# TESTING THE GREENHOUSE GAS EMISSIONS REDUCTION POTENTIAL OF ALTERNATIVE STRATEGIES FOR THE ENGLISH HOUSING STOCK

André Cabrera Serrenho, Michał Drewniok, Cyrille Dunant, Julian M. Allwood

Department of Engineering, University of Cambridge, United Kingdom

## Abstract

Buildings account for around a third of global energy and process emissions, but have been delivering much smaller emissions savings than other sectors. Although clear standards of new building construction and retrofitting options have been developed and are able to reduce building emissions, there is need for a clear prioritisation of policy options capable of delivering the greatest reduction in emissions at minimal costs. This requires an assessment of the trade-offs between new construction and retrofitting in terms of the pace of adoption of improved building standards and the emissions savings achieved to meet current climate targets. In this paper, a dynamic material flow analysis is used to explore the impact of combined mitigation strategies on both new and existing buildings capable of reducing embodied and operational emissions in the English domestic housing stock. The results show that progress in the use of low carbon materials in construction and the deployment of zero-carbon buildings at scale would not be enough to deliver a reduction of building emissions of the scale required nationally (–66% from current levels by 2050). Improvement in building standards for both new and pre-existing construction is essential to meet targets, but its costs are likely to be unreasonable without a reduction in the demand for floor area per capita by promoting flexible design of buildings, house sharing or telecommuting, which are likely to produce far-reaching implications in social organisation and urban planning.

## 1. Introduction

Fuel combustion and industrial processes are responsible for more than two-thirds of anthropogenic greenhouse gases (GHG) emissions worldwide. The International Energy Agency (IEA, 2015a) estimates that the use of buildings alone accounted for 31% of global combustion emissions in 2013, due to their energy requirements. In the UK, 45% of all final energy use took place in buildings over the last decade, which accounts for 27% of national emissions. In 2015, 64% of the energy consumption in UK buildings was used for the sole purpose of space heating or cooling (IEA, 2015b). Such a large proportion of emissions associated with buildings highlights the need to understand the opportunities for emissions savings in buildings. Furthermore, most of current actions are focused on the energy supply system, with clear actions aimed at the reduction of emissions intensity of energy carriers, but a clear identification of opportunities that reduce the demand for energy are essential to reduce emissions at the scale required to meet existing targets.

The Intergovernmental Panel on Climate Change (IPCC) recognises the potential of using demonstrated and existing technologies on building design to achieve up to 10-fold reduction in energy requirements in new buildings, and up to 4-fold reduction in existing buildings (Lucon *et al.*, 2014), but the inertia of current supply chain configuration and design practices, inadequate incentives, and lack of awareness hinder the market uptake of even the most cost-effective opportunities. However, Lucon *et al.* (2014) anticipates that even if the current most ambitious policies are implemented, approximately 80% of energy uses in buildings will be locked-in for decades to come, due to the long lifetime of buildings. To minimise these effects, the IPCC highlights the urgency of the global adoption of best available performance standards for both new and existing buildings.

In the UK, current policies set a target of reducing emissions in 66% of current levels until 2050, but so far the power sector has been the main contributor to this target. The Committee on Climate Change (CCC, 2017) expects a continuation of major contributions from the power sector (–62% emissions from 2016 to 2030), and both industry and buildings are expected to deliver much smaller savings (only –20% emissions from 2016 to 2030), since action is more difficult in these sectors. The CCC (2017) proposes a schedule to finance the refurbishment of existing buildings, namely the insulation of solid and cavity walls by 2030 and an improvement in energy efficiency of existing heating systems, along with the creation of higher standards for new buildings, but Giesekam *et al.* (2016) have concluded that current practices may be insufficient to meet current targets and emissions are heavily dependent on the pace of decarbonisation of the electricity grid. A clear policy schedule requires intelligence on the prioritisation of specific interventions in terms of their potential to reduce emissions. A better understanding of the trade-offs between refurbishing existing buildings and new building construction is essential for the prioritisation of interventions, considering the dynamics of the building stock, the required buildings standards, their pace of adoption and the costs involved.

In this paper, we identify the required standards for new and existing buildings in England, and we compare the rate of deployment of interventions and their costs to prioritise policy options capable of delivering the greatest reduction in emissions at minimal costs. This is accomplished by developing a dynamic flow model of the stock of domestic buildings in England. This model is used to reveal the trade-offs between interventions in new and existing buildings, quantifying the required level of refurbishment, the pace of refurbishment of existing buildings, and the scale of new building construction to reduce embodied and operational emissions of buildings.

## 2. Estimating emissions of the building stock

GHG emissions from buildings are produced both during construction and operation. During construction, embodied emissions depend predominantly on material choice and building design. Operational emissions are determined by energy uses, mostly heating requirements, and the mix of energy vectors used in buildings. However, the embodied emissions of buildings in a country depend on the pace of new construction, and similarly total operational emissions depend on the composition of the building stock, as building standards and heating requirements change over time for new construction but last until refurbishment or demolition. Therefore, both embodied and operational emissions of the building stock depend on the dynamics of construction, demolition and refurbishment. Estimating the future emissions associated with the buildings of a country thus requires a dynamic forecast of the composition of the building stock.

Extensive literature exists on modelling operational energy uses of buildings. For example, Hamilton *et al.* (2013) have characterised operational energy uses of English domestic buildings, and Choudhary (2012) has modelled the variability of energy consumption patterns across different urban areas for non-domestic buildings in Greater London. Other authors have assessed the potential for energy savings by retrofit: Hamilton *et al.* (2016) has shown that building retrofits produce a reduction in energy demand in English buildings, and Andrić *et al.* (2017) have demonstrated that thermal improvements have the greatest potential to improve the environmental performance of buildings.

Although most literature has been focused on strategies to reduce operational energy uses, Pomponi *et al.* (2016) proposed further analysis on mitigation strategies for embodied emissions of buildings. These involve the use of alternative construction materials and change of current practices. For example, Dunant *et al.* (2018) have identified opportunities to change existing practices in order to reuse more steel in construction, although several barriers exist to its implementation (Densley Tingley *et al.*, 2017).

