Limits and uncertainty for energy efficiency in the UK housing stock

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Abstract

The UK government's Clean Growth Strategy unambiguously described the decarbonisation of heat as the UK's greatest policy and technical challenge in meeting our carbon targets. Maximising the potential for energy efficiency in the existing domestic stock is critical to the low-carbon heat transition. Good information exists on the technical potential for energy efficiency measures in the UK stock, however, a lack of knowledge about current stock conditions and in-use factors places considerable uncertainty on how much of this technical potential is achievable in practice.

This study uses data from the fifth carbon budget (CB5) policy projections and updates the in-use factors using measured data from the National Energy Efficiency Database (NEED). This results in a 26% shortfall by 2035 in the anticipated energy savings through cavity, solid wall, and loft insulation compared to what is assumed in the CB5 projections. This will have costly implications for meeting future carbon budgets. Risks and policy implications are discussed. The practical potential for energy efficiency measures beyond cavity, solid wall, and loft insulation is explored.

Keywords: energy efficiency; retrofit; limits; UK housing; low-carbon heat

1. Introduction

The UK's Committee on Climate Change (CCC) has stated that meeting the 2050 emissions reduction target will be much more expensive, and perhaps impossible, without a near complete decarbonisation of the heating sector (CCC, 2015). The Clean Growth Strategy unambiguously described the decarbonisation of heat as the UK's greatest policy and technical challenge in meeting our carbon targets (BEIS, 2017).

There are number of reasons that heat is 'a paradigm case for the developed world' (Eyre & Baruah, 2015). Due to slow stock replacement rates, efficient new builds will contribute only marginally to the heat issue. Heat is a retrofit problem for the inefficient existing stock, which is dependent on an entrenched carbon-based heating system.

Fewer than 2% of buildings are currently heated with low-carbon heat, mostly through biomass and heat pumps (CCC, 2015). Any changes away from carbon-based heating will require downstream changes to heating appliances as well. This means that rather than a few upstream improvements propagating down a supply chain (such as replacing coal with renewables generation), the low carbon heat transition will affect every householder in the UK.

Low-carbon heat will be delivered through a combination of energy efficiency and fuel switching, but how much of each is an evolving question. Any changes that reduce energy demand will not only reduce the costs of providing heat in the short term, but also reduce the size of the low-carbon heating infrastructure that will inevitably replace fossil fuel-based heating over the coming decades.

For these reasons, it is critical to maximise the potential for energy demand reduction. This requires understanding the limits of what can be achieved, and limiting the uncertainty over what demand reduction is truly possible through energy efficiency measures.

Many forecasts suggest cost-effective energy improvements could save up to 25% of demand (Rosenow, et al., 2018). The CCC has created a pathway to meeting the Fifth Carbon Budget (CB5) that calls for a 25% reduction in energy demand by 2035 compared to a 2015 baseline through energy efficiency measures. This is based on a transparent set of assumptions about the uptake of different measures and the savings that will be achieved through each measure. The assumed savings through each measure are based on a 2013 report carried out by Element Energy (2013) based on a combination of surveys and modelling, as well as a series of in-use factors that have since been applied.

The UK has also begun collecting data on the actual performance of energy efficiency measures through the National Energy Efficiency Database (NEED). There is potential to update the assumed in-use factors used by the CCC so far with more recent data from NEED to provide a more realistic view of the demand reduction potential for energy efficiency measures.

This paper will address the following research questions:

RQ1. What uncertainty is created by the gap between the modelled CCC and the measured NEED in-use factors for the performance of energy efficiency measures?
RQ2. What are the impacts of this uncertainty for the Fifth Carbon Budget (CB5) and through 2050?
RQ3. What are the implications for energy efficiency policy, particularly for the uptake of Solid Wall Insulation (SWI)?

The structure of this paper is as follows. Firstly, a literature review will describe the scope of work done thus far and the consensus on the remaining technical potential for energy efficiency in the UK. The assumptions and context for carbon reductions in housing as part of CB5 are described. The review of the approaches to demand reduction will describe the gaps in real data. The method section will describe how the CCC CB5 work will be updated with NEED data. The analysis section will address RQ1 and RQ2. The discussion will then consider RQ3 including unintended consequences and alternative measures.

2. Literature

The UK has among the worst performing domestic stock in the EU, but has made significant improvements in recent decades (BEIS, 2018). In considering where best to focus efforts between energy efficiency and the provision of low carbon heat, it is important to understand what potential truly remains for demand reduction across the stock.

