Evidence Review of the Potential Wider Impacts of Climate Change Mitigation Options: Built Environment Sector

Report to the Scottish Government

January 2017

Report Title	Evidence Review of the Potential Wider Impacts of Climate Change Mitigation Options: Built Environment Sector
Customer	Scottish Government
Report Reference	995

Author(s)	Alison Pridmore, Alison Smith, Keith Baker, Christofer Ahlgren, Tim Williamson
Reviewed by	Tim Williamson
Signature	

Aether Ltd

Oxford Centre for Innovation

New Road

Oxford

OX1 1BY

Registered office: Oxford Centre for Innovation, New Road, Oxford, OX1 1BY. Registered in England 6630896

Acknowledgements

Aether would like to acknowledge and thank all the individuals and organisations that have provided information and advice during this project and through the Call for Evidence. Special thanks are due to the Scottish Government Project Steering Group for their essential guidance and vital input throughout the project. The views expressed, however, are those of the authors.

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List of Abbreviations

CHP – Combined Heat and Power

DALYs – Disability Adjusted Life Years

DECC – Department for Energy and Climate Change

DEFRA – Department for Environment, Food and Rural Affairs

EEA – European Environment Agency

EEP – Energy and Environment Prediction

EHS – English Housing Survey

EPSRC – Engineering and Physical Sciences Research Council

ESRC – Economic and Social Research Council

GDP – Gross Domestic Product

GHG – Greenhouse Gas

HIDEEM – Health Impact of Domestic Energy Efficiency Measures

IDEAL – Intelligent Domestic Energy Advice Loop

IEA – International Energy Agency

MVHR – Mechanical Ventilation and Heat Recovery

NERC – Natural Environment Research Council

NICE – National Institute for Health and Care Excellence

NSIPs – Naturally Structurally Insulated Panels

PM – Particulate Matter

RCUK – Research Councils UK

RPP - Report on Proposals and Policies

SPLiCE – Sustainable Pathways to Low Carbon Energy

QALYs – Quality Adjusted Life Years

UHI – Urban Heat Island

UNEP – United Nations Environment Programme

VOCs – Volatile Organic Compounds

WHO – World Health Organisation

Executive summary

- This evidence review is based on a systematic literature review of over 80 papers on the wider impacts of climate change mitigation in the built environment sector. The review looked at qualitative and quantitative sources of relevance to the Scottish context. Particular consideration was given to the impacts from an equalities perspective.
- Overall the evidence base suggests there are a number of potential co-benefits associated with climate change mitigation measures in the built environment sector, with health and fuel poverty reduction benefits associated with increased energy efficiency identified as a key theme. It is important to note that the extent of co-benefits is dependent on how and where policies are implemented and consumer understanding and uptake.
- There is strong evidence that improved energy efficiency (e.g. through insulation) can result in warmer homes which can lead to substantial physical health benefits. These health benefits relate to reductions in disease and mortality. The elderly and young children, in particular, may benefit. Mental health benefits are also identified and include reductions in stress, e.g. due to mitigation of concerns over high energy bills and household debt.
- For physical health benefits, several methods exist to quantify and to capture these benefits. To quantify in the Scottish context further work is required. In terms of quantifying impacts, household dynamics (e.g. in relation to differing thermal comfort levels and ventilation needs) and the challenges inherent in quantifying human behaviour need to be acknowledged.
- The fuel savings associated with increased energy efficiency can be substantial. There is, however, the potential for rebound effects where cost savings may result in the uptake of more carbon intensive behaviours or increased consumption. However, these could be considered as co-benefits if they help increase quality of life and reduce social inequality.
- Energy efficiency also offers benefits for the non-domestic sector including cost savings and increased productivity.
- There is increasing interest in and correspondingly an emerging literature on Green infrastructure (strategically planned and managed networks of green spaces). Green infrastructure offers many benefits including reducing the urban heat island effect, which can reduce health risks to occupants especially the elderly. It can also offer well-being benefits, reflecting the importance of access to green spaces on the health of people of all ages.
- Behaviour change, e.g. turning down the thermostat, can result in carbon reduction in the short term, and offers participants financial benefits. Challenges include the provision of clear guidance and the scalability of results. Though the literature is in the early stages, smart metering has been shown to bring sustained changes in behaviour and can act as a tool for engagement at the community level.

- The reduction in use of fossil fuels, either through avoided energy consumption, the use of less energy-intensive materials or the use of low carbon energy sources (e.g. solar) and more efficient heating, cooling and lighting technologies can offer air quality benefits. Emission savings depend on the source of heat or power currently used.
- The use of sustainable building materials offers several potential co-benefits, e.g. through the diversification of forestry and agricultural co-products. Further research is required to better understand the implications for employment.

1 Introduction

1.1 Background

The statutory framework for greenhouse gas (GHG) reduction created by the Climate Change (Scotland) Act 2009 sets the ambition to reduce GHG emissions by 42% by 2020 and 80% by 2050 compared to 1990 levels (Scottish Government, 2009). As of today Scotland is on track to meet this target, with recently published data for 2014 indicating that the 2020 interim target had been met six years ahead of schedule (Scottish Government, 2016a). According to Section 35 of the Act, Scottish Ministers are under a duty to present a Report on Proposals and Policies (RPP) to the Scottish Parliament, defining specific measures to reduce GHG emissions to meet Scotland's statutory targets. The Scottish Government published the second Report (RPP2) in June 2013, covering the period 2013 – 2027 (Scottish Government, 2013). The Climate Change Plan sets out proposals and policies for meeting targets to 2032.

There is increasing recognition that actions designed to reduce GHG emissions not only mitigate the risks of climate change but may also either help or restrict the achievement of other societal objectives such as improved air quality, health and energy security (Committee on Climate Change, 2016). Together, these benefits and potential adverse impacts of climate change mitigation might provide additional incentives or potentially disincentives for strong actions to reduce GHG emissions or at least to heavily influence the design and implementation of emission reduction policies and measures.

A more detailed understanding of such potential co-benefits and adverse side effects is an important part of the foundation underpinning the development of future Scottish Government policies. Information on the impacts of climate change mitigation across the built environment policy area helps improve understanding of social and economic benefits and the role these could play in helping to create a fair, more equal and prosperous Scotland.

The Scottish Government commissioned Aether and Aether Associates to provide a synthesis of qualitative and quantitative evidence relevant to the Scottish context, indicating the direction and magnitude of any potential wider impacts of climate change mitigation actions in the built environment sector. Where possible the study identifies quantitative models and tools, and evaluates impacts in terms of social equality. This is the final report of the study.

1.2 Definitions and framing

Climate change mitigation action is typically evaluated in terms of the GHG emissions avoided per unit of expenditure, often expressed as cost per tonnes of CO_2 equivalent. The GHG savings will lead to benefits arising from reduced climate change, such as lower sea level rise and fewer extreme weather events. However, these actions usually have other impacts – both positive and negative – beyond the benefits of avoided climate change and the direct financial costs of the mitigation action. These wider impacts are referred to as co-benefits if they are positive and adverse side-effects if they are negative, sometimes jointly referred to as co-impacts. In the built environment sector, for example, increased levels of insulation and draught-proofing could give rise to a range of co-benefits including the health and wellbeing benefits from more comfortable living conditions (Smith et al., 2015). However, an increase in concentrations of air pollutants if ventilation is reduced could subsequently lead to adverse health impacts (Citizens Advice Scotland, 2016; Wilkinson et al. 2009). It is often possible to mitigate adverse side-effects, in this example through installing additional ventilation options (e.g. Vardoulakis et al., 2015).

When considering the financial costs of energy consumption, it can be hard to define the boundary between direct costs and benefits and co-impacts. For example, energy efficiency in buildings should lead to reduced energy costs. These energy cost savings are widely treated as a co-benefit in the literature, but they are also often included in the cost-benefit assessments that contribute to the GHG mitigation investment decision – in other words, they are included in the calculation of the cost per tonne of CO_2 avoided. It is important to avoid double-counting these benefits. Conversely, the literature does not generally treat any increases in household energy prices arising from investment in low carbon energy generation as an adverse side-effect, as these are generally assumed to be factored into climate policy assessments. In both cases, however, changes in energy costs can be treated as co-impacts if they have unintended side-effects, e.g. if they fall disproportionately on particular sectors of society – either increasing or decreasing fuel poverty and social inequality.

Although most co-benefit studies refer to the wider impacts of climate change mitigation policies, as described above, some address the impacts of non-climate policies, such as air quality legislation, on greenhouse gas emissions. For example, the use of biomass stoves in built-up areas can be restricted to protect urban air quality, and this could limit the potential for low-carbon heating in buildings[1]. There are also studies that take a more holistic view, assessing all the impacts of a technology or policy on an equal basis, including both climate and non-climate impacts. Although some early studies defined co-benefits as ‘benefits not related to

[1] Conversely, this can be presented as a policy option to mitigate the potential adverse air quality impacts of an increased uptake of biomass fuelled heating.

the primary aim of a policy or action', it is now acknowledged that not all policies or actions have a single primary aim, and it could be better to assess all impacts within a 'multiple objective, multiple impact' framework (Ürge-Vorsatz et al., 2014). A number of papers now refer to 'multiple benefits', including GHG savings alongside other impacts, rather than co-benefits. All these different framings are addressed in this report.

This report focuses on the wider impacts of GHG reduction measures. These wider impacts need to be considered alongside the cost-effectiveness and abatement potential of each mitigation option for greenhouse gas reduction, so that policies can be designed to meet climate targets while maximising co-benefits and reducing adverse side-effects.

1.3 Research aim and objectives

The aim of this project is to increase the Scottish Government's understanding of the potential wider impacts for Scotland of climate change mitigation actions to support the development of the Climate Change Plan.

The objectives of this project are:

- To produce a synthesis of qualitative evidence which indicates the direction (positive/ negative) and potential magnitude of the potential wider impacts of climate change mitigation actions which would be relevant to the Scottish context.
- To identify the most robust quantitative models and tools which would enable quantification and, where possible, monetisation of the potential wider impacts of climate change mitigation actions which would be relevant to the Scottish context.

These objectives are underpinned by the following research questions:

1) What is the evidence, both quantitative and qualitative, of potential wider impacts (co-benefits and adverse side effects) arising from climate change mitigation actions which would be relevant to the Scottish context?
2) Based on a review and synthesis of qualitative evidence: what are the key sources of robust evidence; and what is the balance of evidence, in terms of direction (positive/negative) and potential magnitude, of those wider impacts relevant to Scotland?
3) Based on a review and synthesis of quantitative evidence: which models and tools are assessed as the most robust to quantify and, where possible, monetise such wider impacts? What quantitative data would be required to apply these models to Scotland? What key assumptions are required?
4) From an equalities perspective, what evidence is there about the potential distribution of wider impacts relevant to Scotland across the population?

5) What are the most significant gaps in research and evidence about potential wider impacts which are relevant to Scotland?

2 Approach to the evidence review

The study incorporated a detailed search of the available evidence to improve the understanding of the current knowledge base. The search used a three-way methodology:

- Systematic literature search,
- Call for evidence,
- Review of current research grant programmes.

Specific areas of interest had already been covered by two recent studies. The Department of Energy and Climate Change (DECC)[2] funded co-benefits project (Smith et al., 2017) identified a number of key research areas and developed a database of literature relevant to the UK context, providing a good coverage of health-related co-benefits in the built environment sector. Secondly, the Department for Environment, Food and Rural Affairs (Defra) funded Sustainable Pathways to Low Carbon Energy (SPLiCE) project, published in 2015, summarised evidence on impacts (positive and negative) of energy technologies through conducting a 'review of reviews'. This present work, for the Scottish Government, reflects outcomes and recommendations from the above two research projects and, in particular, provides an opportunity to consider the role of quantitative modelling and the implications of the wider impacts on social equity in greater detail.

