: Side fins showing the Horizontal Shading Angle of 51° on 1st and 21st of June at 4pm
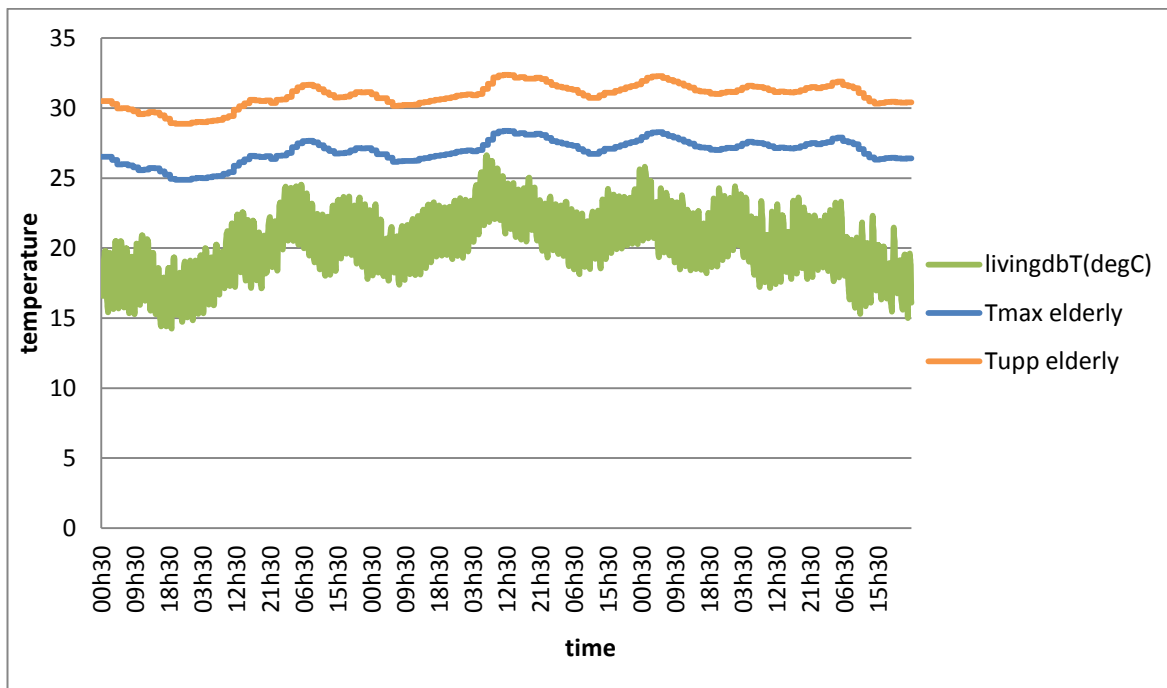
Figure 5.46: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with external overhang 0.9 cm deep and side fins 1.3m deep

Ideally this system would consist of a retractable type of shading, made of fabric, like a tent, that is removed during the heating season. Fabric tents in front of patio doors are widely used in Italy to shade the surface of balconies and transform them into habitable spaces in the summer. A similar solution is to use demountable gazebos that create some

extra space outside the houses. When the fins are used on their own the results from the simulations are very similar to those previously found for an overhang 0.9 cm deep (Figure 5.44). The extra cooling needed is 1.8 kWh/year and two out of the three criteria of TM52 are passed (Figure 5.47).
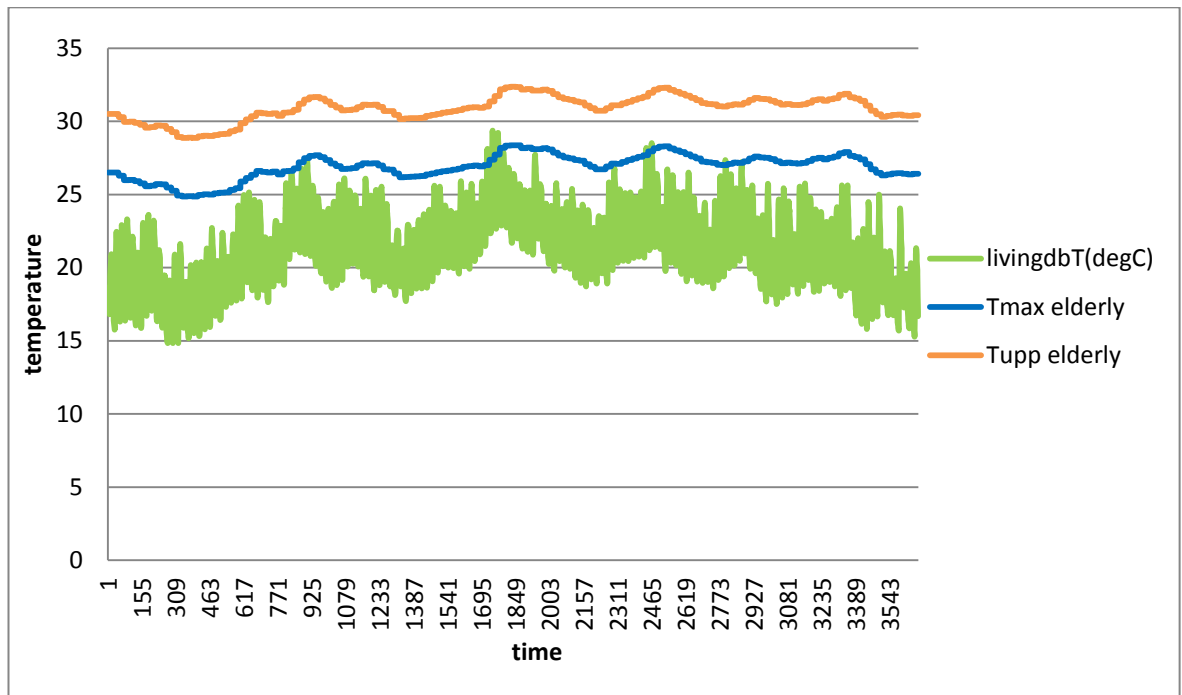
Figure 5.47: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with side fins 1.3m deep

5.5.1.5 Complex fenestration components (CFC)

A number of internal shading systems were modelled in ESP-r using the complex fenestration components database.

- Figure 5.48 shows that the 3 criteria of TM52 are met when using Venetian blinds. The cooling load in the living room is 1kWh/year.
- When internal dark drapes are modelled, 2 out of three criteria are failed (Figure 5.49) and the cooling load in the living room is 8.8 kWh/year.
- Internal opaque white roller blinds block the solar radiation very effectively, the three criteria are met and there is no extra cooling load required in the living room (Figure 5.50).

209
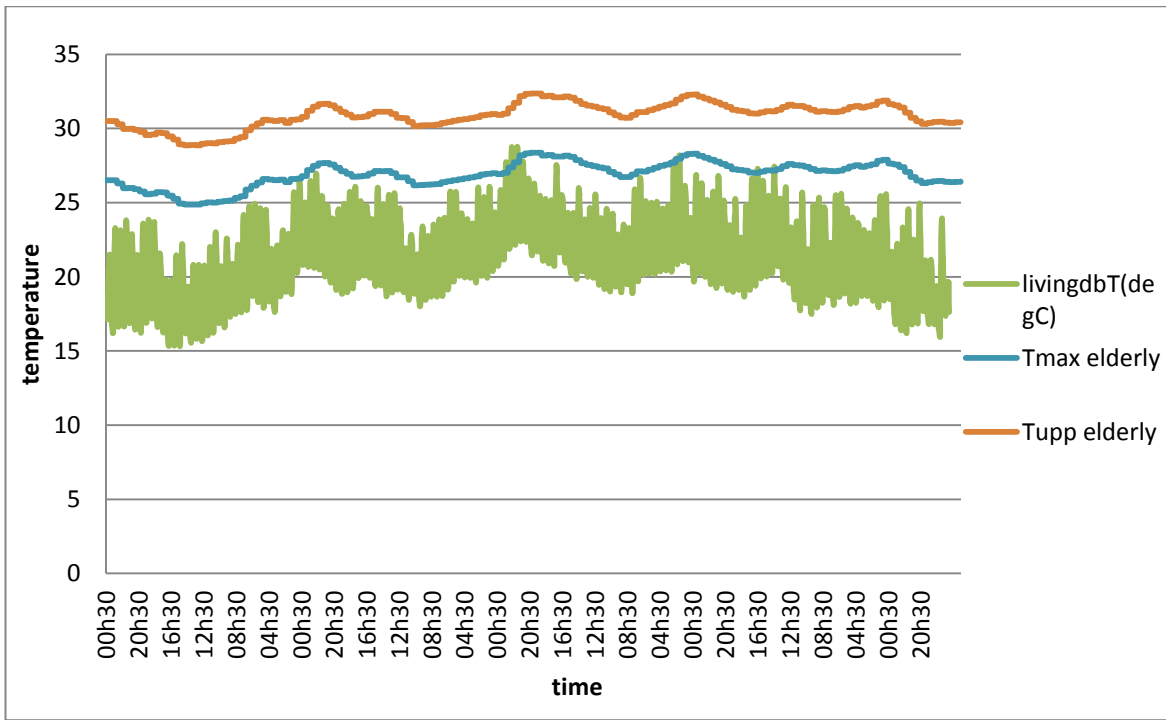
Figure 5.48: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with venetian blinds
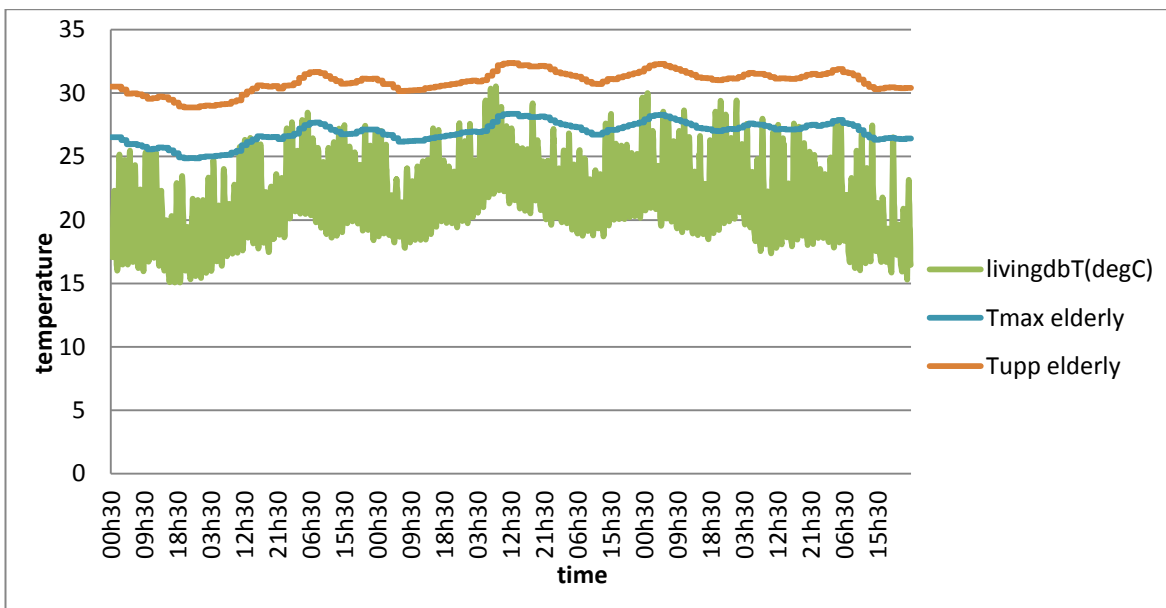
Figure 5.49: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with dark drapes

210
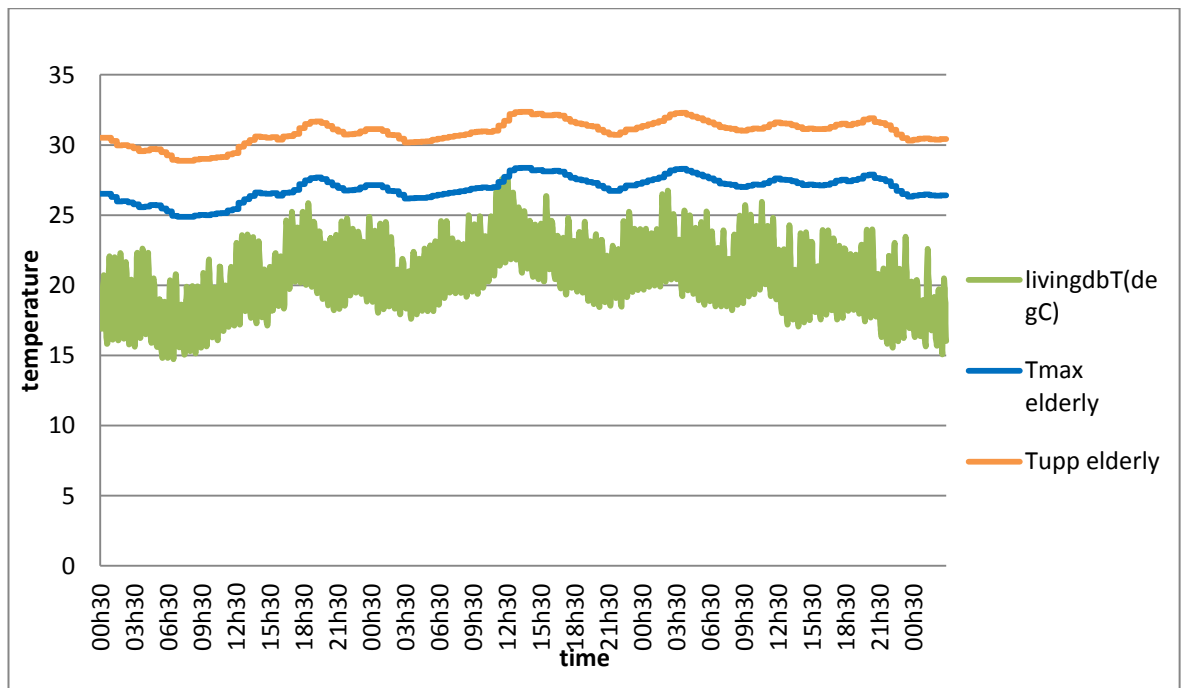
Figure 5.50: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with white internal roller blinds

5.5.1.6 Trees

At this latitude a better solution would be to plant trees in the garden to shade the living room. These vertical elements opposite the windows will more effectively block the solar radiation and in the winter some species will allow the sun in. The only problem with planting trees in Rushenden is that the soil on the Isle of Sheppey is very salty and trees have been planted in the past with no great success.

However, there are currently a few species of trees successfully growing in Rushenden. During the one-to-one questionnaires that the author carried out in 2012, the occupants expressed a favourable opinion about planting trees in their back gardens. Most of them would enjoy trees and would also appreciate their shading properties. A couple of residents, however, expressed their concerns if trees were planted in their back gardens. One of them asked the housing association to cut down an existing tree because it was reducing too much of the daylight available in winter.

The author carried out a preliminary assessment of the effect of tree shading in reducing the cooling load of the single storey terrace, which was presented at the e-Sim conference in Halifax, Canada (Sdei, 2012). What is reported here is a summary of the paper with some necessary changes that take into account the evolution of the author's research. The simulations were re-run herein to include the summertime maximum comfort temperature for Rushenden that had not yet been assessed at the time of the conference.

Plants and trees have been used for shading throughout the history of humankind. As the climate is predicted to change and the temperature to increase, shading the buildings we live in with trees can help to keep the indoor environment comfortable. Virtually no direct sunlight gets through the canopy of a healthy shade tree. As a result, complete shading by trees eliminates over 90% of the solar energy falling on a surface (Wulfinghoff 1999).