The UK heat strategy models energy efficiency improvements for reducing heat demand at 20% (DECC, 2013) and it has been argued that this is too low given past rates of refurbishment (Eyre & Baruah, 2015). The IEA 450 scenario has improved energy efficiency accounting for 71% of emissions reductions relative to the baseline in the period to 2020 and 48% in the period to 2035 (IEA, 2012) as referenced in (Sorrell, 2015). Their 2015 ‘Bridge Scenario’ (IEA, 2015) found energy efficiency to be the largest contribution to greenhouse gas abatement globally, responsible for 49% savings in 2030 against the INDC scenario (Nationally Determined Contribution).

Eyre and Baruah note that "2004-2012 may be an atypical period characterised by the availability of relatively easy, low cost energy efficiency improvements and an effective policy framework to deliver them and that this trend is now likely to change due to the declining availability of low cost measures and the recent large reductions in the scale of UK residential energy efficiency programmes." Pg 642 (Eyre & Baruah, 2015).

The rapid decline in energy efficiency activity since 2012 due to policy changes indicate that public policy rather than prices tend to be the key driver for energy efficiency (Eyre & Baruah, 2015).

This is not surprising, and is consistent with other findings that thermal retrofit as a market is not yet capable of standing on its own and requires both policy push and pull cues to drive demand. (see e.g. (Gillich, et al., 2017). Thus policy will play a critical role in driving the retrofits needed for the low carbon heat transition, and an accurate evidence base is essential. However, despite past success, there remains a gap between what forecasts deem to be cost effective energy efficiency reductions, and what is actually achieved in demand reduction.

Sorrell is careful to note the distinction between energy efficiency and energy demand. The linkage between the two is complex and rebound effects are frequently large. A failure to acknowledge these complexities may partly account for the accumulation of estimates of 'energy savings' from specific interventions, while aggregate energy consumption continues to rise. (Sorrell, 2015)

Energy demand may be reduced by improving the thermodynamic efficiency of the energy conversion device such as the boiler or engine, preserving energy in passive systems such as homes, or in reducing demand for the energy service itself such as comfort (Sorrell, 2015).

Remaining Potential for Energy Demand Reduction

The remaining potential for demand reduction can be considered as the product of two terms: the number of measures, and the savings achieved per measure. Of these two, the number of remaining measures is the most straightforward, as summarised in Table 1.

Table 1: Remaining Technical Potential for Energy Efficiency Measures in UK homes (Rosenow, et al., 2018).

	Millions of homes remaining
Solid Wall Insulation (SWI)	7.6 m
Cavity Wall Insulation (CWI)	5.2 m
Loft Insulation	7.1 m
Floor Insulation	19.5 m
Enhanced Double Glazing	17.9 m

While the technical potential for the number of remaining measures is echoed across a number of surveys from the BRE, BEIS, and the CCC, all of these surveys focus on the number of measures that are 'technically feasible'. Very few efforts have investigated the fraction of these measures that are 'practically feasible'. In practice, factors such as planning, space restrictions, or other site logistics could dramatically increase the cost of the measure, or even make the measure outright impossible. Determining the fraction of technically feasible measures that are also practically feasible at reasonable cost is a vital constraint in determining the overall potential for energy demand reduction.

One such effort was carried out by the BRE for solid walls. Their study found that of the 7.6M remaining, roughly 6.6M would be considered hard to treat. Under the broad assumptions that a) all

rendered and non-masonry natural dwelling could be insulated externally b) all masonry pointed dwellings with a floor area greater than 60 m^2 could be insulated internally, and c) 50% of the mixed wall structure types could be insulated; it can be calculated that 5.3 million dwellings can be treated. Assuming solid walls without masonry pointing finish are suitable for SWI, then 46% of solid wall area in the UK is suitable for SWI. If one assume areas in the back view of a dwelling can also be insulated, then this increases to 69%. (BRE, 2008a) (BRE, 2008b)

Another study estimated that 1.2 million homes are likely to be in conservation areas (Bottrill, 2005) and therefore measures such as SWI may be subject to planning restrictions. Where external SWI insulation is not practically feasible, internal insulation could be used. However, this faces a number of separate challenges which will be considered throughout this paper.

There remain considerable gaps in the available data sets with which to determine the fraction of technically feasible measures that are also practically feasible at reasonable cost. Determining the true savings attributable to each of these measures is more complicated still. The energy savings attributed to a given measure can be considered as the product of two components: 1) the deemed savings based on the laws of thermodynamics, and 2) a reduction factor due to individual building site or user behaviour issues. This reduction factor goes by a range of terms, and this paper will adopt and describe 'in-use factor', as it is used for modelling and policy impact studies in the UK.

Predicting UK residential heating is fraught with uncertainties for a number of reasons including future heat demand, comfort needs and insulation levels, penetration rates of low carbon heating fuels, rates of technical change, prices, social norms, building industry skills, and supply chain capacity (Eyre & Baruah, 2015). Still other uncertainties at the system level include basic drivers of housing demand such as population growth and household size.