2.1 Literature search

The literature search performed for the Scottish context study took place from July to August 2016, and covered four key sources:

- ResearchGate (articles, working papers and conference papers)
- Repec (economics articles and working papers)
- Scopus (research articles and working papers)
- Google Scholar (all of the above)

The research further incorporated an additional literature search of relevant grey literature, searching the websites of key organisations, including the International Energy Agency (IEA), the National Institute for Health and Care Excellence (NICE), the European Environment Agency (EEA) and the World Bank. Additional references were included by 'snowballing', i.e. including important papers referenced by some of the reviewed papers. A particular point of relevance is the large body of built environment research evidence not necessarily framed as co-benefits. For example, there is historic literature on energy efficiency improvement and fuel poverty that does not necessarily utilise a co-benefits terminology. Consequently, more focused literature searches were undertaken, for these areas, where appropriate.

[2] In July, 2016, the Department of Energy and Climate Change was merged with the Department for Business, Innovation and Skills (BIS), creating a new department for Business, Energy and Industrial Strategy (BEIS).

In total over 80 papers relevant to Scotland and the built environment sector were identified through the literature search, and their bibliographic details were added to a database. Most of these papers addressed the use of energy efficient technology in buildings, or were framed in terms of general action to achieve GHG reduction targets, but a number also considered lower carbon fuels, building insulation and energy saving behaviour.

2.2 Call for evidence and research grant analysis

A call for evidence was directed at key research organisations that had been identified from the literature search, as well as relevant organisations identified from networks in Scotland, the UK, or internationally. This resulted in over ten submissions with responses from a range of organisations. These responses were added to the database as appropriate. Furthermore, the review incorporated a research grant analysis to understand current and planned research funding relevant to the co-benefits agenda in the UK and internationally. Research funding sites reviewed included the Engineering and Physical Sciences Research Council (EPSRC), the Economic and Social Research Council (ESRC), the Scottish Government, Innovate UK, the European Union (EU), the Research Councils UK (RCUK) and the Natural Environment Research Council (NERC). Relevant examples include the EPSRC-funded IDEAL (Intelligent Domestic Energy Advice Loop) project, which examines behaviour change and home energy use, and research into energy use behaviour and smart meters. The University of Edinburgh are the Principal Investigator for both projects, due for completion in 2017.

2.3 Framework for the report

Climate change mitigation in the built environment sector can be framed around an avoid/shift/improve framework (see e.g. Dalkmann and Brannigan, 2007 for the use of this approach in the transport sector). It has been adopted in this report to reflect the wide range of potential mitigation options available to the Scottish Government. The framework comprises:

- Avoid: reduce energy demand [Chapter 4]
    - Insulation and other building fabric improvements
    - Behaviour change
    - Building design
- Shift: a more sustainable built environment [Chapter 5]
    - Low carbon building materials
    - Green and blue infrastructure
- Improve: low carbon energy options [Chapter 6]
    - Renewable electricity and heat sources

The above framework is used to set out the findings from the literature review in Chapters 4 to 6 with an overview of results presented in Chapter 3. Chapter 7 summarises cross theme co-benefits relating to air quality and future energy security. Chapter 8 presents conclusions and recommendations.

3 Overview of results

This Chapter provides an overview of the direction and magnitude of impacts under the shift, reduce, avoid framework, this is complemented by a summary table, and outcomes are then framed within the research questions identified in Section 1.3.

3.1 Direction and magnitude of impacts

Avoid: reduce energy demand

- **Insulation and other building fabric improvements.** There is a rich established evidence base on the introduction of building energy efficiency measures including wall, floor and roof insulation; air-tightness; lagging of pipes and boilers; and double or triple-glazed windows. Co-benefits include health and well-being improvements from improved thermal comfort and reduced dampness and mould, as well as fuel cost savings. Although these cost savings may result in the uptake of more carbon intensive behaviours or increased consumption (rebound effect). A key benefit is that reductions in fuel poverty may occur. Productivity associated with commercial buildings can be significantly improved, which can have considerable economic benefits.
- Insulation in existing buildings can be improved through **retrofitting**, which can generate local socio-economic benefits. Retrofitting is the process of refurbishing the existing housing stock, for example, by fitting energy efficiency measures such as insulation.
- It is cost-effective to ensure that new buildings are as energy-efficient as possible. **Building standards** for energy efficiency will influence the sustainability of buildings constructed in Scotland for decades to come, with new buildings representing ~ 1% of the building stock each year. Care must be taken to ensure that adequate ventilation is provided in air-tight buildings, to avoid build-up of radon and other indoor air pollutants.
- **Behaviour change** in the built environment sector, such as turning down the thermostat and turning off unused lights and appliances, can achieve significant carbon savings in the short term, unlike infrastructure development with timescales ranging from years to decades. Benefits include consumer fuel cost savings. Behaviour change can be facilitated in several ways, such as through price incentives or information provision e.g. through the introduction of smart metering.

Shift: a more sustainable built environment

- Use of more **sustainable building materials** such as timber, and ensuring end-of-life re-use of materials, can provide co-benefits by reducing the overall life cycle impact of buildings. This is consistent with a circular economy approach to building materials and waste arising from the construction and demolition of buildings. Co-benefits include avoided environmental damage from the extraction, processing and manufacture of high carbon building materials such as steel, bricks and concrete, e.g. the land use impacts and reduced air and water pollution arising from quarrying, mining and smelting.

- **Building regulations** can be used to promote the use of sustainable building materials, as well as being used in the more familiar way to enforce energy efficiency standards (see below).
- In the Scottish context, there are opportunities for **production and diversification of forestry and agricultural co-products** such as timber for construction and sheep's wool for insulation, which can lead to socio-economic co-benefits for rural economies.
- **Green infrastructure** such as green roofs and walls can provide insulation, reducing heat demand during cold periods, and cooling, reducing the need for air conditioning during heat waves. Trees close to buildings can also provide shade and shelter, and parks, gardens and water features help to provide urban cooling on hot days. Co-benefits include positive impacts on biodiversity and urban wildlife, aesthetic value, places for outdoor recreation, reduced storm-water runoff, air and water quality improvements and carbon sequestration. **Planning regulations** can be used to promote green infrastructure, e.g. by specifying the amount of green space that should be included in new developments, and encouraging multifunctional green infrastructure such as green roofs.

Improve: low carbon energy options

- Adoption of low carbon energy sources such as **solar panels** can lead to air quality co-benefits from avoided fossil fuel emissions and energy security benefits. However, there could be adverse side-effects from the adoption of **biomass** for heating (if biomass replaces gas in urban areas), unless combustion emissions are controlled or a targeted approach is used. Biomass also needs to be from a sustainable source - to minimise potential negative impacts on biodiversity and soil fertility that can occur.

Magnitude of impacts

Several studies conclude that the magnitude of the co-benefits outweighs potential adverse side effects in the built environment sector (e.g. Clarke et al., 2014). Modelling studies conclude that for home energy efficiency, the health benefits arising from increased thermal comfort outweigh the risks associated with deteriorating indoor air quality such as the accumulation of radon, and that such risks can be mitigated through the adoption of improved ventilation (Vardoulakis et al., 2015; Wilkinson et al., 2009). A major study of the multiple benefits of energy efficiency by the IEA concluded that health improvements from warmer buildings in cost-benefit analyses can result in cost-benefit ratios of up to 4:1, and the value of industrial productivity and operational benefits can be up to 2.5 times greater than the value of energy savings (IEA, 2014).

A qualitative summary is provided below in Table 3.1 which sets out the direction and magnitude of impacts for the different mitigation actions with the rationale covered in the following Chapters.

Table 3-1. Magnitude and direction of co-impacts in the built environment

Mitigation action	Economic competitiveness Resource costs, resource security, innovation*	Health (AQ, lifestyle, accidents)	Social (equity community, poverty)	Natural Capital (incl. water, soil, biodiversity, waste)**
Energy efficiency including insulation	++	++	++	+
Behaviour change including optimal heating and ventilation	++	++	+	+
Building design	+	+	+	+
Sustainable building materials	+	+	+	++
Green and blue infrastructure	+	++	+	++
Renewable electricity and heat sources	++	+	+	+/ -
Biomass	+	+/-	+	+

*** Excludes direct investment cost – this focuses only on additional costs or benefits**
** **Includes upstream impacts of avoided fuel production**

Legend	
++	Strong positive effect
+	Positive effect
0	No significant effect
+/-	Variable effect
-	Negative effect
- -	Strong negative effect
	Weak evidence
	Moderate evidence
	Robust evidence

Weak evidence relates to there being limited evidence currently available or that the available evidence is less robust. Robust evidence relates to stronger evidence base relating to the quality of and number of papers.

4 Avoid: reduce energy demand

Mitigation options such as insulation and consumer behaviour change can help reduce energy consumption. These options and their potential co-benefits are considered below.

4.1 Insulation and other building fabric improvements

Qualitative evidence – health and comfort benefits

Building fabric improvements, including insulation and draught-proofing, form a key focus of the literature associated with climate change mitigation in the built environment. Insulation can provide **health benefits** by maintaining more comfortable indoor temperatures that are warmer in winter and avoid over-heating in summer (Liddell and Morris, 2010). In the Scottish context, under-heating is currently more of a problem than over-heating. There are mortality impacts associated with cold temperatures in the UK – more deaths occur in winter (National Records of Scotland, 2015) and cold indoor temperatures are closely linked to this, with the risks being greatest for residents in homes which are not well insulated (Wilkinson et al., 2009). The World Health Organisation recommends a minimum temperature of 21^{o}C in living rooms, and 18^{o}C in all other rooms (for a period of 9 hours in every 24, or 16 hours in 24 over the weekend). For elderly and infirm households, the recommendation is 23^{o}C in the living room and 18°C in other rooms, to be achieved for 16 hours in every 24.

Warmth and energy efficiency improvements can result in improved general, respiratory and mental health as well as reductions in absence from work. These improvements are most significant when action is targeted at individuals experiencing chronic respiratory disease or inadequate heating (Thomson et al., 2013). Improvements in insulation can result in direct effects on winter mortality and potentially morbidity as well indirect effects e.g. through reductions in mould growth (Wilkinson, 2009), which in turn can reduce Disability Adjusted Life Years (DALYs), with a DALY considered one lost year of “healthy” life (WHO, 2016).

Table 4-1 Health effects of the UK Stock Scenarios

	Fabric improvements	Improved ventilation control
Premature death	-7	-6
DALYs	-62	-48

Data are change per million population compared with baseline (2010). Negative values show reductions in disease burdens.

Source Wilkinson et al. (2009)

Caution is required, however, as there is an increasing evidence base on the possible adverse impacts of air tightness on indoor air pollution from radon and other pollutants, and the need for better (and correctly used) ventilation to address this (e.g. Wilkinson et al. 2009; Gupta and Kapsali 2015; Shrubsole et al., 2015, Shrubsole et al., 2012).

Furthermore, **over-heating**, must not be dismissed as an issue. Research examining the potential for overheating in existing building stock (e.g. AECOM, 2012 and references within) which suggests that type of building (e.g. small, top floor, purpose built flats) and age of building (with the 1960s being identified) can be linked to the potential for overheating. There is currently limited research on overheating (in existing building stock) specific to Scotland; research on overheating risk in buildings housing vulnerable people is planned by ClimateXChange (2016). There is emerging research on new build low energy buildings in Scotland, with a focus on the Passivhaus approach of lightweight, airtight construction and mechanical ventilation and heat recovery (MVHR). This suggests that a combination of poor design, effective heat retention and occupant behaviour has created health concerns due to overheating, especially among vulnerable groups (Morgan, et al., 2015). Morgan et al. (2015) suggests that there has been a lack of awareness of overheating in Scotland and its links to occupant behaviour and energy efficiency measures. Aspects relating to an individual's personal level of comfort and discomfort also need to be taken into consideration (e.g. Lamond, 2011). Further research is, therefore, necessary on how best to adapt the Passivhaus approach to the **Scottish climate and culture**, and on the potential benefits of the approach for carbon savings and occupant health (Citizens Advice Scotland, 2016). In terms of potential **adverse side effects,** over-reliance on MVHR to draw in air from the outside can potentially lead to increased levels of Volatile Organic Compounds (VOCs) and pathogens (Roaf et al., 2009). Others suggest that naturally ventilated buildings designed not to require MVHR are more beneficial both for thermal comfort and the general quality of indoor environments (Aynsley, 1999). Finally, there are also some concerns over the ability of householders to understand and use MVHR systems to optimise their benefits (Macintosh and Steemers, 2005). Lack of user understanding can be linked to poor guidance and inadequate training (Gupta and Kapsali, 2015). While inadequate commissioning of the systems can also cause insufficient air supply and corresponding poor indoor air quality (Gupta and Kapsali, 2015).