The dynamic of buildings stocks has been assessed by Müller (2006), who has modelled the dynamics of the Dutch housing stock and its implications for future concrete demand at various levels of floor area per capita. This work introduced a stock modelling approach to assess the dynamics of construction and demolition, and more recently Sandberg *et al.* (2017) have developed a dynamic model to anticipate the impacts of refurbishment in Norwegian buildings energy uses.

Estimating future embodied emissions requires a dynamic characterisation of the material composition of building stocks, but the majority of existing analyses is retrospective. For example, Ley (2003) has estimated the historical use of steel in British buildings from existing statistics, but few studies report dynamic assessments of material composition. Fishman *et al.* (2014) introduced a top-down dynamic method to estimate the stocks of timber, minerals, iron and other metals in Japan and in the USA from existing statistics on annual material inflows and outflows. More recently, bottom-up dynamic methods were developed to assess material stocks in construction: Tanikawa *et al.* (2015) have estimated material stocks at the level of local authorities in Japan from existing building GIS data, Yoshida *et al.* (2017) have developed GIS tools to estimate volumes of mobilised materials for construction, and Marcellus-Zamora *et al.* (2016) estimated material stocks in Philadelphia from a combination of GIS data with a characterisation of land uses.

Existing literature has been able to model the dynamics of new domestic building construction and demolition, and to anticipate the impacts of retrofitting strategies on operational emissions. The characterisation of material composition of buildings has been used to estimate embodied emissions, but the trade-offs between retrofitting and new building construction have not been assessed and thus it is still unclear what are the combination and pace of implementation of strategies that leads to meaningful savings in total emissions. This would require the use of dynamic building stock models and information on material composition to explore the impact of combined mitigation strategies on both new and existing buildings in terms of both embodied and operational emissions. In this article, a dynamic material flow assessment is performed to characterise the temporal development of the housing stock, with floor area demand, material composition, and embodied and operational GHG emissions of the English housing stock. This model enables the prioritisation of strategies to reduce total building emissions.

# 3. A dynamic model for the housing stock in England

A dynamic model for the housing stock is required to test the impact of future interventions in the standards of new construction and the refurbishment of existing buildings. Figure 1 shows a representation of the modelling approach used in this paper and described in this section. Every year, a certain level of housing demand (section 3.1.1) determines the amount of new construction required, given pre-existing stock and demolished buildings (section 3.1.2). The emissions associated with the building stock include the embodied emissions of producing materials used in new construction (section 3.2.1) and operational emissions produced by existing buildings (section 3.2.2). Various paces of improvement from current embodied and operational emissions are defined in section 3.3.

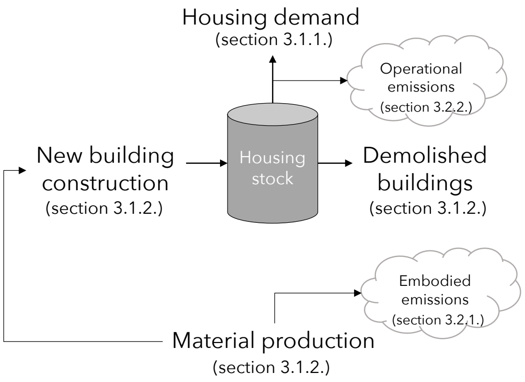


**Figure 1.** Architecture of the dynamic model for the housing stock.

## 3.1. Dynamic material flow assessment of the housing stock

The composition of the future housing stock depends both on pre-existing buildings and on the future demand for housing. Each year $(n)$, new built area $\left(B_{in,n}\right)$ should be as much as required to provide the total demand for floor area $(S_n)$, considering the floor area removed in demolished buildings $\left(B_{out,n}\right)$:

$$B_{in,n} = S_n - S_{n-1} + B_{out,n} \quad . \tag{1}$$

The next sections describe the estimate of future demand for floor area (section 3.1.1), and future demolished buildings, and consequent demand for new construction until 2050 (section 3.1.2).

### 3.1.1. Housing demand

Detailed data sources on the composition of the domestic housing stock are only available for England, and therefore this analysis is focused in England only rather than the whole of the United Kingdom. The English Housing Survey (Department for Communities and Local Government, 2017) reports the physical conditions, age, and floor area of houses in England every two years since 2008. Previously, similar information was collected by the English House Condition Survey (Department for Communities and Local Government, 2016), with data available for 1996 and 2001. The average floor area of domestic housing per capita has been quite stable over the last decades and it is currently one of the lowest in Western European countries — 38.8 m$^2$ per capita in England, when the average for Western Europe is 47.2 m$^2$ (Eurostat, 2018). These figures already include the area of vacant dwellings — 4% of all stock by area in 2013 (Department for Communities and Local Government, 2017) —, which is considered constant in this modelling. Figure 2 shows the recent historical housing area and possible projected demand for a change from -30% to +30% of current levels of floor area per capita and considering the population projections published by the Office for National Statistics (ONS, 2017). Although a variation from -30% to +30% in floor area per capita may cover a large span of possibilities, this is within the range considered by existing international reports. For example, IPCC (Lucon *et al.*, 2014) uses scenarios considering a wide range of reduction in floor area per capita from 2010 levels by 2050, which spans from -10% to -50%. The levels of projected demand for housing resulting from different ranges of change in the average floor area per capita by 2050 shown in Figure 2, and calculated according to eq. (2) for each year $n$ are tested to determine the annual requirements for new construction described in section 3.1.2 and for the results shown in section 4.

$$S_n = \text{floor area per capita}_{\text{n}} \times \text{population}_{\text{n}} \qquad (2)$$