Trees in leaf in the summer are an affordable natural resource; they shade buildings in the summer but allow the sun's rays to pass through their branches in the winter. A survey of Rushenden done by the author as part of the work in this paper shows that in Manor Close, (the single storey house types) there are several fruit trees (mainly cherry). Around Rushenden Road, a few tall birches shade the two storey houses although their small leaves are retained throughout the winter. In the areas around the housing one can also find other ornamental species such as the field maple (acer campestre) and the alder (alnus glutinosa).

In this study the field maple, a deciduous tree found in Rushenden, was chosen for its characteristics of slow growth rate and long life span. In fact this species can live up to 100 years (Simon, 1966), it grows fast initially and then the growth rate slows. It can reach a total height of 6-12m, its branches spread irregularly and it has an expanded posture (Simon, 1966). When not pruned at the bottom of the crown its branches spread horizontally and the shape is round.

It is also very suitable when, like as is the case for the single storey houses in Manor Close, there is a limited area of garden (Figure 5.51). The planting of trees can also substantially improve the appearance of buildings and the air quality of their

surroundings. Trees not only regulate the indoor temperature of a building by providing shading but also by evapo-transpiration. This topic will be described on more detail in the Discussion Chapter. For simplicity, this thesis focuses only on the cooling effect of shading the south-west facing of retrofitted single and two storey-terraces in Rushenden.
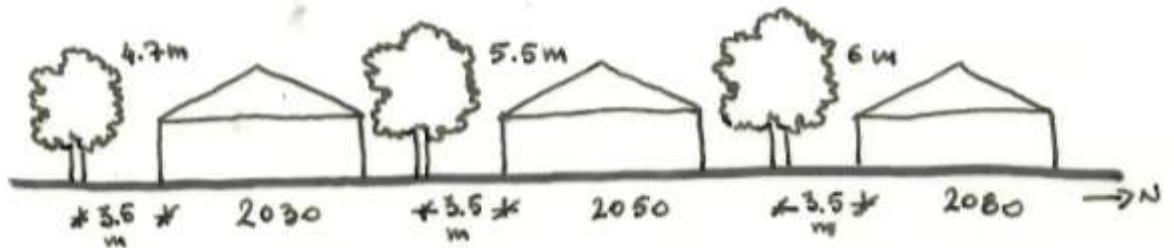
Figure 5.51: Trees planted on the south – west facade of the single storey house, type 2

The energy saving is the difference between the cooling energy consumption with and without vegetation (Dimoudi et al 1999). The tree crowns were given the opacity of 0.9 in summer to account for some sun penetration. As well as reducing the cooling load in summer, trees increase slightly the heating load in winter, as was shown by the author in the paper (Sdei, 2012).

The trees were realistically placed 3.5m away from the house to prevent the roots interacting with the foundations. By 2030s the tree trunks would have grown to a diameter of 0.5m and the crowns a diameter of 2.4m. The simulations were run and the cooling load in the living room was found to be 4.5 kWh/year when trees are planted to face the back elevation of the house. A plot of the internal temperature (Figure 5.52) shows that two out of the three criteria of TM52 are met.
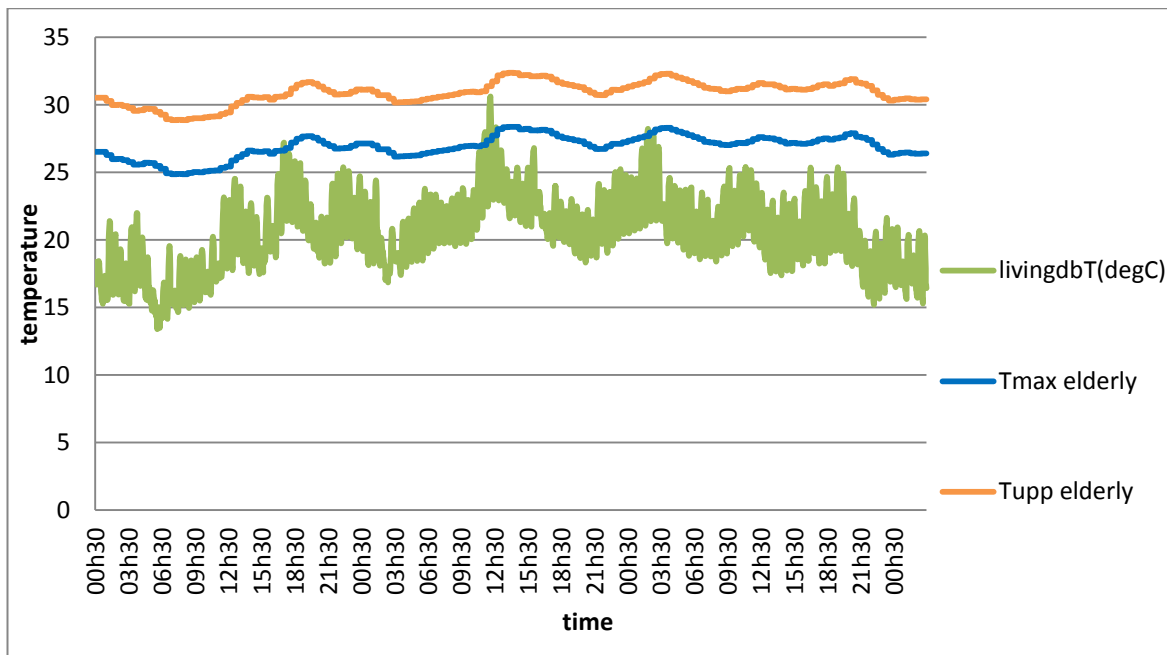
Figure 5.52: Living room temperature from 1st of May to 30th of September 2030s, single storey house, type 2 with trees

5.5.2 Two storey house, type 4

The two storey house met the criteria of TM52 and therefore the analysis of the adaptations for this house type was less extensive than it was for the single storey. Even if the two storey house should not be classed as "overheating", the occupants at present experience overheating as discussed in the Field Study Chapter. Simulations were run using the comfort temperature of 27.6 °C in the living room and 25.6 °C in the bedroom. For this analysis the internal temperatures are not shown because they do not pose any problem from the point of view of TM52. The results for the un-adapted two storey house in 2030s are shown in Table 5.24. In order to eliminate or reduce the cooling loads some adaptation measures are applied to the case study to lower the indoor temperature to a more comfortable level. First of all, night ventilation in the two bedrooms was modelled by increasing the air-flow rate to 3ACH at night.

Cooling loads 2030s	kWh/year
Living room	5.19
Bedroom 1	11.26
Bedroom 2	12.22
total	29

Table 5.24: Cooling loads, two storey house, type 4, May to September 2030s using the maximum comfort temperature of 27.6 °C in the living room and 25.6 °C in the bedrooms, kWh/year.

When night ventilation is adopted in the two bedrooms of the two-storey dwelling the temperature lowers considerably at night and slightly during the day. There is still a small amount of cooling load needed (Table 5.25), it is useful to notice that night ventilation in the bedrooms will lower the cooling load in the living room as well. The best way to eliminate the cooling needed would be to use some shading devices. Several shading systems were tested in the single storey dwelling. A similar procedure is applied to the two storey house. However, in this case, the author used some of the tests carried out in the single storey house, to select and exclude some of the systems, since the two storey dwelling has the same orientation as the single storey.

Cooling loads 2030s	kWh/year
Living room	4.21
Bedroom 1	0.85
Bedroom 2	2.34
total	7.4

Table 5.25: Cooling loads, two storey house, type 4, May to September 2030s using the maximum comfort temperature of 27.6 °C in the living room and 25.6 °C in the bedrooms, with night ventilation, kWh/year.

When external shutters or roller blinds are applied to the living room and bedroom windows the cooling load in these rooms is completely eliminated. However, since this

shading type cannot be applied immediately, what follows is an analysis of some more practical shading elements. An external overhang or awning can be applied above the living room window. A Vertical Shading Angle of 66° was used to design an external overhang since it produced a similar temperature reduction to that achieved by 51° Vertical Shading Angle in the living room of the single storey dwelling with the same orientation. The depth of the overhang above the living room's window is 0.5 m (Figure 5.53). Since the window in this case is 2 m wide, side fins would need to be 1.6 m deep when using the Horizontal Shading Angle of 51°. This depth for the side fins is impracticable and it would be better to have several vertical elements, 0.5 m deep, positioned at a regular distance one from the other. However this would require either a careful design or the replacement of the current windows.
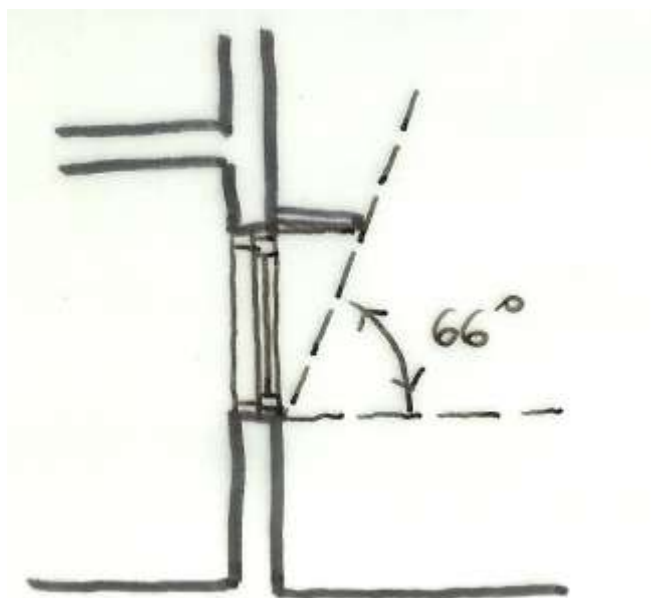
Figure 5.53: Horizontal overhangs 0.5 m showing vertical shading angles on 21st of June at 12 noon, 66°

Table 5.26 shows the cooling loads when an external overhang is applied to the living room's window. The results of the simulations show that the cooling load reduction will be significant in the living room and the cooling requirements in the bedrooms will reduce as a result. Similarly, when night ventilation (in the bedrooms) is combined with an external overhang above the living room's window the cooling load reduces not only in the living room but also in the bedrooms (Table 5.27).

Cooling loads 2030s	kWh/year
Living room	0.28
Bedroom 1	4.98
Bedroom 2	9.67
total	14.9

Table 5.26: Cooling loads, two storey house, type 4, May to September 2030s using the maximum comfort temperature of 27.6 °C in the living room and 25.6 °C in the bedrooms, with an external overhang above living room's window, kWh/year.

Cooling loads 2030s	kWh/year
Living room	0.15
Bedroom 1	0.53
Bedroom 2	1.88
total	2.6

Table 5.27: Cooling loads, two storey house, type 4, May to September 2030s using the maximum comfort temperature of 27.6 °C in the living room and 25.6 °C in the bedrooms, with external overhang above living room's window and night ventilation, kWh/year.

- When side fins are combined with an external overhang the need for cooling is eliminated in the living room.
- When a tree is planted in the front garden of the two storey dwelling the cooling load in the living room becomes 2.21 kWh/year.
- When venetian blinds are applied to the windows of the living room and bedrooms the cooling load in the living room is 1.91kWh/year, in bedroom 1 is 2.75 kWh/year and in bedroom 2 is 7.26 kWh/year
- When internal roller blinds are applied to the windows of the living room and bedrooms the cooling load in the living room is eliminated, in bedroom 1 is 0.26kWh/year and in bedroom 2 is 1.71 kWh/year.

- When venetian blinds are used in the living room and bedrooms combined with night ventilation the need for cooling is very small, 1.34 kWh/year in the living room, 0.14 kWh/year in bedroom 1 and 1.05 kWh/year in bedroom 2 (Table 5.28).

Cooling loads 2030s	kWh/year
Living room	1.34
Bedroom 1	0.14
Bedroom 2	1.05
total	2.5

Table 5.28: Cooling loads, two storey house, type 4, May to September 2030s using the maximum comfort temperature of 27.6 °C in the living room and 25.6 °C in the bedrooms, with venetian blinds and night ventilation, kWh/year.

- The combination of internal roller blinds installed in the bedrooms and living room and night ventilation with a total air-flow rate of 3ACH in the bedrooms eliminate the need for cooling in the living room and reduce the cooling load to 0.02 kWh/year in bedroom 1 and 0.11 kWh/year in bedroom 2.
- When internal roller blinds are combined with night ventilation using an increased air-flow rate of 4 ACH the need for cooling is completely eliminated in the living room and in the bedrooms.

In order to maximize the benefits of night ventilation a portion of the bedrooms' windows and doors need to be open at night to allow for cross ventilation. Night ventilation was discussed with the residents during focus groups and some barriers to use this technique that improves summertime comfort emerged from the discussion. Some solutions to overcome these problems will be suggested later in the Discussion Chapter.

5.5.3 Summary of the adaptations

Table 5.29 presents a summary of the cooling loads resulting from the simulations of the single and the two storey terraced houses using the maximum comfort temperature for this group of residents derived from the comfort survey. In the single storey dwelling the problem of reducing the internal temperature in the living room that failed TM52 can be resolved using different types of shading devices that can be installed immediately on the existing windows: external overhang with side fins, internal opaque white roller blinds or internal white venetian blinds. Among these three types, external overhang with side fins and internal roller blinds will also guarantee that the indoor temperature is below the maximum comfort temperature for this group of residents from May to September in the 2030s. External shutters or external roller blinds will also guarantee that the criteria of TM52 are met in the living room and will reduce the temperature substantially. However they cannot be installed immediately on the existing windows.

The bedroom of the single storey house does not pose any problem from the point of view of comfort. The criteria of TM52 are met and the simulation run using 25.6 °C shows that the maximum comfort temperature chosen for this group of people is not surpassed at any time between May and September in the 2030s. However some residents may have a lower threshold and still experience overheating. In that case night-time ventilation, modelled using an air-flow rate of 3 ACH (sum of ventilation and infiltration rates) will lower the temperature in the bedroom at night and also help lowering down the temperature in the living room during the day.

Both the living room and the bedroom of the two storey dwelling pass the comfort criteria from TM52 and will not be classed as overheating. However some residents may still experience discomfort. The simulations show that the cooling needed using the maximum comfort temperature for Rushenden will be substantial in both bedrooms and the living room of the two storey houses in the 2030s. The cooling loads shown in Table 5.24 above, relative to the un-adapted two storey house, correspond to 91 hours of cooling needed in the living room, 104 hours in bedroom 1 and 158 hours in bedroom 2. These are equal to 3 days of overheating in the living room, 4 days in bedroom 1 and 7 days in bedroom 2.

Even if the two storey dwelling passes the comfort criteria from TM52, these levels of overheating may induce the residents to buy an air conditioning unit. The simulations show that in order to avoid the use of air conditioning, either the installation of external roller blinds on new windows or a combination of night ventilation and other shading types need to be implemented on the existing windows of the two storey dwelling. An external overhang with side fins or internal opaque roller blinds can be installed on existing windows and eliminate the need for cooling in the living room. In the bedrooms on the first floor however some night ventilation will be needed to lower the temperature to a more comfortable level. If internal roller blinds are used then an air-flow rate of 4 ACH in the bedrooms at night (sum of infiltration and ventilation) will ensure that the need for cooling in the living room and bedrooms is eliminated. The same measures are advised in the case of the house with the family in employment.

