RESEARCH

Decarbonising the Welsh housing stock: from practice to policy

Ed Green[1], Simon Lannon[2], Jo Patterson[3], Fabrizio Variale[4] and Heledd Iorwerth[5]

Abstract

This paper examines whether and how the challenging target of 95% decarbonisation can be achieved for the Welsh building stock. First, a critical review of the literature and relevant case studies are presented to understand the effectiveness of different retrofit approaches in practice, and the degree to which these approaches are evidence based, and applicable to the Welsh context. These findings are synthesised into a collection of 14 recurrent dwelling 'archetypes', with appropriate retrofit strategies developed for each. The impacts of these strategies are modelled in terms of capital cost, primary energy use, fuel bills and carbon emissions. Conclusions provide an evidence base for future policy and a decarbonisation strategy. Retrofit strategies should include fabric first-measures to minimise increases in household fuel bills and a consequent increase in fuel poverty. Retrofit options for a significant percentage of housing are constrained by character, which would limit changes to the external fabric. Given that decarbonisation of the future energy supply is currently uncertain, all other housing should be retrofitted to perform beyond SAP90. A flexible approach that pushes all housing to achieve stringent standards by 2050 is the only way to achieve targeted reductions in carbon emissions under the assumed energy supply scenarios.

Policy relevance

The Welsh housing stock, among the oldest and least efficient in Europe, is responsible for 21% of Welsh carbon emissions. In 2019, the UK Committee for Climate Change (CCC) determined that Wales should target a 95% reduction in emissions by 2050. This paper assesses whether this challenging target can be achieved, and potential strategies for doing so. Key recommendations are drawn from the research, which encompass technical, social and organisational issues, and the importance of a holistic approach to decarbonisation is identified. These findings informed the Independent Steering Group recent report *Better Homes, Better Wales, Better World* (2019), and the report's recommendations were adopted by the Welsh Government on 24 September 2019. This work should continue to provide an evidence base upon which future policy can be developed through the development of retrofit strategies for recurring dwelling archetypes and a decarbonisation strategy for Wales that is likely to include legislation, regulation, incentives and penalties.

Keywords: building stock; carbon; decarbonisation; housing; policy; retrofit; Wales

1. Introduction

The UK contains more than 26 million homes. […] Collectively, those homes emit more than a quarter of the UK's emissions […] 23 to 25 million of the homes already standing will still be lived in half a century from now….
(Communities and Local Government Committee 2008: 3)

The Welsh Government, along with the other UK governments, was legally bound via the Environment (Wales) Act 2016 to reduce carbon emissions in Wales by at least 80% by 2050 (versus 1990 baseline levels), and this target

[1] Welsh School of Architecture, Cardiff University, Cardiff, UK. ORCID: 0000-0001-6491-3480

[2] Welsh School of Architecture, Cardiff University, Cardiff, UK. ORCID: 0000-0003-4677-7184

[3] Welsh School of Architecture, Cardiff University, Cardiff, UK. ORCID: 0000-0002-4440-159X

[4] Welsh School of Architecture, Cardiff University, Cardiff, UK. ORCID: 0000-0001-7165-2469

[5] Welsh School of Architecture, Cardiff University, Cardiff, UK. ORCID: 0000-0002-9071-4124

Corresponding author: Ed Green (GreenE11@cardiff.ac.uk)

was embedded in the Welsh Government's first low carbon plan, *Prosperity for All: A Low Carbon Wales* (Welsh Government 2019c). Just a few months later, widespread acknowledgement of a climate emergency culminated in the UK government's legislation re-setting the UK target to net zero emissions by 2050, in line with advice from the UK Committee for Climate Change (CCC). The same advice, recommending that Wales achieve a 95% reduction in emissions by 2050 (CCC 2019), was accepted by the Welsh Government on 12 June 2020. (The CCC is an independent public body formed under the Climate Change Act 2008 with powers to advise the UK and devolved governments parliaments on emissions targets and it report to parliament on progress made in reducing greenhouse gas (GHG) emissions and preparing for and adapting to the impacts of climate change.)

In 2016, total UK GHG emissions were 41% lower than 1990 levels, but much of this improvement is attributed to improvements in the national energy supply (CCC 2018). While cleaner electricity generation is a clear achievement of the last decade, progress in the energy sector masks a failure to decarbonise other sectors, including housing. The UK is not on course to meet the legally binding fourth and fifth UK carbon budgets (BEIS 2017b), and will not do so unless barriers to decarbonisation of the housing sector are diminished and new policies drive an increased rate of decarbonisation (see section 3). Housing is responsible for 29% of UK anthropogenic carbon emissions (ONS 2018). The Welsh housing stock produces 21% of national carbon emissions (ONS 2018), reflecting a relatively high level of emissions from industry in Wales, and increasing the importance of effective decarbonisation of the housing sector.

The Welsh housing stock was estimated at 1.4 million dwellings in 2019. The only significant change to the stock in recent years is an increase in the proportion of homes in the private rented sector (PRS) (StatsWales 2019). As a result, each year in Wales, fewer than half the new homes needed are constructed (PPIW 2015). Meanwhile, very low levels of demolition keep the rate of replacement at <0.1% per year. Low rates of replacement and an underperforming housebuilding sector mean that >90% of existing homes are predicted to remain in use by 2050 (PPIW 2015).

The Welsh housing stock is the oldest in the UK, with over one-quarter of homes built before 1919 and just 13% built in the last 30 years (VOA 2011). The distribution of dwelling types is also distinct, with far fewer flats than elsewhere (11% in Wales compared with 21% in England) and more detached properties (22% in Wales compared with 16% in England'; Welsh Government 2018). As a consequence, the space-heating energy demand is higher than in other UK nations, as are fuel poverty levels. Despite energy efficiency initiatives, almost one-quarter of households in Wales are purported to experience fuel poverty (NEA 2017a). These statistics do not capture households in unmetered off-grid or rural locations. In such locations, fuel options are typically limited, increasingly expensive and carbon intensive. As a result, particularly in more rural areas, true fuel poverty levels may be higher than reported statistics.

Through the passing of time and as a result of broad geographic and demographic variations, Welsh housing has become increasingly varied in terms of type, age, physical form, construction and condition (Knight, Iorwerth, & Lannon 2017). There is no single 'solution' to decarbonise such a varied housing stock, and it is important that any approach to decarbonisation through retrofit be developed with an understanding of the specific characteristics of the Welsh housing stock.

Work completed during the early stages of the project (Green *et al.* 2018) indicates that the ongoing decarbonisation of the national energy supply network (principally electricity) and associated retrofit of dwelling heating and hot water systems can reduce the degree to which the dwelling fabric must be improved to achieve national decarbonisation targets, but it misses opportunities to improve dwelling quality and—more critically—could increase energy costs for residents, and consequently fuel poverty.

The key aim of this study is to understand the potential of the Welsh housing stock to be retrofitted to meet current (2019) decarbonisation targets by 2050, and to establish reasonable and appropriate retrofit strategies to do so. To achieve this aim, the research uses data describing the Welsh housing stock to establish a taxonomy of digital models representing the more commonly occurring housing archetypes in Wales. A review of case studies and literature supports the development of 'best practice' retrofit strategies. The models are then used to simulate energy consumption and associated emissions for each dwelling archetype—in 1990 (as a baseline), in 2016 (representing their current condition) and in 2050 (after retrofit). The results of this modelling are recombined to provide an indication of the standard of retrofit needed nationally for the housing sector to meet decarbonisation targets, along with an indication of the likely capital cost (based on current practice). Attendant to these conclusions are investigations of both the significance of cleaner primary energy supply and the potential impact on domestic fuel bills.