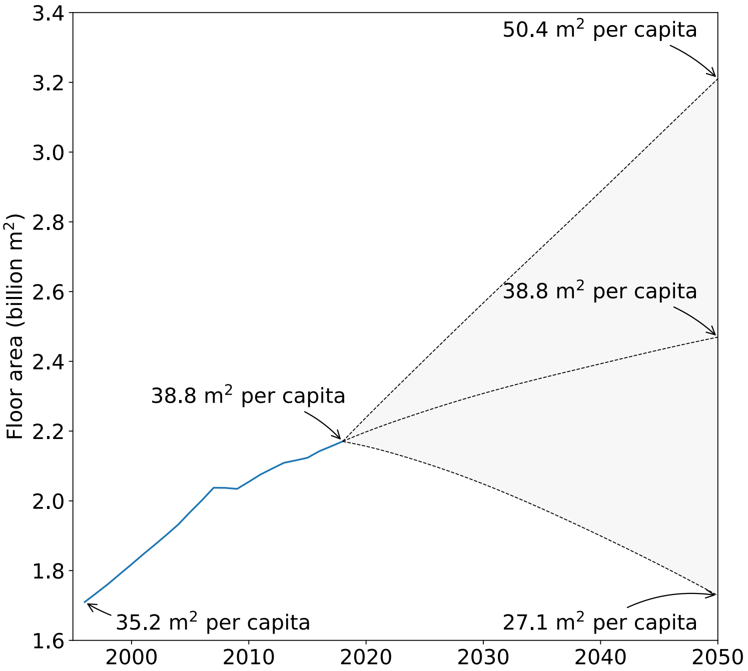


**Figure 2.** Demand for housing floor area in England. Historical values were obtained from the Department for Communities and Local Government (2016, 2017). Future projections are represented assuming a change from -30% to +30% of current values of floor area per capita until 2050.

### 3.1.2. New and demolished buildings

Provided the estimates of housing demand described in section 3.1.1, the new construction required each year is obtained using equation (1) and it depends on the estimated demolished buildings ($B_{out,n}$). These are estimated by the failure rate of a Weibull distribution, which has been found well suited to model building lifetimes at a national scale (Miatto *et al.*, 2017). This is done according to eq. (3), as a function of the parameters of the Weibull distribution for each cohort of buildings with age $t$. However, distribution functions do not capture well the effect of classical buildings in estimating demolition rates. This is a similar effect to modelling the reduced rate of scrapping classical cars, as discussed by Serrenho *et al.* (2017), and therefore demolishing rates estimated using the Weibull distribution are overridden for very old buildings. The details, parameter estimation, and assumptions used to model demolition rates are provided in section 1 of supplementary information file.

$$B_{out,n} = \sum_{t=0}^{\infty} S_{n-1,t} \frac{\gamma}{\alpha} \left(\frac{t}{\alpha}\right)^{\gamma-1} \qquad (3)$$

The shape ($\gamma$) and scale ($\alpha$) parameters of the Weibull distribution can be estimated from historical data of housing stock (Department for Communities and Local Government, 2016, 2017). Using this historical data, the parameters for the English domestic housing stock have been estimated by regression and these are shown in row B of Table 1. Although these values are within the ranges estimated by OECD (2009) for the building stock in the Netherlands, these estimates are uncertain due to the reduced number of data points in the historical data of the housing stock. In addition, the future pace of building demolition and replacement may change from current trends. Therefore, in this analysis we have considered a range of values of the shape parameter ($\gamma$) of the Weibull distribution (rows A and C of Table 1). This parameter determines the rates of demolition, and thus the various levels of $\gamma$ used in this analysis are used to test the effects of different regimes of future rates of demolition of buildings. The values of the shape parameter, and hence the rate of demolition of buildings, can be expressed in terms of a more intuitive metric: the age beyond which the probability of survival is less than 10%, which indicates the age at which most buildings (90%) have already been demolished. This correspondence is presented in Table 1 and the calculation details are shown in section 1 of the supplementary information file.

**Table 1.** Parameters of the Weibull distribution used to model the dynamics of the housing stock. Parameters in row B were regressed from historical demolition rates reported by the Department for Communities and Local Government (2016, 2017) and are used for baseline scenario projections unless stated otherwise.

| | Weibull parameters | | Average lifetime (years) | Age beyond which the probability of survival is less than 10% (years) |
|---|---|---|---|---|
| | $\alpha$ | $\gamma$ | | |
| A | 56.23 | 1.77 | 50 | 90 |
| B | 56.23 | 1.28 | 52 | 107 |
| C | 56.23 | 0.85 | 61 | 150 |

## 3.2. Impacts of the housing stock

Both the operation and construction of buildings generates GHG emissions. The Standard EN 15978:2011 for the assessment of environmental performance of buildings (BSI, 2011) defines the various stages of environmental assessment in buildings. However, most emissions are associated with energy uses in buildings and material production. Thus in this analysis, only a subset of these modules is considered: modules A1–A3 for building construction (hereafter embodied emissions) and module B6 for building use (hereafter operational emissions). The next sections describe the approach used to estimate embodied emissions (section 3.2.1) and operational emissions (section 3.2.2) of the current and future housing stock.

### 3.2.1. Embodied emissions

Embodied emissions of buildings are the emissions required to initially produce a building, and in this analysis we consider the emissions associated to the production of structural materials. Buildings use wide range of materials, but steel, concrete, and bricks are consistently identified as the main contributors to embodied emissions, both because these materials are responsible for the highest emissions produced per unit of mass and because of the large quantities used per building. However, English housing statistics (Department for Communities and Local Government, 2016, 2017) show that 96% of current dwellings were built using either masonry cavity or solid brick walls, and thus the amount of steel used in domestic buildings is negligible compared to the concrete, mortar, or bricks. Therefore, in this analysis embodied emissions were estimated considering only material production emissions associated with concrete, mortar, and bricks, considering that new dwellings will be built using masonry cavity walls with concrete blocks. Although this is a limited scope of embodied emissions, it includes the most ubiquitous and emissions-intensive materials, since almost no steel is used in domestic building construction in the UK. Embodied emissions of other construction materials, transport, on site building construction activities, material use for maintenance, repair and replacement, and end-of-life treatment of demolished materials are not included in this analysis.

For the same construction materials, embodied emissions depend on the mass of these materials used in new construction. Mass of each material $i$ is estimated from volume of walls and floors for projected new construction area obtained from the stock model described in section 3.1.2. Embodied emissions ($E$) are thus obtained according to equation (4) as a sum of:

- Embodied emissions of walls: a function of the total length of walls in new construction ($l$), the average width ($w$) and height ($h$) of walls, and density ($d_i$) and emissions intensity per unit of mass ($e_i$) of each material $i$.
- Embodied emissions of floors: a function of total floor area ($A$), number of floors ($f$), depth of floor slabs ($p$), and density ($d_c$) and emissions intensity per unit of mass of concrete ($e_c$).