Adaptation	House type	Living room kWh/year	Bedroom 1 kWh/year	Bedroom 2 kWh/year	Comment pros/cons
Overhang	Type 2	1.8	0	n/a	Orientation
	Type 4	0.28	4.98	9.67	
Overhang + side fins	Type 2	0	0	n/a	Large dimensions
	Type 4	0	3.93	8.54	
Trees	Type 2	4.5	0	n/a	Salty soil
	Type 4	2.87	6.20	10.81	
Venetian blinds	Type 2	1	0	n/a	Already in use
	Type 4	1.91	2.75	7.26	
Internal Roller blinds	Type 2	0	0	n/a	Already in use
	Type 4	0	0.26	1.71	
Night ventilation	Type 2	17.2	0	n/a	Insect screens
	Type 4	4.21	0.85	7.4	
External shutters	Type 2	0	0	n/a	Replacement of windows
	Type 4	0	0	0	

Table 5.29: Cooling load reduction with single adaptation measures showing in blue cooling loads equal to zero and in orange cooling loads above zero, commented with pros in green and cons in red

Chapter 6. Discussion

6.1 Three levels of low carbon retrofit

The aim of IFORE was to reduce the carbon emissions of the houses in Rushenden and Outreau by 80% compared with 1990s figures. Different levels of low carbon retrofit are possible and some of them were explored in detail in the Results Chapter. A lighter type of retrofit can be paid for by ECO funding.

ECO (Energy Company Obligation) is a government initiative launched in 2012 and includes funding destined for social housing providers. *"Under ECO, the big six energy suppliers are required to help householders save on their energy bills and carbon emissions"* (Energy Saving Trust, 2014). The amount of money given by ECO is inferior to the amount spent on each IFORE house, which in Rushenden was about £15,000. The ECO type of retrofit therefore provides a lighter retrofit than IFORE.

The IFORE retrofit is intermediate between ECO and EnerPHit (Passivhaus). The external insulation cladding installed during IFORE was only 60 mm thick and the air tightness was reduced in the best performing houses by up to 3ACH at 50Pa. The original windows were not replaced, just repaired, however old boilers were replaced with new ones. Renewable energy systems such as solar thermal and photovoltaic panels were applied to the houses. A small number of houses within the development benefitted further from the installation of air and ground source heat pumps. IFORE benefitted from grants given by DECC and by the feed-in tariff for the photovoltaic panels.

ECO funding does not allow the installation of all these measures. If some measures have to be excluded the best solution would be to exclude the renewable systems and concentrate on the application of the insulation and air tightening the houses. The cost of installing a new boiler is also covered by ECO. This type of retrofit is a first step towards reducing the heating demand. Compared to IFORE it is not as comprehensive because it does not include renewable systems, but it can be quite similar from a thermal point of view.

EnerPHit (Passivhaus) includes a high insulation levels, up to 200mm, high air tightness levels down to 1ACH and mechanical ventilation heat recovery (MVHR). This type of retrofit reduces to the minimum the demand for energy heating in the winter. However, in the summer overheating can occur if the supply for ventilation is not adequate for the needs of the household.

6.1.1 Heating and cooling loads

When we look at the results from the simulations of the heating load, in the single storey dwelling, the air tightness improvement is more effective at reducing the heating requirements than the external and loft insulation. The reason is that the air tightness improvement in the single storey house was very substantial, it reduced from 0.9 ACH before the retrofit to 0.23 ACH after the retrofit. Since MVHR was installed in the bungalows, it was modelled in ESP-r by reducing the amount of ventilation air that enters into the house since the heat exchange provides some free heating and less air needs to be heated. In the two storey dwelling, however, there is no MVHR, the air tightness reduction provided by the retrofit was only in the order of 0.2 ACH, not as substantial as in the single storey dwelling. Therefore, in this case, the insulation is more effective at reducing the heating load than the improved air-tightness.

In the future, because of global warming, there will be a substantial reduction of the heating load and an increase of the cooling load in both the single and the two storey dwellings analysed. Since the heating load is going to reduce anyway because of a warming climate, some may wonder why we are retrofitting in the first place. The results show that these reductions and increases will be more substantial for the houses un-retrofitted and less noticeable for the houses retrofitted proving that the low carbon retrofit makes the houses more resilient and climate proof (Figure 5.5, 5.6). Moreover, the retrofit will reduce the need for cooling in the future in both the single and two storey houses helping to counteract the effects of global warming. The installation of low carbon retrofit measures such as external and loft insulation and, to some extent, the air-tightness improvement, serves both purposes: mitigation and adaptation.

The external and loft insulation are the elements of the retrofit that will reduce the cooling load. The air-tightness improvement on the other hand will generally cause an increase of the cooling load in both the single and the two storey dwellings when is modelled as constant throughout the year. Only in 2080s it will be possible to notice in both models a slight reduction of the cooling load caused by the air-tightness improvement. This may be because as it gets warmer there are some benefits in keeping the outdoor warm air out of the dwellings. In the two storey house, the reduction of the cooling load caused by the insulation is more than the increase caused by the air-tightness.

The results chapter showed that among the three levels of retrofit described above, the levels corresponding to IFORE, will reduce the cooling load in the single storey and in the two-storey terrace. First of all, the sum of heating and cooling loads and the assessment of the carbon emissions in the single storey house (Figure 5.14, 5.16 Results Chapter) show that the improvement after the retrofit is very substantial. When we look at the two occupancy types for the two storey dwelling, the family in employment and the one unemployed, we see that the heating load is slightly lower in the case of the family in employment. The cooling load is substantially lower in the case of the family in employment. It is lower in bedroom 1, the master bedroom, than in bedroom 2, because the family in employment is composed of a single parent and two children.

By Insulating further the external envelope and increasing the air-tightness to comply with EnerPHit (Passivhaus) standard, on the other hand, the cooling demand will increase. The benefits from the extra insulation and air tightness are manifested, in terms of reduction of the overheating risk, only in 2080s. The Results Chapter showed that a deeper retrofit like EnerPHit (Passivhaus) will cause a house to overheat more than a lighter retrofit such as ECO and IFORE.

6.1.2 Carbon emissions and price weighted loads

The assessment shows that the sum of heating and cooling loads will decrease more as a percentage in the un-retrofitted single and two storey houses than in the retrofitted ones. This is because, as it was described previously, the retrofitted houses are more resilient to

temperature changes. The retrofit is definitely cost effective since it reduces substantially the total running cost in £/year at present and in the future in both, the single and the two storey houses (Table 5.12, 5.15, Results Chapter). The reduction in the price of heating the single storey house is very substantial after the retrofit. By 2030s, the price of heating will be lower than what would have been if the house had not been retrofitted. The price of cooling reduces more gradually, around 2050 and by the end of the century it reduces by 26% compared with a similar house left un-retrofitted.

In both, the single and two storey retrofitted houses, the price of heating will be consistently lower in 2030s, 2050s, and 2080s than what it would have been if the house had not been retrofitted. In the two storey house the price of heating will not reduce as substantially per m² as in the single storey house because the two storey house is less air tight. The price of cooling as well will be consistently lower in the retrofitted single and two storey houses. It will increase very rapidly and in the two storey house it will almost double between 2030s and 2050s and it will increase more than double between 2050s and 2080s. The price for cooling will increase less as a percentage by the end of the century in the retrofitted houses than it would have if the houses had not been retrofitted.

Figure 5.21 (Results and Analysis Chapter) shows a summary of the running costs in the two storey house. This shows that the total savings, thanks to the retrofit, will be substantial. The retrofit will reduce the total price of heating and cooling by 16% by the 2080s.

Monitoring results show that the temperature in the retrofitted houses is lower and more stable than it was in the un-retrofitted houses. The comparison between the simulations and the monitoring results shows that there is a close correspondence between the temperature plots. Similar patterns can be found in both the monitoring and the modelling temperatures recorded in the living room and the bedrooms of the single and two storey houses. In July 2014 the indoor temperature peaked at 29 °C in the living rooms of the retrofitted single and two storey houses. The models showed that in 2030s, using the high emission scenario with 90% probability, there will be peaks of temperature

up to 31 °C in the living room of the single storey house and up to 30 °C in the living room of the two storey house.

6.2 Three levels of adaptation

The analysis of the overheating hours using the adaptive comfort set of criteria showed that the living room of the single storey house fails TM52 and should be classed as overheating. Some adaptations are necessary to re-establish a comfortable condition in both, the single and the two storey terraces since the residents already experience overheating. Even if the European Standard on adaptive comfort set up by TM52 (CIBSE, 2013) is met without further adaptation measures in the bedroom of the retrofitted single storey house and in the retrofitted two-storey house by 2030s, the indoor temperature reaches peaks of 30 °C. It is suggested here that some shading devices are applied now in the single and two storey houses, combined with night ventilation techniques, to lower the indoor temperature. This represents a first level of adaptation that can be implemented upon the existing building fabric after the low carbon retrofit measures have been installed by IFORE in 2012.

The installation of external roller blinds or shutters is a second level of adaptation. It requires the replacement of the existing windows and can only be applied in a few years time since it is unlikely that the Housing Association will implement this type of improvement work in the near future. During IFORE the existing windows have been refurbished to a standard that will last for some years to come and a corresponding level of funding has been invested.

A third level of adaptation includes some of the options that were not analysed in this thesis because the tests carried out herein were targeted at reducing the indoor temperatures and cooling loads by the 2030s using the high emission scenario with a probability of 90% by the interaction between occupants and technology. These options are the installation of phase change materials on the internal walls of the houses, tinted film on windows, a change of the roof's albedo, and solar air conditioning. These require in some cases a bigger investment by the housing association or do not require any occupant interaction.

226

The assessment of the cooling loads showed that the overheating risk in Rushenden is low. The IFORE project focused on the interaction between the occupants and technology, and this thesis also, in line with the project that started it, looks at this interaction. This represents the very essence of this thesis and it is what makes it unique in relation to previous studies on climate change adaptation. That is why the first level of adaptation described above was analysed in more detail.

6.2.1 Adaptation measures - summary

A summary of the adaptation measures described, simulated, and analysed is included in the Results Chapter together with a discussion of the pros and cons for each measure. The author discusses what is more suitable or appropriate in Rushenden and presents in the following sections solutions and suggestions targeted at social housing residents.

The recommended adaptation measures such as internal shading and night ventilation can be adopted immediately by the residents of Rushenden. External shading such as awnings, side fins and overhangs can be retrofitted into the existing facades. Trees can be planted on Manor Road and in the back gardens of the single-storey houses; this will shade the living rooms of the single and two-storey houses and improve the microclimate.

If in future the existing windows are replaced, some external shading such as external roller blinds and shutters can be integrated into the window system. These will be more effective that internal shading at blocking the solar radiation. The housing association may decide to start acting in ten years time when the existing windows will likely need to be replaced. At that point a choice can be made between external roller blinds or shutters if tilt and turn windows, for example, are installed. These measures are strongly advised especially for elderly occupants and residents in fuel poverty.

As a result, the indoor temperature will decrease to a comfortable level that will make the use of electric fans unnecessary within the development now and in the next few years. As the temperature rises throughout the century these measures can be adopted gradually starting from now. The obstacles to adopting some of these measures have

been discussed and ways to overcome these obstacles suggested. The education of the residents in the use of these methods and the adaptation of their behaviour to withstand a higher temperature will be necessary as part of the adaptation process.

6.2.1.1 Night ventilation

Night ventilation is a very effective measure and reduces the overheating hours considerably. The models in ESP-r showed that ventilating at night when the outside temperature is lower can purge the walls of the house from the heat accumulated during the day. Night ventilation used in association with internal shading devices and external overhangs, awnings or trees can reduce the overheating hours to ensure a comfortable temperature day and night. However, there are concerns about night ventilation in both the single and the two storey houses. Special attention has to be paid by the housing association to ensure that this practice is encouraged and that any obstacles to it are removed.

Some of the residents of Rushenden expressed, during focus groups, their concerns when opening the first floor bedroom windows in the two-storey houses at night, because of a fear of insects. This is the reason why they use fans in the bedrooms to aid sleep at night. The problems of insects can be easily resolved with the installation of insect screens on the windows, although insect screens can reduce the ventilation rate. This solution can be applied to the outward opening bedrooms' windows of the single and two-storey houses in Rushenden to ensure that night ventilation is practiced and not avoided.

In the single storey houses the residents had a general fear of someone breaking in on the ground floor. As a result the bedroom windows are generally opened only by a very small amount, and it is usually only the top pane of glass which is opened. The simulations showed that the bedroom of the single storey house is not at risk of overheating. However the residents may still perceive the temperature to be too high to sleep. In order to achieve 3ACH it may be enough to open the top part of the bedroom's window and keep the doors open to allow for some cross ventilation especially since some of the windows at the front remain open as there is a security latch and this allows for a minimum amount of air to circulate.

In order to eliminate the need for cooling and to keep the indoor temperature in the two bedrooms of the two storey house below the maximum comfort temperature an air-flow rate of 4 ACH is required. This will require that the doors are open to ensure a good air circulation throughout the house. The difficulty in leaving open the bedroom doors because of privacy issues was expressed by some mothers of young children and teenagers living in the two-storey houses. Privacy issues are raised especially for this age group and a common family habit in Rushenden during the summertime period is to sleep with fans on, with all the windows and all the doors closed. During focus groups the suggestion was to make the top pane of glass above the internal doors into an opening. This solution was accepted by the teenagers; it is not an expensive modification but can make a real difference in terms of air flow and cooling during the summer months. These obstacles can also be overcome by installing vents within doors that ensure air circulation throughout the house without opening the doors.

This is a very important lesson for other housing developments in the South-East and throughout the country. It is crucial to encourage the opening of windows to night ventilate homes during the hot summertime months. However, in urban areas there may be bigger obstacles that prevent the residents from opening the windows at night, such as pollution and noise. This solution may then not be possible to implement, especially in retrofit but also in new build properties.

The solution to these problems is, however, beyond the scope of this thesis. The solution to reducing pollution and noise in urban areas may well be to electrify all transport and to allow for more bicycles in town etc, a further step beyond this research.

Urban environments have very specific problems and require a deeper investigation. This thesis has investigated solutions targeted at Rushenden but with implications for similar social housing developments in similar rural areas of the South East. It also offers pointers for new housing developments with regards to climate change adaptation.

Being able to cope with hot weather is just as challenging as saving energy in the winter. In this country the practice of using shading devices during the day and ventilation at night is maybe less intuitive than the winter practice of keeping all windows and doors

shut to preserve the heat. That is why the process of education needs to continue in the case of summertime comfort. In summer, as in winter, the correct use of techniques that improve comfort and minimize energy waste can make a big financial difference.

6.2.1.2 External shading

Several types of shading are available on the market. Some of them were tested in the Results and Analysis Chapter to identify the reduction of the cooling load that their use allows. Pros and cons for each shading type are summarized in Table 5.29.

External roller blinds are a very valid solution because they completely block the direct and diffuse solar radiation from entering the rooms. They require the replacement of the windows in Rushenden and this may prevent their use... This is unfortunate because external shutters or roller blinds achieved the highest reduction in cooling load and as it gets hotter they may be a good solution (Figure 6.1).

The positive aspect of horizontal overhangs is that they can be easily installed during a retrofit. The results from the simulations showed that with the orientation of the single and two storey houses the depths of 1.8 m and 0.9 m will produce similar reduction of the indoor temperature. With this orientation however it is more efficient to combine an external overhang with side fins to block the low afternoon sun's rays. In the case of both living rooms, these will have to be quite deep, 1.3 m in the single storey and 1.6 m in the two storey house. In the two storey house the total depth can be split into 4 fins, however this will require careful design or the replacement of the windows.

Side fins can then be applied to the external wall to further shade and block the solar radiation. The fins could be hinged to the walls in a way that they can be folded back during the winter to allow for some passive solar gain. The fins may look like traditional shutters that are applied to the external facade of many houses in England for aesthetic reasons. The important point is that they are hinged and can rotate and have a manual system that in the summer fixes them in a position perpendicular to the wall (Figure 6.2).