2. Methods

The research underpinning this paper was commissioned by the Welsh Government in two stages. The key objective of Stage 1 was to begin the process of mapping out pathways towards decarbonisation of the Welsh housing stock, by establishing a baseline understanding of retrofit actions, along with an empirical basis for their effectiveness. A review was produced of relevant case studies and literature (see section 3). The case studies and literature were then used as an evidence base from which to discuss established retrofit actions for the UK housing sector in terms of their applicability, key challenges likely to reduce or prevent their effective implementation, and their effectiveness in terms of capital costs and impact on energy efficiency and carbon emissions (using empirical data where possible). Key Stage 1 outputs include:

- a summary of the existing Welsh policy and housing statistics in order to understand the distinctiveness of the Welsh context
- a database of the 39 'best practice' retrofit case studies, with empirical evidence of effectiveness

- a literature review of 46 publications (academic, policy, industry and advisory sources) and
- a thematically structured evaluation of retrofit, cross-referenced against case studies and a literature review.

A total of 39 domestic retrofit case studies were identified with clear evidence of reduced energy use and GHG emissions. Case studies were selected based on their relevance to the decarbonisation programme. The intention was to find at least one case study for every established retrofit action to facilitate an informed discussion of the full range of retrofit actions currently being employed in the UK. A total of 14 of the case studies are located in Wales, increasing their relevance to the Welsh housing stock in particular; 22 case studies are located elsewhere in the UK, with only three located overseas. Several of the case studies also capture the work of pre-existing retrofit programmes/funding streams, notably the Retrofit for the Future and Welsh European Funding Office (WEFO) funding programmes. Each case study describes the retrofit actions undertaken, as well as the key challenges encountered. The impact of each retrofit is described in terms of capital cost, primary energy use and carbon emissions, where data are available (see section 3).

The review of case studies was undertaken to develop an understanding of current retrofit practice, but was not expected to deliver learning related to emerging practice or future innovation, or to related and relevant subjects such as energy supply or policy change. The literature was therefore reviewed from a wide range of grey and academic sources, with the intention of addressing these gaps. In total, 46 published pieces of literature were reviewed, including academic papers, industry standards and best-practice advice, stakeholder reports and guidance for policy-makers. Initial search terms included: 'housing', 'retrofit', 'energy efficiency', 'fabric improvement' and 'domestic renewable'. The terms listed by Swan (2013: 42) in his 'Technical Regime for Domestic Energy Use' were then used as the basis for further searches, along with the snowball method and input from the Welsh Government's Decarbonisation Advisory Group (DAG). Additional focused searches were carried out when a gap was found in the literature identified. The assembled material was scrutinised to ensure relevance (to Wales), impartiality and replicability.

For discussion purposes, retrofit actions were then organised according to key themes: thinking strategically; building fabric; renewables; services; financial; supply chain; and people. The discussion of each retrofit action cross-references both case studies and the literature to provide a clear account of each action, supported by evidence wherever possible. In addition, an assessment was made of each retrofit action in terms of confidence and timescale, based on the data and reporting available. This culminated in a classification of existing and emerging retrofit actions into 'what works', 'needs exploring' and 'big challenge' categories (see section 3).

Stage 2 began with a statistical review of existing data—including the Valuation Office Agency (VOA) data set, the Energy Performance Certificate (EPC) data set (MHCLG 2016) and the Welsh House Condition Survey (Welsh Government 2018)—to establish a collection of dwelling archetypes that collectively represent the Welsh housing stock. Modelling the housing stock using archetypes is a well-established method (Jones, Patterson, & Lannon 2007) and is particularly useful when modelling retrofit options (Swan & Ugursal 2009). A total of 14 dominant dwelling archetypes were identified and modelled using a Standard Assessment Procedure (SAP) (BRE 1998) (see section 4). These models were used to simulate the Welsh housing stock in 1990, 2016 and 2050. To simulate the condition of the stock in 2050, learning from the Stage 1 review was used to establish four distinct retrofit strategies. The four strategies simulated were:

- **'historic':** where retrofit is limited by the character of the dwelling (*e.g.* historic buildings)
- **'good practice':** retrofit to a standard commensurate with UK Building Regulations Part L (2016)
- **'best practice':** retrofit to a standard commensurate with SAP90 and
- **'rural':** retrofit to a standard commensurate with SAP90 in an off-grid situation.

To assess the significance of decarbonisation of the energy supply, three energy supply 'scenarios' (for the gas and electricity networks combined) were also considered:

- **'minor change':** energy supplied with 40% fewer emissions overall than 1990 levels
- **'significant change':** energy supplied with 60% fewer emissions overall than 1990 levels and
- **'transformational change':** energy supplied with 80% fewer emissions overall than 1990 levels.

The resulting research (see sections 4 and 5) provides a collection of 14 retrofit simulations that broadly reflect the Welsh housing stock. The simulations describe the impact of the four retrofit strategies in terms of capital cost, energy use, fuel bills and carbon emissions, and illustrate the implications of the three distinct energy supply scenarios. (To model all these permutations, the 14 retrofit simulations are underpinned by 2016 distinct SAP calculations.) Together, they have been used to draw conclusions about the potential to decarbonise the Welsh housing stock. These conclusions have informed recommendations that have been adopted by the Welsh Government in the ongoing development of a route map for decarbonisation. Key recommendations are outlined and explained in section 6.

3. Stage 1: A review of the literature and case studies
A total of 39 case studies were reviewed based on their relevance to the Welsh stock, their ability collectively to capture the breadth of retrofit actions being employed in the UK, and on the quality of the reported underpinning empirical evidence (see Appendix A in the supplemental data online and section 2 above).

Other projects were considered for review, but deemed to have less relevance, or insufficient data to warrant inclusion. The review of the case studies established that retrofit actions affecting dwelling fabric are the best understood. The effectiveness of renewables and systems-based actions is less well understood, being more influenced by innovation and emerging technologies. There is limited clarity over the most effective combinations of actions that together constitute a retrofit strategy. There is also conflicting evidence around the effectiveness of retrofit, which appears to be heavily influenced by the level of occupant engagement in the process. Where occupants were not involved, case studies consistently reported a significant performance gap (with limits to effectiveness and abortive work), compared with retrofit where occupants were active participants. The influence of people is the least understood aspect of retrofit generally (Van den Brom, Meijer, & Visscher 2019), making future work around lifestyle choices and behaviour change particularly important.

Some case studies reduced carbon emissions by 80% or more (demonstrating technical feasibility), but capital costs were generally high (>£800/m²). High capital costs were attributed to bespoke approaches focusing on maximum impact on emissions by using a broad range of retrofit actions, as well as innovative techniques and technologies.

A subgroup of case studies (predominantly WEFO-funded projects) targeted a similar impact on emissions, but at lower cost. Retrofit strategies typically reduced carbon emissions by between 50% and 80% of benchmark levels, with capital costs between £300 and £400/m². Lesser costs were a consequence of focusing on more effective retrofit actions and using better understood techniques/technologies. These case studies also tended to be more recently completed.