Many savings estimates, including those used by the CCC, originate from a 2013 Element Energy paper (Element Energy, 2013). This extensive report used a combination of thermal modelling and survey information to establish the gas and electrical savings for a wide range of energy efficiency measures, a selection of which is summarised in Table 2.

Table 2. Gas and electrical savings per measure (Element Energy, 2013).

Measure	Gas (kWh)	Elect (kWh)	Total (kWh)
SWI - External	6410	290	6700
SWI - Internal	5530	480	6010
CWI - Easy to treat	4210	190	4400
CWI - Hard to treat (low cost)	4050	210	4260
Loft insulation 50-125mm	790	30	820
Loft insulation 125-200mm	360	0	360
Suspended timber floor	880	70	950
Solid floor	950	50	1000
Single to double glazing	2470	310	2780
Pre 2002 double to double glazing	1170	90	1260
Insulated doors	210	20	230
Reduced infiltration	450	30	480
Hot water tank insulation from none	2050	380	2430
Hot water tank insulation from jacket	570	70	640
Hot water tank insulation from foam	190	20	210

The Element Energy report and the CCC updated these estimates with in-use factors based on early data from the National Energy Efficiency Database (NEED). These reduction factors were also introduced to bring home building regulations calculations through the Standard Assessment Procedure (SAP) in line with NEED values for a number of measures (CCC, 2013). These in-use factors are the ones used by the CCC in the Fifth Carbon Budget (CB5) calculations referenced throughout this paper. They are summarised in Table 3.

Table 3: In use factors used by the CCC for CB5. As given in (Element Energy, 2013) and Table B3.1 in (CCC, 2013)

Measure	In-use	Comfort	Inaccessibility	Total in-use reduction factor
Solid wall	33%	15%	10%	49%
Cavity wall	35%	15%	10%	50%
Loft insulation	35%	15%	10%	50%

Where:

- In-use factor: accounts for the physical underperformance or systematic difference between the theoretical model of building energy demand and in-situ performance. This factor is applicable to a cross section of measures.
- Comfort factor: takes into account the underperformance of a measure which is attributed to the rebound effect, whereby householders for example may decide to increase the temperature in their home following the installation of loft insulation. This factor is applicable to fabric insulation measures only.
- Inaccessibility: applicable to solid wall, cavity wall, and loft insulation only. Reduced energy savings reflect the loss of performance by not being able to treat the whole surface area (e.g. architectural features on the façade of a house may prevent the whole wall being externally insulated).

These rates naturally have a strong impact on the overall savings and the ability for combinations of measures to meet the UK's carbon targets. There is a clear gap in our approach between modelling predictions and measured performance.

Modelling predictions versus measured performance

The gap between modelled and measured energy performance is a broad topic. The causes of the performance gap are varied and systemic, and well covered in a range of reviews in the UK and abroad (see e.g. (Menezes, et al., 2012) (de Wilde, 2014) (Calì, et al., 2016)). This paper focuses only on the difference between the predicted and realised savings for a specific set of energy efficiency measures (see Table 2).

Most modelling efforts attempt to compensate for the performance gap using some form of 'in-use factor' to adjust for building and behaviour specific issues. The in-use factors that are used to adjust modelling predictions are subject to continuous review. For example a test of 93 solid wall homes found an average U-value of 1.4W/m^{2}K not the 2.1 assumed by SAP (Stevens & Bradford, 2013). Overall a range of recent studies have measured in situ U-values for solid walls and found on average 1.3-1.4 Wm^2/K (Li, et al., 2015).

Studies such as the Energy Follow-Up Survey (EFUS) (BEIS, 2011) have also found that up to a third of homes are under-heated (<18°C), leading to rebound effects when improvement measures are installed. The impact of starting from a lower-than-modelled energy use, combined with comfort take back through the rebound effect has been termed the 'prebound' effect and could lead to as little as half of the anticipated savings overall (Sunikka-Blank & Galvin, 2012).

Models and in-use factors therefore logically struggle to accurately reflect and forecast energy use. Variations in occupancy patterns and end user behaviours are difficult to capture in models (Marshall, et al., 2016). Models also often fail to adequately deal with interactions between different aspects of energy demand, particularly socio-technical factors (Kavgic, et al., 2010).

Booth et. al. (2012) reviewed the issue of uncertainty in models, and defined the issue across four areas;

- Chance variability due to a random outcome for a single individual, also called first order uncertainty.
- Heterogeneity due to variation in characteristics and individuals in a population.
- Parameter uncertainty. This is further divided into things that can be known if evidence was available, and things that must be assumed such as future discount rates.
- Ignorance due to lack of knowledge about how to model a true process.