A detailed list of these parameters is presented in section 2 of the supplementary information file.

$$E = lwh \sum_i d_i e_i + Afpd_c e_c \tag{4}$$

### 3.2.2. Operational emissions

Operational emissions depend mostly on the energy uses inside buildings, hence emissions associated with maintenance and replacement during building operation are not included. Housing statistics (Department for Communities and Local Government, 2016, 2017) report an Environmental Impact Rating (EIR) for each dwelling in England, according to their annual operational emissions in a scale from 0 to 100. HM Government (2014) instructs that the emissions used in the calculation of the EIR should include the direct emissions of fuel combustion for water and space heating and the emissions of generating electricity used water and space heating or cooling and lighting. This government standard (HM Government, 2014) also defines how the EIR can be converted back into annual emissions ($O$ in annual kg $CO_2$) using equation (5), given the floor area ($A$ in m$^2$) of each dwelling.

$$O = \begin{cases} (A+45) \times 10^{\left(\frac{40}{19} - \frac{EIR}{95}\right)}, & \text{if } \dfrac{O}{A+45} \geq 28.3 \\ (A+45) \times \dfrac{100 - EIR}{1.34}, & \text{if } \dfrac{O}{A+45} < 28.3 \end{cases} \tag{5}$$

For each dwelling, eq. (5) provides an estimate of operational emissions for permanently occupied buildings. The English Housing Survey (Department for Communities and Local Government, 2017) reported that 4.0% of dwellings by floor area were vacant in 2013, 49% of which were vacant in the long-term. These figures are used as constants to estimate future operational emissions, assuming no operational emissions in long-term vacant dwellings and 50% of operational emissions obtained from eq. (5) for short-term vacant dwellings.

Future operational emissions for occupied dwellings can be estimated using the initial values obtained from eq. (5) and by assuming the paces of implementation of improved standards for new and existing buildings described in Table 2. The English housing survey (Department for Communities and Local Government, 2017) reports disaggregated information by age and type of wall structure, thus future estimates consider the effect of changes in operational emissions of new buildings between now and 2050 and refurbishment interventions that improve operational emissions of existing buildings for each cohort and type of wall structure.

Using data from the most recent English housing survey (Department for Communities and Local Government, 2017), the composition of the domestic housing stock by type of wall structure and year of construction could be determined. This composition could be combined with information on the EIR reported in the same survey in order to compare the current composition of the stock with current operational emissions. This comparison is shown in Figure 3, using the stock demographics representation (Serrenho *et al.*, 2016). The right-hand side of Figure 3 shows that most of the stock was built since 1945, but the operational emissions of pre-war buildings shown in the left-hand side are disproportionately higher, due to poor design and construction techniques of old buildings that result in high heating requirements. Operational emissions have thus been improving, from an average of 86.3 kg $CO_2$ / $m^2$ per year for pre-1850 solid wall dwellings to an average of 19.1 kg $CO_2$ / $m^2$ per year for post-2010 masonry cavity buildings. Section 2 of the supplementary information file shows a characterisation of the current typology of the housing stock and details the emissions intensity per floor area for each cohort and type of wall.

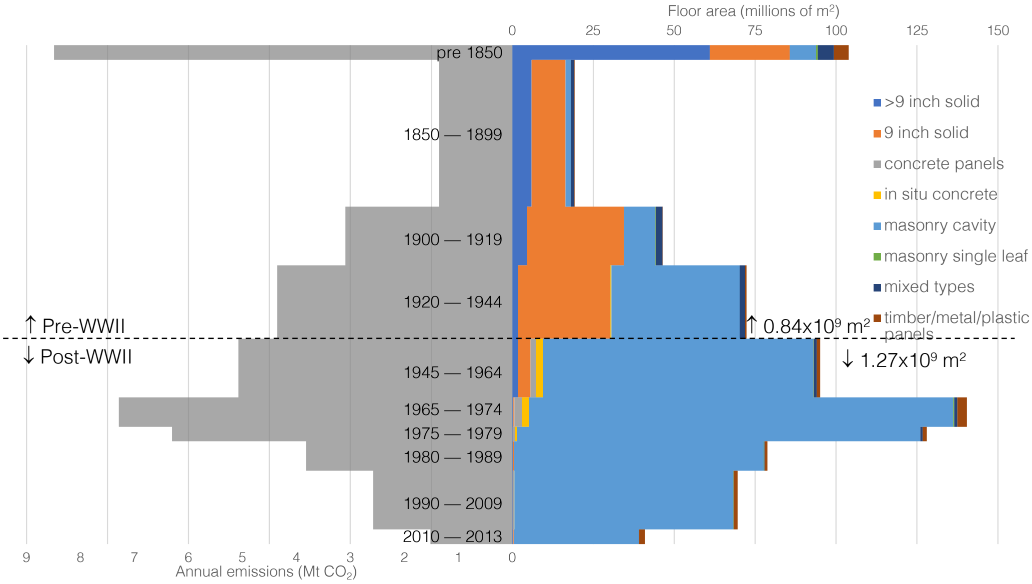


**Figure 3.** Operational emissions and composition by floor area of the English housing stock in 2013 by year of construction and by type of wall structure, regardless of any insulation (Department for Communities and Local Government, 2017).

### 3.3. Rates of future improvement of building standards

The model described in section 3 can be used to test the influence of future demand for floor area and demolition rates (as described in sections 3.1.1 and 3.1.2, respectively) on emissions savings until 2050. Besides changes in these parameters, future emissions savings will also depend on the rate of implementation of improved standards in new buildings constructed between now and 2050, and on retrofitting interventions that reduce the operational emissions of pre-existing buildings. Four different strategies of implementation of new standards for both new and existing buildings are tested, and Table 2 summarises them. These strategies are defined in terms of target average operational emissions for both new and existing buildings for the year 2050. Current operational emissions (19.1 kg $CO_2$ / $m^2$ for current new construction and 54.2 kg $CO_2$ / $m^2$ for an average pre-2018 building) were obtained directly from the English Housing Survey (Department for Communities and Local Government, 2017), by converting reported EIR to operational emissions using eq. (5). Operational emissions for all years between the current state and the target values of each strategy described in Table 2 were obtained by linear interpolation, and all these values can be found in section 2.3 of the supplementary information file. These strategies (Table 2) define extreme cases of improving either or both new and existing buildings, and no claim of plausibility of neither of these strategies is made. Yet, these strategies enable a comparison of the sensitivity of emissions in the use of buildings to a wide range of options for future actions.