Mental health benefits complement the above **physical health** benefits. Inefficiently warmed homes cause thermal discomfort (Gilbertson, Grimsley and Green, 2012), and the associated fuel poverty can result in a range of stress responses including financial concerns over high energy bills (Anderson et al., 2000) and debt (Tod et al., 2012). Mental health impacts have been quantified in an innovative study relating to the Kirklees Warm Front programme. An overall cost benefit ratio of 0.2:1 was calculated for the whole project indicating that 20% of all costs were recouped due to health benefits. Of this 50% were attributed to mental health benefits (Liddell, Morris and Langdon, 2011).

The introduction of energy efficiency measures results in statistically significant reductions in stress (IEA, 2014). The extent to which these benefits can be captured and used in the assessment of the impacts of energy efficiency policy is an area of current academic discussion (IEA, 2014).

Heating only part of a home can be deployed as a measure to reduce fuel costs (e.g. Chard and Walker, 2016). There is therefore the potential for an increase in usable space if energy efficiency measures result in more rooms being heated, thus improving an individual's relationship with their home and offering increased privacy and opportunities for studying and entertaining (Thomson, et al., 2013). Further research to understand these relationships in more detail is required in order to identify where and how policy measures can be targeted to maximise co-benefits to those most in need. There are also evidence gaps regarding the impact that housing improvements may have on reducing health inequalities (Thomson et al., 2013).

Qualitative evidence - fuel cost savings

Fuel cost savings arising from increased efficiency are also a key feature of research studies, with the potential to address fuel poverty discussed in the next section. There is the potential for substantial financial benefits through investment in energy efficiency. Sovacool (2015) indicates that £1 invested in UK Warm Front programme produced as much as £1 to £36.30 in benefits over a 20-year period. These benefits include monetised energy savings and resulting reductions in household costs but not health benefits. How these savings are spent by households determines the size of the net energy saving and any related co-benefits. Actual energy savings are often lower than anticipated, due to the **'rebound effect'**. This can be because households choose to spend some or all of the money saved on fuel or on other goods and services (with associated GHG emissions), and because they tend to take some of the energy efficiency gains in the form of increased thermal comfort rather than reduced energy use. The results of various studies, including emerging evidence on Scottish households from a project undertaken by the Centre for Energy Policy at Strathclyde University (CEP, forthcoming), show that the rebound effect is generally larger than is often assumed and that it applies asymmetrically across the population, with households on lower incomes taking back greater amounts of the savings from energy efficiency interventions as heat (and light).

The **'prebound'** effect is a related but much less understood phenomenon that arises from under-consumption of energy by householders, leading to models over-predicting actual consumption and the savings from energy efficiency measures. This effect may result from householders choosing or adapting to lower internal temperatures, but it also results from behaviours to limit energy use, and so is a strong indicator of fuel poverty (Galvin and Sunikka-Blank, 2016). More research is needed on the prevalence, causes and impacts of self-limiting energy behaviours as the evidence for this, whilst consistent, remains largely anecdotal. New research indicating self-limiting behaviours with a group of households on the Isle of Skye contributes to this evidence base (Baker et al., 2016; Citizens Advice Scotland, 2016).

The magnitude of the fuel and GHG emissions savings from fabric improvements thus depends on how households choose to spend the money they save from lower energy bills. If the house was previously underheated, they may choose to turn the thermostat up, thus taking some or all of the savings as increased thermal comfort. There could also be a rebound effect if the money saved is spent on other high-carbon goods or services such as foreign travel or electrical appliances. Comfort savings or increased expenditure could be considered as co-benefits if this helps to increase quality of life and reduce social inequality, though the climate mitigation benefit may be lower than expected (IEA, 2014). Energy efficiency and associated financial savings can, therefore, help address fuel poverty and have social equity benefits.

An increased understanding of these effects would enable better targeting of energy efficiency and fuel poverty schemes at households and communities where they can leverage the greatest co-benefits to poverty and health. Such an understanding would also enable a better understanding of geographic and socio-economic differences in householders' responses to energy efficiency interventions, as well as better modelling and forecasting of energy demand and emissions from the Scottish housing stock. Finally, it would enable the identification of, and support for, more effective and individualised behavioural and lifestyle change measures.

Qualitative evidence - fuel poverty

Fuel poverty can be defined in different ways - 1) As greater than ten percent of income being spent on staying warm (Boardman, 2010) and 2) Where the required fuel costs are above the median level and if the household were to spend that amount their residual income would be below the official poverty line (Hills, 2012). Fuel poverty is due to a mixture of factors including high energy costs, poor housing quality and lower incomes (IEA, 2014). Poorly constructed and poorly maintained houses are more likely to be inhabited by people with low incomes and this has indirect impacts on equity and health outcomes (Liddell and Morris, 2010).

The energy efficiency measures identified in this report offer opportunities to reduce fuel poverty, reflecting upfront fuel cost savings to consumers. Energy efficiency measures can be a longer term solution rather than for example, fuel payments, because they address a key cause of fuel poverty (IEA, 2014). The potential rebound effect can be considered to be positive if it helps reduce poverty or achieve broader well-being (IEA, 2014). With regard to equity impacts there is an emerging literature that considers which socioeconomic groups could benefit most from grant based schemes. This can make a substantial contribution from an equalities perspective reflecting that the health and well-being benefits are greatest amongst vulnerable groups. This includes the elderly, children in low income households[3] and those with existing illnesses (e.g. respiratory problems). These benefits can have broader implications for example the link between healthy homes and reductions in absenteeism from school and work. Reduced school absences have been identified in Howden-Chapman et al., 2008, 2009, 2012, and Preval et al., 2010 and reduced work absences in Howden-Chapman et al, 2007; Laing and Baker, 2006.

Health, and mental health, are generally thought to be both influences on and outcomes of energy behaviours and vulnerability to fuel poverty (Annesi-Maesano et al., 2014; Bernstein et al., 2008; Bornehag et al., 2001; CASD, 2010; Citizens advice Scotland, 2016; Fisk et al., 2007; Grant et al., 1989; Howden-Chapman et al., 2012; Jones, 1999; Kim et al., 2013; Liddell and Morris, 2010; Mendell et al., 2011; Nandasena et al., 2012; Thomson et al., 2003). Research is needed to understand these relationships in more detail including where and how policy measures can be targeted to maximise co-benefits to those most in need.

Qualitative evidence – economic benefits

The literature also indicates that there could be broader **economic benefits** from energy efficiency in the built environment, including supporting local jobs, with investment potentially supporting 9.2 to 17.1 jobs per million EUR invested (Copenhagen Economics, 2012; European Commission, 2011; Lehr, et al., 2012 in IEA, 2014). Retrofitting insulation has the possibility of providing **local 'green' jobs** (see e.g. Cecere and Mazzanti, 2015; Consoli et al., 2015; Lehr et al., 2012; Ryan and Campbell, 2012; UNEP, 2008; WHO, 2014).

A UK based study (Verco and Cambridge Econometrics, 2014) suggests that energy efficiency programs can deliver substantial positive economic impacts, with energy efficiency measures identified including draft proofing and loft insulation. The study used English Household survey data and found that energy efficiency programs could deliver £3.20 through increased Gross Domestic Product (GDP) for every pound invested by the government, and the equivalent of a 0.6% GDP increase by 2030 compared to a baseline scenario. The investment assumed in the modelling totals £127.5 billion over a 20-year period, this covers direct government funding to low income homes (£26.9bn) and £73.2 bn from able-to-pay homes (which is supported by £27.4 bn of government loan schemes). The model also estimated a net growth of 108,000 jobs per annum over the period 2020 – 2030. Research (Lecca, et al., 2014) also suggests that if householders were to, because of cost

[3] The Scottish House Condition Survey (2002) found that households where the female has the highest income are at greater risk of being fuel poor, and women in particular are at greater risk of experiencing fuel poverty and living in unsuitable housing conditions (Scottish Government, 2012). The majority of women over the age of 75 also live alone which, combined with women being the main dependents on Scottish State Pensions and Pension Credits, increases risk of fuel poverty and living in suboptimal housing arrangements

savings, spend more money on goods and services then this would have positive impacts on GDP.

Energy efficiency in the non-domestic sector can also bring a number of benefits including reducing costs, increasing value and risk reduction (IEA, 2014). Reductions in costs include less money spent on energy but also on maintenance. Risk reduction and the helping of companies maintain a competitive advantage while increasing value relates to Corporate Social Responsibility opportunities. The value of industrial productivity and operational benefits can be up to 2.5 times greater than the value of energy savings (IEA, 2014). Improvements in productivity include reduced operating costs, reduced energy use and a resulting increased profit. It is possible that the increased competitiveness achieved through energy efficiency can filter down to the individual level, increasing job satisfaction and improving working conditions (Ryan and Campbell, 2012).

Quantitative models

Two key existing sets of models were identified which were of relevance to the Scottish context. These models are:

- Health Impact of Domestic Energy Efficiency Measures (HIDEEM)
- Energy and Environmental Prediction model

Health Impact of Domestic Energy Efficiency Measures

The HIDEEM model enables the quantification of co-benefits such as economic energy savings, comfort benefits, air quality benefits, and the quantified impacts of improved life expectancy. HIDEEM was developed for DECC by the UCL Energy Institute and the Complex Built Environment Systems Group, in collaboration with the London School of Hygiene and Tropical Medicine (Hamilton et al., 2015; Payne et al., 2015; UCL, 2016).

The model provides a bottom-up household-level estimate of indoor environmental exposure in the housing stock of Great Britain. It captures changes in exposures following the application of energy efficiency measures, with resulting changes in health. This includes impacts on heart and circulatory disease, strokes, cancers, as well as respiratory illness and mental health disorders (Payne et al., 2015).

The aim of HIDEEM is to quantify indoor environmental conditions and monetise health impacts associated with energy efficiency changes in houses, in line with DECC’s policy measures and interventions. The model’s two main components are a physics-based model of the indoor environment in UK houses, and models quantifying associated health impacts of exposure changes using life table methods. Health impacts are monetised through Quality Adjusted Life Years (QALYs). For example, HIDEEM estimates the value of health benefits arising from cavity wall insulation for a typical home as approximately £1,000, assuming an investment lifetime of 42 years. This is double the up-front investment cost for an easy-to-treat cavity wall, estimated as approximately £500 (Payne et al., 2015).

Data requirements

Example: HIDEEM

Hamilton et al., (2015) use the HIDEEM model to assess potential public health impacts arising from changes to indoor air quality and temperature if energy efficiency retrofits are undertaken in English dwellings to meet the 2030 carbon reduction targets. The study incorporates three retrofit scenarios: Scenario 1 assumes that fabric and ventilation retrofits are installed to meet building regulations. Scenario 2 utilises the same assumptions as Scenario 1, but with additional ventilation for houses at risk of poor ventilation and subsequent air quality. Finally, Scenario 3 utilises the same assumptions as Scenario 1, but with no additional ventilation.

The study identified changes in the QALYs over 50 years. QALYs are quality-adjusted life years and are a measure of length and quality of life in relation to health (NICE, 2016). The study found a positive impact of Scenario 1 due to improved temperatures and a reduced exposure to air pollutants, while Scenarios 2 and 3 led to an overall negative health impact due to an overall increase in indoor pollutant exposure.

Scenario	Net mortality (QALYs) per 10 000 individuals age >50	95% credible intervals
Scenario 1	2,241	2,085 to 2,397
Scenario 2	-728	-864 to – 592
Scenario 3	-539	-678 to – 399

HIDEEM uses survey data from the English Housing Survey (EHS), including data on the archetype dwelling forms, to inform assumptions on English dwelling stock (e.g. in relation to property type – detached, semi-detached, terraces and flats, floor area and notional permeability). EHS data incorporates information on age, sex and specific exposure changes. Life Tables are set up using age-specific population and mortality data.