They considered how these uncertainties applied to housing models specifically, noting that the mostly likely barrier to the development of housing stock models is the lack of high resolution energy data for calibration (Booth, et al., 2012). Researchers have made use of data from the Home Energy Efficiency Database (HEED) to build profiles of the UK stock and retrofit uptake (Hamilton, et al., 2013). But the lack of publicly available energy consumption data to validate models and inputs has been noted in the past. This is beginning to be addressed with the release of the National Energy Efficiency Database (NEED - detailed below), which uses meter readings and not model predictions.

Demand Reduction and the UK Carbon Budgets

The CCC has released the data set for a Central Scenario that meets the Fifth Carbon Budget (CB5) (CCC, 2016). This is summarised in Figure 1, which shows that grid electricity and domestic transport sectors will require the greatest abatements contributing 87 and 69 $MtCO_2e$ respectively, or around 60% of the 267 $MtCO_2e$ reduction that will be required against the 2015 baseline. The residential sector (which is heating dominated) contributes only 21 MtCO2e, or 8% of the needed carbon abatement.

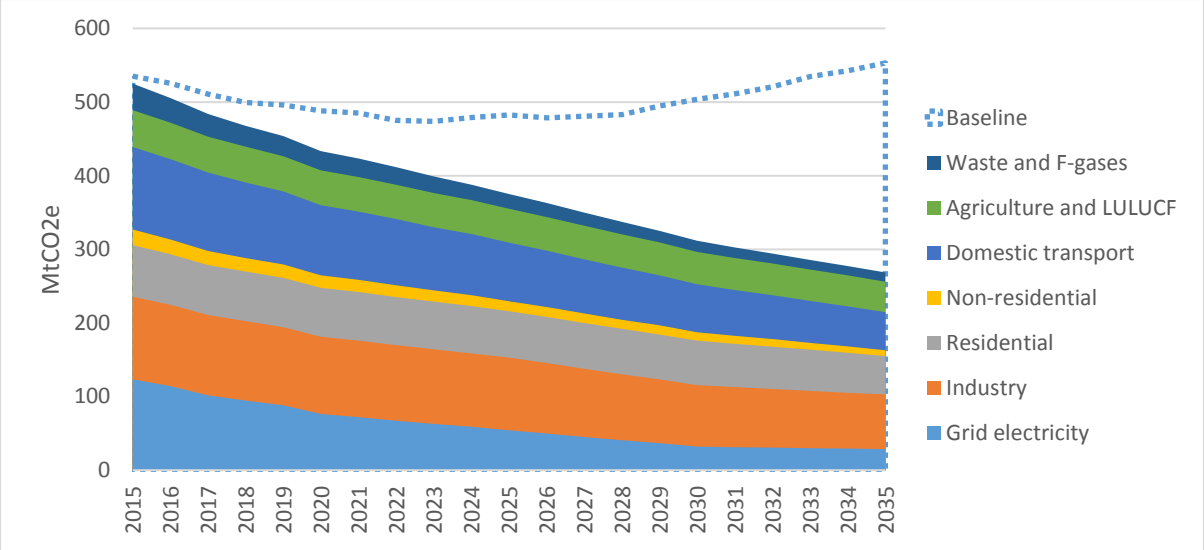

Figure 1: Central Scenario for CB5 by sector (CCC, 2016).

Note that the relationship between energy and carbon savings is non-trivial, particularly given that the carbon content of electricity is set to decrease to near zero over the coming decades. The carbon content of electricity also varies throughout the year, meaning that a kWh in January is likely to have considerably higher carbon content than a kWh in July. The CB5 calculations naturally centre on carbon, but this paper focuses on uncertainty in energy savings. How this uncertainty is reflected in carbon emissions will be approximated and the limitations discussed.

The CCC CB5 central scenario breaks down the residential energy savings as shown in Table 4. The central scenario anticipates 49% the needed energy reductions will come from energy efficiency improvements in insulation, lighting, behaviour, and appliances, while 51% will come from low carbon heating system uptake, driven largely by an assumed 3 million heat pumps in new build homes, and 2.8 million in existing homes for a combined reduction of 41 TWh in heating demand by 2035 compared to the baseline.

Table 4: Breakdown of Central Scenario energy savings in Residential Sector (CCC, 2016).

	2035 CCC Central Reduction (TWh)	% of Total Abatement	% of Total Abatement
Insulation	32.7	28%	
Lighting	1.9	2%	
Behaviour	8.7	7%	
Appliances	14.4	12%	49% EE
District heating	16.5	14%	
Heat pumps	41.3	35%	
Biomass boiler	-1.8	-2%	
Heating controls	4.1	3%	51% Heat
Total Abatement	117.9	100%	

The largest source of energy efficiency savings is through insulation measures (making up over half of projected energy efficiency-related abatement). Uncertainties in this figure not only affect the heat demand directly avoided through energy efficiency, but have inevitable knock on effects for sizing of

systems. This can be particularly costly given that any low carbon heat system, be it through hydrogen, heat pumps, or other, will have new infrastructure implications.