A more general finding was that different sectors of the housing stock require different incentives to make retrofit happen. Tenure is likely to have a particularly big influence on the most appropriate incentive. Smaller, lower value, privately owned dwellings are among the 'hardest to reach'. Smaller, off-grid, privately owned dwellings are currently among the 'hardest to treat', while dwellings located in conservation areas also present specific challenges.

Throughout the Stage 1 review, the importance of holistic retrofit was consistently emphasised. This includes the provision of technical, legal and financial advice, aftercare follow-up for occupants, and post-occupancy evaluation to capture and validate learning. The influence, and unpredictability, of occupants' behaviour was another consistent Stage 1 finding. For this reason, the Stage 2 strategic modelling did not attempt to understand this complex area, but relied on statistically established assumptions for occupancy (as per the SAP; BRE 1998).

The literature relating to decarbonisation of the housing sector, domestic energy-efficient retrofit and associated UK policy is extensive, dating back to the energy crises of 1973 and 1979. A total of 46 pieces of literature were included in the review, based on their relevance, currency and potential contribution to the project (see section 2). Within the review, each publication (listed in Appendix B in the supplemental data online) is outlined with links, cross-referenced (to other literature and case studies), thematically indexed and key findings are summarised.

In 2013, the Low Carbon Routemap for the UK Built Environment (Green Construction Board 2013) provided a summary of challenges and opportunities arising from an understanding of the existing housing stock (UK). While it did not look at the Welsh stock in particular, this study identified the technical feasibility of an 80% emissions reduction in the built environment, but only through the maximum uptake of technically viable solutions, including technologies that do not currently have a financial return on investment over their lifetime. (Before this, academic studies used detailed scenario-based modelling to establish the technical feasibility of reductions in excess of 60% by 2050 (Johnston, Lowe, & Bell 2005), and identified synergies that might make larger reductions possible.) The route map identified the most significant source of carbon emissions in the built environment as domestic emissions from space heating. While a change in fuel source and/or heating system is typically required to achieve the level of emissions reductions needed, the building fabric still has a role to play by reducing energy demand and, consequently, the scale of the challenge. However, even when fabric improvements have been made to a dwelling, the standard to which they have been retrofitted is very varied (*e.g.* approximately 14% of dwellings still have <15 cm of loft insulation; BEIS 2017a). Lighting alone represented about 25% of energy use in 2010, with significant opportunities to reduce associated emissions, as much of the technology needed already exists and payback periods are often short.

The Routemap (Green Construction Board 2013) proposed that emissions could be reduced by 80% (relative to 1990 levels) by assuming that 95% of easy-to-treat homes and 70% of hard-to-treat homes will be retrofitted with insulation, draught-proofing and higher performance glazing. Delivery is reliant on a substantial increase in the pace of retrofit, particularly hard-to-treat homes. This in turn requires that responsibility be taken for carbon reduction across the sector, to drive uptake and deliver results as quickly as possible, because a sufficiently incentivised and skilled workforce does not currently exist to implement even the measures that could have a return on investment over their lifetime (Warren & Griffiths 2017; Patterson 2016). The performance gap has also been identified as a major issue (Palmer *et al.* 2016). By diminishing it, the efficiency of (and returns from) retrofit initiatives can be improved, along with a reduced risk and increased confidence from investors and homeowners. The impact of occupant behaviour was also recognised, with the potential to impact either positively or negatively on performance and emissions.

The lack of impartial, reliable advice around both technical and financial issues is one of the main barriers to uptake of improvements in the private sector (Severn Wye Energy Agency 2014; NEA 2017b). With a view to understanding these issues, Dr Peter Bonfield was commissioned in 2015 to chair an independent review of Consumer Advice, Protection, Standards and Enforcement for UK home energy efficiency and renewable energy measures. The *Each Homes Counts* report (Bonfield 2016: 4) identified that:

> despite long term energy price rises, increasing publicity and awareness of energy efficiency and renewable energy options, considerable investment by the private sector, and several government enabling policies, we have not seen a large scale increase in the level of public demand for [energy efficiency] measures.

The report recommends a new approach to the provision of energy efficiency measures for the domestic sector:

> underpinned by strong standards and enforcement, to bring clarity and confidence to consumers, whilst providing a simplified and certain route to market for those companies, large and small, wishing to operate and do business in the energy efficiency and renewable energy sector in the United Kingdom.   (Bonfield 2016: 4)

The report sets out a new quality and standards framework for the retrofit sector (currently in development as the PAS2035 retrofit standards framework), which would include: a quality mark against which all those engaged in design and installation of energy efficiency and renewable energy measures will be assessed and certified; a consumer charter to set out the positive experience that the consumer can expect under the quality mark, including response times, financial protections and access to redress procedures when things go wrong; a code of conduct to set out clear requirements and guidance on how companies behave, operate and report in order to be awarded and hold the quality mark; and technical codes of practice and standards for the installation of home renewable energy and energy-efficiency measures so that the risk of poor-quality installation is minimised.

Building renovation passports, developed by the Buildings Performance Institute Europe (BPIE)[1] offer a more systemic approach for the production of customised (building-specific) roadmaps towards deep renovation and better homes, focused on dwelling performance. The approach has been trialled in several European countries, and provides a model for a phased approach to retrofit. Iterative improvements are made in an augmented EPC model, providing a series of quantifiable improvements to an individual dwelling or dwelling type. Each phase is explained in terms of impact on energy and carbon and associated financial cost. Together the cumulative phased improvements deliver a roadmap that can be tailored to meet a targeted level of improvement.

The *Energy Efficient Scotland* route map (Scottish Government 2018) provides an example of a legible high-level strategy designed to deliver decarbonisation of the Scottish housing stock by 2050. It also uses existing EPC targets, based on pre-existing mechanisms for performance measurement and 'understood' actions/pathways. The route map recognises the importance of tenure, subdividing targets and levers into 'private rented', 'owner occupied' and 'social housing', with an additional focus on affordable warmth for all. However, because of this low level of specificity, there is limited detail to the route map, and many of the more challenging aspects remain at consultation stage.

Bringing the literature review up to date, the most recent *Progress Report to Parliament* (CCC 2018) and subsequent report *Net Zero—The UK's Contribution to Stopping Global Warming* (CCC 2019) provide high-level guidance for UK policy-makers. These reports focus on looking forwards, and include a Wales-specific sub-document, but findings are not underpinned by a detailed analysis of the Welsh housing stock. The CCC reports support the implementation of simple, low-cost retrofit options that reduce emissions, noting that the withdrawal of incentives has reduced home insulation installations to 5% of their 2012 level. The CCC argues that concerns over short-term costs are misguided, as the overall economic cost of meeting decarbonisation targets will be higher without cost-effective measures in place. The reports recommend a commitment to effective, evidence-based regulation and enforcement, along with tougher, more consistent long-term standards for construction to cut emissions while also driving demand (building UK-based supply chains), innovation and cost-effectiveness. They advocate retrofit actions that keep long-term options open and support growth in the low carbon sector due to uncertainties around the future of cleaner energy generation and carbon capture, an inevitable part of any decarbonisation strategy.