For the Scottish context, data from the Scottish Household survey would need to be applied. The Scottish Household survey collects data relating to property and information on age and sex of occupants, which suggests that this could be used as a base for adaptation of the HIDEEM model to the Scottish context.

As with the use of all models, limits need to be acknowledged and model outcomes caveated accordingly. For example, Baker (2016) identifies two key weaknesses, 1) the uncertainties introduced by insufficient consideration of occupant behaviour, and 2) those introduced through insufficient consideration of toxicity. The former is a problem inherent in all housing models and so in this respect HIDEEM is the best currently available option however, the latter is potentially highly problematic as the range of VOCs covered is very limited and evidence from toxicological studies shows that mixtures of VOCs behave differently to individual VOCs in isolation (e.g. Groten, Feron, & Suhnel, 2001). This is unlikely to be a significant problem for applying HIDEEM to existing unimproved stock. However, it will become more significant when the approach is applied to the use of more complex manufactured materials and PassivHaus-type buildings. It is important therefore to take these impacts into consideration when the model is used. It is also worth noting the uncertainties in modelling economic savings for the health benefits of energy efficiency interventions, with a recent evidence review (Citizens Advice Scotland, 2016) finding that energy efficiency interventions generally only act to delay the first reporting of symptoms. In this respect, there are no doubt some savings to be had from reduced numbers of GP appointments and associated support, but given the dominance of lifestyle factors in determining the severity and outcomes of health problems any further estimates of savings should be treated with a high degree of caution.

The Energy and Environment Prediction (EEP) Model

Addressing aggregate emissions of larger urban areas will be crucial to reduce emissions, as opposed to a more ad-hoc house-by-house methodology. However, there are only a limited number of modelling tools attempting to quantify the impact of energy efficiency measures on a city scale. One such model is the Energy and Environment Prediction (EEP) tool developed in collaboration with local authorities in Wales to estimate impacts on energy use in the existing urban built environment (Jones et al., 2007). The model consists of a user interface linked to a GIS database which is in turn linked to a series of sub-models on housing energy, non-domestic energy and health.

Data from the EEP tool (e.g. on housing stock) was used in a study by Jones et al. (2007) to identify whether people's physical and mental health was affected by the quality of their housing (for the former) and the characteristics of the surrounding neighbourhood (for the latter). Physical health aspects examined home injuries alongside population data. While mental health aspects used two tools - one to assess neighbourhood quality and one to assess the mental health of the people. Findings show that mental health was overwhelmingly associated with economic factors such as jobs and income, and significantly associated with area deprivation and social capital (Jones et al., 2007). However, the research could not verify that older buildings had more negative effects on physical health (relating to hazards) than new buildings.

Data requirements

The EEP model and associated analysis suffers from several potentials barriers to use in a Scottish context. These include the substantial amount of data processing required to collect and process the data (Jones et al., 2007). The EEP housing sub-model for example, requires information on the size, shape and age of properties, with the method employed using a desktop survey, historical data to help estimate buildings age and a drive by survey of 55,000 dwellings (Jones et al., 2007). While the domestic energy sub-model is based on the UK government Standard

Assessment procedure and data including information on glazing, fabric, space heating and fuel costs is used.

4.2 Behaviour change

Qualitative evidence

Addressing behaviour change is complex; behaviours are shaped by a great many factors which are not only individual but are also contextual (Lopes et al., 2012). Studies of behaviour change require an interdisciplinary approach including both qualitative and quantitative evidence and can, therefore, be complex and resource intensive. Behaviours are not constant, but change over time depending on accumulated experiences (Lopes et al., 2012).

A range of benefits might stem from behaviour change in the built environment sector, and unlike infrastructure development with timescales ranging from years to decades, savings stemming from behaviour change can often be achieved in the much shorter term (Cabinet Office, 2011).

Improved energy use behaviours through optimal heating and ventilation behaviour can also lead to improved health and increased wellbeing through improved indoor temperature, reduced air pollution from pollutants such as such as radon, reduced mould and more comfortable variations of indoor temperatures (e.g. Citizens advice Scotland, 2016; Johnson et al., 2009). Improved indoor heating and ventilation can also hold social benefits as insufficient warmth, comfort and 'social acceptability' of a home might limit opportunities and willingness to build social networks by inviting friends and peers home (DECC, 2014b). Recent Scottish research (Ellsworth-Krebs, 2016) explores meanings and concepts of thermal and home comfort in the context of energy demand highlighting the importance of acknowledging homemaking (e.g. the potential preference for heritage features) when providing energy advice.

Furthermore, behaviour change including proportionately larger energy use during off-peak periods might provide indirect benefits to users through macroeconomic stability, reduced network losses and better energy services achieved at a lower cost (European Environment Agency, 2013; Ryan and Campbell, 2012). Energy efficiency improvements, and thus a reduced expenditure on energy bills, can drive increased consumer spending and, together with increased spending on energy efficiency products and reduced energy prices, can have the indirect effect of improving national competitiveness and supporting employment (Ryan and Campbell, 2012).

One of the challenges in achieving behaviour change is that people cannot fully understand the costs and benefits to themselves due to incomplete or uncertain information (DECC, 2014a). Inadequate information and a lack of understanding or access to information on energy efficiency measures lead to ill-informed choices that may not be optimal for individuals and the environment (DECC, 2014a). For example, a study conducted in Scotland looked at the effectiveness of installing new heating systems in houses. It revealed that many of the selected home owners did not fully understand how to operate their new heating systems, therefore, they were not being used in the most sustainable manner (Foster et al., 2016). Similarly, experiences of cold weather and houses that are expensive to heat created a perception that any heat is good. However, this was leading to inefficient systems, for example, hot water pipework that released heat due to insufficient insulation (Foster et al., 2016). A UK study found that the daily and seasonal operation of heating and ventilation systems was poorly understood due to a lack of easy-to-follow user guides and insufficient training during handover to users (Gupta and Kapsali, 2016). It can, therefore, be seen that both suppliers and occupiers need access to information to make choices that lead to efficient, sustainable homes and lifestyles. Research of relevance in the Scottish context is ESRC funded work on Smarter Homes which looks at how domestic low carbon technology influences demand with the work being undertaken (between 2013 and 2017), in part at the University of St Andrews.

A further challenge is that of **scalability** and this is important in understanding the quantification of potential benefits. Many policy actions that target behaviour change are focused on small changes at the individual level, the justification being that they are a precursor to larger scale behaviour change or that they initiate increased involvement in the political process of change (Creamer, 2015). However, the effects of these small, individual level behaviour changes are often hard to predict. It is uncertain to what extent they contribute to the overall, high level sustainability agenda. For example, some evidence suggests that individuals who change one part of their lifestyle to be more 'pro-environmental' may view this as off-setting another behaviour that is detrimental to the environment, thus provoking a negative rebound effect rather than an overall uptake of a sustainable lifestyle (Creamer, 2015).

Perhaps the most apparent and quantifiable co-benefits associated with behaviour change are both short and longer term financial impacts. However, the cost savings could be used to purchase more goods and services with an associated carbon impact (the previously discussed 'rebound effect'). However, modelling by Druckman et al. (2011) estimates that the rebound effect for lowering the household thermostat is relatively low, with just 7% of the energy savings being lost if households spend their energy cost savings following their usual consumption patterns.

Unlike investments such as insulation and new appliances, behaviour changes can often be achieved at no upfront cost (Cabinet Office, 2011). Savings from smart-metering, altered consumption patterns and optimised heating and ventilation behaviour can thus free up capital for other requirements, which is particularly relevant for households in economically disadvantaged communities (European Environment Agency, 2013; Kobus et al., 2015). Although potential rebound effects pose challenges to measures targeting energy efficiency and reduced energy use, households can be encouraged to recycle the financial benefits reaped through initial behaviour changes to finance more extensive infrastructure improvements such as insulation, which can address fuel poverty in the longer term.

Whilst campaigns to encourage energy-saving behaviour need to be simple, policymakers need to be wary of the 'blanket' approach as they are more successful if they are tailored to the community or to the level of innovation (McMichael and Shipworth, 2013). For example, in rural Scotland, it was found that the role of **community-led organisations** in encouraging behaviour change was crucial (Creamer, 2015). These organisations are embedded in the community and are therefore best placed to use local knowledge and establish networks to promote more sustainable lifestyles. They also have the necessary connections to build community capacity and increase individuals' willingness to change (Creamer, 2015). Research currently being led by the University of Edinburgh aims to analyse how the patterns of energy efficiency and heating demand differ between societies. This work, due to finish in June 2018, could be key in creating campaigns that are tailored to communities and society groups.

In the UK, 18% of the country's carbon footprint is made up of carbon dioxide emissions from non-domestic buildings, in particular, workplaces (Lockton et al., 2011). Promoting behaviour change in the commercial setting presents a challenge, as the individuals who are required to make the change do not pay the energy bills. This means that the financial incentive for change is significantly reduced (Christina et al., 2015). Business tasks often take priority and energy management can be seen as an additional task. In some cases, energy management can be seen as conflicting with business operations due to competition for individual workers' time (Christina et al., 2015). Research at the Edinburgh Napier University is seeking to investigate the energy consumption patterns in small to medium enterprises, assessing the possibility for behavioural change to reduce energy consumption. This work started in October 2014 and is due to be completed at the end October 2016.

The reduction in financial incentives for behaviour change in terms of investment in energy efficiency measures can also be seen in **rental houses**. The cost of energy efficiency improvements are borne by landlords whilst the benefits (lower energy bills) are received by the tenant and therefore there is less incentive for landlords to make energy savings.

Quantitative evidence

There is limited modelling of these benefits and challenges within a co-benefits framework and there is recognition (Smith et al., 2016) that further research on behaviour change from a social and behavioural science perspective is required to more fully understand how savings can be achieved in the longer term. Quantitative modelling outcomes of relevance e.g. regarding the rebound effect (e.g. Druckman et al., 2011) have been detailed in the previous section, with the rebound effect identified as a key future research area (discussed in Chapter 8).

4.3 Building design

A number of building design criteria exist which can help reduce energy demands. These include the orientation of buildings; shading of buildings; passive cooling and passive heating (e.g. Pacheco et al. 2012) as well as optimisation for natural light. The benefits of associated energy demand reduction include future energy security and air quality benefits and are detailed in Chapter 7. The optimisation for natural light can result in increased worker productivity (Figueiro et al., 2002).

5 Shift: a more sustainable built environment

Mitigation options which involve a shift to a lower-carbon built environment include the use of more sustainable building materials and the provision of green and blue infrastructure.

5.1 Sustainable building materials

Qualitative evidence

The built environment co-benefits literature addresses potential impacts arising from a shift towards **sustainable buildings** and **associated building standards** (Allen et al., 2015; Chauvin et al, 2016) including utilised building materials (e.g. Sutton et al., 2011).

The adoption of **sustainable building materials** (e.g. Sutton et al., 2011) can reduce the embodied energy of buildings by increasing the production of timber for structural and insulation products. These products can include cross-laminated structural components from both hardwood and softwood timber as well as recycled cellulose, sheep wool insulation materials and Naturally Structurally Insulated Panels (NSIPs) in new buildings (see e.g. Ecocel, 2016; MAKAR, 2016; NEES, 2013; Sutton et al., 2011; Thermafleece, 2016). Related to the adoption of sustainable building materials in the Scottish context, there are co-benefits relating to the use of forestry, woodland, and agricultural products for reducing operational and embodied emissions from buildings, through increasing the supply of timber products for manufacturing structural components and insulation materials. There was a clear consensus in the Scottish Forestry Strategy (Forestry Commission Scotland, 2006) that more could be done to achieve its aims, and that this could also leverage a wide range of co-benefits, including:

- increasing forest and woodland coverage (and sequestering carbon);
- socio-economic benefits for rural communities through increasing the production and diversification of forestry and agricultural co-products;
- supporting tourism and public health through better managing forestry and woodlands for biodiversity and recreation.

Research also suggests that natural and sustainable building and furnishing materials can improve indoor **air quality** by absorbing VOCs and regulating moisture and heat (James and Yang, 2005; Lee et al., 2005; NEES, 2013; Osanyintola and Simonson, 2006; Simonson et al., 2002).

