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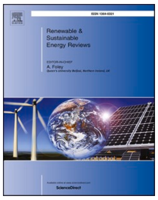

Net zero by 2050: Investigating carbon-budget compliant retrofit measures for the English housing stock

X. Li [a,*], H. Arbabi [a], G. Bennett [b], T. Oreszczyn [b], D. Densley Tingley [a]

[a] Department of Civil & Structural Engineering, University of Sheffield, Sir Frederick Mapping Building, Sheffield, S1 3JD, United Kingdom
[b] UCL Energy Institute, University College London, 14 Upper Woburn Place, WC1H 0NN, United Kingdom

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ABSTRACT

The UK has enacted one of the most ambitious carbon reduction targets striving for net zero emissions by 2050. A major challenge to achieving this is decarbonizing heating demand with almost 25 m homes in need of retrofit. This paper explores a range of retrofit interventions to the English residential stock. These are deployed immediately in 2021 to investigate the maximum carbon reduction that could be achieved. The impact of these interventions on embodied and operational carbon emissions is estimated from 2021 to 2050. The resulting emissions are compared to estimated national carbon budgets, in order to ascertain, if, and with what combination of retrofit measures, the English housing stock can stay within carbon budgets. The results show that mass deployment of air source or ground source heat pumps can reliably achieve combined embodied and operational emissions within national carbon budgets by 2050. The careful selection of insulation materials is key in bringing down the embodied emissions, particularly to meet stricter carbon budgets. The identified scale and pace of deployment thus needed to stay within carbon budgets is likely to pose enormous practical challenges. To overcome these challenges, we argue for (a) urgently increasing both heat pump deployment, and renewable generation targets beyond existing pledges, (b) increasing social awareness of residential retrofit benefits, and (c) providing more attractive financing options to incentivise and facilitate retrofit uptake.

1. Introduction

To keep the global temperature rise to within 1.5 °C, in line with the Paris climate accord, drastic decarbonisation measures are needed [1]. In 2019, the UK became one of the first advanced economies to pass legislation to target net zero greenhouse gas emissions by 2050 [2]. Prior to the disruption caused by the COVID-19 pandemic, the UK was projected to miss its previously set 2030s fourth and fifth carbon budgets even though it overachieved the targets set for 2020 [3]. As the world recovers from the pandemic, global carbon emissions have rebounded to near pre-pandemic levels [4]. Therefore, efforts are still urgently needed to keep UK carbon emissions within the pre-set carbon budgets.

1.1. UK residential emissions and retrofit

Direct and indirect greenhouse gas (GHG) emissions from the residential building sector accounted for 16% of the UK's total emissions in 2019 [5]. A recent report by the Committee on Climate Change points out that achieving the net zero emissions goal is all but impossible without decarbonizing England's existing residential stock of almost 25 m homes [6]. Between 1990 and 2004 the residential stock saw next to no reduction in direct carbon dioxide emissions, and between 2004 and 2019 it saw a 25% reduction [6]. Decarbonisation of the English stock can be achieved by a range of measures, applied both on the supply side and demand side. Upgrades to deliver a net zero carbon energy supply system include switching to decarbonised electricity, e.g. on and offshore wind, district heating with biomass, and repurposing the existing gas network for 100% hydrogen. These, however, often need to be designed in conjunction with building level retrofit measures. For example, an increased renewable electricity grid mix/capacity still requires building retrofit to electrify heating, i.e. through installation of heat pumps. Whereas hydrogen, at least in the UK, is unlikely to be reliably available in the network before 2030 [7]. This would leave nearly a decade of unmitigated residential emissions. Building level retrofit measures on the demand side, include improving the efficiency of the building fabric, heating systems, lighting and appliances. In England, more than half the stock has an energy efficiency band of D or worse (rated from A-G, with A being the top rating) with a large portion of the housing stock built before 1980 [8]. The significant size and age of

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* Corresponding author.
E-mail address: xinyi.li@sheffield.ac.uk (X. Li).