Figure 6.1: External roller blinds (Source: Enviroblinds, no date)

Awnings and other fabric types of shading device can be retracted in the heating months to allow all the solar radiation to enter the rooms in the winter. In summer they help to create an outdoor area in the garden that can be very liveable and can be used as an extension of the house. In some of the two-storey houses awnings are already present. However in the single storey there is not enough space between the living room window and the roof's eaves to install the cassette.

Figure 6.2: Examples of external shutters used in the Mediterranean regions (CREW, 2013)

Trees (Figure 6.3 - 6.6) are effective at reducing the solar radiation in the summer and deciduous trees lose their leaves in the winter allowing the sun to penetrate. However, the salty soil in Rushenden does not allow for the large-scale planting of trees. Trees are

present on the Isle of Sheppey and in Rushenden, mainly in back gardens, however, unfortunately some residents have cut down their trees to allow more daylight into their houses. It would be a benefit if trees were planted on Manor Road, the main road in Rushenden, as this would effectively shade the living rooms of the two-storey houses in the summer, thus contributing to a reduction in temperature.

Figure 6.3: Trees in Manor Close (Rushenden, September 2014)

Figure 6.4: Trees in Manor Close (Rushenden, September 2014)

Figure 6.5: Trees in Manor Close (Rushenden, September 2014)

Figure 6.6: Trees in Manor Close (Rushenden, September 2014)

The effect of the evapo-transpiration of trees is not assessed here, however as summarized in the Literature Review, previous studies (Akbari, 2002; Huang *et al.*, 1987;

Saxena, 2001) calculated that the effect of trees can result in a substantial temperature reduction. Saxena (2001) calculated that the effect of surrounding an individual house with trees is a reduction of up to 1.34°F when using the weather data for Phoenix, Arizona. A study by Taha *et al.,* (1996) reported by Akbari (2002), found that the effect of planting trees in ten US metropolitan areas could result in a temperature reduction by up to 3 °C.

In the meantime trees can be planted immediately, which will start shading in less than ten years. Awnings and internal blinds that are already present in some households can be retrofitted into the existing windows. Some changes can be made to the internal fabric of the two-storey houses to allow for night ventilation and the installation of insect screens to the existing windows. Those screens can then be reused when the existing windows are replaced.

If the occupants are educated to embrace a different lifestyle through an education program similar to the Green Doctor's visits during IFORE the use of electric fans can be avoided. There are also other education methods such as the distribution of leaflets that can be used to inform the residents about the dangers of overheating and how to avoid them. Focus groups can be organized to discuss particular issues. Most importantly, efforts to build community resilience have to be part of a bigger picture that includes social engagement as well as the installation of physical measures in order to be effective.

6.2.1.3 Internal shading

Internal blinds are an easier and more cost-effective option in Rushenden. These systems are already widely used in Rushenden. Most residents, especially the elderly who make up the majority of households in Rushenden expressed a preference for having net curtains on the inside of their windows (Figure 6.9 c). They liked the fact that net curtains allow you to see out from the inside but block the view from the outside. A few residents did point out that venetian blinds, on the other hand, do not block the view from outside in (Figure 6.9 b). They were especially concerned about the rooms on the ground floor.

However, venetian blinds are widely used in Rushenden and one of the residents, during interviews with the author, showed her a tool to clean inside the slats of the blinds (Figure 6.7). A simple solution could be to have both net curtains and venetian blinds on the ground floor, a solution that is already widespread in social housing. Venetian blinds are quite effective at reducing the indoor temperature, however they do not eliminate completely the need for cooling in both, the single and the two storey houses.

In the models no control was imposed on the blinds, which are assumed that the light-coloured venetian blinds are closed throughout the day. When venetian blinds are used in Rushenden (Figure 6.8), the slats are tilted towards the inside and do not effectively block the solar radiation. The advice that the author gives is to keep blinds closed throughout the summer, with the slats tilted towards the outside to form a 60° angle with the horizontal; this will allow daylight to enter the house most of the day. However, in this way, as well as the daylight, some solar radiation will also enter the room.

Figure 6.7: Resident's tool to clean slats of venetian blinds

Figure 6.8: Existing venetian blinds in a resident's house in Rushenden

Internal roller blinds are also widely used in Rushenden on the ground and first floors. These simple and economic shading devices can be very effective at reducing overheating as proved in the results chapter. They eliminate completely the need for cooling and reduce the internal temperature below the maximum comfort threshold. The residents are prepared to accept them and these devices are cheap and easy to use. The important is that they are made completely opaque and of a light colour possibly white. A survey in Rushenden showed that the roller blinds installed at present are not opaque and are generally printed with dark colours. It is important to explain to the residents that using opaque, light coloured blinds will make a big difference in terms of summertime comfort.

Dark drapes were also tested in the simulations because they are a very common choice in housing since they are believed by residents to block the solar radiation and therefore guarantee the maximum comfort. However the black fabric becomes very hot and the heat is transferred into the room by convection and radiation. The simulations showed that dark drapes applied on the inside face of the windows in the living room of the single storey house will not reduce the temperature to a comfortable level in the summer of 2030s.

Figure 6.9 a, b, c: Internal shading present in Rushenden, roller blind (Source: Bruce Blinds, no date), venetian blinds (Source: Houzz, no date), net curtains (Source: IKEA, 2012)

Some residents may still experience discomfort despite the external shading. They may have a lower comfort threshold than that used for this assessment. Or the temperature may increase more than +2 °C towards the end of the century. In this case the use of electric fans may be considered, as they are already widespread in Rushenden. Although fans do not lower the indoor temperature, the air movement increases comfort during the day. The fan power can be offset by the photovoltaic panels that have been installed during the retrofit. The electricity produced in the summer by the panels will increase, considering future projections of drier and warmer summers, as cloud cover reduces.

6.3 Cost-saving analysis and calculation of payback times

There is a cost related to the retrofitting of these adaptation measures and this can be quite high. An evaluation of the costs and benefits will allow the housing association to establish whether it is more economical to keep the existing windows and retrofit external and internal shading devices or to change the windows and install external roller blinds or shutters. Other considerations may come into play in this choice, such as the age of the existing windows. These are discussed in this section.

Firstly, the price paid by the residents or the housing association or a combination of both is presented in the table below. The cooling loads before the adaptation measures were

installed were calculated at the beginning of the Results and Analysis Chapter using the CIBSE A (2006) set point temperatures of 25 °C in the living rooms and 23 °C in the bedrooms. In accord with the fact that in the absence of air conditioning people adapt to higher temperatures by wearing different clothing, showering and drinking more, the cooling loads after each adaptation measure was applied were calculated using the higher comfort temperatures of 27.6 °C in the living room and 25.6 °C in the bedroom. This is because when the occupants adapt by using shading and ventilation techniques they can have a higher comfort threshold. The savings of each adaptation measures were therefore calculated as the difference between the cooling loads of the un-adapted houses using the CIBSE temperature set points and the adapted houses using the comfort temperature set points.

In the single-storey house where there are glazed French doors to the garden it will be necessary to replace them with patio doors and that will be very expensive. If the price of external blinds is added to the cost of replacing the patio doors, this solution then becomes very expensive for the housing association. The housing association, however, may consider replacing the windows as part of its "ordinary maintenance" operations. In that case only the cost of the blinds will be part of the adaptation cost. External wooden shutters appear to be much more affordable as they are "low tech" and can be made locally.

Firstly, adapting the existing windows will be a cheaper solution. Economies of scale will also play a part in reducing the cost. As these elements become more and more common and they are installed as an integral part of the construction of new build housing, the price will decrease. If the choice of replacing the windows is made then new tilt and turn windows for the living room and bedrooms of the two-storey house will be needed. Table 6.1 shows the price of new UPVC windows for the single and two storey houses.

Bedroom single storey house uPVC double[5] glazing (1800X1050) mm	£ 386.23[6]
Living room single storey house uPVC sliding patio door size (1700X2075) mm	£ 902.68[7]
Bedrooms two storey houses (1800X1350) mm	£ 463.49[8]
Living room two storey house (2400X1350) mm	£ 594.88[9]

Table 6.1: price of new tilt and turn and patio windows for the single and two storey houses in Rushenden

The payback time of the most common adaptation measures is presented below for the single-storey house. The fuel price is £0.125/kWh, the same price that was used in the results to calculate the yearly price for cooling. This is followed by a calculation of payback times of one adaptation package for the two house types analyses.

Using the higher comfort temperatures, it is evident that there is not much difference between the energy savings of the different shading devices analysed in the Results and Analysis Chapter (Table 6.2). The calculated payback times are therefore determined essentially by the price of the devices, the higher the price, the longer the time to pay them back. Central air conditioning units are normally sized by suppliers using 140-150 W/m² (private conversation, 7-9-2015). The units therefore overestimates the actual cooling needed that will be 6 W/m² in 2030s in the living room of the single storey house, calculated using 103 kWh/year and 898 hours of cooling extracted from the ESP-r modelling. The installation of a central unit may induce the residents to run the air conditioning at a lower temperature than that used in the modelling, lowering their comfort temperature threshold and therefore making the adaptation process impossible.

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[5] New windows. UPVC windows are virtually maintenance free, they do not need painting (Anglian website)
[6] Laxton's (2013) pp. 445
[7] Spon's house improvement house book (2005) pp. 33
[8] Laxton's (2013) pp. 445
[9] Laxton's (2013) pp. 445

		Price of adaptation first year £	maintenance cost per year £	energy saving = energy needed before the adaptation – energy needed after adaptation, kWh/year		
				living room	bedroom 1	bedroom 2
Overhang	type2	189	4.8	122.2	1	
	type4	119	4.8	67.7	73	59.3
Overhang + side fins	type2	787	9.6	124	1.0	
	type4	470	9.6	68	74.1	60.5
Trees	type2	37	11.8	119.5	1.0	
	type4	37	11.8	65.1	71.8	61.7
Venetian blinds	type2	188		123	1	
	type4	281		66.1	75.3	61.7
Internal roller blinds	type2	218		124	1	
	type4	327		68	77.7	67.3
Night ventilation (insect screens)	type2	300	16	106.8	1	
	type4	560	16	63.79	77.2	61.6
External shutters	type2	400	4.8	124	1	
	type4	230	4.8	68	78	69
external roller blinds	type2	602	6.5	124	1.0	
	type4	1086	6.5	68	78	69

Table 6.2: Summary of the cost of the adaptations and the savings

Some adaptations have been installed directly by the residents, such as Venetian and roller blinds and awnings in some of the two storey houses. However as it was discussed earlier, residents need some support from the Housing Association, in order to choose the right type of internal shading and to use it in the right way. Otherwise the benefits in terms of comfort and reduction of overheating hours will be less than that calculated by modelling. It is therefore very important to educate the residents about what measures will be more effective in terms of overheating reduction and how to use them. Insect screens can also be installed directly by the residents and they are marketed in the UK.

On the other hand, the installation of some measures such as external overhangs, trees and external shutters or roller blinds (that will require the installation of new windows),

necessitates intervention by the Housing Association. The benefits for the Housing Association will be very substantial because if a central air conditioning unit was to be installed, instead of adapting the houses, the price would be very high (£ 2169 for the single storey house and £6366 for the two storey house)[10]. Furthermore, since some of the residents may run the AC unit at lower temperature set points than those assumed in the calculations they will use more energy than needed.

Portable air conditioners can be bought on-line or off the shelf of most DIY shops. This is what the residents would do in the likelihood of a prolonged heat wave, in the same way that in the winter they use electric heaters. The cheapest available portable air conditioner on-line cost £186[11]. The warrantee of the portable unit is 1 year that can be extended to two years by paying £40 extra. Two years is therefore considered as the asset life of the item. Since in the two storey house there are two bedrooms on the first floor, two units were considered in the calculation of the savings.

The number of years (n) to pay the investment back (Table 6.3) is given by Equation 6.1. Table 6.3 shows that most payback times are very low, in some cases equal to a fraction of a year. In the case of external roller blinds and overhang with side fins the return of the investment is 8 and 7 years, within their asset life. The price of new windows was not included in the calculation below because the replacement of the windows is part of the maintenance that the Housing Association regularly undertake.

Equation 6.1

n= (price of adaptation + maintenance)/(price of air conditioning + electricity used)

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[10] The price for central air conditioning was quoted by ALLSEASONS (9-9-2015) and includes the price for the installation
[11] Debenhams extra (12-09-2015)

		price (£) of portable air conditioning unit per year	electricity used by A/C (£/year) from Results and Analysis	number of years to payback the investment
Overhang	type2	113	4	2
	type4	226	7	0.5
Overhang + side fins	type2	113	4	7
	type4	226	7	2.1
Trees	type2	113	4	0.4
	type4	226	7	0.2
Venetian blinds	type2	113	4	1.6
	type4	226	7	1
Internal roller blinds	type2	113	4	2
	type4	226	7	1
Night ventilation	type2	113	4	2.7
(insect screens)	type4	226	7	2.5
External shutters	type2	113	4	3
	type4	226	7	1
external roller blinds	type2	113	4	5
	type4	226	7	8

Table 6.3: n: number of years to payback the investment

6.3.1 Adaptation scale and package

In the Results and Analysis chapter the author mainly analysed shading and ventilation and the combination of these techniques. As a way of limiting the possible alternatives, this research focused on the solutions that CREW, SNACC and other similar studies suggested, plus some others, as presented in the Methodology Chapter. The adaptation measures were discussed with the residents during the field study and then were applied to the models to find bespoke solutions that can be used in Rushenden and in similar social housing developments in the South East of England.

The simulations in the Result and Analysis Chapter showed that the combination of internal roller blinds and night ventilation insures comfort in the single and the two storey houses. Table 6.4 shows the payback times when using these options together in the two

case studies. The number of years to pay the investment back is very reasonable, 3.9 in the two storey house and 4.6 in the single storey.

		cost first year	maintenance cost per year	number of years to payback the investment
Internal roller blinds + night ventilation (insect screen)	type2	518	16	4.6
	type4	887	16	3.9

Table 6.4: payback times of internal roller blinds and insect screens

The housing association can help the residents financially with either the cost of education or partially with the cost of installation. There are some clear financial benefits for the residents in investing in adaptation, once the investment is paid back, there will be ongoing savings. There are also benefits for the Housing Association apart from avoiding the installation of an expensive central air conditioning unit in the case of the extreme discomfort of the residents. Keeping households in a comfortable environment, happy to live in their homes, benefits the housing association because they are more likely to stay resident for a long time. This is especially true for the families living in Rushenden, because in the case of the elderly, they are more likely to remain in their homes anyway. So it is an issue for the Housing Association as to what type of community Rushenden will become, i.e.what mix of elderly residents, families, and children.

Enhancing shading and ventilation are universal techniques useful in reducing the indoor temperature. Internal shading and night ventilation are cheap and easy to use. Talking to the residents about ways of adapting to a warmer climate requires time and effort. It is part of the education process that the Green Doctor has started during IFORE regarding wintertime comfort. In the process of adapting to a changing climate this education program needs to continue to ensure that the residents are fully prepared for a warmer climate.

6.4 Health concerns and the elderly

Just less than half of the population (47.5%) living in Rushenden are the retired elderly. The problems of heat stroke and overheating are especially felt by this group of people as they are most vulnerable to changes in the climate. The elderly are also slower than other groups to react to changes and that is why there is a greater health risk in the case of overheating, which can result in death.

Professor Martin Parry from Imperial College London (Building for Change, 24-6-2014) warned that fatalities resulting from higher summertime temperatures could increase significantly. Hajat *et al.,* (2002) as reported by Baizee *et al*., (2013) analyses the causes of summertime mortality in a 21 year period and concluded that at an average internal temperature of about 19 °C heat-related death increases. The health cost of the elderly admitted to hospital with heat stroke may increase in the future and become very high.