Quantitative evidence

There is currently limited quantitative evidence and modelling related to the above benefits, and there is a particular need for increased and improved data on Scottish imports and exports of sustainable building materials in order to better understand

and quantify the potential for these industries to contribute to sustainable economic growth.

5.2 Green and blue infrastructure

Qualitative evidence

Green infrastructure includes natural and semi-natural features such as parks, gardens, woodlands and urban trees, as well as man-made features such as green walls and roofs. Blue infrastructure includes lakes, rivers, wetlands and smaller water features such as ponds and ditches for sustainable urban drainage (Sandström, 2002). These networks of structures and facilities are essential for maintaining connectivity in landscapes and deliver a multitude of social, economic and environmental benefits (Forest Research, 2010; Tzoulas et al., 2007). Increasing green and blue infrastructure in urban areas has significant potential to deliver co-benefits as part of climate change mitigation, climate change adaptation and sustainable development strategies for cities (e.g. Hollas, 2014; Huseynov, 2011).

The provision of green infrastructure has been cited as a prerequisite for forming healthy communities (Mazza and Rydin, 1997), and there is a large and growing volume of evidence of the benefits of access to green spaces on the health and wellbeing of people of all ages (e.g. Curl et al., 2016 and Teedon et al., 2014). Green infrastructure in urban areas can also help reduce the **urban heat island (UHI) effect**, thus reducing building energy demand for cooling and reducing the health risks to occupants, and particularly to elderly and vulnerable householders (Emmanuel and Krüger, 2012; Emmanuel and Loconsole, 2015; Glasgow Clyde Valley Green Partnership, 2013; Hollas, 2014; M'Ikiugu et al., 2012).

Green roofs, often referred to as living roofs, and green walls are vegetative layers on the roofs or walls of buildings with waterproofing, drainage and irrigation characteristics (Castleton et al., 2010). They have become increasingly recognised for the benefits they offer (Bianchini and Hewage, 2012; Kowalczyk, 2011), which compensate for the expenditure required in installing them, including:

1. Energy demand reductions from insulating the property
2. Reduction of Urban Heat Island (UHI) effects
3. Management of surface-water run-off
4. Improved external air quality
5. Absorption of GHG emissions
6. Habitat creation and biodiversity enhancement (Bianchini and Hewage, 2012; Castleton et al., 2010; Rosenzweig et al., 2006).

Quantitative evidence

Quantitative models and associated analysis as they relate to air quality aspects are covered in Chapter 7. There is currently limited consideration of green and blue infrastructure within a co-benefits modelling framework and it is recognised that there are challenges in evaluating the benefits of certain aspects e.g. the difficultly in attributing wellbeing related changes (in relation to physical activity or mental health) to a specific green infrastructure improvement (Smith et al., 2016). There is, however, a broader range of evidence e.g. in terms of impacts of energy demand reductions (as discussed in Chapter 4) which could be drawn upon in potential future model development.

6 Improve: low carbon energy supply

Low carbon energy supply options for buildings include renewable energy options (solar PV, solar hot water, solid biomass and biogas) and more efficient heating technology (heat pumps, efficient boilers and CHP).

6.1 Renewable energy sources

Qualitative evidence

Lower-carbon energy sources applicable for the urban built environment include the use of solar PV panels, solar hot water panels, heat pumps, combined heat and power (CHP), solid biomass and biogas.

These low carbon energy sources can offer **air quality benefits** by displacing emissions from fossil fuel combustion (apart from solid biomass – see below). These air quality benefits can have wider reaching distributional impacts, with research (Boyce and Pastor, 2012) indicating that lower income and minority groups are more likely to live next to polluting point sources such as fossil fuel power stations. There is also the potential to improve future **energy security** by reducing dependence on imported energy sources, and to avoid adverse side effects associated with **fossil fuel extraction**, such as the landscape impacts of opencast coal mining, the risk of oil spills, and emissions from gas flaring.

Most energy supply technologies have some potential adverse side-effects. Solar PV panels use rare metals and there is a need to better understand the sourcing of materials for use in solar panels including ways to minimise environmental impacts through reuse and recycling initiatives (Smith et al., 2016).

Although solar panels and solar walls require a high capital investment, the low running costs mean that there is potential for fuel poverty reduction benefits even in Scotland, and a detailed analysis of this potential in Dundee has been undertaken (Andreadis et al., 2013). The study suggested that city level solar installation programmes could play a key role in reducing fuel poverty at an acceptable cost.

Air and ground source heat pumps are covered by UK's Renewable Heat Incentive. By 2050, the embedded carbon could be reduced by 32% when comparing heat pump systems with gas boilers (Gupta & Irving, 2014)[4]. However, as their operation requires electricity, heat pumps often lead to an increase in electricity consumption and therefore the extent to which emissions are reduced depends on how 'clean' is the source of electricity (Onyango, et al., 2016). One promising solution is the combination of heat pumps with thermal energy storage which would allow heat demand to be shifted to off peak time or times of renewable electricity surplus (Renaldi, et al., 2016). By integrating thermal energy storage and time-of-use tariffs,

[4] With embedded carbon being defined as the carbon cost (in CO_2 or CO_2e) of construction or manufacturing. It refers to the total primary energy consumed (carbon dioxide released) from direct and process associated with the lifecycles of products and services.

the operational costs of heat pump systems will decline and, in combination with the Renewable Heat Incentive, the system will become cost competitive with conventional systems (Renaldi, et al., 2016).

In the rural Scottish context, there is evidence on the contribution from **woody biomass** for private space and water heating in North East Scotland. This is a relatively low-cost energy source that can help to address the impact of rising energy prices, help to address fuel poverty (Feliciano et al., 2014) and improve energy security. Potential adverse side effects include that for solid biomass, there can be an increase in particulate and nitrogen oxides emissions if it is replacing gas. However, there are net benefits if replacing coal or oil (Environmental Protection UK, 2013), depending on the technology used. Focussing on off gas-grid uptake, i.e. replacing coal or oil fired systems, will also tend to avoid uptake in urban air quality hotspots.

The introduction of the **heat planning law,** whereby developers of major sources of waste heat are required to install infrastructure to capture and deliver it to local homes and businesses, will deliver benefits including reducing the ecological impacts of dumping waste heat into natural environments (Daly and Farley, 2011), and encouraging the co-location of housing and employment which will reduce transport impacts.

Quantitative evidence

The quantification of air quality aspects is covered in Chapter 7. In terms of wider impacts there is comparatively limited consideration in the co-benefits literature, however, Energy system modelling could help assess the benefits of diversified energy supplies and the cost of using ‘fluctuating’ sources (Smith et al., 2016).

7 Cross-cutting themes

Climate change mitigation options in the built environment which are aimed at reducing the use of fossil fuels, either through avoided energy consumption (chapter 4), the use of less energy-intensive materials (chapter 5) or the use of low carbon energy sources (chapter 6) offer air quality and future energy security benefits and these are addressed in turn below.

7.1 Air quality

As fossil fuels are the main source of air pollution, most of these mitigation options will, therefore, have the co-benefit of improving air quality, with the exact level of benefits depending on the fuel displaced and on the magnitude of the energy savings. In the case of biomass combustion, emissions displaced from fossil fuel combustion will be diminished (or increased, if replacing gas) by those produced by the biomass, unless appropriate mitigation is put in place.

Building fabric improvements reduce the total energy consumption for heating. Insulation can also prevent over-heating, leading to electricity savings in cases where fans or air conditioning are used for cooling. Air pollutant emission savings therefore depend on the heating fuel and technology. This could be a gas or oil boiler or electric heating. For reductions in electricity used for heating or cooling, the emission savings depend on the mix of sources used to generate electricity across the whole network. Both the location of emissions and the pollution abatement technologies will be different for boilers located in residential or commercial buildings compared to gas or coal-fired power stations used to generate electricity.

Behaviour change has similar impacts except that there is potential to also address energy used for lighting and appliances, thus saving additional emissions from electricity generation.

The use of more sustainable building materials such as timber, cellulosic material or sheep's wool insulation can reduce the emissions of air pollutants from extraction, processing and manufacture of the building materials that are displaced, such as steel, aluminium, concrete, bricks or synthetic insulation foam. Life-cycle analysis would be needed to properly compare the total emissions embodied in these different materials.

Green infrastructure can reduce emissions in a different way, by absorbing or adsorbing pollutants on to vegetation. The amount of pollution removed is generally thought to be proportional to the leaf area, and so is greater for larger trees with a dense canopy. There are numerous modelling studies in the literature, and the iTree-Eco model has been used to estimate the value of air pollution removal at various sites in the UK, but empirical data to demonstrate the size of the effect in real life is scarce. Most studies of urban trees estimate that pollution levels are reduced by only a few percent, but the economic value of this removal can still be significant because of the high levels of mortality and morbidity related to urban air pollution.

Solar PV panels will displace the national electricity generation mix, and solar hot water panels will displace the fuel that would have been used for hot water – probably gas, oil or electricity. Both heat pumps and more efficient boilers will displace the gas, oil or electricity that would have been used for space heating, but in the case of heat pumps the emission savings will be offset by emissions from the electricity used to run the pump. More efficient lighting and cooling technologies will reduce the use of electricity.

A key potential adverse side-effect is emissions of particulate matter (PM) from biomass combustion. Emissions vary considerably depending on the nature of the fuel and the combustion device, so estimates are highly uncertain, but although biomass boilers produce less PM than residential coal combustion, they produce more than oil-fired boilers. PM emissions from gas and biogas are negligible.

Quantitative evidence

There are numerous articles in the literature that show substantial air quality co-benefits from climate change mitigation actions, but few of these present separate estimates for the building sector, and none were found that quantify potential co-benefits specifically for Scotland. However, a study for the whole of the UK was carried out in 2013 for the UK Committee on Climate Change, which estimated the air quality benefits that would arise from achieving the CCC's Medium Abatement Scenario by 2030. This scenario involved a shift to biomass boilers, biomass district heating, biogas, solar hot water and heat pumps in residential and non-residential buildings and industry, plus a range of building energy efficiency measures.

Using emission factors for different heating technologies and standard DEFRA estimates of damage costs per tonne of each pollutant, the study estimated the costs of health impacts from emissions of NO_X, SO_2 and PM_{10} for biomass and biogas heating, and the costs avoided from savings in coal, gas and oil (changes in electricity use were assessed as part of the whole power sector, not just for buildings, so are not shown here). The findings are summarised in Table 7.1. This shows that the cost of emissions from biomass and biogas boilers, which totals £169 million in 2030 for the residential and non-residential sectors, partly offsets the large savings from avoided coal, oil and gas combustion (£316 million in 2030 for the shift to biomass, solar and heat pumps, and £92 million for building energy efficiency measures). However, there is still a large net benefit of £239 million.

The study emphasises that the estimates of emissions from biomass boilers are highly uncertain: the main estimate assumes that the Renewable Heat Incentive standard can be met, whereas the sensitivity test assumes a value measured for Swan Eco-stoves, which is a factor of ten larger. If this value was used, the biomass emissions would more than offset the savings from avoided coal, oil and gas for this scenario. This emphasises the importance of optimising biomass combustion devices to reduce emissions as far as possible, and avoiding the use of biomass in urban areas where population exposure is high.

Table 7.1: UK Estimates of the value of air quality co-benefits from climate change mitigation action in the buildings and industry sector (building energy efficiency and shift to solar, biomass and biogas) for the UK, based on damage costs for emissions of NO_X, SO_2 and PM_{10}.