On the subject of energy supply, 80% of UK homes currently use mains gas for heat (National Grid 2018). In the long term, the decarbonisation of electricity at the point of generation may mean that where mains electricity is available, these dwellings are retrofitted for heat from all-electric supply (and generation) via the national grid. There is also the possibility of a less carbon-intensive gas supply (National Grid 2018; see also Freedom Project 2018). Regardless of the heat source, around 20,000 homes per week must be transitioned to a low carbon heat source between 2025 and 2050. This will require considerable coordination and communication, resources, and a reliable supply chain (Lowe 2007). Decarbonisation of the energy supply could increase energy costs, putting additional homes into fuel poverty. It may not be easy to persuade consumers to move to low-carbon alternatives, which are more expensive and potentially less effective (NEA 2017a; National Grid 2018).

Together, the review of case studies and the literature identified recurring retrofit actions and challenges, and enabled a discussion of their relevance to the decarbonisation programme, linked back to supporting evidence. The discussion included an attempt to classify each action or challenge in terms of 'timescale' and 'evidence'. 'Timescale' reflects whether the retrofit action or challenge is applicable in the short term (now), medium term (currently being piloted or likely to be implemented soon) or long term (currently in development). 'Evidence' reflects whether observations are anecdotal (no evidence provided), documented (evidenced, but without independent validation) or understood (robust, and validated by a third party). Together, these factors enable recurring retrofit actions to be given an 'overall' classification of either green ('what works'), amber ('needs exploring') or red ('big challenges') (**Table 1**), and the associated key for its 'traffic light' classification.

Table 1: Retrofit actions and challenges structured thematically and classified based on evidence and applicability, with links (see Stage 1 report) to case studies and literature.

Theme	Action / Challenge	Evidence	Applicability	Overall	Theme	Action / Challenge	Evidence	Applicability	Overall
1 Thinking strategically	1.1 Taking advantage of funding	✓	S	green	4 Services	4.1 Gas	✓	S	green
	1.2 Energy sources	×	L	red		4.2 Oil	×	S	orange
	1.3 Changing primary energy supply	–	S	green		4.3 Biomass	×	S	orange
	1.4 Fabric first approach	–	S	green		4.4 Heat pumps	–	S	orange
	1.5 Development constraints	×	S	orange		4.5 Radiant heat	–	S	green
	1.6 Addressing overheating	–	M	orange		4.6 Underfloor	×	S	orange
	1.7 Going beyond Building Regulations	–	S	green		4.7 Storage	–	M	orange
	1.8 Void reductions	×	S	orange		4.8 Ventilation	×	S	orange
2 Building fabric	2.1 Spatial constraints	×	S	orange		4.9 District heat networks	×	M	red
	2.2 Unexpected construction/condition	–	S	orange	5 Financial	5.1 Availability of finance	×	S	orange
	2.3 Roof upgrade	✓	S	green		5.2 High cost of actions	×	S	orange
	2.4 Wall upgrade	–	S	green		5.3 Unexpected costs	×	S	orange
	2.5 Floor upgrade	–	S	green		5.4 Payback periods	×	S	orange
	2.6 Windows	✓	S	green		5.5 Maintenance costs	×	S	orange
	2.7 Shading	×	M	red		5.6 Locked-in investment	×	S	orange
	2.8 Air tightness	–	S	green	6 Supply chain	6.1 Knowledge	×	S	orange
3 Renewables	3.1 Heat recovery	–	S	green		6.2 Materials	×	S	orange
	3.2 Combined heat and power (CHP)	–	M	orange		6.3 Skills—workforce	–	S	green
	3.3 Photovoltaics (PV)	✓	S	green		6.4 Skills—training	×	S	orange
	3.4 Electric battery	–	M	orange	7 People	7.1 Occupant engagement	✓	S	green
	3.5 Wind	–	M	orange		7.2 Occupants stay put	–	S	orange
	3.6 Solar thermal	✓	S	green		7.3 Simple controls	–	S	green
	3.7 Transpired solar collectors	–	M	orange		7.4 Smart meters and homes	×	M	red
						7.5 Entrenched behaviour	–	S	green
						7.6 Health issues	–	M	orange
						7.7 Influencing lifestyle	×	M	red

Key to the classification:

Applicability	Evidence		
	Anecdotal (×)	Documented (–)	Understood (✓)
Long term (L)	Big challenges		
Medium term (M)		Needs exploring	
Short term (S)			What works

4. Modelling the Welsh housing stock

The primary aim of the Stage 2 research (Green *et al.* 2019) was to understand the degree to which the specific nature of the Welsh housing stock informs retrofit strategies for reducing carbon emissions, and establishes realistic limits for the decarbonisation of the housing sector through physical retrofit.

To conduct urban-scale modelling of energy performance techniques (Swan & Ugursal 2009), a bottom-up approach (Lannon *et al.* 2018) was used to develop a taxonomy of commonly occurring dwelling archetypes that collectively represent the make-up and condition of the existing Welsh housing stock. Two domestic data sets, both disaggregated by 'age of construction' and 'built form' (Lannon *et al.* 2018), were combined to establish the dwelling archetypes. A strategic (low detail) data set from the Valuation Office Agency (VOA) describing around 60% of all homes in Wales was combined with a high-detail data set from the Welsh Housing Condition Survey (WHCS) describing about 2500 dwellings within the Welsh housing stock (collected in 2016–18; Welsh Government 2018). Because the scale and scope of the data sets are so different, there were no significant discrepancies or issues in combining them. Together, they provide a breakdown of the housing stock (**Table 2**).

Models were then created for each archetype to simulate the decarbonisation of the housing stock using understood approaches to retrofit. (The physical characteristics associated with each archetype are assumed to be constant.) Implications for energy efficiency, fuel costs and affordable warmth were considered to be an important part of the modelling process. The modelling techniques used in this report are based on the government's Standard Assessment Procedure for Energy Rating of Dwellings (SAP) 2012 version. The SAP tool has received criticism regarding its accuracy (*e.g.* Kelly, Crawford-Brown, & Pollitt 2012), particularly in its ability to represent specific situations. Criticisms focus on assumptions that are necessarily made during the input stage and the dominant output being cost based. These issues can be mitigated through the careful selection of input variables, by focusing on carbon emissions and by making observations regarding the stock as a whole. (Prior work has demonstrated that with the careful selection of inputs, SAP-based models can deliver stock-level simulation that is close to measured performance (Iorwerth *et al.* 2013).) In this case, the archetype dwellings have no specific context to model, so stock level defaults of East/West orientation, moderate overshadowing and occupancy patterns were taken from the SAP guidance (BRE 1998). Other modelling assumptions are outlined in Appendix F in the supplemental data online.

The SAP-derived energy requirement (energy required for space heating, water heating, lighting and contributions from renewable technologies) is then used to predict carbon emissions and the associated energy costs. (A spreadsheet version of the SAP 2012 9.92 worksheet was developed by the Welsh School of Architecture (Cardiff University) and tested against approved software Stroma FSAP 2012. The spreadsheet version allows the modelling of different fuel costs and emissions rates, which is critical to understand the different outcomes for 1990, 2016 and the three 'future' energy supply scenarios. See Appendix F in the supplemental data online for details.)