Based on the CCC Central Scenario, energy efficiency measures are expected to deliver 6.1 MtCO2e or 32.7 TWh reduction against the 2015 baseline by 2035, broken down in Table 5.

Table 5: CCC Central Scenario Residential Emissions and Energy Reductions Relative to Baseline for Insulation Measures.

	Emissions		Energy	
	2035 CCC Central Reduction ($MtCO_2e$)	% decrease on 2015	2035 CCC Central Reduction (TWh)	% decrease on 2015
SWI	1.1	1.6%	7.1	1.4%
CWI	2.3	3.2%	11.9	2.4%
Loft	0.6	0.8%	3.1	0.6%
Underfloor	0.5	0.6%	2.5	0.5%
Glazing and Doors	0.7	0.9%	3.7	0.7%
Infiltration	0.5	0.6%	2.4	0.5%
HW Tank	0.4	0.5%	2.2	0.4%
Total Abatement	6.1	8.3%	32.7	6.6%

The CB5 targets a 1.1 $MtCO_2e$ savings through the installation of SWI. This represents a reduced ambition compared to previous carbon budgets. The UK has long struggled to increase the uptake of solid wall insulation. The 4th Carbon Budget states: "our Extended Ambition scenario, which forms the basis for our Interim target, assumes that effective new policies […] successfully address barriers to action and deliver significant energy efficiency improvements in the UK housing stock, including the insulation of […] 2 million solid walls by 2020 (CCC, 2010). The High end potential of 4.8 $MtCO_2e$ for insulating all 7M solid walls in the UK (CCC, 2015).

A review (CCC, 2013) concluded that the technical potential for measures was correct, but that it would be more expensive to install and that it would deliver less carbon emissions savings than previously expected.

In light of new evidence on energy use in homes they reduced their assessment of the savings potential from SWI for CB5 (CCC, 2015). Evidence from NEED reduces the estimated energy savings by 49% (CCC, 2015).

Their 2013 Technical Report gave revised assumptions for the uptake of solid wall insulation measures through 2030. The continually reducing ambitions for SWI in each carbon budget analysis is summarised in Table 6.

Table 6: Summary of changes in SWI ambitions by carbon budget

Carbon Budget	# Additional Solid Walls Insulated (million)	Carbon Abatement ($MtCO_2$)	Notes/Source
Pre-CB4	3.5	4.9	2010 advice (CCC, 2010) as referenced in (CCC, 2013) pg 66
CB4	3.5	2.5	Savings per measure reduced. In use factors updated with NEED data (CCC, 2013) pg 66
CB5	2	1	Reduction in the number of homes for which SWI deemed cost effective (CCC, 2015)

Note that the CCC CB5 central scenario explored in this paper still aims to deploy 2.4 M solid wall insulation measures by 2035, while current policy projections only see 290,000 by 2032 (ACE, 2016). Despite the reduced ambitions for SWI over the past several years, the current CCC goal still far exceeds what is likely to be delivered through current policy.

3. Method

The previous sections described uncertainty in demand reduction as a product of two variables: the number of measures installed and the savings per measure.

The number of measures installed is difficult to estimate and, as noted in the literature review, is highly dependent on policy, which is subject to much debate. This study will therefore continue assuming that policy ambitions are adjusted in the coming years to reflect the CB5 ambition. This means for example delivering 2.4M SWI upgrades by 2035 rather than the current path towards 290,000 (ACE, 2016).

The savings per measure that can be achieved is less prone to political change. This study will therefore calculate the uncertainty in this variable as defined by the difference between the savings rates currently used by the CCC (based on the Element Energy report and in-use factor adjustments), and comparing these values with more recent measured performance data from the National Energy Efficiency Database (NEED). The CCC's CB5 spreadsheet will be used to determine the effects of these changes to the overall carbon budget as well as through 2050.

The NEED database (BEIS, 2018) combines data from four different sources:

1. HEED/Ofgem/BEIS – Info on energy efficiency measures
2. Energy suppliers – Info on electricity and gas consumption
3. Valuation Office Agency (VOA) – Property attributes
4. Experian – Household characteristics

These four databases are linked using Address Base unique property reference numbers.

Info on the energy efficiency measures installed are obtained through a combination of three sources. Homes Energy Efficiency Database (HEED), Central Feed-in Tariff Register, and Green Deal and ECO data held by BEIS. NEED has included savings from a number of measures including CWI, LI, condensing boilers, and SWI. The estimates from NEED were used to inform the 'in-use factors' for

the Green Deal and EPCs. The impact of measures since 2010 are shown in Table 7. This study will consider a weighted average of these values summarised in Table 8.