Numbers in brackets are a sensitivity test with a much larger PM_{10} emission factor for biomass stoves (see text). Source: ApSimon and Oxley (2013)

	Value in 2030 (£ million) UK	NPV 2010-2030 (£ million) UK
Residential biomass	42 (364)	95 (814)
Non-residential biomass	37 (313)	282 (2384)
Industrial heat	227	1140
Biogas	7	29
District heating biomass	83	474
TOTAL	**396**	**2020**
Heat sector: fuel savings		
Residential sector	-264	-1416
Non-residential	- 52	- 321
Industry	-377	-1397
TOTAL	**-693**	**-3134**
Efficiency measures		
Residential	- 78	- 642
Non-residential	- 14	- 138
Industry	-134	- 869
TOTAL	**226**	**-1649**

7.2 Energy security

The climate mitigation methods that reduce building energy consumption will also have benefits for future energy security, by reducing reliance on fossil fuels. Despite production of North Sea oil and gas, a considerable proportion of the UK's fossil fuel energy is imported from other countries. For the energy supply technologies, solar energy is of course provided locally and therefore will also provide energy security benefits. Biogas is also generally provided locally, typically from anaerobic digestion of farm or household organic waste. For solid biomass, it is important to ensure that supply is from a sustainable source, such as sustainable forestry waste, rather than from forests of high biodiversity value. The size of the forestry sector in Scotland should ensure that sustainable biomass can be provided locally, so this option should also improve energy security. However, for both biomass and biogas it is necessary to ensure that a continuous supply is available locally to avoid short term disruptions, ideally with a choice of suppliers.

8 Recommendations

This evidence review found a large literature base demonstrating that the co-benefits of climate change mitigation action in the built environment sector could be substantial. In determining policy, consideration needs to be given to the carbon reduction offered and the potential for additional benefits. Ambitious use of increased efficiency measures could help achieve GHG reduction targets as well as contributing to other key objectives such as improving health. The use of sustainable materials could offer opportunities in terms of forestry diversification, while the provision of green infrastructure could help reduce urban heat island effects.

Significant research gaps are detailed below.

Avoid: reduce energy demand

- Further in-depth research on the co-benefits of improving energy performance of housing on occupant health is necessary if there is a requirement to directly quantify how investment in energy efficiency could lead to reductions in costs to health services.
- Physical and mental health are identified as being influences on and outcomes of energy behaviours and vulnerability to fuel poverty. Research is needed to understand these relationships in more detail including where and how policy measures can be targeted to maximise co-benefits to those most in need.
- Further evidence is required to better understand and quantify the benefits of energy efficiency in the non-domestic sector, especially in the Scottish context. Opportunities here relate to cost savings, strengthening of corporate values and risk mitigation.
- Further research is required to quantify the rebound and prebound effects of improving energy efficiency, particularly amongst fuel poor and vulnerable households, and to incorporate the updated results into models such as DEMScot2 and NHM.

Shift: a more sustainable built environment

- Increased and improved data is required on Scottish imports and exports of sustainable building materials in order to better understand and quantify the potential for these industries to contribute to sustainable economic growth.
- Linked to the use of timber based sustainable building materials there is a need for more research to capture the value of ecosystem services[5], and particularly how the co-benefits of forestry and agricultural strategies can be captured and incorporated into strategies for the built environment.

[5] eftec, 2011. Scoping Study on Valuing Ecosystem Services of Forests Across Great Britain. Report for the Forestry Commission, October 2011.

- Increased understanding of the equalities opportunities in relation to local job creation, e.g. through the production of sustainable building materials, is required.

Improve: low carbon energy options

- Further research is needed on the sustainability impacts of increasing demand for bioenergy.

References

AECOM (2012) Investigations into Overheating in Homes: A Literature Review. Report to Department for Communities and Local Government. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7604/2185850.pdf

Allen, J.G., MacNaughton, P., Laurent, J.G.C., Flanigan, S.S., Eitland, E.S., Spengler, J.D., 2015. Green Buildings and Health. Curr. Environ. Health Rep. 2, 250–258. doi:10.1007/s40572-015-0063-y

Anderson, D.R. et al. (2000), “The relationship between modifiable health risks and group level health care expenditures”, American Journal of Health Promotion, Vol. 15, No. 1, pp. 45-52,

Andreadis, G., Roaf S., and Mallick, T., (2013) Tackling fuel poverty with building-integrated solar technologies: The case of the city of Dundee in Scotland. Energy and Buildings 59 (2013) 310–320

Annesi-Maesano, I., Lundbäck, B., Viegi, G., 2014. Respiratory epidemiology, 1st edition. ed. Sheffield: European Respiratory Society.

ApSimon, H. and Oxley, T. (2013) Analysis of the air quality impacts of potential CCC scenarios. Report to the UK Committee on Climate Change by Imperial Consultants Ltd.

Aynsley, R., 1999. Estimating summer wind driven natural ventilation potential for indoor thermal comfort. J. Wind Eng. Ind. Aerodyn. 83, 515–525. doi:10.1016/S0167-6105(99)00098-7

Baker, K., 2015. Reducing demand: Energy efficiency and behaviour change, in: Wood, G., & Baker, K.J., (Eds.), A Critical Review of Scottish Renewable Energy Policy. Palgrave.

Baker, K.J., 2016 Personal communication

Baker, K.J., Emmanuel, R., Phillipson, M., 2012. Final Report: Support for RPP2 Housing Futures. ClimateXChange Scotland.

Baker, K.J., Mould, R., Restrick, S., 2016. The Speird Project - Final report to the Eaga Charitable Trust.

Barker, T., Ekins, P., Foxon, T., 2007. The macro-economic rebound effect and the UK economy. Energy Policy 35, 4935–4946. doi:10.1016/j.enpol.2007.04.009

Barker, T., Jenkins, K., 2007. The Domestic Energy Sub-Model in MDM-E3.

Becker, R., Goldberger, I., Paciuk, M., 2007. Improving energy performance of school buildings while ensuring indoor air quality ventilation. Build. Environ. 42, 3261–3276. doi:10.1016/j.buildenv.2006.08.016

Bernstein, J.A., Alexis, N., Bacchus, H., Bernstein, I.L., Fritz, P., Horner, E., Li, N., Mason, S., Nel, A., Oullette, J., Reijula, K., Reponen, T., Seltzer, J., Smith, A., Tarlo, S.M., 2008. The health effects of non-industrial indoor air pollution. J. Allergy Clin. Immunol. 121, 585–591. doi:10.1016/j.jaci.2007.10.045

Bianchini, F., Hewage, K., 2012. How “green” are the green roofs? Lifecycle analysis of green roof materials. Build. Environ. 48, 57–65. doi:10.1016/j.buildenv.2011.08.019

Biran, A., Hunt, C., 2003. WELL - Resource Centre Network for Water, Sanitation and Environmental Health [WWW Document]. Indoor Air Pollut. Cook. Stoves Health. URL http://www.lboro.ac.uk/well/resources/fact-sheets/fact-sheets-htm/iap.htm (accessed 2.9.16).

Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C.N., Palmer, J., Sinden, G., 2005. 40% House. Environmental Change Institute, Oxford.

Boardman, B. (2010), Fixing Fuel Poverty: Challenges and Solutions, Earthscan, London

Bornehag, C.G., Blomquist, G., Gyntelberg, F., Järvholm, B., Malmberg, P., Nordvall, L., Nielsen, A., Pershagen, G., Sundell, J., 2001. Dampness in buildings and health. Nordic interdisciplinary review of the scientific evidence on associations between exposure to “dampness” in buildings and health effects (NORDDAMP). Indoor Air 11, 72–86.

Boyce. J. & Pastor, M. (2012) Cooling the Planet, Clearing the Air: Climate Policy, Carbon Pricing, and Co-Benefits.Political Economy Research Institute, University of Massachusetts at Amherst, 79 pages

Bruce, N., Perez-Padilla, R., Albalak, R., 2000. Indoor air pollution in developing countries: a major environmental and public health challenge. Bull. World Health Organ. 78, 1078–1092.

Cabinet Office, 2011. Behaviour change and energy use.

CASD, 2010. A Select Review of Literature on the Relationship Between Housing and Health.

Castleton, H.F., Stovin, V., Beck, S.B.M., Davison, J.B., 2010. Green roofs; building energy savings and the potential for retrofit. Energy Build. 42, 1582–1591. doi:10.1016/j.enbuild.2010.05.004

Cecere, G., Mazzanti, M., 2015. Green jobs, innovation and environmentally oriented strategies in European SMEs.

Centre for Energy Policy (CEP) 2016 Research into the rebound effect

Chard R., and Walker G., (2016) Living with fuel poverty in older age: Coping strategies and their problematic implications. Energy Research & Social Science 18 (2016) 62–70

Chauvin, J., Pauls, J., Strobl, L., 2016. Building codes: An often overlooked determinant of health. J. Public Health Policy 37, 136–148. doi:10.1057/jphp.2016.5

Christina, S., Waterson, P., Dainty, A., Daniels, K., 2015. A socio-technical approach to improving retail energy efficiency behaviours. Appl. Ergon. 47, 324–335. doi:10.1016/j.apergo.2014.08.003

Citizens Advice Scotland, Consumer Futures Unit, 2016. Taking the Temperature: A review of energy efficiency and fuel poverty schemes in Scotland. Consumer Futures Unit, Scotland.

Clarke et al., 2014. Assessing Transformation Pathways, in: Edonhofer et al., (Ed.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

ClimateXChange (2016) Overheating Risk in Buildings Housing Vulnerable People http://www.climatexchange.org.uk/files/9414/8214/5669/CXC_Scoping_Study_Specification_-_Assessment_of_Overheating_Risk.pdf

Commission on Housing & Wellbeing, 2015. A blueprint for Scotland's future. Commission on Housing & Wellbeing.

Committee on Climate Change, 2016. "Reducing emissions in Scotland 2016 progress report". Committee on Climate Change: London.

Consoli, D., Marin, G., Marzucchi, A., Vona, F., 2015. Do green jobs differ from non-green jobs in terms of skills and human capital?

Copenhagen Economics, 2012. Multiple Benefits of Investing in Energy-efficient Renovation of Buildings - Impact on Finances in IEA, 2014

Creamer, E., 2015. The double-edged sword of grant funding: a study of community-led climate change initiatives in remote rural Scotland. Local Environ. 20, 981–999. doi:10.1080/13549839.2014.885937

Curl, A., Thompson, C.W., Alves, S., Aspinall, P., 2016. Outdoor Environmental Supportiveness and Older People's Quality of Life: A Personal Projects Approach. J. Hous. Elder. 30, 1–17. doi:10.1080/02763893.2015.1087925

Dalkmann, H., Brannigan, C., 2007. Transport and Climate Change, Sourcebook Module 5e.

Daly, H.E., Farley, J., 2011. Ecological Economics: Principles and Applications, 2 edition. ed. Island Press, Washington.

Danish Energy Agency, 2005. Heat supply in Denmark [WWW Document]. Energistyrelsen. URL http://www.seas.columbia.edu/earth/wtert/sofos/DEA_Heat_supply_in_denmark.pdf

DCLG, 2006. Building a Greener Future: Towards Zero Carbon Development.

DECC, 2014a. Consultation Stage Impact Assessment for the Private Rented Sector Regulations.

DECC, 2014b. Understanding the behaviours of households in fuel poverty.

Department for Business, Energy & Industrial Strategy, 2016. Renewable Heat Incentive statistics [WWW Document]. URL https://www.gov.uk/government/collections/renewable-heat-incentive-statistics (accessed 30.8.16).

Druckman, A., Chitnis, M., Sorrell, S., Jackson, T. (2011) Missing carbon reductions? Exploring rebound and backfire effects in UK households. Energy Policy, Volume 39, Issue 6, June 2011, Pages 3572–3581

Dunnett, N., Kingsbury, N., 2004. Planting Green Roofs and Living Walls. Timber Press.

Ecocel, 2016. Eco friendly home insulation product. Sustainable Insulation [WWW Document]. Ecocel. URL http://www.ecocel.ie/ (accessed 30.8.16).

EEP, 2013. Europe's Energy Portal - Fuel, Natural Gas and Electricity Prices From Past to Present [WWW Document]. URL https://www.energy.eu/ (accessed 30.8.16).

Ekins, P., Etheridge, B., 2006. The environmental and economic impacts of the UK climate change agreements. Energy Policy 34, 2071–2086. doi:10.1016/j.enpol.2005.01.008

Ellsworth-Krebs (2016) PhD Thesis: Home-ing in on Domestic Energy Research, University of St Andrews.

Emmanuel, R., Baker, K., 2012. Carbon Management in the Built Environment. Routledge.