**Table 2.** Average operational emissions of existing and new constructed buildings in 2050 for four different strategies of implementation of new standards.

| Strategies | | Average operational emissions in 2050 (kg $CO_2$ / $m^2$) | |
|---|---|---|---|
| | | Post-2018 dwellings | Pre-2018 dwellings |
| (a) | No change from current practice. | 19.1 | 54.2 |
| (b) | Pre-2018 buildings are refurbished up to the standards of 2018 new construction by 2050. | 19.1 | 19.1 |
| (c) | All post-2018 construction are zero-carbon houses by 2050, and pre-2018 buildings are kept unchanged. | 0.0 | 54.2 |
| (d) | All post-2018 construction are zero-carbon houses by 2050, and pre-2018 buildings are refurbished up to the standards of 2018 new construction by 2050. | 0.0 | 19.1 |

## 4. Potential for emissions savings of alternative strategies

Figure 4 shows the estimated emissions savings that would be achieved by 2050 for the levels of housing demand described in Figure 2, the demolition rates that would result from the parameters described in Table 1 and for the levels of implementation of building standards shown in Table 2. Even without any change from current practices, a small reduction in total emissions is anticipated by 2050, only as consequence of the replacement of old inefficient buildings with new construction with better standards. Regardless of the levels of demand or demolition rates, emission savings of the scale required nationally to meet current targets (–66% from current levels by 2050) can only be achieved with improvements in standards of both new (post-2018) and existing (pre-2018) buildings for current levels of demand. Greater savings are achieved for lower levels of demand for floor area, and for higher demolition rates if buildings standards of new construction keep improving. Refurbishing all surviving pre-2018 buildings by 2050 up to the average standards of 2018 construction would alone generate substantial savings, but would have to be combined with a reduction in floor area per person and improvements in new construction to achieve savings of at least 66% of current emissions. Operational emissions of buildings are currently one order of magnitude greater than embodied emissions of new construction (more details in section 2.4 of the supplementary information file). Therefore, favouring the replacement by newer and more efficient buildings results in emissions savings up to a point of very short building lifetimes beyond which embodied emissions offset the gains obtained with new construction. A complete characterisation of the space of emissions savings for various levels of implementation of improved standards, floor area per capita, and demolition rates is provided in section 3 of the supplementary information file.

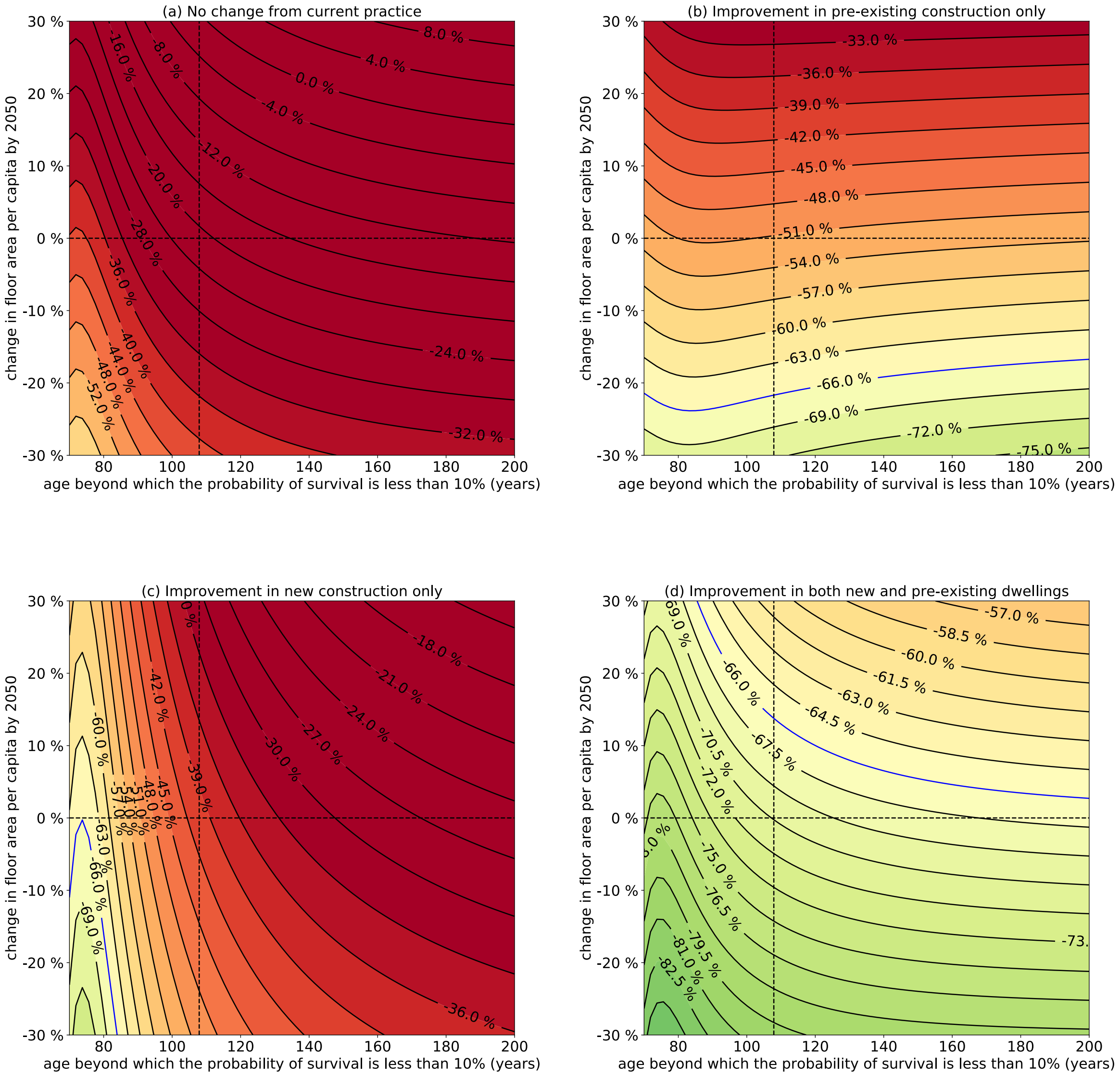


**Figure 4.** Emissions savings from current levels (0% = 129 Mt $CO_2$ / year; –100% = 0 Mt $CO_2$ / year) that would be achieved by 2050 for various levels of demand for housing (in terms of change of current floor area per capita within the ranges represented in Figure 2) and demolishing rates (in terms of the age beyond which the probability of survival is less than 10%, calculated using the Weibull parameters of Table 1 and eq.(7) of the supplementary information file) for each of the four levels of implementation of buildings standards (a) to (d) described in Table 2. The dashed lines shown the current values for both axes. The contour in blue represents the desired 66% emissions reduction by 2050.