Johnson *et al*., (2003) assessed the increase in mortality and hospital admissions following the 2003 heat wave. The paper states that in England, the mortality of the over 75s increased by 23% during the heat wave of 2003, which was more than the increase seen in other age groups. This was especially high in the South East, surmounted only by London where the Heat Island effect is very strong. The number of daily emergency hospital admissions in London increased dramatically during the August heat wave in those aged over 75.

Heat currently contributes to 2,000 premature deaths per year in the UK and the number of deaths is projected to increase to 7,000 by 2050 (Adaptation Sub Committee progress report, 2014). At present the threshold temperature at which the population begins to suffer heat-related mortality varies regionally from 17 °C to 20 °C (Adaptation Sub Committee progress report, 2014). This temperature is quite low and it changes regionally in relation to the frequency of the heat wave. The social cost of failing to address this problem will be huge.

Moreover, this will also dramatically increase the cost of heat-related hospital admissions, which have a similar pattern to heat-related mortality (Aecom, 2012), although hospital

admissions have a weaker association to high temperatures than mortality (Aecom, 2012). Between the years 2021-2050 approximately 0.4% of the annual number of respiratory hospital admissions in Europe are estimated to be due to heat (Astrom *et al.,* 2013). The range of absolute increase in the number of hospital admissions in the UK attributed to heat between the two periods 1981-2010, 2021-2050, as a proportion of the annual expected number of respiratory hospital admissions, is estimated to be between 0.1% and 0.37% (Astrom *et al.,* 2013; Figure 6.7).
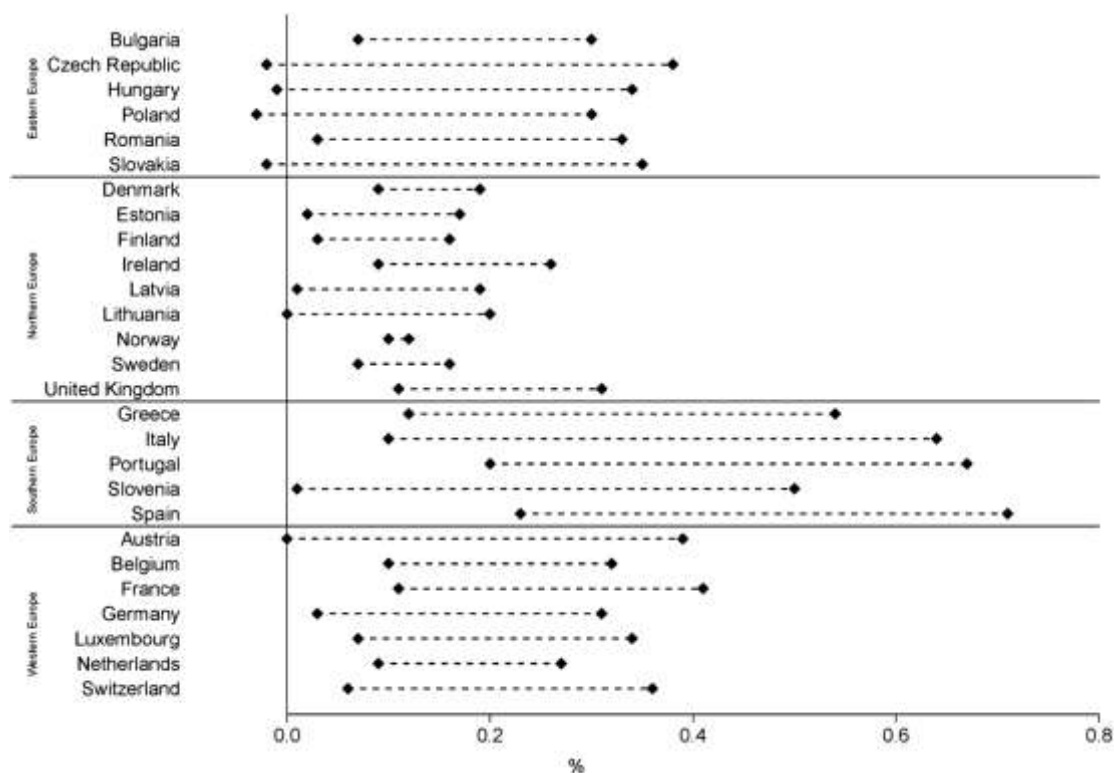
Figure 6.10: Future increase in heat-related RHAs (Respiratory Hospital Admissions) based on the four climate models, under two emission scenarios. (Source: Astrom *et al.,* 2013)

England has an ageing population and the over 75s are particularly vulnerable to hot weather (Adaptation Sub Committee progress report, 2014). Rushenden represents the ideal case study to analyse ways of tackling overheating in the case of particularly vulnerable residents. This will have a cost and the measures described above will need to be justified financially. It is suggested herein that the social and economic cost of the

temperature increase will be higher than the cost of the adaptations, although to fully analyse and prove this suggestion falls outside the remit of this thesis.

However, there is definitely an interest in tackling climate change and encouraging climate change adaptation that goes beyond the cost of offsetting and payback time although these are valid methods to persuade investors. Preserving the good health of the residents through adaptation and education is in the interest of the Housing Association.

6.5 The question of fuel poverty and occupant behaviour

At present, the residents in Rushenden use fans to increase comfort, ventilation and to be able to sleep. With a rise in temperature the follow up to this behaviour is to buy air conditioning units. The tables above show that quite simple adaptation measures such as internal roller blinds, combined together with night ventilation can guarantee comfort and their price can easily offset the price of air conditioning unit.

These techniques and strategies can then be translated into common practice to be adopted in social housing in the South East of England. This process of sharing knowledge and common practice can be enabled by the Housing Association, which can organize events to establish connections with the residents living in the community and with other housing associations around the country.

This research is therefore specific to social housing and is specifically targeting those residents often in fuel poverty. A fuel poor household is defined as one which needs to spend more than 10% of its income on fuel, which includes heating the home to an adequate level of warmth (Energy UK, 2014). Fuel poverty in England is measured by the Low Income High Costs definition, which considers a household to be in fuel poverty (GOV.UK, 2013):

1. If their fuel costs are above average (the national median level), and
2. Were they to spend that amount, they would be left with a residual income below the official poverty line.

The Community Engagement Officer, Tina Miles, described many examples of the financial difficulties endured by the residents in Rushenden. From the questionnaires that the Green Doctor carried out the majority of the residents receive some sort of income support as they live in very difficult financial circumstances. The use of appropriate adaptation techniques will reduce fuel poverty in Rushenden because, as the need for heating reduces in the future, the need for cooling is eliminated.

6.5.1 The engagement of residents and participation

During IFORE the Housing Association had very ambitious targets for resident engagement by finding employment for them within the retrofit program. As it was described above in the Results and Analysis Chapter, the efforts of the Housing Association to find a job for their residents also has the positive side-effect of improving their summertime comfort. To be in employment means not only to have financial security but also a more comfortable home.

It is not by chance that there are at present so many unemployed and elderly in Rushenden. Some of the residents in Rushenden were employed in the old pottery industry that has since shut down. When that happened, the area plunged into a deep depression that the newly designed Queenborough and Rushenden Masterplan is trying to cure. However, by speaking with the residents during focus groups it became evident that some of the ideas suggested by the residents to the planners were not fully achieved. The Masterplan identifies an area for a new supermarket in Rushenden but no parks, piazzas, or other public areas for social gatherings.

The other positive aspect of the occupant's engagement activities was to established links between the residents in the community of Rushenden. The residents' engagement activities helped them to come together in an informal setting, to share their time and exchange their experiences, discussing issues related to energy saving. It established a culture of participation and created the basis for a continuous engagement of the residents in the future. All the residents were invited and encouraged to participate in these activities and all age groups were represented.

The author is advocating a type of community engagement or residents' association where the residents get together regularly after the IFORE project ends, supported by the Housing Association, and find through discussions their own ways to cope with a warmer climate. This community change in behaviour is complementary to the technical efforts of using shading and night ventilation. This thesis suggests some of the possible changes that can take place and some of the topics for future discussion. This is the author's legacy that will be left to the housing association and the community to carry on in the future, when IFORE is over.

6.5.2 Behavioural adaptation, a change in lifestyle

In order to answer the following research questions:
- What else the community can do to adapt to a warmer climate?
- Which behavioural aspects adopted in other countries might be applicable to the south-east of England - offering extra comfort in the event of a heat wave?

The author presents a number of behaviours adopted in warmer countries and discusses their applicability to social housing in the South-East of England. There are common ways of living in warm countries such as Italy and Spain where there is a long tradition of using outdoor areas. We can learn from countries that currently experience a warm climate and explore both behavioural and architectural adaptation methods. Culturally, the cool and humid English weather encouraged people and communities to spend time indoors. It created buildings and indoor spaces that encourage gathering and exchanges such as pubs and clubs. A warmer climate can become an opportunity to exploit outdoor spaces and create deeper cohesion within the community.

Gaitani *et al.*, (2005) analysed the thermal comfort conditions experienced in several types of outdoor areas in Athens. The analysis shows that the thermal comfort conditions were significantly improved in the presence of green spaces and water spots. It is especially important in a warmer climate to take advantage of the opportunity offered to gather outdoors in shaded and ventilated areas (Figures 6.8, 6.11). This behaviour change was described and discussed with the residents and represents the social aspect of climate change adaptation. Together with the installation of physical measures in the

houses, a change in the occupants' behaviour will enable the community to withstand higher temperatures without the use of air conditioning.

Single and two-storey houses in Rushenden have a back garden, which could be used as an outdoor shaded area in the summer. In some cases this will be more comfortable than being indoors during hot summer days. Many of the residents in Rushenden are elderly but most of them are not infirm; they can easily walk short distances, and to be able to reach the back garden and spend time in the shade under a tree can make them more comfortable on hot summer days.

The elderly people living in Rushenden are mostly independent and can benefit from outdoor activities that will also beat the loneliness that sometimes they experience. The coastal breeze creates the ideal environment to carry out different kinds of activities that can become socially inclusive for the elderly. Within small towns and housing developments in Southern Europe, gardening, sitting in the shade, socializing, resting and playing are common outdoor activities that families with children also benefit from. These will only be possible if the outdoor areas are prepared to embrace these activities. Outdoor areas as well as buildings require financial investment to enable them to be adapted to climate change. The establishment of habits common in Southern Europe such as having an afternoon nap can also help in coping with extreme heat waves.

Outdoor canopies are useful when they are between buildings. A series of architectural elements may be required to furnish outdoor areas (Figures 6.9 a, b, 6.10). Hotter and drier summers will affect the way buildings are designed as well as the way outdoor spaces are designed and maintained. The way people behave will be affected by higher temperatures and this is something to be encouraged because it can offer an opportunity to both people and the environment.

A certain degree of physiological adaptation as stated in the Literature Review is likely to occur in response to the gradual increase in summer mean temperature (Adaptation Sub Committee Progress Report, 2014). This corresponds with the adaptive comfort equation that considers the running mean temperature and therefore the temperature for the previous week to assess comfort. Physiological adaptation however will be gradual and

people will adapt over the years. There may be other ways to adapt in the South East of England, because although we used projections for the modelling phase there is still a level of uncertainty about the future climate. This is the challenge that the community faces over the next century. Solutions will have to be focused on the local area so as to guarantee that the problem is tackled in the best possible way.

Figure 6.11: The beach in Santa Severa near Rome (2011)

Figure 6.12a, b: Green canopies (Source: Google search)

Figure 6.13: Green corridors (Source: Google search)

Figure 6.14: Open air cinema (Source: Brisbane, Concrete Playground, no date)

6.5.3 Accuracy and limitations of the method

The IFORE light retrofit helped reducing the overheating risk in the single and two storey houses. This is because of the relatively small thickness of external insulation, 60mm of phenolic foam, the loft insulation and the relatively high air permeability. The IFORE

retrofit therefore helps the houses to withstand higher temperatures and increases the lifespan of the dwellings. The adaptation options discussed above further increase the dwellings' lifespan up to the 2080s if the low emission scenario with a probability of 10% becomes a reality.

These results are indicative and highly notional. The method used simulations run with weather files for the 1970s, 2030s, 2050s and 2080s for Dover downloaded from the Prometheus project website (University of Exeter 2010). These weather files are averages whereas buildings tend to respond very quickly to a change in temperature.

For assessment of the summertime comfort temperature, using monitoring and surveys, the indoor temperature was used instead of the operative temperature. These two temperatures are most similar for a lightweight envelope and differ most in the case of a heavyweight envelope. This is because, in a lightweight construction the ambient temperature is more similar to the surface temperature than is the case in a medium or heavy weight envelope.

Air velocity can improve the perception of comfort in summer when temperatures are high. Comfort indicators include indoor air velocity and measurements for the occupants' thermal sensation. Comfort ventilation is considered as a passive cooling technique. However the aim of this thesis is not to carry out a detailed comfort study focused on analysing the indoor comfort levels and measures of comfort such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). That is why the models used ACH, and a simplified method to estimate the ventilation rate in the bedrooms and living room of the single and two storey terraces.

Chapter 7. Conclusions

Ms Solnit cited the following conditions that make it more likely that people will engage in mutually supportive activities in the face of disaster: "You have to feel like part of a community, that you have a voice, agency, that you are able to participate"

Daisaku Ikeda, Peace Proposal to the UN, 2014

7.1 Findings and answers to the research questions

This thesis has analysed the social housing in Rushenden which has been retrofitted through the EU-funded IFORE project. The aim of IFORE was to reduce greenhouse gas emissions by 80% compared with 1990 figures and improve the residents' comfort. When IFORE started in 2010 and this PhD started taking shape, the first philosophical questions that arose in the minds of the author and her supervisor were: are we doing the right thing in retrofitting with insulation and air tightness from the point of view of climate change? Are these techniques increasing the overheating risk? In the case of the Passivhaus retrofit standard called EnerPHit where insulation and air tightness levels are extreme, what will the effects be when considering higher outdoor temperatures in the future?

The research started by looking at previous studies, which demonstrated that unless adaptation is integrated with mitigation for the retrofitting of existing dwellings, one could end up with a building stock that overheats and becomes harder and more expensive to treat (Shao, 2012). In the meantime, the IFORE low carbon retrofitting also started and the author's research on adaptation became broader and encompassed all the documents currently available on this subject in the UK. The author identified two main projects, CREW (Shao, 2012) and SNACC (Williams *et al.,* 2012) that have been funded in recent years to answer the above questions. Both projects offered great insight into the subject but looked at very generic house types and occupancy patterns.

Gaps in knowledge were identified in these studies which the author then set out to fill. Those gaps mainly concerned the occupant's behaviour and the analysis of different

shading types. Working on IFORE as a Research Fellow in charge of the thermal modelling tasks offered the author an invaluable opportunity to look at real houses that were retrofitted with low carbon measures and at the real people living in them. Compared with previous studies, such as CREW and SNACC, this thesis aims to represent a step forward and originality in moving beyond the generic.

During the course of IFORE, occupant engagement was carried out on site by the Green Doctor to enable the uptake of the technologies installed and to ensure the success of the project. IFORE offered the author a unique opportunity to use the existing participative structure set up during the project to carry out the focus groups, questionnaires and interviews necessary to fill in the gaps in knowledge. The occupants' engagement process in this thesis represented a unique opportunity to make the occupants more aware of how to cope with higher temperatures and overheating, as it enabled the author to gather suggestions about adaptation methods and identify barriers to their application. The first important finding was that currently the residents are not aware of behavioural adaptation techniques because there have been rare occasions of overheating. In the case of high temperatures the occupants use fans to re-establish comfortable conditions.

Specific occupancy patterns were identified from the questionnaires that the Green Doctor submitted to the residents during IFORE. The majority of the occupants living in Rushenden are elderly, or unemployed, both living in poverty. They live in very vulnerable circumstances as is the case for many social housing residents. Their vulnerability is increased by the difficulty they face in paying for adaptations.