Emmanuel, R., Krüger, E., 2012. Urban heat island and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK. Build. Environ. 53, 137–149. doi:10.1016/j.buildenv.2012.01.020

Emmanuel, R., Loconsole, A., 2015. Green infrastructure as an adaptation approach to tackling urban overheating in the Glasgow Clyde Valley Region, UK. Landsc. Urban Plan. 138, 71–86. doi:10.1016/j.landurbplan.2015.02.012

Environmental Protection UK (2013) *Solid Fuel and Air Quality An Update for Local Authorities.* http://www.environmental-protection.org.uk/wp-content/uploads/2013/07/Solid-Fuel-and-Air-Quality-Update-for-LAs-final-060413.pdf

Equal Rights Center, 2014. Opening Doors: An investigation of barriers to senior housing for same-sex couples.

European Commission, 2011. Background on energy in Europe.

EC (European Commission) (2011), Commission Staff Working Paper Impact Assessment, Accompanying the document Directive of the European Parliament and of the Council on Energy Efficiency and amending and subsequently repealing Directives 2004/8/EC and 2006/32/EC, SEC(2011) 779 final, Brussels, 22.6.2011 in IEA, 2014

European Environment Agency, 2013. Achieving energy efficiency through behaviour change: what does it take? (No. EEA Technical report | No 5/2013). European Environment Agency, Copenhagen, Denmark.

Feliciano, D., Slee, B., Smith, P., 2014. The potential uptake of domestic woodfuel heating systems and its contribution to tackling climate change: A case study from the North East Scotland. Renew. Energy 72, 344–353. doi:10.1016/j.renene.2014.07.039

Figueiro M.G, Mark S. Rea, M.S and Rea, A.C. (2002) Daylight and Productivity – A Field Study. ACEEE Summer Study on Energy Efficiency in Buildings.

http://www.eceee.org/library/conference_proceedings/ACEEE_buildings/2002/Panel_8/p8_6

Fisk, W.J., Lei-Gomez, Q., Mendell, M.J., 2007. Meta-analyses of the associations of respiratory health effects with dampness and mold in homes. Indoor Air 17, 284–296. doi:10.1111/j.1600-0668.2007.00475.x

Forest Research, 2010. Benefits of green infrastructure. Forest Research.

Forestry Commission Scotland, 2006. The Scottish Forestry Strategy. Forestry Commission Scotland, National Office, Silvan House, Edinburgh.

Foster, J., Shape, T., Morgan, C., Musau, F., 2016. Scottish Passive House: Insights into Environmental Conditions in Monitored Passive Houses. Sustainability 8, 24.

Friedman, S., Reynolds, A., Scovill, S., Brassier, F.R., Campbell, R., Ballou, M., 2013. An Estimate of Housing Discrimination Against Same-Sex Couples | HUD USER.

Galvin, R., 2015. The rebound effect, gender and social justice: A case study in Germany. Energy Policy 86, 759–769. doi:10.1016/j.enpol.2015.08.026

Galvin, R., Sunikka-Blank, M., 2016. Quantification of (p)rebound effects in retrofit policies – Why does it matter? Energy 95, 415–424. doi:10.1016/j.energy.2015.12.034

Garrett, H., Piddington, J., Nicol, S., 2014. The Housing Conditions of Minority Ethnic Households in England.

Glasgow Clyde Valley Green Partnership, 2013. Green Infrastructure for overheating adaptation in Glasgow. Glasgow Clyde Valley Green Partnership.

Gilbertson, J., Grimsley, M. and Green, G. (2012), “Psychosocial routes from housing investment to health gain. Evidence from England’s home energy efficiency scheme”, for the Warm Front Study Group, Energy Policy, Vol. 49, Elsevier Ltd., Amsterdam, pp. 122-133

Grant, C., Hunter, C.A., Flannigan, B., Bravery, A.F., 1989. The moisture requirements of moulds isolated from domestic dwellings. Int. Biodeterior. 25, 259–284. doi:10.1016/0265-3036(89)90002-X

Green Roof Guide, 2016. Green Roof Guide [WWW Document]. URL http://www.greenroofguide.co.uk/ (accessed 30.8.16).

Green Roof Technology, 2014. Green Roof Technology.

Groten, J.P., Feron, V.J., & Suhnel, J., 2001. Toxicology of simple and complex mixtures. Trends in Pharmacological Sciences. Vol. 22, No. 6., June 2001, pp. 316-322.

Gupta, R., Irving, R., 2014. "Possible effects of future domestic heat pump installation on the UK energy supply". Energy and Buildings. Vol 84. Pp. 94-110.

Gupta, R., Kapsali, M., 2015. Empirical assessment of indoor air quality and overheating in low-carbon social housing dwellings in England, UK. Adv. Build. Energy Res. 10, 46–68. doi:10.1080/17512549.2015.1014843

Hamilton, I., Milner, J., Chalabi, Z., Das, P., Jones, B., Shrubsole, C., Davies, M., Wilkinson, P., 2015. Health effects of home energy efficiency interventions in England: a modelling study. BMJ Open 5, e007298. doi:10.1136/bmjopen-2014-007298

Haney, A.B., Jamasb, T., Platchkov, L.M., Pollitt, M., 2010. Demand-side Management Strategies and the Residential Sector: Lessons from International Experience. EPRG, Cambridge.

Haney, A.B., Jamasb, T., Pollitt, M., 2009. Smart Metering and Electricity Demand: Technology, economics and international experience. University of Cambridge, Electricity Policy Research Group, Cambridge.

Hills J., 2012. Getting the Measure of Fuel Poverty

http://sticerd.lse.ac.uk/dps/case/cr/CASEreport72.pdf

Hollas, L., 2014. Promoting climate change mitigation and the health of communities in urban areas using green infrastructure in the UK (Dissertation). Glasgow Caledonian University, School of Engineering and the Built Environment.

Howden-Chapman, P., Viggers, H., Chapman, R., O'Sullivan, K., Telfar Barnard, L., Lloyd, B., 2012. Tackling cold housing and fuel poverty in New Zealand: A review of policies, research, and health impacts. Energy Policy, Special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy 49, 134–142. doi:10.1016/j.enpol.2011.09.044

Huseynov, E.F.O., 2011. Planning of sustainable cities in view of green architecture. Procedia Eng. 21, 534.

International Energy Agency, 2014. Capturing the Multiple Benefits of Energy Efficiency. International Energy Agency, Paris.

IPCC, 2014. Fifth Assessment Report.

James, J.P., Yang, X., 2005. Emissions of Volatile Organic Compounds from Several Green and Non-Green Building Materials: A Comparison. Indoor Built Environ. 14, 69–74. doi:10.1177/1420326X05050504

Johnson, L., Ciaccio, C., Barnes, C., Kennedy, K., Forrest, E., Gard, L., Pacheco, F., Dowling, P., & Portnoy, J., 2009. Low-cost interventions improve indoor air quality and children's health. Allergy and Asthma Proceedings. 30 (4), pp.377-385.

Jones, A.P., 1999. Indoor air quality and health. Atmos. Environ. 33, 4535–4564. doi:10.1016/S1352-2310(99)00272-1

Jones, P., Patterson, J., Lannon, S., 2007. Modelling the built environment at an urban scale—Energy and health impacts in relation to housing. Landsc. Urban Plan. 83, 39–49.

Kim, K.-H., Jahan, S.A., Kabir, E., 2013. A review on s perspective of air pollution with respect to allergies and asthma. Environ. Int. 59, 41–52. doi:10.1016/j.envint.2013.05.007

Kobus, C.B.A., Klaassen, E.A.M., Mugge, R., Schoormans, J.P.L., 2015. A real-life assessment on the effect of smart appliances for shifting households' electricity demand. Appl. Energy 147, 335–343. doi:10.1016/j.apenergy.2015.01.073

Kowalczyk, A., 2011. Green roofs as an opportunity for sustainable development in urban areas. Sustain. Dev. Appl. 2 63–77.

Laing P. and A. Baker 2006, The Healthy Housing Program Evaluation: Synthesis and Discussion of Findings, report prepared for Housing New Zealand Corporation, Housing New Zealand Corporation, Wellington,

Lamond W., (2015) Investigation of Summer Overheating of the Passive House Design in the Scottish Climate. http://www.esru.strath.ac.uk/Documents/MSc_2011/Lamond.pdf

Lecca, P., McGregor, P. G., Swales, J. K., & Turner, K. (2014). The added value from a general equilibrium analysis of increased efficiency in household energy use. Ecological Economics. 100, 51–62.

Lee, C.-S., Haghighat, F., Ghaly, W.S., 2005. A study on VOC source and sink behavior in porous building materials - analytical model development and assessment. Indoor Air 15, 183–196. doi:10.1111/j.1600-0668.2005.00335.x

Lehr, U., C. Lutz and D. Edler (2012), "Green jobs? Economic impacts of renewable energy in Germany", Energy Policy, Vol. 47, Elsevier B.V., Amsterdam, pp. 358–36

Liddell, C., Morris, C., 2010. Fuel poverty and human : A review of recent evidence. Energy Policy, The Role of Trust in Managing Uncertainties in the Transition to a Sustainable Energy Economy, Special Section with Regular Papers 38, 2987–2997. doi:10.1016/j.enpol.2010.01.037

Liddell C., C. Morris and S. Langdon (2011), Kirklees Warm Zone. The Project and its Impacts on Well-being, report commissioned by The Department For Social Development Northern Ireland, University of Ulster, Coleraine, http://fuelpoverty.thehealthwell.info/node/92600?&content=resource&member=572160&catalogue=none&collection=Fuel%20Poverty,Health%20Inequalities%20&tokens_complete=true

Lockton, D., Cain, R., Harrison, D.J., Giudice, S., Nicholson, L., Jennings, P., 2011. Behaviour change at work: Empowering energy efficiency in the workplace through user-centred design. University of California eScholarship Repository.

Lopes, M.A.R., Antunes, C.H., Martins, N., 2012. Energy behaviours as promoters of energy efficiency: A 21st century review. Renew. Sustain. Energy Rev. 16, 4095–4104. doi:10.1016/j.rser.2012.03.034

Low Carbon Scotland, 2016. RPP2/RPP3 STRATEGY. Low Carbon Scotl.

Lowe, R., 2007. Technical options and strategies for decarbonizing UK housing. Build. Res. Inf. 35, 412–425.

Macintosh, A., Steemers, K., 2005. Ventilation strategies for urban housing: lessons from a PoE case study. Build. Res. Inf. 33, 17–31. doi:10.1080/0961321042000322771

Maidment, C.D.. et al. (2014), “The impact of household energy efficiency measures on health: A meta-analysis”, Energy Policy, Vol. 65, pp. 583-593.

MAKAR, 2016. Makar Construction Inverness [WWW Document]. Who Are MAKAR. URL http://www.makar.co.uk/ (accessed 30.8.16).

Mazza, L., Rydin, Y., 1997. Urban Sustainability: Discourses, Networks and Policy Tools. Prog. Plan. 1, 1–74.

McMichael, M., Shipworth, D., 2013. The value of social networks in the diffusion of energy-efficiency innovations in UK households. Energy Policy 53, 159–168. doi:10.1016/j.enpol.2012.10.039

Mendell, M.J., Mirer, A.G., Cheung, K., Tong, M., Douwes, J., 2011. Respiratory and allergic health effects of dampness, mold, and dampness-related agents: a review of the epidemiologic evidence. Environ. Health Perspect. 119, 748–756. doi:10.1289/ehp.1002410

M’Ikiugu, M.M., QianNa, W., Kinoshita, I., 2012. Green Infrastructure Gauge: A Tool for Evaluating Green Infrastructure Inclusion in Existing and Future Urban Areas. Procedia - Soc. Behav. Sci. 68, 815–825. doi:10.1016/j.sbspro.2012.12.269

Missia, D.A., Demetriou, E., Michael, N., Tolis, E.I., Bartzis, J.G., 2010. Indoor exposure from building materials: A field study. Atmos. Environ. 44, 4388–4395. doi:10.1016/j.atmosenv.2010.07.049

Morgan, C., Foster J.A., Sharpe T., and Poston 2015. "Overheating in Scotland: Lessons from 26 monitored low energy homes". CISBAT: Lausanne.