The pace of new building construction has been stable over the last two decades, with an average of 16 million new square metres of domestic housing being built in England every year. Population growth estimates may lead to higher rates of construction if similar levels of floor area per capita are to be maintained. Similarly, the rate of demolition of old buildings influences the demand for new construction. Figure 5 shows the estimated average annual demand for new construction. If the current demand for floor area per capita is to be maintained, population growth and the current age structure of the housing stock would lead to a substantial increase in the annual requirements for new construction. Thus, current levels of new construction could only be sustained with a substantial reduction in demolition rates and floor area per capita.

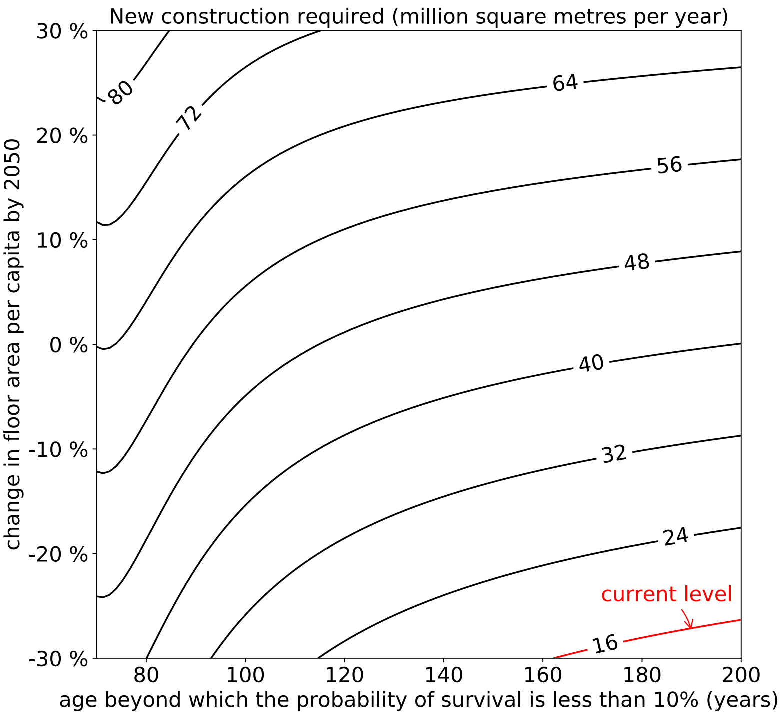
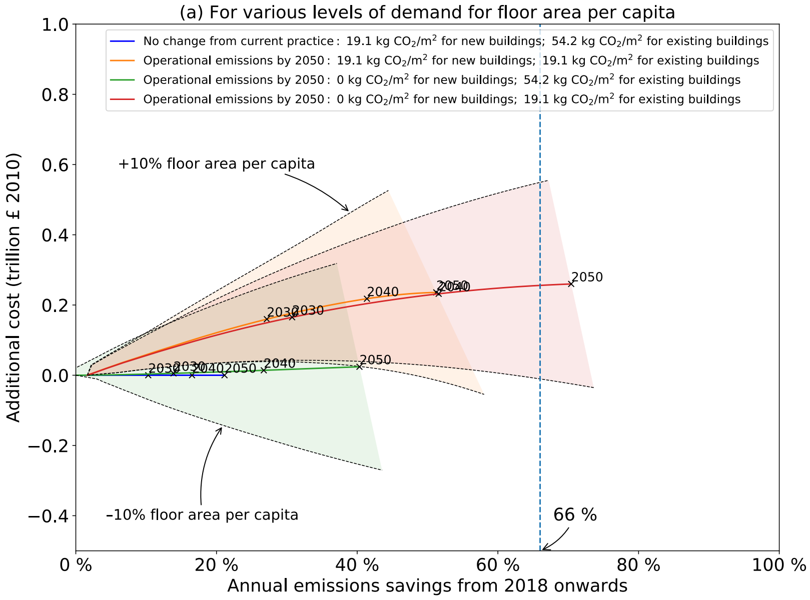


**Figure 5.** Estimated annual construction requirements until 2050 for various levels of demand for floor area per capita and demolition rates.

The results shown in Figure 4 and Figure 5 show that in the future more building construction is likely to occur and the implementation of improved building standards is required to meet climate targets. However, the costs involved in the required scale of new building construction and in the refurbishment of the pre-existing dwellings are likely to constrain decision-making processes in the sector. Using the stock model described in this paper and assuming current prices for construction and refurbishment (details are described in section 4 of the supplementary information file), the costs involved in the implementation scenarios described in Table 2 are compared in order to prioritise actions. Figure 6 shows a comparison of emissions savings by 2050 and the costs involved in implementing improved standards. No change in current practice will result in limited emissions savings due to the progressive replacement of existing buildings with new and more efficient buildings. However, the scale of emissions savings required at national level can only be achieved with more expenditure in refurbishment to reduce operational emissions of pre-existing buildings to the levels of current new construction.