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List of abbreviations

ASHP	Air Source Heat Pump
AWI	All Walls Insulated
BL	Baseline
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CI	Cavity Insulation
COP	Coefficient Of Performance
DG	Double Glazing
EHS	English Housing Survey
EI	External Insulation
EPC	Energy Performance Certificate
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HBHP	Hybrid Heat Pump
II	Internal Insulation
NHM	National Household Model
PV	Photovoltaic
TG	Triple Glazing

the stock means that, in addition to its importance to the decarbonisation targets, building retrofit can also provide a significant opportunity to boost economic activity by increasing employment and wages [9]. Although there are many options for achieving net zero, practically delivering this transition will pose several challenges, including identifying the stock most in need of intervention, the deployment of the right mix of intervention measures that are practical, and most cost effective, for both homeowners and the wider energy system.

The 2020-released UK Energy Performance Certificate (EPC) action plan aims to make energy performance data more accurate, reliable, and accessible in order to better plan for the net zero transition [10]. By November 2021, 11 of the 35 actions were already completed, and the remaining had commenced [11]. Furthermore, the UK Government's Green Industrial Revolution aims to reduce carbon emissions by 71MtCO$_2$e between 2023 and 2032 by installing 600 thousand heat pumps annually by 2028, improving the energy efficiency of 2.8 m houses by 2030, and ensuring 'zero carbon ready' new build construction [12]. Concurrently, the government has made a pledge to invest in offshore wind capacity such that every home in the country can be wind powered by 2030 [13].

1.2. Whole-life emissions and emissions budget

Many aspects of residential building retrofit have already been explored within the literature, from financing and governance requirements to the development of various scenario modelling tools to support decision making in the area. Ahlrichs et al. [14] have studied retrofit investment and financial barriers highlighting a need for increased carbon taxes to influence retrofit-related investment decisions. Meanwhile, a recent study of British landlords' behaviour relating to retrofit activity points at diversifying information channels targeted at landlords. This is seen as a key factor in ensuring policy and financial incentives are adopted despite differing financial means and attitudes among landlords [15]. Decision support studies have also looked at susceptibility of various geodemographic groups of homeowners to invest in retrofit measures [16] and the potential unintended consequences of thermal retrofit resulting in a consumption rebound [17]. Studies in a UK context, have focused particularly on identifying retrofit actions required to meet decarbonisation targets [18,19] or the potential role for various public and private stakeholders to enable these [20,21]. However, currently the majority of the UK residential stock retrofit studies focus on operational impacts, largely excluding embodied impacts [22]. There is little research investigating the whole life carbon performance of building stock retrofit, which includes accounting for the embodied carbon emissions from the retrofit measures themselves [22], and it is this research gap that this study is aiming to fill. Moreover, with the current UK housing retrofit rates too low to achieve net zero by 2050 [23], a novel research question arises: what retrofit measures need to be deployed to keep the English residential stock within carbon budgets?

In summary existing knowledge gaps include:

- understanding of the embodied impacts of retrofit,
- whole-life carbon performance of various retrofit measures globally, and
- compatibility of retrofit measures with Paris-compliant national and sectoral emissions budgets.

To answer these questions, we scale down the total UK carbon budget into a carbon budget for English residential buildings. The whole life carbon emissions of the English housing stock, including the embodied carbon emissions from retrofit measures and the buildings' operational carbon emissions post-retrofit operation, are then estimated for 2021–2050. Making an assumption that wide-spread residential retrofit is essential, we identify the retrofit measure combinations that meet residential carbon budgets, estimating these budgets using two different interpretations of global to national budget allocations. The results of this study provide insights for decision and policy makers working on retrofit or decarbonisation in the UK, as well as providing broader insights into the potential solutions that drastically decarbonise similarly aged housing stock in similar climates.

2. Methodology

This study starts by estimating carbon budgets for the English residential sector from 2021 to 2050. It then models deployment of a series of retrofit measures across the English housing stock. The whole life carbon emissions of English residential stock retrofit, including both operational emissions and embodied emissions, are estimated. Finally, the combined emissions over the period 2021–2050 are compared against the developed budget to determine the ability of retrofit scenarios to meet the budget or the additional renewables required to accelerate grid decarbonisation in order to meet the pre-set carbon budget.