Table 7: Impact of Measures Time Series Tables from NEED (BEIS, 2018)

	Solid Wall Insulation		Cavity Wall		Loft Insulation	
Year	Number in Group	Mean Annual Savings (kWh)	Number in Group	Mean Savings (kWh)	Number in Group	Mean Savings (kWh)
2010	790	2,400	16,050	1,400	21,030	400
2011	830	2,000	12,480	1,400	20,470	400
2012	1,740	2,100	5,910	1,300	14,120	400
2013	3,060	2,100	21,730	1,300	19,530	400
2014	4,350	1,900	43,240	1,400	21,510	700
2015	1,670	1,700	7,970	1,000	6,130	400
Weighted Average		*1,989*		*1,345*		*463*

The full list of measures used in the original CCC calculation and NEED updates are given in Table 8 below. The values from Table 7 that have been used to estimate uncertainty for this study are given in bold italics (made possible due to updated NEED data).

Table 8: Summary of CCC and NEED estimates of performance of energy efficiency measures. CCC factors from (Element Energy, 2013), bold italics from NEED (BEIS, 2018).

Category	CCC (MWh)	NEED (MWh)
SWI - External (cost-effective)	2.741	***1.989***
SWI - Internal (cost-effective)	2.741	***1.989***
SWI - External (wider benefits e.g. fuel poverty)	3.214	***1.989***
SWI - Internal (wider benefits e.g. fuel poverty)	3.214	***1.989***
Cavity wall insulation (CWI) - Easy to treat	1.958	***1.345***
Cavity wall insulation (CWI) - Hard to treat (low cost)	1.958	***1.345***
Cavity wall insulation (CWI) - Hard to treat (high cost)	1.958	***1.345***
Loft insulation 50-125mm	0.417	***0.463***
Loft insulation 125-200mm	0.186	0.186
Suspended timber floor	0.690	0.690
Solid floor	0.720	0.720
Single to double glazing	1.983	1.983
Pre 2002 double to double glazing	0.895	0.895
Insulated doors	0.168	0.168
Reduced infiltration	0.351	0.351
Hot water cylinder thermostat	0.379	0.379
Hot water tank insulation from none	2.053	2.053
Hot water tank insulation from jacket	0.538	0.538
Hot water tank insulation from foam	0.183	0.183

4. Analysis

By inserting the data from Table 8 into the CCC calculator Table 9 is generated.

Table 9: CCC vs NEED in CB5.

	CCC (TWh)	NEED (TWh)	% Discrepancy in Demand Reductions
SWI	-7.1	-4.7	-33%
CWI	-11.9	-8.1	-31%
Loft	-3.1	-3.3	9%
Total Abatement	-22.0	-16.2	-26%

The total discrepancy between the in-use factors used by the CCC in CB5 and the NEED actual energy savings per measure for SWI, CWI, and loft insulation is 26% by 2035.

The CCC central scenario seeks 22 TWh savings through SWI, CWI, and loft insulation combined. The 26% discrepancy quantified through the NEED data corresponds to 5.8 TWh. While this is a large number in itself (representing approximately ~£600M in utility bills), it is a relatively small portion of the UK's 495 TWh 2015 baseline energy consumption for residential buildings.

Extrapolating to 2050 exacerbates the shortfall in energy savings, since loft insulation is expected to reach saturation in the early 2020s and CWI by 2030, but rates of SWI are estimated to increase. If all 7.2 M technically feasible homes receive SWI by 2050, as many hope they do, then the shortfall increases to 29% (or 10.6 TWh) as shown in Table 10. To put this in context, this was roughly 3% of all electricity generation in the UK in 2017, or approximately all PV generation in that year (11.5 TWh; BEIS, 2018).

Table 10: Projected energy savings using CCC vs NEED estimates to 2050, in TWh.

	CCC (TWh)	NEED (TWh)	% Discrepancy
SWI	-21.4	-14.3	-33%
CWI	-11.9	-8.1	-31%
Loft	-3.1	-3.3	-9%
Total Abatement	-36.4	-25.8	-29%

This suggests considerable uncertainty for the three most fundamental energy efficiency measures delivered through UK residential retrofit policy.

The kWh savings given by the NEED data cannot be directly inserted into the CB5 spreadsheet to calculate the CO_2 impacts due to varying fuel types and emissions factors. However, by applying the same 26% discrepancy to the CO_2 abatement assumed from SWI, CWI, and loft insulation this corresponds to a reduction in the estimated GHG mitigation of ~1 $MtCO_2e$, or according to Table 5, approximately what we anticipate saving through double glazing upgrades and underfloor insulation combined.