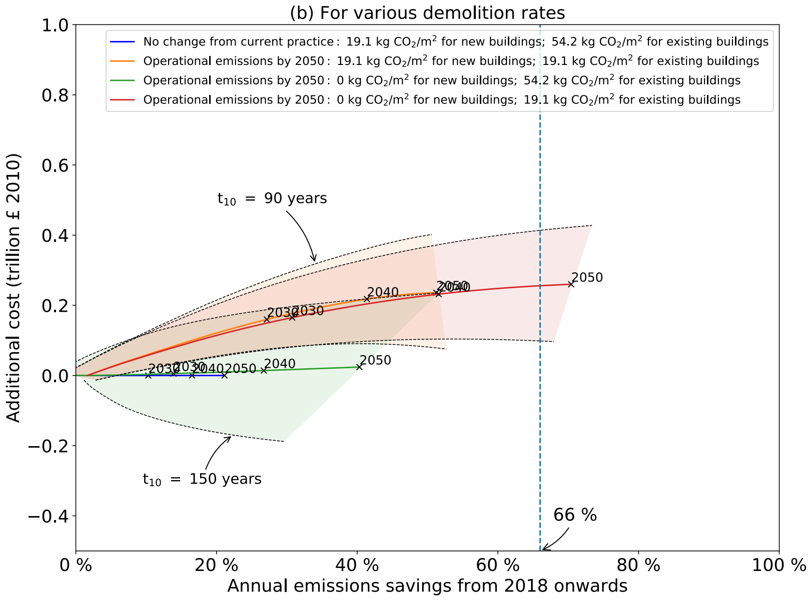


**Figure 6.** Emissions savings by 2050 and costs involved in implementing the improved standards for new and existing buildings described in Table 2 compared to a scenario of no change in current practice (strategy (a) from Table 2, here represented with a blue line). (a) Effect of varying demand for floor area per capita from -10% to +10% by 2050; central line for no change from current floor area per capita. (b) Effect of varying demolition rates – age beyond which the probability of survival is less than 10% ($t_{10}$) varying from 90 to 150 years; central line for current rate ($t_{10}$ = 107 years).

The scale of required transformation of the building stock that produces a meaningful reduction in emissions may not be possible with the current levels of spending in the construction sector. Over the last decade, the construction sector accounted for an average of 1.7% of GDP every year. Figure 7 shows that this level of expenditure constrains the potential for emissions savings obtained by the most ambitious option from Table 2: refurbishing all surviving post-2018 buildings up to the standards of new construction in 2018 by 2050 and progressively improving new construction standards so that all new dwellings built in 2050 are zero-carbon houses. For various levels of expenditure, Figure 7 shows the total costs and emissions savings obtained by 2050, assuming that in the eventuality of a budget shortfall, priority is given to new building construction required as a result of population growth over retrofitting. This figure also compares the effects of immediate action and a delayed implementation of improved standards from 2030 and 2035, which would limit the potential for emissions savings at similar costs.

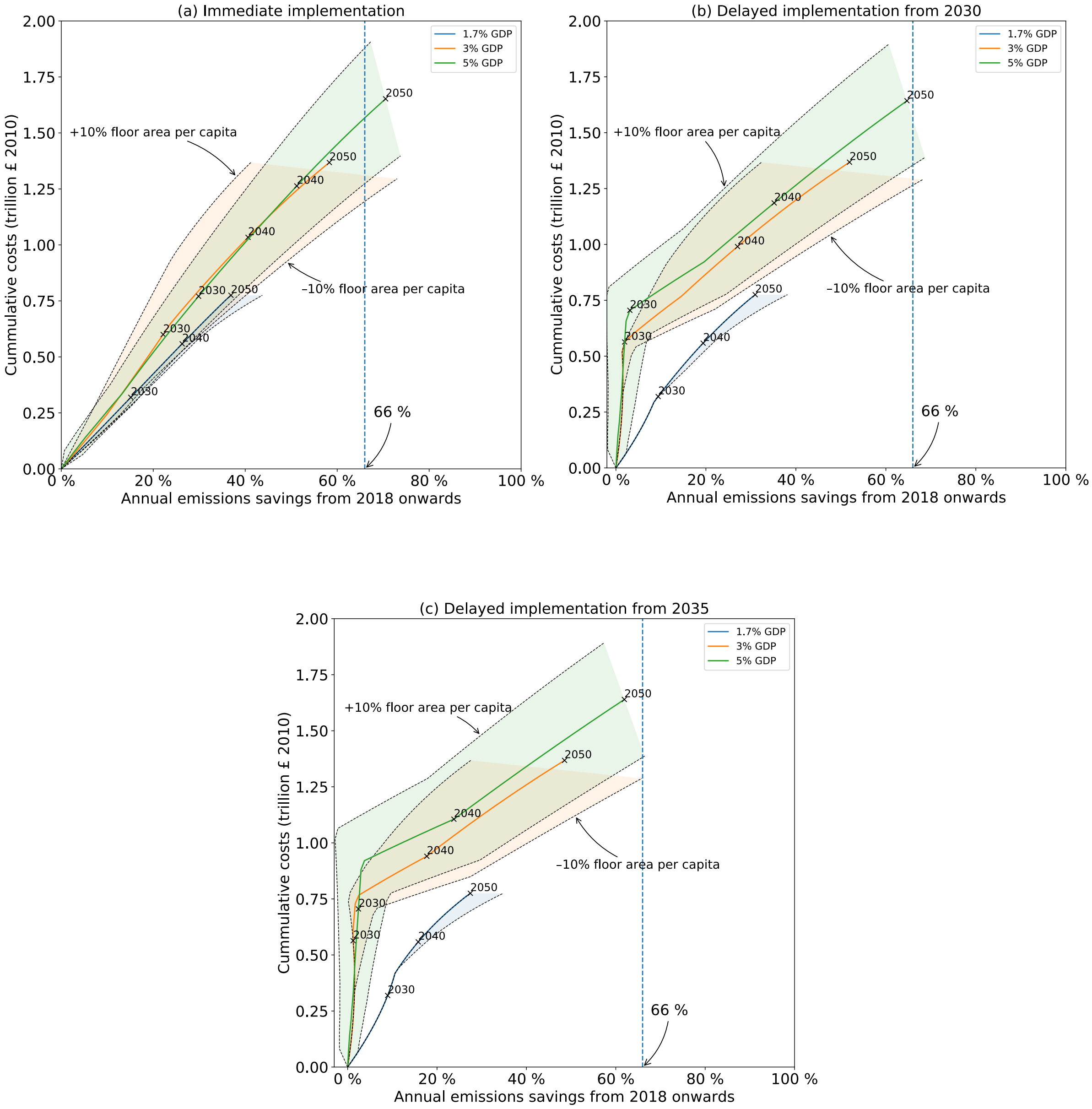


**Figure 7.** Emissions savings by 2050 and costs involved in implementing the most demanding scenario of Table 2 for various levels share of GDP used in construction and for two timescales: (a) immediate progressive adoption of improved standards, (b) delayed start in 2030, and (c) delayed start in 2035. An annual GDP growth rate of 2% is assumed until 2050.