In the case of elderly occupants, CREW (Shao, 2012) assessed that the cost of adaptation increases for daytime occupancy and therefore penalises the elderly. This is also the case of the unemployed who spend most of their time at home. This thesis therefore engaged with the theme of finding low cost adaptation solutions for Rushenden. It focused especially on those elements that are already in place in people's homes and outdoors such as internal shading, awnings and trees.

The SNACC research (Williams *et al.*, 2012) identified a requirement for further research into whether the most vulnerable will be unable or unwilling to take on operational

adaptation measures such as thermal mass and night ventilation. Night ventilation can be very effective in Rushenden especially because the houses have internal thermal mass; this thesis identified, through field studies, several barriers to the uptake of this technique.

These barriers focus mainly on the fear of intruders, in the case of the elderly. The discussions during focus groups and one-to-one questionnaires that involved people of all ages, highlighted more barriers to adopting this technique. Families with children and especially with teenagers found it difficult to keep doors and windows open at night, to allow the air to circulate and cool down the space, because of privacy issues and the fear of insects. During the process of interviewing the residents and having discussions with them, questions about adopting common adaptation measures arose from various age groups.

Occupant engagement is essential in the case of the fuel poor because it allows a reduction in the cost of adaptation by looking at what is already there and trying to remove the barriers to adapt that are currently in place. This process of engagement and participation enabled the author to identify a low-cost adaptation package that work for the residents of Rushenden. This knowledge is transferable to other housing associations in the South East that host social housing residents who often live in similar circumstances. Climate change will impact less in other parts of England than in the South East and the same measures suggested for the South East will also be valid for similar developments around the country. The wider message that includes all housing, and maybe all buildings, is that the occupants need to be engaged in the process of transformation that allows the establishment of tailor-made solutions, overcoming barriers and ultimately save money.

The author modelled two different house types, single and two storey, different occupancy patterns, elderly occupants and families. Through the modelling of the houses, detailed research questions were answered. The author looked at the costs of a wide range of adaptation options and found the more affordable solutions for the people living in Rushenden. She analysed the future price that the occupants will have to pay for heating and cooling.

The adaptation strategies tested in this thesis can be divided into three categories:

1. The measures that can be applied now and start acting immediately;

2. The measures that can be applied now and start acting in the future, for example, planting trees;

3. The measures that need some modifications to be applied to the current building. This is the case for external shading that requires replacement of the existing windows.

If adaptation measures are retrofitted into the existing houses in Rushenden, the start of an education program such as that carried out by the Green Doctor during IFORE is suggested by the author as part of the journey. A change in the occupants' behaviour can save money and in the case of social housing tenants, elderly and vulnerable occupants, it can maybe save lives. Behavioural adaptation strategies are often very intuitive in Southern European countries but in the South East of England they need to be learnt.

The author analysed different scenarios of climate change and different adaptation measures. During focus groups and as part of the questionnaires the occupants of Rushenden suggested alternative measures and packages to those described by previous studies. Adaptation measures specifically targeted at the occupants in Rushenden have been modelled in ESP-r. Through simulations the specific solutions for Rushenden were tested and these solutions can be extended to social housing tenants throughout the country that, like the people in Rushenden, live on a very small income and in some cases are unemployed or elderly.

Different ways of living indoors are suggested as part of the adaptation process. These behavioural adaptation strategies are integral to the process of climate change adaptation. A change in the way the occupants behave in the summer, in relation to the physical adaptation measures, is crucial to the health and well-being of the residents. Keeping doors and windows open as much as possible at night for instance will allow the cool air from outside to ventilate and purge the building's fabric from the warmth accumulated during the day.

This is the originality of this research; it has tested general adaptation measures suggested by previous studies and added those suggested by the residents of Rushenden. This made the list of general adaptation measures specific to Rushenden, and this was achieved by engaging with the residents on a one-to-one basis in 2012 and during several focus groups held in the summer of 2013. The author found solutions to overcome general adaptation problems encountered in social housing and tested them using dynamic thermal modelling and future probabilistic weather files.

Measures such as shading and ventilation as suggested by the residents formed an adaptation package that was tested using the adaptive comfort criteria from TM52 (CIBSE, 2013). The best adaptation package for the houses in Rushenden, consisting of white and opaque internal roller blinds and insect screens was analysed in terms of cost. The originality of this research lies in the combination of the social engagement process with the application of technical analysis. This identified the best adaptation measures that applied to social housing in the South East of England can lower the indoor temperature to comfortable levels without the use of mechanical cooling.

In response to the research questions posed in the introduction:

1. **In the future, will the retrofitted social housing at Rushenden overheat to a greater extent than if the work had not been carried out?**

The retrofitted houses will overheat less in the future than if the works had not been carried out, therefore the IFORE retrofit will help reduce the overheating risk in Rushenden in the event of a warming climate. A comparison of the cooling loads of the un-retrofitted and retrofitted single storey house shows that the retrofitted house performs better in that the cooling load decreases by 11% for the 1970s base-case, 19% in 2030s and as it gets warmer the cooling load decreases by 24% in 2050s and by 30% in 2080s (Figure 5.7). In the retrofitted two storey house (no MVHR, less air-tight), the cooling load decreases by 9% in 2030s, 17% in 2050s and 22% in 2080s. In summer the MVHR in the single storey house is assumed to be switched off, ventilation is provided either by the mechanical ventilation or by windows opening.

When the indoor summer temperature is plotted, assuming that the MVHR is switched off or in summer mode, or that windows are open providing a total air-flow rate between 0.5 and 1.5 ACH, it is evident that in 2030s the retrofit reduces the temperature. During a heat wave in July 2030s the retrofit reduces the temperature in both the bedroom and the living room of the single storey house by 2.15 °C during peak times and by an average of 1.2 °C. In the two storey dwelling this reduction is less substantial than in the single storey because of the different form of the building. In the living room the retrofit improvement reduces the temperature by 1.25 °C maximum and by an average of 0.75 °C. In the bedrooms this reduction is visible but very minimal.

2. **If so, what type of retrofit, light retrofit or deep retrofit would tend to overheat more? For social housing (given limited financial resources) a reduced level of retrofit is the norm, how does that compare with deeper retrofit solutions (such as Enerphit) in terms of overheating risk?**

The thickness of the external wall insulation was increased in the model of the single storey dwelling to comply with the Passivhaus standard. The single storey dwelling was chosen for this test because it uses a mechanical ventilation heat recovery system as required by Passivhaus that was installed during the retrofit. The simulations showed that the extra external insulation causes a reduction of the heating load and does not change the cooling load. The extra air-tightness, reduced the heating load and it increases slightly the cooling load. When both, the extra insulation and the air-tightness are applied to the model, the heating load decreases more dramatically and the cooling load increases slightly up to the 2050s. In the 2080s, however the cooling load decreases slightly showing that, as the temperature increases, by the end of the century for instance, the extra insulation and air-tightness help keeping the warm air outside of the building. By the 2030s therefore, the single storey dwelling retrofitted by IFORE using a light type of retrofit will overheat less than if it had been retrofitted to comply for instance with the Passivhaus standards of external wall insulation and air-tightness.

3. **If retrofit might increase the overheating risk, which measures are likely to cause this increase - more insulation, air-tightness, or both?**

An assessment of the cooling loads using the high emissions scenarios for 2030s, 2050s and 2080s with a probability of 90%, was carried out with and without the retrofit measures applied to the two case studies. It showed that, external and loft insulation reduces the need for cooling up to the 2080s, but air tightness generally increases it. As it gets warmer, by the 2080s, the air tightness improvement seems to slightly reduce the cooling load. This could be because as it gets warmer there may be some benefits in keeping the warm outside air out.

4. **In which respects might the retrofit be helping to reduce the overheating risk, and which elements are the most beneficial?**

External insulation generally helps reducing the overheating risk when applied to an envelope that is not very tight as in the examples retrofitted by the IFORE program. A low infiltration rate can help reducing the indoor temperature during peak times, when the temperature outdoors is higher than indoors. An assessment carried out using the single storey house model during a July 2030s heat wave showed that an optimum air-flow rate between 0.5-1.5 ACH does guarantee that the indoor temperature remains below the maximum acceptable temperature set up by TM52 (CIBSE, 2013). A lower air-flow rate however, 0.23 ACH for instance, dramatically increases the indoor temperature above the upper limit. A higher air-flow rate, 3 and 6 ACH, reduces the indoor temperature when the outdoor temperature is lower than indoors and it increases it when it is higher, during peak temperatures.

The external and loft insulation lowers the indoor temperature considerably enabling the living room in a retrofitted single storey house to pass the third criterion of TM52 (CIBSE, 2013). However the first and second criteria are not satisfied therefore the retrofitted living room should be classed as overheating. The bedroom meets all three criteria and is not classed as overheating according to TM52. In the two storey dwelling similarly the insulation reduces the indoor temperature while the air-tightness improvement from 1.26 ACH to 1.06 ACH does not increase substantially the indoor temperature. The living room

of the retrofitted two storey dwelling meet two out of three criteria from TM52 and therefore should not be classed as overheating. The bedrooms on the first floor become very hot during the day, when unoccupied but at night the three criteria are met and they should not be classed as overheating. Even when a more stringent standard is used, for instance that for elderly occupants, the two storey dwelling will meet the criteria from TM52 and should not be classed as overheating.

5. How can these retrofitted houses be adapted to a warmer future climate?

The assessment carried out in this thesis focused on 2030s, using the high emission scenario. By 2030s, only the living room of the single storey house poses problems in terms of summertime comfort. By the end of the century however, the cooling load in the bedroom will also increase and it may cause overheating problems. In the two storey dwelling, the need for cooling is more equally distributed between the living room and the bedrooms. The assessment shows that the overheating risk is low. However, for behavioural reasons, the residents experience overheating. These retrofitted houses can be adapted to a warmer future climate by using a combination of night ventilation and internal or external shading devices.

6. How can a specific adaptation strategy be established for these houses?

A specific adaptation strategy can be established using the maximum comfort temperatures of 27.6 °C and 25.6 °C derived from summertime comfort survey for this particular group of residents, as the cooling set point in the simulations. By reducing the air-flow rate to a minimum during the day, between 0.5 and 1.5 ACH, and by opening the windows at night to allow 3 and 4 ACH, the need for cooling by 2030s is eliminated in the bedroom of the single and two storey dwellings when using the temperature thresholds derived from the summertime comfort survey.

The living room of the single storey dwellings and the living room and bedrooms of the two storey dwelling also need some internal shading to keep the temperature down to a comfortable level. Among all shading types analysed, opaque and white internal roller blinds are a good solution in that they offer a substantial reduction in the indoor

temperature. When combined with night ventilation they eliminate the need for cooling and keep the temperature below the comfort thresholds in the single and two storey houses. In the living room of the single storey house, this combination also ensures that the criteria of TM52 are met. White and opaque internal roller blinds are effective and affordable solutions, when combined with night ventilation that require the installation of insect screens, they have the low time of return of the investment of 4.6 years in the single storey house and 3.9 years in the two storey house.

7.   What else the community can do to adapt to a warmer climate?

A change in behaviour requires the education of the residents. For instance, at present night ventilation is not always adopted as a measure to reduce the indoor temperature at night. The survey showed that the reasons that stop the residents from adopting this technique are privacy, insects and the fear of someone breaking in. The installation of insect screens together with the education of the residents will enable them to adapt to a warmer climate. The partial opening of the bedroom's window on the back of the single storey house may be enough to guarantee the 3 ACH needed for comfort when doors are open and cross ventilation is allowed. In the two storey house similarly night ventilation can be encouraged by the installation of meshes on windows and by opening the doors at night. Privacy issues can be overcome by opening the doors only partially or by the installation of vents on doors that allow the air to circulate.

The type of shading device chosen is also crucial to insure an effective reduction of solar gain and therefore a reduction of the indoor temperature. At present internal shading is used more for reasons of privacy than as an overheating reduction measure. That is why the colour chosen for the internal roller blinds is often dark and not opaque. Net curtains are preferred to venetian blinds because they block the view from the outside. And when venetian blinds are used, their slats are not always tilted in the best way to reflect the solar radiation.

The Housing Association needs to help residents either with a program of education or by contributing financially to outsourcing and installing the physical adaptation measures. Education can be organized in various ways: through the organization of residents

associations, group meetings and/or through the distribution of leaflets. There are some obvious financial benefits for both the Housing Association and the residents in adapting the houses to a warmer climate. For the residents there will be financial savings in using internal roller blinds and insect screens rather than portable air conditioning. For the Housing Association, is will be more affordable to help the residents in the adaptation process rather than installing costly central air conditioning units in the event of extreme discomfort. There are also other benefits for the Housing Association. If the residents are healthy, happy and comfortable they will be more likely to remain in their houses for a longer time. This is true especially in the case of families, therefore creating a more diverse community. The adaptations will also increase the dwellings' lifespan.

8. **Which behavioural aspects adopted in other countries might be applicable to the south-east of England - offering extra comfort in the event of a heat wave?**

Living more outdoors is one of the behavioural aspects adopted in warmer countries that can be also applied to the South-East of England. The tradition of the English garden is well established. Other outdoor activities also offer the opportunity to engage with the residents in a change of lifestyle. Street cafes and other outdoor activities can enhance the sense of community, a process that was started during IFORE by the housing association. This means that, especially in social housing where there is a high number of elderly and unemployed, engaging the residents in outdoor activities such as gardening or volunteering can be a useful way to help them adapt to a warmer climate.

The housing association, Amicus Horizon and the community engagement team in Rushenden embarked on a programme to offer jobs to the unemployed through IFORE. This policy can be very useful in the case of climate change adaptation because the shading systems can be installed by the residents themselves, adequately trained. To have residents in employment means not only that they can afford a better lifestyle but also that they have a more comfortable home. In the case of creating and maintaining the local areas were the residents can gather in the shade the residents can also be employed or volunteer to carry out the necessary measures. To have employment also means having a more comfortable house to live in.

Concerted action by the local council, the housing association and the residents will ensure that both the houses and their residents keep cool. There are definitely some very vulnerable residents living in Rushenden, the very old and the infirm; special attention must be given to these residents and again this will be the task of the social housing provider and the local authority to protect these people by providing, for example, a door-to-door service to take residents to shaded outdoor areas. The case of those residents who are sick or infirm is different and requires special care and a case-by-case assessment.

9. **In terms of public policy for the retrofit of social housing in England, is the current approach, which is principally directed towards improving insulation and air tightness, the optimal strategy in view of climate change?**

The IFORE retrofit helped to reduce the future overheating risk and made the houses more resilient to climate change. If summertime comfort is the main focus, a light type of retrofit is recommended, especially in social housing where there are limited funds available. This type of retrofit will be cheaper but still guarantees some level of additional comfort all year round. In the IFORE houses in Rushenden it will be possible to avoid the use of air conditioning by 2030s using the high emission scenario if affordable adaptation measures are implemented. If more robust retrofit measures are installed, such as external roller blinds or shutters, which will require replacement of the existing windows, comfort may last up to the end of the century if mitigation targets are met.

Adding extra insulation to the external envelope to comply for instance with Passivhaus standard, might help to slightly reduce the heating load in the winter but it will not make any difference to the overheating hours in the summer. A further reduction of the air-flow rate will increase the future overheating risk in the event of global warming. The balance between infiltration and ventilation is very delicate; it requires good design and testing using dynamic thermal modelling.

However, if the focus is on reducing energy use and global carbon emissions, then increasing the insulation of the external walls (of the loft and of other building components to comply with the Passivhaus standard) and reducing air permeability will

achieve the goal. This is difficult and expensive to achieve and in the retrofit of social housing it may not be possible. It may be a more justified approach in new build housing. As the heating load decreases throughout the century and the cooling load increases the sum of heating and cooling remains almost constant in the houses retrofitted. Lower energy use due to super insulation and air tightness will produce lower global carbon emissions even in a warmer climate.