Nandasena, S., Wickremasinghe, A.R., Sathiakumar, N., 2012. Respiratory health status of children from two different air pollution exposure settings of Sri Lanka: a cross-sectional study. Am. J. Ind. Med. 55, 1137–1145. doi:10.1002/ajim.22020

National Records of Scotland, 2015. Winter Mortality in Scotland - 2014 - 15 [WWW Document]. URL http://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/vital-events/deaths/winter-mortality/winter-mortality-in-scotland-201415 (accessed 30.8.16).

NEES, 2013. Home [WWW Document]. NEES. URL http://www.neesonline.org/ (accessed 30.8.16).

NICE, 2016. Preventing excess winter deaths and illness associated with cold homes [WWW Document]. Prev. Excess Winter Deaths Illn. Assoc. Cold Homes. URL https://www.nice.org.uk/guidance/qs117 (accessed 30.8.16).

Niven, R., Fletcher, A.M., Pickering, A.C., Custovic, A., Sivour, J.B., Preece, A.R., Oldham, L.A., Francis, H.C., 1999. Attempting to control mite allergens with mechanical ventilation and dehumidification in British houses. J. Allergy Clin. Immunol. 103, 756–762.

Onyango, V., Burford, N., Wright, F., Moyo, D., 2016. "The effectiveness of greenhouse gas emission policies in Scottish local development plans". ClimateXChange.

Osanyintola, O.F., Simonson, C.J., 2006. Moisture buffering capacity of hygroscopic building materials: Experimental facilities and energy impact. Energy Build. 38, 1270–1282. doi:10.1016/j.enbuild.2006.03.026

Pacheco R., Ordez J., and Martnez G., (2012) Energy efficient design of building: a review. Renewable and Sustainable Energy Reviews, 16 (6) (2012), pp. 3559–3573

Payne, J., Weatherall, D., Downy, F., 2015. Capturing the "multiple benefits" of energy efficiency in practice: the UK example. ECEEE, London.

Penttinen, L., 2012. Smart metering - Breakthrough in consumer empowerment and behaviour change?

Pierpoint, K., 2014. The impact of long-term engagement on empowerment & behaviour change.

Pindyck, R.S., 2015. The Use and Misusre of Models for Climate Policy (No. 21097). NBER, NBER.

Preval N. et al. (2010), "Evaluating energy, health and carbon co-benefits from improved domestic space heating: A randomised community trial", Energy Policy Vol. 38, No. 8, , pp. 3965-3972,

Renaldi, R., Kiprakis, A., Friedrich, D., 2016. "An optimisation framework for thermal energy storage in a residential heat pump heating system". Applied Energy: In Press.

RICS, 2014. Building a Better Scotland: The RICS Scottish Housing Commission Report. RICS, London.

Roaf, S., Crichton, D., Nicol, F., 2009. Adapting Buildings and Cities for Climate Change, 2nd ed. ed. Architectural Press, Amsterdam.

Rosenzweig, C., Gaffin, S., Parshall, L. (Eds.), 2006. Green Roofs in New York Metropolitan Region: Research Report. Columbia University, Columbia University.

RSPB Scotland, 2016. RSPB Scotland response to Scottish Government call for evidence.

Ryan, L., Campbell, N., 2012. Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements (IEA Energy Papers). Organisation for Economic Co-operation and Development, Paris.

Sandström, U.G., 2002. Green Infrastructure Planning in Urban Sweden. Plan. Pract. Res. 17, 373–385. doi:10.1080/02697450216356

Schwanitz, V.J., Longden, T., Knopf, B., Capros, P., 2015. The implications of initiating immediate climate change mitigation — A potential for co-benefits? Technol. Forecast. Soc. Change 90, Part A, 166–177. doi:10.1016/j.techfore.2014.01.003

Scotland's Census, 2016. Housing and Accommodation [WWW Document]. Hous. Accommod. URL http://www.scotlandscensus.gov.uk/housing-and-accommodation (accessed 30.8.16).

Scottish Government, 2016a. Scottish Greenhouse Gas Emissions 2014 [WWW Document]. Scott. Greenh. Gas Emiss. 2014. URL http://www.gov.scot/Publications/2016/06/2307 (accessed 1.9.16).

Scottish Government, 2016c. Housing Statistics for Scotland [WWW Document]. URL http://www.gov.scot/Topics/Statistics/Browse/Housing-Regeneration/HSfS (accessed 30.8.16).

Scottish Government, 2016d. Housing Statistics for Scotland 2015: Key Trends Summary.

Scottish Government, 2016b. Scottish Government Health Statistics [WWW Document]. URL http://www.gov.scot/Topics/Statistics/Browse/Health?utm_source=website&utm_medium=navigation&utm_campaign=statistics-topics (accessed 30.8.16).

Scottish Government, 2015a. Scotland's People Annual Report: Results from 2014 Scottish Household Survey [WWW Document]. URL http://www.gov.scot/Publications/2015/08/3720/downloads (accessed 30.8.16).

Scottish Government, 2015b. Energy in Scotland 2015.

Scottish Government, 2013. Low Carbon Scotland - Meeting our Emissions Reduction Targets 2013 - 2027 [WWW Document]. URL http://www.gov.scot/Topics/Environment/climatechange/scotlands-action/lowcarbon/meetingthetargets (accessed 30.8.16).

Scottish Government, 2009. The Climate Change (Scotland) Act 2009.

Scottish Government, S.A.H., 2012. Towards 2016 - The Future of Fuel Poverty Policy in Scotland - Energy Assistance Package (EAP) [WWW Document]. URL http://www.gov.scot/Topics/People/Equality/18507/EQIASearch/2016EnergyAssistPackge (accessed 2.9.16).

Scottish Government, S.A.H., 2003. Review of Scotland's Cities - The Analysis [WWW Document]. URL http://www.gov.scot/Publications/2003/01/15950/15154 (accessed 2.9.16).

Shrubsole C, Ridley I, Biddulph P, Milner J, Vardoulakis S, Ucci M, Wilkinson P, Chalabi Z, Davies M. 2012 Indoor $PM_{2.5}$ exposure in London's domestic stock: modelling current and future exposures following energy efficient refurbishment. Atmos. Environ. 2012;62:336–343.

Shrubsole, C; Das, P; Milner, J; Hamilton, IG; Spadaro, JV; Oikonomou, E; Davies, M; Wilkinson, P. (2015) A tale of two cities: Comparison of impacts on CO2 emissions, the indoor environment and health of home energy efficiency strategies in London and Milton Keynes. *Atmospheric Environment* 120: 100-108.

Simonson, C.J., Salonvaara, M., Ojanen, T., 2002. The effect of structures on indoor humidity – possibility to improve comfort and perceived air quality. Indoor Air 12, 243–251. doi:10.1034/j.1600-0668.2002.01128.x

Smith, A., Pridmore, A., Hampshire, K., Ahlgren, C., Goodwin, J., 2017 (forthcoming). Scoping study on the co-benefits and possible adverse side effects of climate change mitigation: Final report. Report to DECC. Aether Ltd., Oxford.

Smith, A. (2013) The climate bonus: co-benefits of climate policy. Routledge, Abingdon.

Smith, A., Holland, M., Korkeala, O., Warmington, J., Forster, D., Apsimon, H., Oxley, T., Dickens, R. and Smith, S. 2015. "Health and environmental co-benefits and conflicts of actions to meet UK carbon targets. Climate Policy, DOI: 10.1080/14693062.2014.980212.

Snodin, H.M., 2008. Fuel Poverty in Great Britain, Germany, Denmark and Spain - relation to grid charging and renewable energy (No. Rep 1028/001/001A).

Sood, A., 2012. Indoor fuel exposure and the lung in both developing and developed countries: An update. Clin. Chest Med. 33, 649–665. doi:10.1016/j.ccm.2012.08.003

Sovacool, B.K., 2015. Fuel poverty, affordability, and energy justice in England: Policy insights from the Warm Front Program. Energy 93, 361–371.

Stechow, C. von, McCollum, D., Riahi, K., Minx, J.C., Kriegler, E., Vuuren, D.P. van, Jewell, J., Robledo-Abad, C., Hertwich, E., Tavoni, M., Mirasgedis, S., Lah, O., Roy, J., Mulugetta, Y., Dubash, N.K., Bollen, J., Ürge-Vorsatz, D., Edenhofer, O., 2015. Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. Annu. Rev. Environ. Resour. 40, 363–394. doi:10.1146/annurev-environ-021113-095626

Sutton, A., Black, D., Walker, P., 2011. Cross-laminated timber - An introduction to low-impact building materials.

Teedon, P., Gillespie, M., Lindsay, K., Baker, K., 2014. Parental perceptions of the impacts the built environment has on young children′s health: A qualitative examination and lay assessment amongst residents in four Scottish communities. Health Place 28, 50–57. doi:10.1016/j.healthplace.2014.03.010

Teubler, J., Bienge, K., Wiesen, K., 2015. Literature review on resource benefits.

Thermafleece, 2016. Thermafleece [WWW Document]. URL http://www.thermafleece.com/ (accessed 30.8.16).

Thomson, H., Petticrew, M., Douglas, M., 2003. Health impact assessment of housing improvements: incorporating research evidence. J. Epidemiol. Community Health 57, 11–16. doi:10.1136/jech.57.1.11

Thomson, H., Thomas, S., Sellstrom, E., Petticrew, M., 2013. Housing improvements for health and associated socio-economic outcomes. Cochrane Database Syst. Rev. CD008657. doi:10.1002/14651858.CD008657.pub2

Tod A.M. et al. (2012), “Understanding factors influencing vulnerable older people keeping warm and well in winter: a qualitative study using social marketing techniques”, BMJ Open 20

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J., James, P., 2007. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. Landsc. Urban Plan. 81, 167–178. doi:10.1016/j.landurbplan.2007.02.001

UCL, 2016. HIDEEM [WWW Document]. HIDEEM. URL https://www.ucl.ac.uk/energy-models/models/hideem (accessed 30.8.16).

UCL, 2014. Demolition or Refurbishment of Social Housing? A review of the evidence.

Uhde, E., Salthammer, T., 2007. Impact of reaction products from building materials and furnishings on indoor air quality—A review of recent advances in indoor chemistry. Atmos. Environ., Indoor Air 2005 - 10th International Conference on Indoor Air Quality and Climate (Part I) 41, 3111–3128. doi:10.1016/j.atmosenv.2006.05.082

UNEP, 2008. Green jobs: towards decent work in a sustainable, low-carbon world.

Ürge-Vorsatz, D., Herrero, S.T., Dubash, N.K., Lecocq, F., 2014. Measuring the Co-Benefits of Climate Change Mitigation. Annu. Rev. Environ. Resour. 39, 549–582. doi:10.1146/annurev-environ-031312-125456

Vardoulakis, S., Dimitroulopoulou, C., Thornes, J., Lai, K.-M., Taylor, J., Myers, I., Heaviside, C., Mavrogianni, A., Shrubsole, C., Chalabi, Z., Davies, M., Wilkinson, P., 2015. Impact of climate change on the domestic indoor environment and associated health risks in the UK. Environ. Int. 85, 299–313. doi:10.1016/j.envint.2015.09.010

Verco, Cambridge Econometrics, 2014. Building the Future: The economic and fiscal impacts of making homes energy efficient. Verco, London.

von Stechow, C., Minx, J.C., Riahi, K., Jewell, J., McCollum, D.L., Callaghan, M.W., Bertram, C., Luderer, G., Baiocchi, G., 2016. 2 °C and SDGs: united they stand, divided they fall? Environ. Res. Lett. 11, 34022. doi:10.1088/1748-9326/11/3/034022

WHO, 2014. Unlocking new opportunities - Jobs in green and healthy transport.

World Health Organisation 2016, Metrics

http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/

Wilkinson, P., Smith, K.R., Davies, M., Adair, H., Armstrong, B.G., Barrett, M., Bruce, N., Haines, A., Hamilton, I., Oreszczyn, T., Ridley, I., Tonne, C., Chalabi, Z., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. The Lancet 374, 1917–1929. doi:10.1016/S0140-6736(09)61713-X

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Any enquiries regarding this publication should be sent to us at
The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-78652-754-7

Published by The Scottish Government, January 2017

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS86528 (01/17)