## 5. Discussion

The results presented in section 4 show that progress in the use of low carbon materials in construction and the deployment of zero-carbon buildings at scale would likely not be enough to deliver a reduction of building emissions of the scale required nationally to meet existing targets by 2050. Every year, operational emissions are one order of magnitude greater than embodied emissions of new construction and thus meeting existing targets would only be possible with an improvement in energy standards for both new and pre-existing construction. This confirms the concerns raised by Giesekam *et al.* (2014); and Giesekam *et al.* (2016) regarding the need for further policy intervention to promote better buildings standards, by showing that the maintenance of current practices fails to deliver meaningful savings by 2050 for any reasonable changes in the occupancy of dwellings or in the rate of demolition (Figure 4).

Transformations in the building stock are very slow, given the long lifetime of buildings. Thus, a progressive improvement in new construction standards to an average of zero-carbon buildings for all new construction by 2050 is not enough to deliver the required emissions savings. Achieving these savings requires the refurbishment of pre-existing buildings, because of the inertia of building stocks. Although shorter building lifetimes and higher demolition rates would be able to accelerate the reduction of operational emissions in buildings, the costs associated with high levels of new construction seem likely to limit this option. Similarly, retrofitting all existing dwellings (54.2 kg $CO_2$ / $m^2$) to the same standards of current new buildings construction (19.1 kg $CO_2$ / $m^2$, strategy (b) of Table 2) would be able to deliver substantial emission savings, but the costs of refurbishment at that scale would likely be seen as unreasonable.

The average dwelling floor area per capita in England is already one of the lowest in Western Europe, but future changes in occupancy of dwellings or the average area per dwelling seem to have important implications in determining future costs and potential for emissions reduction. A reduction of 10% of current floor area per capita by 2050 would be able to reduce operational emissions by up to 30% compared to not changing current practices at the same or even lower costs. This would be motivated by a replacement of more area of old and inefficient houses by less area of new and efficient construction until 2050. However, the potential for emissions reduction in the housing stock is critically dependent on the levels of expenditure. Until 2050, population growth will likely lead to higher demand for new construction, probably up to two to fourfold the average of the last decade (Figure 5). This pace of new construction and the need to refurbish pre-existing dwellings is costly and will require larger budgets than have been spent historically. Maintaining an average annual expenditure of 1.7% of GDP in domestic construction will limit the potential for emissions reduction by almost 50%. For these levels of expenditure, it won't be possible to supply all new building requirements demanded by population growth for current levels of floor area per capita. Estimated potential for emissions savings can only be realised with expenditures of around 5% of GDP per year in domestic housing. However, a reduction in the demand for floor area per capita can substantially reduce costs and enhance emissions savings.

A reduction in the demand for floor area per capita reduces the total costs with domestic housing, both with refurbishment and new construction, and thus increases the likelihood of emissions savings in buildings at the scale required by 2050. Each dwelling in England on average is home for 2.4 people, but each dwelling is likely to be empty for several hours every day. Flexible designs that expand the use of spaces, telecommuting, and house sharing are options capable of increasing the number of activities and services done at dwellings. These options have far-reaching implications for social organisation, urban planning, architectural designs, and land use, but will have to be considered in addition to improvements in standards of new building construction and extensive refurbishment if meaningful emission savings from building use are to be delivered.

Figure 5 suggests that the pace of new building construction is likely to accelerate. This offers a privileged opportunity to change substantially the composition of the building stock and to reduce operational emissions for decades to come. However, a delay in implementing improved standards may reduce the environmental benefits for the same costs. Figure 7 shows that a delay until 2030 in the implementation of improved standards may result in a reduction of up to 15% in the emissions savings obtained by 2050 for the same expenditure in the dwelling stock. Therefore, unlocking the greatest emissions savings at minimum costs requires the immediate adoption of higher standards for new construction and a refurbishment schedule for pre-existing dwellings. Zero-carbon houses can already be built at little additional costs (Lucon *et al.*, 2014), and thus a policy schedule to progressively improve required standards of new construction may foster the performance of new dwellings. Refurbishment costs are considerable, but essential to deliver the scale of emissions reduction required to meet existing targets. However, current financing models do not produce the best investment incentives. Although more efficient dwellings lead to lower operational costs, these do not benefit contractors and non-resident owners, who thus do not have the appropriate incentives. Progress in pre-existing buildings could be fostered by a clear policy schedule to refurbish the oldest buildings and the development of alternative financing models. However, a prioritisation of refurbishment actions and target buildings is required to accelerate emissions reduction in the building stock.

This analysis assessed the trade-offs between refurbishment and new building construction to reduce emissions of the housing stock in England. Retrofitting old buildings and new building construction is likely to lead to rebound effects, either by increasing average indoor temperatures or by heating spaces for longer than they are occupied, since it would be more affordable to heat spaces with high building standards. This effect is likely to reduce emissions savings and cost effectiveness of the options considered in this analysis, being the results estimated here maximum potentials in the absence of rebound.

The results reflect the particular composition of the English dwelling stock, but the methods and most results could be valid for other countries with an old dwelling stock with low rates of new construction. Countries with high levels of population growth and consequently high demand for new building construction are thus more likely to face a unique opportunity to be able to substantially reduce future energy demand and emissions in buildings with a clear focus on meaningful progress in standards of new construction over the next few decades. Buildings account for around a third of global energy and process emissions, but transformations in the building stock are slow and while immediate action may lead to environmental benefits for future decades, delaying change will lock-in future energy uses and emissions in buildings for decades to come.

## 6. Conclusion

Buildings are responsible for around a third of GHG emissions globally and 27% in the UK. Yet, little progress has been made in reducing building emissions, because of the inertia of building stocks. Although technological solutions are available to improve the performance of buildings and reduce their energy demand and emissions, a clear prioritisation is required to balance costs and effectiveness in emissions reduction between retrofitting and new building construction. For the first time, the trade-offs between demolition and retrofitting have been assessed in this paper for the English domestic housing stock. This required a dynamic material flow analysis for the dwelling stock, distinguishing material composition associated with different types of wall structure. This enabled the identification of the required level of improvement in standards of new and existing buildings to achieve the scale of emissions savings required nationally until 2050. The scale of emissions savings is limited by levels of future expenditure and demand for housing, and the influence of these factors on emissions savings was also quantified.

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