If the global efforts are successful in reducing greenhouse gas emissions to reach the targets of the medium or low emission scenarios, the houses will be climate proof for much longer than the 2030s, and may be climate proof to the end of the century. However, if that is not the case it will be more financially viable, at some point in the future, to demolish the houses and rebuild.

7.2 Limitations and suggestions for further research

The first main limitation of this thesis is that only the aspect of overheating was addressed in the calculation. All other aspects of climate change adaptation were purposefully omitted from this research, such as water, increased precipitation and flooding because they fell outside the scope of this PhD. The focus herein is on the IFORE retrofit and how that will withstand the passage of time. All other aspects of climate change had to be disregarded in order to fully explore this very topical subject.

Another limitation is represented by the fact that only the future weather for the 2030s, high emission scenario 90 percentile was used to assess future overheating risk in Rushenden. This represents a limitation because considering the average life span of UK housing, the houses in Rushenden may exist well beyond the 2030s, even up to the 2050s and maybe longer. However, the 2030s high emission scenario 90 percentile roughly corresponds to an increase of 2 °C in the average global temperature. It also roughly corresponds to a medium emission scenario by the 2050s and to a low emission scenario by the 2080s.

This means that if policies of mitigation achieve the goal of keeping the temperature rise below 2 °C then the houses will be resilient until the end of the century. If, on the other

hand, the temperature increase rises above 2 °C beyond the 2030s, then the houses will need to be adapted further to the new temperature increase. This is a limitation of this thesis as it could not look, in terms of adaptation, at all the possible scenarios of climate change, however it focuses on the current main line of thought that the author decided to follow given the state-of-the-art outlined in the Literature Review.

Two house types in Rushenden were modelled and tested against overheating before and after the retrofit. Real data from pressure tests, thermographic photos and construction details were gathered before the retrofit. The specific case of the occupants of Rushenden was considered and information about the occupants' demographic, employment status and behaviour towards energy consumption was gathered through questionnaires before and during the low energy retrofit.

Specific questions about adaptation preferences, climate change and overheating were discussed with a small sample of residents through one-to-one questionnaires and focus groups. Measurements were taken over the summer, of the comfort levels before the retrofit using a longitudinal questionnaire, which was completed on a daily basis by a small sample of residents over two and a half months. The longitudinal questionnaire was similar to that used by Nicol *et al.,* (2013) to derive the equations for the European Standard on adaptive comfort (TM52). The fabric and form of these two house types as well as the people living in them is very common to social housing in the UK and the lessons learned by these case studies can be generalized to social housing throughout the country. The conclusions of this research will be relevant for the other 775000 mid terrace social housing throughout the country, 70% of which has cavity wall structure.

The data used for the modelling is specific to these two house types and other house characteristics, such as higher or lower air permeability before retrofit, were not assessed. Other building orientations were also not tested as the testing herein was very specific in contrast with other studies which have tended to be more generic. Some of the specific aspects modelled in this research will benefit from further investigation using different variables.

The specificity and focus of this argument however also represents the originality of this research. While all the other similar studies looked at generic house types, the author focused on the community of Rushenden retrofitted by the IFORE project. This represents the unique selling point of this research, the interrelation between science and sociology. The author made this study very specific to the community living in Rushenden but the findings can be generalized to other social housing developments.

The evaporative cooling effect of trees was not calculated but their shading effect was investigated. A simple shading calculation underestimates the cooling effect of trees and this is a limitation because the cooling effect of trees can be very powerful, but also very variable. The cooling effect of trees has been studied in several pieces of work that the author summarized in the literature review. This thesis focused more on the analysis of shading devices.

Finally suggestions for further research are: the derivation of a specific adaptive comfort algorithm for housing, which will involve more surveys of the internal temperature, questionnaires and also other parameters of comfort such as air velocity. To project this investigation into practical action will require development with manufacturers of packages that include internal roller blinds, and insect screens, for retrofitting into existing windows in the UK. Further research into behavioural adaptation techniques is also needed, especially targeted at understanding what will work in the UK, a further step to ensuring that communities become resilient to a warming climate.

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Appendix A.1

Final IFORE questionnaire 2013

RESIDENT DETAILS

case_number _____

visit_type (1) IFORE Resident   (2) Non IFORE resident

date _____   date_last_visit _____

Same respondent as previous visit: Yes/ No [if yes, go to Q1]

If no:

title _____ first_name _____surname _____ dob

_____

(1) Full time employed (2) Part-time employed (3) Unemployed (4) Retired (5) Long-term

sick (6) Other.

Has there been a change of tenancy since the last visit? Yes/ No 1/2

If yes, when did you move in to the property? _____ [DD/MM/YY]

How many people live in your house? _____

Of these how many children (under 18)? _____

What is your total annual house income? (1) £0- £10,000, (2) £10,000- £15,000 (3)

£15,000- £20,000   (4) £20,000- £25,000 (5) £25-30,000 (6) 30,000+

Email address _____

CHANGES TO HOUSE

1a. Did the IFORE project make any of the following changes to your home?

Draughtproofing	(1) Yes since last visit (2) Yes before last visit (3) No
New door(s)	(1) Yes since last visit (2) Yes before last visit (3) No

Windows refurbishment	(1) Yes since last visit (2) Yes before last visit (3) No
New boiler	(1) Yes since last visit (2) Yes before last visit (3) No
Increased/ new loft insulation	(1) Yes since last visit (2) Yes before last visit (3) No
Increased/ new cavity wall insulation	(1) Yes since last visit (2) Yes before last visit (3) No
External wall insulation	(1) Yes since last visit (2) Yes before last visit (3) No
Solar PV	(1) Yes since last visit (2) Yes before last visit (3) No
Solar thermal	(1) Yes since last visit (2) Yes before last visit (3) No
Trombe walls	(1) Yes since last visit (2) Yes before last visit (3) No

Heat pumps   (1) Yes since last visit (2) Yes before last visit (3) No

Other   (1) Yes since last visit (2) Yes before last visit (3) No

If other, please

specify:_____

1b. How satisfied were you with the measures on a scale of 1-5 (5= very happy) in terms of a) process/ convenience of fitting b) information about c) appearance d) usefulness/ impact

	process		**info**		**appearance**		**impact**	
Draughtproofing		1-5		1-5				1-5
New door(s)		1-5		1-5		1-5		1-5
New window(s)		1-5		1-5		1-5		1-5
New boiler		1-5		1-5		1-5		1-5
Increased/ new loft insulation		1-5		1-5				1-5
Increased/ new cavity wall insulation		1-5		1-5				1-5
Solar panels		1-5		1-5		1-5		1-5
Trombe walls		1-5		1-5		1-5		1-5
Other		1-5		1-5		1-5		1-5

Since the last GD visit, have you made any other (non-IFORE) changes to your home which may increase energy efficiency? 1) Yes 2) No

If yes, please specify_____

NEW DEVICES

2a) Which of the following did you receive from the IFORE project?

2b) How would you rate how easy to use they are on a scale of 1-5 (5= very easy, 1= not at all easy)

2c) How would you rate how useful they are on a scale of 1-5 (5= very easy, 1= not at all easy)

2d) How would you rate the support received to use these? (1= poor, 5= excellent)

	Received		Easy to use		Useful		Support	
OWL monitor		1) Yes 2) No		1-5		1-5		1-5
Alert me		1) Yes 2) No		1-5		1-5		1-5
Wattbox GroundSource Air Source		1) Yes 2) No 1) Yes 2) No 1) Yes 2) No		1-5 1-5 1-5		1-5 1-5 1-5		1-5 1-5 1-5
Solarthermal SolarPV Heatrecovery		1) Yes 2) No 1) Yes 2) No 1) Yes 2) No		1-5 1-5 1-5		1-5 1-5 1-5		1-5 1-5 1-5

Some of the above devices offer feedback on your energy consumption, would you like any other feedback/ information about your energy consumption?

(1) Yes (2) No

If yes, what kind of extra information would be useful?

HEATING

How many hours PER DAY do you/ your household normally have central heating on for in winter?

Monday – Friday _____

At the weekend _____

When your central heating is on, what temperature is your thermostat normally set to during the winter? _____

Would you prefer to have the heating on for longer or set to a higher temperature?

Longer/Higher 1/2

How often did you notice feeling too cold in your house:

This winter (after retrofit measures):

(1) Every day (2) Most days (3) Some days (4) Rarely (5) Never

Previous winters (before retrofit):

(1) Every day (2) Most days (3) Some days (4) Rarely (5) Never

How do you (or other members of household) normally regulate the temperature at home (in winter)?

(1) Use the main temperature thermostat

(2) Use the thermostat on the radiators

(3) Turn on/ off at boiler/ use the heating booster

(4) Use heating on timer/programmer

(5) Open the windows

(6) AlertMe

(7) Wattbox

(8) Other

Do you usually wear a jumper/cardigan in the house in winter (i.e. pre-retrofit)?

Yes/No   1/ 2

Did you usually wear a jumper/cardigan in the house durning the previous winter (i.e. pre-retrofit)? Yes/no 1/ 2

Do you switch off your central heating when you go out (if no-one is at home)?

(1) Always (2) Usually (3) Sometimes (4) Never (5) Leave on timer

Do other members of the household switch off the central heating when they go out (if nno-one is at home)

(1) Always (2) Usually (3) Sometimes (4) Never (5) Leave on timer (6) Do not know

Has there been any change, since the last visit in the number of hours your house is empty? Yes/ No1/2

If yes, approximately how many hours on an average day is your home empty?

On weekdays

(1) Less than 3 hours (2) 3-6 hours (3) >6-10 hours (4) >10-15 hours (5) Over 15 hours

At the weekend

(1) Less than 3 hours (2) 3-6 hours (3) >6-10 hours (4) >10-15 hours (5) Over 15 hours

How many electric heaters do you have in your home?

How many hours per day have you used it/ them during the winter (2012/2013)?

(1) 1-3hours

(2) 4-5 hours

(3) 6-7 hours

(4) 8 or more hours

AIR CONDITIONING

Did you or other household members ever use any electric fans or other cooling devices last summer? (1)Yes (2) No

How often do you use it/ them last summer? (1) Most days (2) Some days (3) Rarely

During hot summer days when the outside temperature reaches 25C (77F), how would you rate the overall comfort of your home?

(1) Very uncomfortable (2) Slightly uncomfortable (3) Reasonably comfortable (4) Very comfortable

WATER

Do you normally take baths or showers? (1) Baths (2) Showers (3) It varies

[If applicable] Do other members of your household normally take baths or showers?

Children (under 18) (1) Baths (2) Showers (3) It varies (4) Do not know

Partner (1) Baths (2) Showers (3) It varies (4) Do not know

Other household members   (1) Baths (2) Showers (3) It varies (4) Do not know

How long do you spend in the shower on average:

1) Under 15 mins 2)15-30 mins 3) Over 30mins

How long would you estimate other members of the household spend in the shower?

Children (under 18) (1) Under 15 mins (2) 15 mins or more (3) Do not know

Other household members (1) Under 15 mins (2) 15 mins or more (3) Do not know

Do you think having a water meter influences/ would influence you to use less water?

(1) Yes (2) No (3) Not sure

Since the last GD visit, have you made any other changes to reduce the amount of water you use? (1) Yes (2) No (3) Not sure

If yes, please describe:

_____

USE OF APPLIANCES

How often on average do you and other members of the household normally use the following appliances?

	TV	DVD/ video player	Laptop	PC	Video game console	Hifi/ CD player/ radio
How often in use?						

1) Every day (2) 4-6 days a week (3) 2-3 days a week (4) Approx once a week (5) Less often

How many hours on average do you have a TV on per day? (1) Less than 3 hours (2) 3-6 hours (3) >6-10 hours (4) >10-14 hours (5) Over 14 hours

Do you leave your television on standby when not in use?

(1) Always or usually (2) Sometimes (3) Occasionally (4) Never

[If applicable] **How many hours on average do you have a computer (desk top or lap top) in use per day?** (1) Less than 3 hours (2) 3-6 hours (3) >6-10 hours (4) >10-14 hours (5) Over 14 hours

Do you leave your computer switched on when not in use?

(1) Always or usually (2) Sometimes (3) Occasionally (4) Never

How often do you (household) use the following appliances in a week?

	Tumble dryer	Dishwasher	Washing machine	Microwave
How often?				

(1) Every day (2) 4-6 days a week (3) 2-3 days a week (4) Approx once a week (5) Less often

Do you normally switch off these appliances [Q19] when not in use? (1) Yes all (2) Yes some (3) No none

What temperature do you use your washing machine at usually? _____ (0) Cold

How many times on average is your kettle boiled per day? (1) 0-2 (2) 3-5 (3) 6-9 (4) 10-14 (5) 15+

Do you/ other members of hhd, normally fill your kettle to the top? (1) Yes (2) No (3) Depends

Have you bought any new electrical appliances e.g, Fridges, TV's, Digiboxes, in the last 6 months? (1) Yes (2) No

Did the energy efficiency of the appliance affect your choice?

(1) Yes it was the most important factor in my choice

(2) Yes, it was one of the factors I took into consideration (alongside style/price)

(3) No, I was only concerned with other issues (eg style/price)

(4) No, I did not know about or understand the energy labels

(5) No, I did not have the information because I bought second hand

CHANGES IN BEHAVIOUR

Do you think you have been able to reduce the overall amount of energy used in your household compared with this time last year?

(1) Yes (2) No (3) Not sure

If yes, how would you estimate this reduction?

(1) Less than 5% (2) 5-10% (3) 11-20% (4) over 20% (5) Do not know

If yes or not sure, how much of an influence do you think the following have had on reducing your household's consumption?

Concerns over the cost of gas and electricity (1) Large influence (2) Small influence (3) No influence

Concerns about the impact on climate change (1) Large influence (2) Small influence (3) No influence

Concerns about other environmental issues (1) Large influence (2) Small influence (3) No influence

Using the smart meter (OWL or Alert Me) (1) Large influence (2) Small influence (3) No influence

Using more energy efficient appliances (1) Large influence (2) Small influence (3) No influence

Following the Green Doctor advice/ 'prescription' (1) Large influence (2) Small influence (3) No influence

Education of children in hhd about energy issues (1) Large influence (2) Small influence (3) No influence

The retrofit measures (1) Large influence (2) Small influence (3) No influence

Involvement in IFORE community activities (1) Large influence (2) Small influence (3) No influence

The wattbox   (1) Large influence (2) Small influence (3) No influence

Do you remember what was included in your Green Doctor prescription? (1) Yes (2) No (3) In part

If yes or in part, please state what you remember

_____

Have you/ your household made any of the following changes in order to save energy since first seeing the GD?

Turning off lights when leaving room	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Fully loading washing machine	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Hanging washing	
	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Taking showers rather than baths	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Reducing time in shower	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Not overfilling kettle	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Turning off tap when brushing teeth	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Using radiator panels/ foil	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Using save-a-flush bag	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Using TV power-down	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Using low energy light bulbs	(1) Yes (2) No (3) To some extent (4) N/A did anyway
Other	(1) Yes (2) To some exten

If other specify: _____

Of these changes which have you found the easiest/hardest to make?

Are other members of the household more or less likely than you to follow energy saving practices?