5. Discussion

A better understanding of in-use factors is essential. SWI, CWI, and Loft Insulation represent a combined 4 $MtCO_2e$ abatement potential, which is less than a fifth of the 21.7 $MtCO_2e$ abatement from the residential sector that is called for in the CCC central scenario. This study showed a 26% discrepancy based on the measures for which there is already measured data in NEED. Better in-use factors are urgently needed to understand the risk to the remainder of the projected residential abatement.

Good information about the theoretical potential savings is currently available, but information about the practical potential is poor. Insulating all 7.1M solid walls would contribute a total of 3% savings against the 2015 baseline. Solid walls are underperforming, costly, risky, and contribute a relatively small proportion of the overall carbon abatement needed for CB5. This discussion will consider the options for insulating solid walls, the associated risks, and the need for alternative measures.

Risk and uncertainty in Solid Wall Insulation

As stated, SWI represents roughly a third of projected energy savings from residential building envelopes to 2035. The literature review noted that, of the 7.1M uninsulated solid walls in the UK, approximately 1.2 M are likely to be in conservation areas (Bottrill, 2005), and 6.6M overall are likely hard to treat, with anywhere from 30-55% being unsuitable for external insulation altogether (BRE, 2008a) (BRE, 2008b). Homes for which external SWI is unsuitable would require internal insulation, which is fraught with its own difficulties. There is disagreement even among experts about best practice needed for breathable internal wall insulation to avoid moisture damage. There is currently poor evidence on the long-term risks, which may be storing problems for the future (Palmer & Terry, 2018).

Traditional buildings (pre-1919) require a special approach in retrofit. They typically allow moisture from washing, cooking, breathing to move in a controlled way through the semi-permeable fabric (STBA, 2015). Changes to the thermal performance of the home can change how heat and moisture leave the fabric and increase the risk of interstitial mould.

Internal insulation poses particular problems as it cools down the internal surface of the brick and makes it more prone to interstitial condensation between the brick and the insulation. This can be addressed using a vapour barrier on the warm side of the insulation, however in some cases this can also exacerbate problems by trapping rain and other moisture adsorbed through the wall. (May & Sanders, 2016)

Best practice requires a ‘whole-building approach to moisture’ (May & Sanders, 2016), which is rarely undertaken in practice. Foreman (2015) found that 20% of ECO-funded SWI installations had substantial failures, noting that if these practices are typical of wider realities and remain unchanged, then serious problems (i.e., installation failures, health issues) may propagate across many projects if growth in retrofitting continues. The literature is almost entirely devoid of assessment of SWI practice, risks in as-built retrofits, and strategies for improving practices (Forman, 2015).

The effects of installing partial measures such as weatherproofing or insulating part of a dwelling, and how these small changes accumulate over time is a critical question and should be the subject of separate study. In addition to these technical challenges, internal wall insulation also faces practical challenges such as loss of space. In some areas such as parts of London with high property costs, the value of the lost floor space to IWI can exceed the capital cost of the works (Palmer & Terry, 2018).

The need for alternative measures

Many of the barriers and moisture risks can be reduced by applying thinner internal wall insulation (DECC, 2016). This naturally has a reduced impact, but could sufficiently reduce the heat loss coefficient of many homes to make them more suitable for a low-carbon heat source like a heat pump.

Thin wall insulation would not deliver a U-value compliant with building regulations. While a promising option, thin wall insulation would require special regulatory consideration.

Given the high levels of uncertainty in the demand reduction delivered through the UK's most trusted energy efficiency measures (SWI, CWI, loft) and the resultant smaller contribution to total savings that these measures can deliver, the policy implications must be considered.

There is also a clear need to more actively explore alternative measures such as underfloor insulation in order to better understand their practical potential as well associated uncertainty.

Finally, a more nuanced consideration of how measures may be used in combination, and how these can be reflected in building regulations, must also be made. Thin wall insulation for example, has the potential to be an extremely useful tool that addresses the technical challenges facing the millions of hard to treat solid wall homes. The benefits of thin internal wall insulation would currently not be captured in the CB5 calculations nor accepted by building regulations. Rapidly insulating as many homes as possible could result in a costlier solution, deliver less carbon savings than anticipated, and also lock in performance problems for the future.

Uncertainty in the impacts of retrofit policy

The UK retrofit market currently suffers from a policy vacuum. This vacuum was preceded by a series of fits and starts and high profile policy failures such as the Green Deal. The reasons that the Green Deal failed to generate a significant uptake in measures are very well studied (Reid, 2014) (Rosenow & Eyre, 2016) (Gillich, et al., 2017). What is less studied is how poorly the Green Deal and UK policy more broadly predict the likely savings from their programs even if the rate of take-up is as predicted. Most impact assessments are based on the National Housing Model (NHM), which at its core is a spreadsheet-based deterministic model that is ill-equipped to capture uncertainty in its inputs. Recent work has compellingly argued that a probabilistic modelling approach is more suitable for policy development (Sample, 2019).