The 14 dwelling models were then used to evaluate the impact of future retrofit on carbon emissions by comparing the performance of each dwelling as it was in 1990, as it performed in 2016 and as it might perform in 2050 after retrofit. Further information was needed to simulate the physical condition of each archetype at these three points in time. Data came from three sources:

- Historic data for the 1990 'baseline' condition came from the UK Housing Energy Fact File (DECC 2013).
- Data for the condition of the stock in 2016 came from the EPC data for Wales (MHCLG 2016), capturing about 60% of the total Welsh housing stock (over a nine-year period).
- To develop a model for 2050, four retrofit strategies were developed. Retrofit actions were drawn from the Stage 1 review, developing a holistic retrofit specification for each strategy. Each strategy was designed to represent a viable approach for part of the Welsh housing stock. A brief description of each retrofit strategy is provided in **Table 3**.

Through reference to relevant case studies and the published literature, the Stage 1 research informed the development of an outline specification for each retrofit strategy, described in **Table 4**.

Table 2: Fourteen archetypes collectively representing 84% of the Welsh housing stock.

	End terrace	Mid-terrace	Semi-detached	Detached	Flat	Total (%)
Pre-1919	Type 1, 3%	Type 2, 9%	Type 3, 4%	Type 4, 7%		23%
1919–44			Type 5, 5%			5%
1945–64			Type 6, 10%			10%
1965–90	Type 7, 4%	Type 8, 6%	Type 9, 10%	Type 10, 9%	Type 11, 4%	33%
Post-1990			Type 12, 5%	Type 13, 7%	Type 14, 1%	13%
Total (%)	7%	15%	34%	23%	5%	84%

Table 3: Four retrofit strategies developed from the Stage 1 review.

Retrofit strategy	Action
Heritage	Actions are constrained, *e.g.* as a result of listed building status or location within a conservation area. The impact on the dwelling fabric is assumed to be restricted, requiring internal rather than external wall insulation, along with appropriate ventilation. No floor insulation is provided. Windows are secondary glazed rather than replaced. No roof-mounted renewables are provided. The wet (gas-fired) central heating system is retained (assumes mains gas supply to be available). Indicative SAP rating = 71
Good practice	Actions are driven by best value—in terms of affordability, cost effectiveness, and availability of skills and resources in the current marketplace. Roof insulation is topped up. External wall insulation and replacement glazing are provided that meets current (refurbishment) UK Building Regulations. No floor insulation. Modest array of roof-mounted photovoltaic panels provided. Wet (gas-fired) central heating system is retained (assumes mains gas supply to be available). Indicative SAP rating = 88
Best practice	Assumes an aspirational client or owner-occupier, likely to be more concerned with long-term quality than short-term cost. Environmental impact is a priority. Roof insulation is topped up. External wall insulation is provided that meets current (newbuild) UK Building Regulations. Triple glazing and floor insulation are also included. A generous array of roof-mounted photovoltaic panels is provided. Primary heat is whole house mechanical ventilation with heat recovery (MVHR) with an air-source heat pump, and electric immersion heater for hot water. Indicative SAP rating = 90
Rural	Location is assumed to dictate off-grid energy solutions. The focus is on energy conservation and use of locally viable renewables. Roof insulation is topped up. External wall insulation and replacement glazing are provided that meet current (newbuild) UK Building Regulations. Floor insulation is included. A generous array of roof-mounted photovoltaic panels is provided, along with a direct solar hot water system. Primary heat is whole-house MVHR with an air-source heat pump (and electrical top up of hot water). Indicative SAP rating = 90

Note: SAP = Standard Assessment Procedure.

Table 4: Specification for each retrofit strategy, developed from the Stage 1 review.

	Heritage	Good practice	Best practice	Rural
Roof insulation (W/m²°C)	0.16	0.16	0.16	0.16
Wall insulation (internal) (W/m²°C)	0.25			
Wall insulation (external) (W/m²°C)		0.30	0.12	0.12
Floor insulation (W/m²°C)			0.16	0.16
New windows (W/m²°C)		1.80	1.40	1.80
Secondary glazing (W/m²°C)	2.40			
Renewables (photovoltaic) (kWp system)	–	2.6	4	4
Electric battery				For storage
Solar thermal hot water				2 m²
Primary heat source	New, A-rated gas combi boiler	New, A-rated gas combi boiler	MVHR with air-source heat pump	MVHR with air-source heat pump
Hot water	Via gas combi boiler	Via gas combi boiler	Electric immersion	Electric top up of solar hot water

Note: MVHR = mechanical ventilation with heat recovery.

The retrofit of each archetype was then explored in terms of capital costs and the impact on energy demand, fuel costs and emissions. Each retrofit action was costed by quantity surveyor Lee Wakemans. Predicted capital costs are based on current cost data held by the consultants, supported by recent, relevant case studies (see Appendix D in the supplemental data online for a summary of cost assumptions).

A key distinction between the strategies is that the 'best practice' and 'rural' strategies include the transition to electric/renewable sources of heat. The closest widely understood standard to 'best practice' and 'rural' at this time is EPC band A. (With an SAP rating of ≥92, EPC band A makes some allowance for the performance gap between modelled and delivered retrofit.)

By combining the results arising from the study of each individual dwelling archetype in their representative proportions, it was possible to predict the degree to which different approaches to retrofit could achieve carbon emission reductions *for the Welsh housing stock as a whole.* The results of this modelling enabled a balanced discussion of approaches to decarbonisation that considers the impact of four distinct retrofit strategies and three energy supply scenarios in terms of carbon emissions, capital costs, energy use and impact on fuel bills for occupants.

5. Findings

This paper explores retrofit actions that directly affect the housing stock. To date, emissions from the housing sector are estimated to have reduced by >40% from baseline 1990 levels, but three-quarters of this improvement comes from cleaner energy supply (improvement of the mains gas and particularly mains electricity grid) rather than changes to the housing stock itself (CCC 2019).

The degree to which energy supply continues to decarbonise will significantly affect decarbonisation of the housing stock, and could influence the selection and effectiveness of domestic retrofit actions. For this reason, it was deemed necessary to consider decarbonisation of the energy supply within this work. Three distinct energy supply 'scenarios' (for the gas and electricity networks combined) were modelled in order to explore the impact of potential future changes to the energy supply on decarbonisation of the existing housing stock, as follows:

- · Scenario 1: 'minor change': 40% fewer emissions per unit than 1990 levels.
- · Scenario 2: 'significant future improvement': 60% fewer emissions per unit than 1990 levels.
- · Scenario 3: 'transformational change': 80% fewer emissions per unit than 1990 levels.

The resulting discussion established the significance of each of the three energy supply scenarios in informing the development of a decarbonisation strategy, in the context of current uncertainty around future changes to clean energy supply. Findings are observed at the scale of individual dwelling archetypes and in terms of the Welsh housing stock as a whole.

5.1 Dwelling archetypes

The Stage 1 scoping review suggests that there is considerable scope to develop appropriate retrofit strategies for the Welsh housing stock by employing actions that are well understood, and skills and products that are widely available. An example of the output for each individual dwelling archetype (in this case, dwelling type 2: pre-1919 mid-terrace) is provided in **Figures 1** and **2**. In **Figure 1**, the coloured lines describe the decarbonisation of the dwelling archetype via all four retrofit strategies. Each line includes emissions reductions between 1990 and 2018 (columns 1 and 2). (For the rural strategy, the dwelling is assumed to be electrically heated, and starts at a higher level of decarbonisation.)