(1)   More likely (2) less likely (3) about the same

Do you intend to make (further) energy reductions in future Yes/No/Not sure 1/2/3 (if no/not sure go to 35)

If yes, what is the MAIN way you intend to do this? (select the relevant answer without prompting)

(1) By reducing use of appliances or turn off more often when not in use

(2) By reducing water use

(3) By reduce h eating (thermostat or length of time on)

(4) By turning off lights more often when leave room/house

(5) By using more energy efficient appliances/ devices

(6) By turning down the temperature on washing machine

(7) Do not know

If other please specify _____

GD primary recommendation (1) do not overfill kettle (2) close curtains (3) take showers rather than baths (4) use full loads washing machine (5) lower temperature on washing machine (6) hang clothes on line (7) cook food in batches and freeze (8) use energy saving light bulbs (9) other

Otherrecspec _____

Do you feel you will be able to make this change (1) yes (2) no (3) not sure

COMMUNITY ENGAGEMENT AND COMMUNICATION

Have you or other members of your household aware/ involved in any community engagement? (Training day (re. technical measures), Childrens activities, Drop-in support offered at Community house, Exhibitions/ presentations about project, Support with employment/ educational opps, Exchanges with residents in France, Activity groups (e.g. gardening), Coffee afternoons, Residents' ipower Group, Community fun day)

(1)   Yes (2) No

If yes, please specify which engagement activities ------------------------------------

Has your involvement in AH organised community activities changed over the last three years? (1) More involved (2) Less involved (3) About the same

Would you like to be more involved in such community activities?

(1) Yes (2) No (3) Not sure

Would you have liked more information about social activities organised by the IFORE project? (1) Yes (2) No

What format should IFORE related information (social or technical) be provided to residents? (rate top 3 in order of preference)

1) Specific written information through the post (e.g. leaflet, letter, FAQ sheet)

2) Information included in community newsletter

3) Verbal: One to one visit

4) Training/ information session

5) Community centre drop-ins

6) Resident led groups/ ambassadors

7) Online information

8) By telephone

9) Other (please specify)

1st preference 1-9 _____

2nd preference 1-9 _____

3rd preference 1-9 _____

Do you feel the number of GD visits received was: (1) Too many (2) Too few (3) About right?

Would you <u>feel able</u> to help to pass on information you have learnt to new residents?

About new technologies in the retrofitted homes: (1) Yes (2) No (3) Not sure

About energy saving behaviours? (1) Yes (2) No (3) Not sure

About new technologies in the retrofitted homes (1) Yes (2) No (3) Not sure

About energy saving practices? (1) Yes (2) No (3) Not sure

On a scale of 1-5, how positive do you feel about living in Rushenden (5= very positive, 1 = very negative)? (1-5)

Has this changed since 2010? (1) Yes, more positive (2) Yes less positive (3) No, no change (4) Not sure

Do you feel the IFORE project has influenced this change? (1) Yes (2) No (3) Not sure

Did you receive the Warm Home Discount automatically? (1) Yes (2) No (3) Do not know

COST

Has your energy company increased the cost of energy over the last year?

Yes/No/Not sure 1/2/3

Did you have difficulty paying your energy bills this winter? Yes/No 1/ 2

Did you receive any grants advice from the GD? Yes/ No 1/2

If so, how much money did you save through this? (£) _____

What is your yearly household income? (£) _____

ENVIRONMENTAL ISSUES

How informed do you feel you are about issues around climate change?

(1) Very informed (2) Quite informed (3) Little or no knowledge.

Do you think the climate has changed over the past 30 years? (1) Yes (2) No (3) Not sure

If yes, how do you think it has changed?

(1) It has warmed (2) It has cooled (3) It is more unpredictable

Do you think the average temperature will increase in the next 30 years?

(1) Yes (2) No (3) Not sure

How great a threat to the environment do you think climate change is on a scale of 1-5?

(1=no threat, 5=serious threat) 1/2/3/4/5

How do you feel your actions may impact climate change on a scale of 1-5? (1=no

impact, 5=significant impact) 1/2/3/4/5

ANYTHING ELSE?

Is there anything else you would like to say about your household's energy use or about

the IFORE project?

_____

_

GD notes on anything important mentioned/ observed in

interview_____

METER + BILLS CHECK

Gas meter reading _____ Electric meter reading

_____

Current gas supplier

(1) British Gas (2) E-On (3) EDF (4) N Power (5) Southern Electric (6) Scottish Power (7)

Other

If other specify

_____

Current electric supplier

(1) British Gas (2) E-On (3) EDF (4) N Power (5) Southern Electric (6) Scottish Power (7)

Other

If other specify

_____

How do you pay for gas? (1) bills (2) prepayment meter

BILLS/ DD CUSTOMERS

Amount last gas bill/ statement _____ Period of bill/ statement

_____

Amount of energy _____

Measurment: (1) kWh (2) unspecified 'unit'

 (1) bills (2) prepayment meter

Amount last electric bill/ statement _____ Period of statement

_____)

Amount of energy _____

Measurment: (1) kWh (2) unspecified 'unit'

PREPAYMENT CUSTOMERS

How much do you estimate you spend on gas and electricity PER WEEK?

	Summer	Winter
Gas	£	£
Electric	£	£

QUIZ SCORE

Appendix A.2

Adaptation questionnaire Rushenden

1. Would you consider buying an air conditioning unit costing £229-250 @ B&Q if the temperature becomes:

a. A little hotter that this   b. A lot hotter that this (warmer than you have experienced in this house)

2. Have you considered turning off lights and appliances as a way of reducing the internal heat gain during hot summer days

3. Have you considered ways of reducing the internal temperature by using shading such as curtains, blinds and shutters?

4. If so, which types of shading would you buy (or have you bought)?

   A .awnings (76 £[12]) B .internal louvre shutters (from 300 £[13]) C .external louvre shutters (from 600 £ [14])D. External door shutters (from £300 [15])E. internal (roman) blinds (£30[16])D. internal (venetian) blinds (£20[17])

5. In order to reduce the indoor temperature, in the case of global warming, would you consider to plant trees on your back garden? (£25 to £50 maintenance cost every 2-3 years)

6. What is your view about planting trees?
7. Have you considered increasing ventilation (opening windows) during the day in order to remove heat during the summer?

---

[12] From Primrose
[13] From house of shutters
[14] From simply shutters
[15] From simply shutters
[16] From blinds to go
[17] From blinds UK

8. Would you consider opening the windows of your bedroom at night (before going to bed) during hot summer days in order to sleep more comfortably?

9. If not, is security your main concern?

10. Would your perception change if a system to increase security was implemented? (window bars £953[18])

11. For which measures would you be happy to pay yourself? For which measures would you need some help from the housing association?

12. Please rate the following options in a scale from 1 to 5 i.e. 1 = poor; 5 = excellent:

	practicality	cost	appearance	security	Need for financial help
awnings					
Internal louver shutters					
External louvered shutters					
External door shutters					
Internal roman blinds					
Internal venetian blinds					
External overhang over south facing windows					
trees					
Night ventilation					

---

[18] From security direct

Appendix A.3

Questionnaire children 21-08-2013 – Rushenden

In what way have you been part of IFORE?

Did you enjoy being part of IFORE?

What is the activity that you enjoyed the most during the IFORE program?

What is for you the main purpose of saving energy?

What do you know about climate change?

How would you like your place to be? Describe

A lot greener   a lot funnier   ....

What extra activities would you like to do during the day or in the afternoon related to

IFORE?

What type of trees would you like to have in Rushenden?

Would you like to have a lot of trees in Rushenden?

Would you like to have a forest in Rushenden?

Appendix A.4

Summertime comfort longitudinal questionnaire

University of Brighton

Mithras house

Lewes road

Brighton BN2 4AT

Your Address: Your name: Today's date:

Which room are you in: Time: ....am ....pm

FEELINGS   at present I feel:

Cold...	
Cool...	
Slightly cool.............................	
Neutral......................................	
Slightly Warm..........................	
Warm..	
Hot..	

PREFERENCES I would prefer to be:

Much warmer...........................	
A bit warmer............................	
No change.................................	
A bit cooler...............................	
Much cooler..............................	

CLOTHING (tick as appropriate)

Short sleeve shirt/ blouse........	
Long sleeve shirt/ blouse	
Vest	

Trousers/long skirt..................

Shorts/ short skirt..................

Dress..

Pullover...................................

Jacket......................................

Long socks..............................

Short socks.............................

Tights......................................

Tie..

Boots.......................................

Shoes.......................................

Sandals....................................

Other (specify)...

ACTIVITY   in the last 30 minutes:

Sitting watching television.......

Sitting at the computer...........

Sitting reading.........................

Standing cooking.....................

Standing talking.......................

Walking indoors.......................

Cleaning indoors......................

Walking outdoors....................

Working in the garden.............

Other (specify)...

CONTROLS   tick as appropriate:

Internal door open......................	
Window open...........................	
Blinds/curtains down...............	
Lights on	
Heating on...............................	
Fan on.......................................	
Extra heater on........................	
Other (specify)..	

Appendix A.5

<u>Focus groups' open ended questions</u>

1. How people understand the environment and climate change?

2. Climate change adaptation: introduce the topics of climate change and of manmade global warming. Mitigation and adaptation

3. Overheating: how will the climate change?

4. What is the current situation, what is that you are doing at the moment to adapt to climate change, in the case of overheating for instance?

5. What can you do to adapt in the future? Suggestions: roller blinds, other types of shading, behavioural change: spending time along the coast, planting trees on the isle of Sheppey, and spending time outdoors at night watching movies in public areas...give suggestions!

6. What are the limitations to these changes and how can they be overcome?

7. How do you perceive the IFORE retrofit work as having affected understanding and practices in relation to the environment?

Appendix B.1

<u>Pressure tests results pre and post retrofit</u>

house type / no. bedrooms	location	air permeability m^3/m^2.hr @50 Pa un-retrofitted	ach @ 50Pa un-retrofitted	air permeability m^3/m^2.hr @50 Pa retrofitted	ach @ 50Pa retrofitted
Rushenden average test results					
Type 1 single storey 1 bedroom	end-of-terrace	6.7	10.2	6.1	
	mid terrace	4.4	6.7	4.1	
Type 2 single storey 1 bedroom	end-of-terrace	4.3	6.3	3.2	
	mid terrace	3.8	5.7	3.1	
Type 3 single storey 1 bedroom	mid terrace	3.7	5.9	4.7	
	end-of-terrace	6.4	10.3	4.6	
Type 4 2 storey 2 bedroom	end-of-terrace	5.0	6.4	6.0	
	mid terrace	5.9	9.5	5.1	6.0
Type5 2 storey 2 bedroom	end-of-terrace	6.1		6.0	
	mid terrace	7.1		6.7	
Type6 2 storey 3 bedroom	end-of-terrace	5.7		6.0	
	mid terrace	14.2		5.3	
Type7 2 storey 3 bedroom	end-of-terrace	9.7		11	
	mid terrace	10.3		13.2	

Appendix B.2

Heating energy pre and post-retrofit

IFORE modelling specification
Set point temperature ESP-r models = 21 °C
(0) = basecase: building as it stands before retrofitting (cavity insulation was omitted for modelling reasons and added to (1))
(1) = (0) + cavity insulation + 270 mm of loft insulation + 120 mm of external insulation EPS
(2) = (1) + refurbished windows with low-e double glazing + argon filled cavity
(3) = (2) + air tightness improvement + controlled ventilation = total infiltration + ventilation rate = 0.5 ac/h
(4) = (3) + supply air windows with 50% of the heat reclaimed (modelled as a reduction by 50% of the ventilation rate, total ventilation + infiltration rate = 0.375 ac/h)
(5) = (3) + MVHR with 80% of the heat reclaimed (modelled as a reduction by 80% of the ventilation rate, total ventilation + infiltration rate = 0.22 ac/h
(6) = (5) + upgraded boiler

	UK house types kWh/(m²year) primary energy for heating ESP-r						
	Type1	Type2	Type3	Type4	Type5	Type6	Type7
(0)	230	202	253	171	178	204	204
(1)	153	121	170	85	98	119	125
(2)	138	98	145	76	89	108	89
(3)	101	93	122	69	86	98	75
(4)	89	80	109	56	72	84	73
(5)	82	72	100	49	63	76	62
(6)	75	59	92	39	50	60	50
Carbon reduction	67%	71%	64%	77%	72%	70%	76%

UK house types kWh/(m²year) primary energy for heating from SAP 2005 and energy rating						
Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7
359	343	330	273	289	294	320
E	E	E	E	E	E	E

Appendix B.3

Validation of the IFORE models

In order to validate the models, the heating load of the un-retrofitted single storey house, type 2, was calculated using the French software Pleiade+Comfie and the heating load of a similar single storey house in France was calculated using ESP-r. The table below shows that the results were very similar using the two different computer programs.

Heating load [kW.h/(m².yr)]	Pléiade Comfie	Esp-r
Biez	120	116
Type 2 Manor Close	157	172

The table below shows the results of the validation of the models using the bills and the internal temperature from Wattbox. The results were published in Sdei *et. al.*, (2013).

	Energy heating from ESP-r using Wattbox set point temperature kWh/year	kWh/degree day for 2167.4 degree days using ESP-r climate file and wattbox set point	kWh/degree day using the bills and the internal temperature of 15.5 °C = 1734.3 HDD
Type 2	6696	3.09	
Type 3	6878	3.17	3.43
Type 5	9398	4.34	4.07
Type 6	11096	5.12	5.08
Type 7	9123	4.21	

Appendix B.4

Prices of shading devices

- The column O&P and sundries means overhead and profit, sundries are additional costs not included in the main material or labour cost columns (Laxton's, 2013)
- The price of the Acer Campestre was found in Spon's (2005)
- The asset life of the Acer Campestre (50 years) was based on private conversation with Shelley at Debbie's Garden World in Gillingham, 02-06-2015
- The maintenance price of Acer Campestre (£11.77/year) was based on Spon's (2005) p. 86 bag of bulk mulch at £ 188.46/100m² and on private conversation with Shelley at Debbie's Garden World in Gillingham, 02-06-2015
- The price of an external overhang/fins (114/m²) was found in Spon's (2007) pp. 31, 32
- The maintenance price for an external overhang /fins (£4.8/year) was based on the recommendation (to paint timber surfaces every 5 years) given by Anglian home improvements, private conversation, 02-06-2015, and on Spon's 2005 pp. 31, 32
- The price of internal roller blinds was based on Laxton's (2013) 1200mm drop and a width of 2000mm p. 300
- The asset life of internal roller blinds was based on a private conversation with The Blinds Factory, 02-06-2015
- The price of venetian blinds was based on Laxton's (2013) the price given is for aluminium venetian blinds with slats 25mm wide, 1200mm drop and a width of 2000mm p. 299
- The asset life of venetian blinds was based on private conversation with The Blinds Factory, 02-06-2015
- The price of external roller blinds is based on Laxton's (2013) 1200mm drop and a width of 2000mm p. 300
- The asset life of external roller blinds was based on Enviroblinds (private conversation with Hannah Ylitalo 01-06-2015)
- The maintenance of external roller blinds was based on ½ hour of maintenance per year (Hannah Ylitalo, Enviroblinds, private conversation, 01-06-2015) at £ 12.63/hour for a general building operative (Laxton's, 2013)
- The price of awnings is based on Laxton's (2013) foldaway awning acrylic material; natural anodised arms and front rail 2000mm projection, 2000 long p. 300
- The asset life of awnings is based on Enviroblinds (private conversation with Hannah Ylitalo, 01-06-2015)
- The maintenance price of awnings is based on ½ hour of maintenance per year (Hannah Ylitalo, Enviroblinds, private conversation, 01-06-2015) at £ 12.63/hour for a general building operative (Laxton's, 2013)
- The price of external shutters is based on Laxton's (1996) p. 36
- The asset life of external shutters is based on the recommendation of the Shutter Store 04-06-2015
- The maintenance price of external shutters is based on the recommendation to paint timber surfaces every 5 years given by Anglian home improvements, private conversation, 02-06-2015, and on Spon's 2005 pp. 31, 32