Better still, would be a 'pay for performance' model, in which the policy rewards measured savings rather than predictions. California has recently introduced the Cool Savers pay for performance program (Build it Green, 2018), but for a range of technical and feasibility reasons, the UK is unlikely to implement such a policy soon. The main (or only) policy vehicle for subsidising retrofit measures in the UK is the Energy Company Obligation (ECO), which offers rebates based on the amount of carbon saved. The savings is predicted based on an NHM/SAP model compared to a counterfactual. This means that in-use factors must be applied broadly to the measure, and poorly capture building specific circumstances regarding the condition of the building or how it is used. And furthermore because the ECO rebate is tied to the savings of a specific measure, it does not effectively reward combinations of measures through a whole-house approach.

Both of these could be addressed by making ECO a 'pay for performance' policy, and rewarding the metered savings following the installation of measures. However, there are many barriers affecting this. It is challenging to verify and attribute the savings, though innovations in smart meters are reducing this barrier. Secondly, it is problematic for the treasury to fund a program with such uncertain expenditures, predicting changes in savings due to, for example, varying weather, user behaviour, and unknowns in stock conditions that impact the baseline. While precedents such as

California are demonstrating that these barriers can be overcome, UK experience leans towards more established program models such as ECO that incentivise single measures.

Uncertainty in predicting the savings from measures is thus a critical barrier to the development of successful UK retrofit policy. This is particularly true for policies incentivising combinations of measures through a whole-house approach. The recent Each Home Counts Review (Bonfield, 2016) accurately reflects the strong consensus in the literature that measure-by-measure approaches should be replaced with whole-house solutions. The 27 recommendations set out in the Bonfield review include a whole-house QualityMark. The UK is currently exploring options to drive uptake of QualityMark, likely through existing programs like ECO. However, a recent BEIS report (Palmer, et al., 2018) found that most retrofit projects that utilise ECO have entrenched procurement models very accustomed to subsidies linked to single measures. UK retrofit markets will struggle to deliver the whole-house approach required by Bonfield/QualityMark. Policy action that directly addresses retrofit supply chain fragmentation has been proven to drive whole-house uptake in the US (Research Into Action, 2015). This is critically needed, among other factors, to make the UK stock fit for the future (CCC, 2019).

6. Conclusions and Policy Implications

Accurately determining the practical potential for energy demand reduction in the UK is a critical priority. Uncertainties in both the number of measures that can be installed as well as the total savings per measure can have costly implications for delivering the overall carbon budgets. Even if one assumes that the targeted number of measures will be delivered, this study found that the updated impact of measures data from the NEED database reduces the estimated energy savings through SWI, CWI, and loft insulation by up to 26% or 5.8 TWh through 2035, increasing to 29% (10.6 TWh) by 2050.

Together, SWI, CWI, and loft insulation represent two-thirds of the carbon abatement that is to be delivered through energy efficiency measures. The remaining third is anticipated through measures such as underfloor insulation, glazing upgrades, and improved air tightness. There is insufficient data in the public domain to better quantify the uncertainty associated with these measures.

New data is needed to improve our understanding of home energy use based on measured performance rather than modelling predictions. This study shows that the NEED data set is useful towards this goal, but will be inherently limited to homes that have participated in government schemes such as ECO and the Green Deal. This paper forms part of ongoing work to explore how NEED data can better inform EPC/SAP calculations to reduce uncertainty in our predictions of home energy use.

Predictable performance de-risks measures for homeowners, installers, and financiers. At the system level, determining the amount of energy that can be practically offset through demand reduction also very critically informs the sizing of the low-carbon heating infrastructure that will inevitably replace the natural gas network. Current estimates in the CB5 of the number of measures that are technically feasible, and the savings per measure are based on overly optimistic in-use factors.

Finally, given the uncertainty and risk associated with SWI in particular, a greater emphasis needs to be placed on alternative measures, particularly on how to combine alternative measures such as underfloor insulation and thin wall insulation. Improving energy efficiency delivers a range of benefits beyond carbon savings, including greater energy affordability, especially for the fuel poor,

and improving comfort and health benefits associated with living in better quality homes. The CCC notes that these benefits should be factored in when considering measures such as SWI, which are not cost-effective strictly from a carbon perspective (CCC, 2015).

This paper finds that UK policy should seek to reduce the uncertainty associated with the energy savings of various measures, particularly combinations of measures. It must also increase the use of measured data through databases like NEED in policy impact assessments. Reducing the uncertainty, and thus the performance gap will allow a move away from measure specific policies towards whole-house policies that better incentivise the integrated supply chains that the Bonfield review aspires to.

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