The study of 14 distinct archetypes identified that the physical size and shape of a dwelling are not necessarily factors that change the retrofit strategy (although they do have considerable impact on capital cost and energy costs). The selection of 'appropriate' retrofit actions is, however, likely to be informed by the current condition and character of the
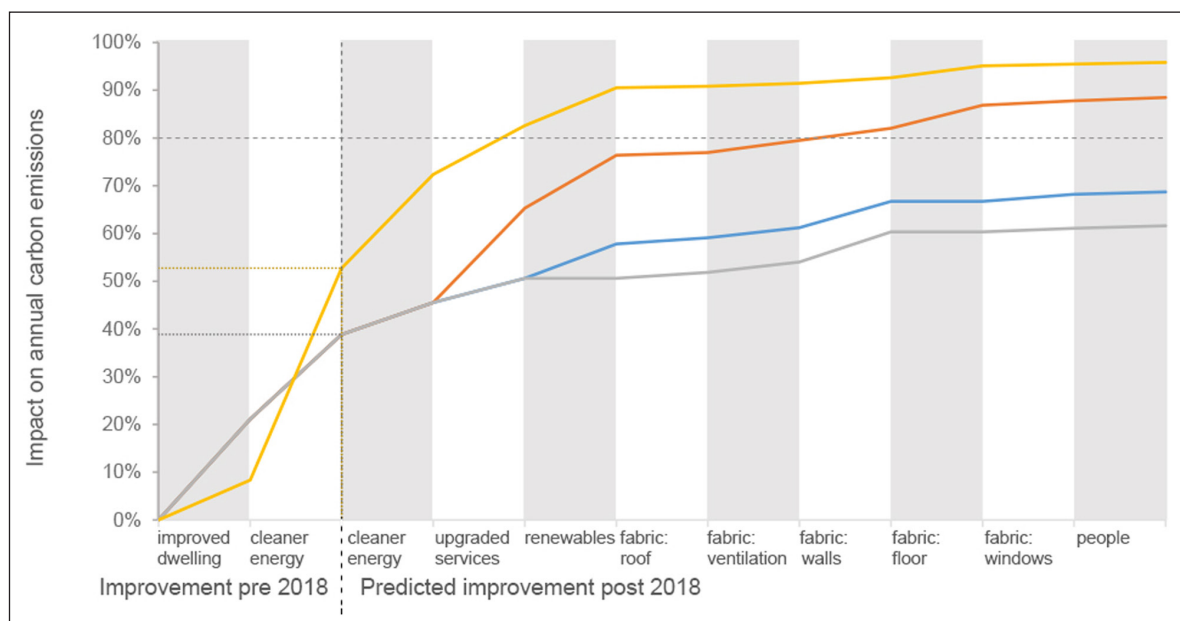

Figure 1: Impact of retrofit on greenhouse gas (GHG) emissions for archetype 2: pre-1919 mid-terraced property. *Note*: yellow line = rural strategy, grey line = heritage strategy, red line = best practice strategy, blue line = good practice strategy.
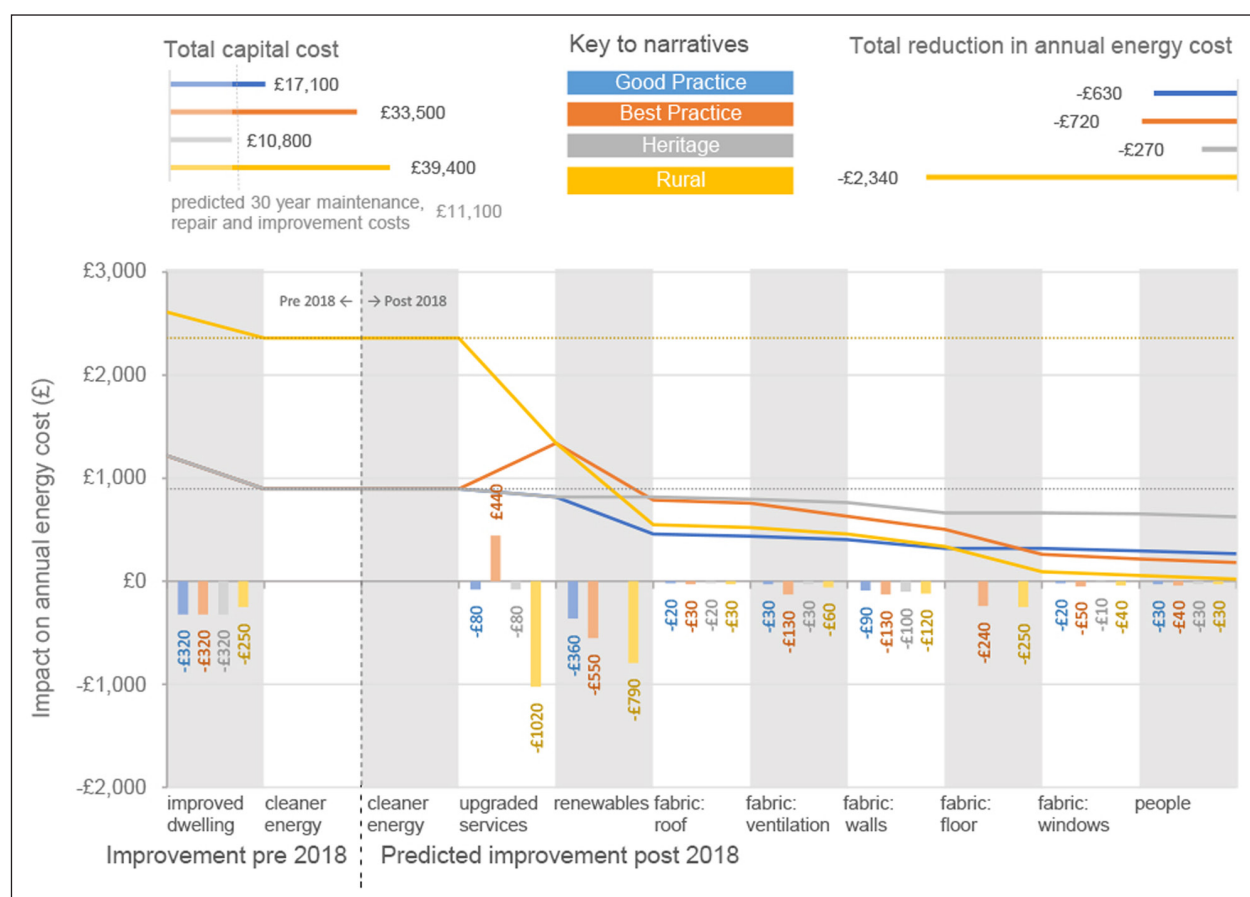
Figure 2: Impact of retrofit on annual energy costs for archetype 2: pre-1919 mid-terraced property. At top are the key to narratives and headline results (capital cost and energy costs).

Table 5: Emissions reductions achieved by all 14 dwelling archetypes (as a range) for four retrofit strategies and three energy supply scenarios.

Retrofit strategy	Carbon reduction by energy supply scenario		
	Scenario 1: 40% clean energy	Scenario 2: 60% clean energy	Scenario 3: 80% clean energy
Heritage	58–66%	78–83%	≥100%
Good practice	64–76%	81–87%	≥100%
Best practice	83–89%	92–95%	≥100%
Rural	86–96%	93–98%	≥100%

dwelling and its surrounding context, by retrofit actions previously undertaken, and to a certain extent by the personal choice of the occupant or owner.

The predicted reductions in emissions resulting from each retrofit strategy are summarised in **Table 5**, and in more detail in Appendix C in the supplemental data online. As can be seen, the level of reduction achievable is significantly influenced by decarbonisation of the energy supply.

Predicted baseline capital costs for the four retrofit strategies are summarised below, based on current 'market' rates (see Appendix D for cost assumptions and Appendix E for cost predictions in the supplemental data online). Results are broadly comparable with the costs identified by relevant Stage 1 case studies (see section 3 for a summary). Lower costs are consistently for older, smaller, mid-terraced properties and high costs are for older, larger detached dwellings. The range of costs for each strategy is as follows:

- good-practice strategy: £17,000–£32,000
- best-practice strategy: £33,500–£63,300
- heritage strategy: £11,000–26,000
- rural strategy: £39,000–67,000.

The precise specification of retrofit actions can have a considerable further impact on capital cost—particularly decisions around the use of materials or products that are ethically sourced, environmentally sustainable or with related health benefits.

For all retrofit strategies other than 'rural', *annual energy costs are predicted to rise considerably when strategies focusing on cleaner energy supply and retrofit of heating systems are employed.* (The 'rural' strategy predicts high existing energy costs because the assumed heating system is Economy 7.) Based on current energy unit costs, the 'best practice' retrofit of heating systems from mains gas to electric supply results in an average increase in annual energy costs of 47% (range of 26–59%). It is therefore reasonable to suppose that strategies focusing on cleaner energy supply and retrofit of heating systems will impact negatively on fuel bills for occupants. In contrast, when a holistic retrofit strategy is implemented, the percentage *reduction* in energy costs compared with current energy costs are:

- good-practice strategy: average of 33% (range = 14–49%)
- best-practice strategy: average of 29% (range = 20–42%)
- heritage strategy: average of 71% (range = 58–78%)
- rural strategy: average of 11% (range = 1–28%)

In the likely event that the costs associated with cleaner energy supply are passed on to households, there could be considerable increases in energy costs for residents, and therefore in fuel poverty. A low level of dwelling fabric retrofit will leave occupants highly vulnerable to future changes in fuel tariffs.

5.2 Welsh housing stock as a whole

To model the housing stock as a whole in 2050, some assumptions were made:

- It was assumed that 15% of homes must be retrofitted to the 'heritage' standard because their retrofit is constrained by character (typically these 'historic' homes would be listed buildings, or located in a conservation area).
- It was assumed that 10% of homes must be retrofitted using the 'rural' strategy because they are situated in off-grid locations.
- It was assumed that the social housing and PRSs (30% of the housing stock) will be retrofitted to 'best practice' because housing standards provide a mechanism for enforcing holistic retrofit.
- It was assumed that a further 15% of the stock, deemed to be in fuel poverty, will be retrofitted to 'best practice', to mitigate against the real risk that decarbonisation increases fuel poverty. (It should be noted that it is the household, not the physical home, that is categorised as being in fuel poverty, which raises questions about the way such an approach would be delivered.)

Initially, no assumptions were made regarding the remaining 30% of the housing stock (owner-occupied homes, with fewer mechanisms for enforcing holistic retrofit). However, the research clearly indicates that unless clean energy supply goes considerably beyond 60%, carbon emissions can only be reduced beyond 90% (in line with current targets) if *all* homes are improved to the 'best practice' standard.

By combining the individual dwelling archetype models in this way, the impact of retrofit of the housing stock as a whole on emissions is simulated as described in **Figure 3**.

Key observations are as follows:

- Under scenario 1 (red line, 40% clean energy supply), it is not currently tenable for the existing housing stock to achieve >90% reduction in carbon emissions using established retrofit practice.
- Under scenario 2 (yellow line, 60% clean energy supply), a >90% reduction in carbon emissions is only achieved when the entire existing housing stock (excepting 15% assumed to be older 'historic' homes) is retrofitted to SAP90 or higher, with a transition to electricity as a source of heat (*i.e.* adoption of best practice or rural strategies).
- Under Scenario 3 (blue line, 80% clean energy supply), target levels of decarbonisation are achieved through improvements in energy supply and services alone. However, a fabric-based retrofit remains an important part of any decarbonisation strategy. It is critical that fabric-based retrofit is employed to reduce demand in primary energy use (as heating systems, hot water supply and transportation all transition to electricity as a primary energy source) and to minimise increases in fuel bills for occupants, and a consequent increase in fuel poverty.
- Capital costs are, on average, £33,850 per dwelling (around £47 billion in total). Wider benefits are difficult to quantify and should be the subject of further research, as they include qualitative benefits around the home, the internal environment and the surrounding community, as well as quantitative savings such as reduced fuel bills and a reduced burden on the National Health Service (NHS), and the potential for investment in local and national economies.
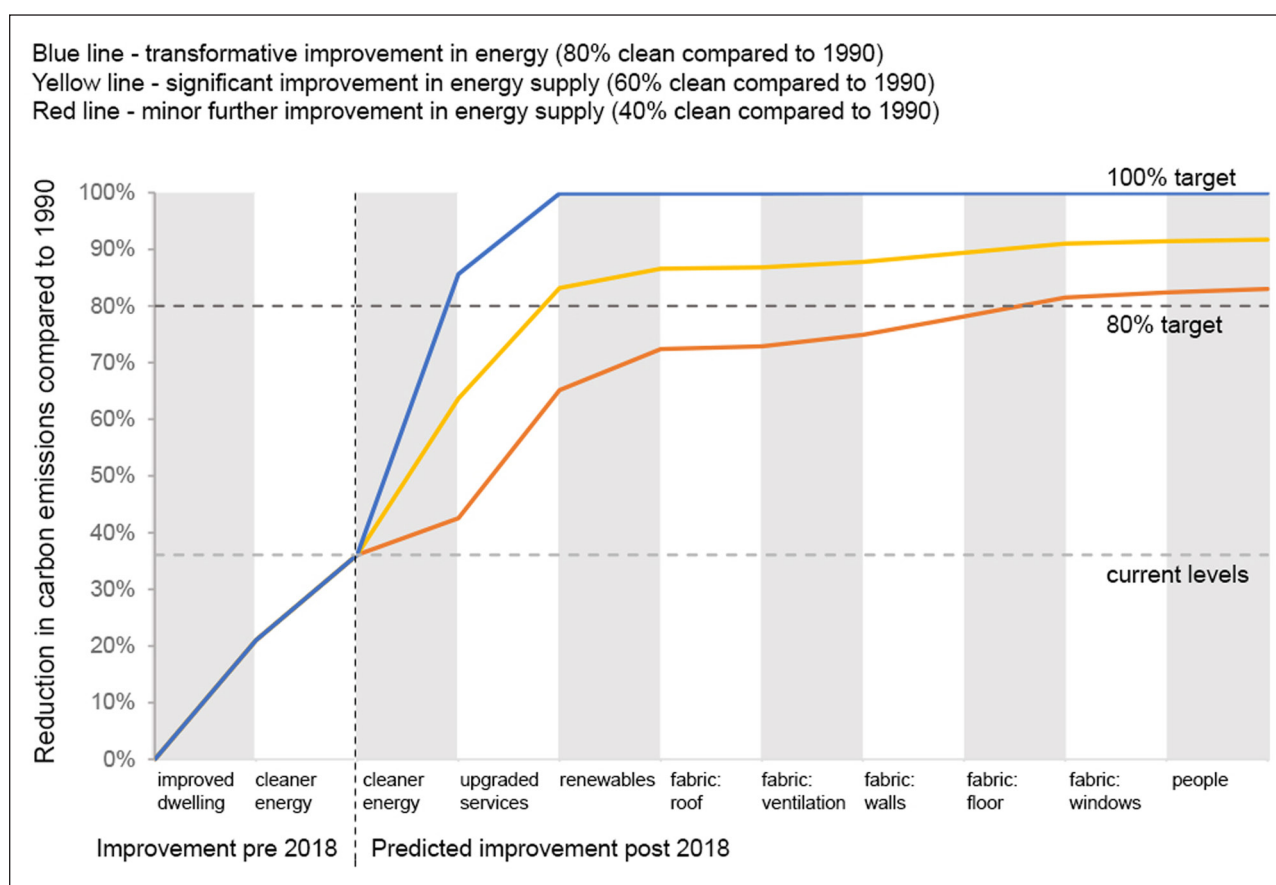
Figure 3: Simulated impact of retrofit on emissions, when adopted across the entire housing stock.

6. Conclusions

Key recommendations drawn from this research consisted of generally accepted conclusions drawn from the literature reviewed during Stage 1, along with conclusions that were drawn specifically from the Stage 2 modelling work (see section 5). Generally accepted conclusions include the following:

· To meet stringent decarbonisation targets, retrofit actions must overcome the performance gap (*i.e.* the results of retrofit should be measured as delivered, not as predicted). A skilled, trained supply chain is needed to ensure that retrofit is appropriately conceived and properly implemented.
· Retrofit standards are easier to enforce for social housing and the private rented sector (PRS). Work must be undertaken exploring how to initiate this level of retrofit in the owner-occupied sector. Point of sale represents an opportunity to drive retrofit in the private sector.
· Phased targets for the retrofit of the entire housing stock, in line with national carbon budgets, may appear to offer stepping stones for decarbonisation. However, the retrofit of most fabric-based actions will be more cost-effective if only undertaken once. Other options, such as boiler replacement, are likely to be undertaken more than once before 2050. There is a risk that phased targets will diminish, or obviate, the benefit of work carried out in early phases. In any case, actions that avoid lock-in should be used, and economies of scale should be explored.
· The impact of people on retrofit remains the least understood part of the process, and the one most likely to impact the effectiveness of retrofit strategies, whether positively or negatively. Occupant behaviour can account for between 7.5% and 9.1% of variance in the predicted energy savings of retrofit (Majcen, Itard, & Visscher 2013). Evidence indicates that occupants must be included in the retrofit process, taking into account their different motivations and actions (Ben & Steemers 2018), and understanding the retrofit actions being undertaken, if the anticipated carbon savings are to be realised.

Conclusions drawn specifically from the Stage 2 modelling work include the following:

· Cleaner national energy supply is an essential part of any decarbonisation route map (**Figure 3**). From Wales's perspective, UK government must be lobbied to ensure that energy supply is at least 60% clean (relative to 1990

levels) by 2050, if decarbonisation targets are to be achievable. The smaller scale generation of clean energy at a local or regional level must also be encouraged.

· Infrastructural work to deliver cleaner primary energy is likely to increase fuel tariffs, and widespread transition to cleaner energy sources is likely to increase household fuel costs (see section 5). Dwelling retrofit strategies that upgrade heating systems must also uplift dwelling fabric to an acceptable standard, to diminish increases in energy costs, and vulnerable households must be protected to ensure that a consequence of a cleaner housing sector is not an increase in fuel poverty.

· Retrofit of some housing is constrained, notably pre-1919 housing with an established character that would be diminished by extensive changes to the physical fabric (**Table 6**). However the justification for 'acceptable fails' must be carefully defined, so as not to jeopardise decarbonisation targets.

On the basis that decarbonisation of energy supply is unpredictable and will have a considerable impact on decarbonisation of the housing sector, all other housing should be retrofitted beyond SAP90 (**Figure 3**). Currently, the most straightforward way to achieve this level of improvement, and protect against increases in fuel poverty, is to target an EPC A rating for retrofit, because it requires SAP92 or higher, which makes an allowance for the performance gap.

The comparison of different retrofit strategies for a taxonomy of distinct dwelling types indicates that a flexible approach, taking advantage of different opportunities for retrofit and pushing all housing to achieve stringent standards by 2050, is the only way to anticipate achieving targeted reductions in carbon emissions under assumed energy supply scenarios.

These conclusions and the underpinning research informed the recent Independent Steering Group report *Better Homes, Better Wales, Better World* (Welsh Government 2019a). The report's recommendations were adopted on behalf of Welsh Government by the Minster for Housing on 24 September 2019, and include the following key actions (Welsh Government 2019b):

· Action 2.1: by 2050 the housing stock must be retrofitted to beyond SAP90 to achieve an Energy Performance Certificate (EPC) Band A rating, recognising that not all homes will be able to achieve this.

· Action 2.2: lobby the UK government to support and encourage the further decarbonisation of the energy supply grids because Wales will not achieve the carbon reduction target without it.

· Action 2.3: the Welsh Government should urgently commence a 10-year programme to prioritise the retrofit of certain homes: (a) the Welsh Government should set a target of EPC Band A for homes in social ownership and homes in fuel poverty; and (b) the Welsh Government should incentivise early adopters to retrofit homes to a target of EPC Band A.

Stage 3 of this work is currently underway. Researchers are assisting local authorities and housing associations in developing the expertise to begin the challenge of retrofitting their housing stock, by identifying 'live' case studies that reflect the housing archetypes. Each case study will enable researchers to test the validity of anticipated retrofit strategies and explore related impacts (cost, carbon and energy use) in more detail. Decarbonisation targets may well drive the wholesale retrofit of the existing housing stock over the coming decades, but it remains vital that emissions reductions are considered in parallel with other factors such as energy use, comfort and affordable warmth. Opportunities for other 'benefits' embedded in retrofit may be key to catalysing improvement of the housing stock, particularly within the private homeowner sector. Stage 3 work aims to validate the results of the Stage 2 work with dwelling-specific data and modelling, and use these case studies to better understand the impact of (and for) occupants. The wider intention of Stage 3 is to establish a current and evolving retrofit resource to ensure that lessons learnt are disseminated efficiently and accurately.

Table 6: Assumptions made regarding the adoption of retrofit strategies, by housing sector.

Housing sector	% of stock	Strategy	Standard Assessment Procedure (SAP) equivalent
Older 'historic' homes	15%	Heritage	71
Off-grid homes	10%	Rural	90
Social housing plus private rented sector	30%	Best practice	90
Fuel-poor households	15%	Best practice	90
Remainder (owner occupied)	30%	Best practice	90

Note

Acknowledgements

Competing interests

Funding

Supplemental data

Additional information for this paper can be found at: http://orca.cf.ac.uk/115442/.

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