We make a simplifying assumption about the deployment of the retrofit interventions, such that all scenarios considered are immediately deployed at the start of 2021. This represents the maximum energy saving potential of all studied retrofit scenarios. In the real world, the deployment of retrofit interventions takes time and results in lower cumulative energy savings.

2.1. Long-term targets and emissions budget

Based on a UK carbon budget developed by the Committee on Climate Change (CCC) [24] and one by the Tyndall Centre [25], we develop two budgets specifically for the English residential building stock, b_p, for the period p following

$$b_p = B_p{*}F_{be}{*}F_d{*}F_e \tag{1}$$

where B_p is the CCC or Tyndall-developed carbon budget for UK for the period p; F_{be} is the fraction of carbon emissions from UK built environment to UK total carbon emissions, which was around 40% in 2019, including embodied carbon emissions from new construction, operational carbon emissions from existing built assets and direct emissions from transportation [26]; F_d is the fraction of UK residential carbon emissions (including both residential embodied and operational carbon emissions) to the UK built environment carbon emissions (considering embodied and operational carbon emissions of three sectors, namely residential buildings, non-residential buildings and infrastructure), which was 61% in 2010 [27]; F_e is the fraction of England's residential carbon emissions to the UK residential carbon emissions which is calculated based on the prediction of Tyndall carbon budget between that for England and the UK (as shown in 3).

The Tyndall carbon budget is more stringent than the CCC carbon budget, as the Tyndall interpretation of the Paris agreement is that developed nations should be apportioned a smaller proportion of the global carbon budget, with developing nations given a larger share to facilitate their development. In addition, global elements of the budget are also allocated to areas such as land use change, see Anderson et al. [28] and Kuriakose et al. [29] for further details. The CCC carbon budgets cover 5-year periods and are set every five years, with the sixth CCC carbon budget (2033–2037) published in December 2020. The Tyndall carbon budgets also cover five-year periods from 2018 to 2047 with additional budgets covering 2048 to 2100. The total budget from 2021 to 2050 is then disaggregated assuming a linear proportionality across the years during the periods 2018–2022 and 2048–2100 according to equation (2).

$$b_{2021-2050} = \frac{2}{5} b_{2018-2022} + b_{2023-2027} + b_{2028-2032} + b_{2033-2037} + b_{2038-2042} + b_{2043-2047} + \frac{3}{53} b_{2048-2100} \tag{2}$$

Table 1 shows the extracted carbon budgets from CCC and Tyndall for the UK and the scaled budget for the English residential stock. It is worth mentioning that the current indicative path to the UK's net zero target shows the annual GHG emissions will not reach this target before 2050 [30], and the CCC carbon budget for 2033–2037 has only just been published [31]. Therefore, our estimated CCC England carbon budget for the period 2021–2050 is likely to be an underestimation. Furthermore, the Tyndall carbon budgets are for carbon dioxide emissions only instead of carbon equivalents. To simplify the comparison of carbon budgets between countries with residential stock of different size, the England residential carbon intensity restriction is also calculated (shown in Table 1), as the England residential carbon budget divided by total floor area nationally, which is around 2.44E+09 m^2 according to EHS 2012 [32].

With this study focusing on how to successfully mitigate English residential stock's carbon emissions, whilst keeping to the 2050 carbon budget, we only consider the total carbon budget between 2021 and 2050 as an aggregated benchmark, instead of trying to meet periodic intermediate 5-year targets. The study takes a consumption-based approach [33] to carbon accounting, including the embodied emissions from all materials whether they are produced in the UK or internationally.

2.2. Retrofit scenarios

We consider four main types of retrofit measures in this study: wall insulation, glazing replacement, PV modules and heating system upgrades. They are applied individually and combined. In the combined retrofit measures, only double glazing is considered due to its higher financial effectiveness in retrofitting UK residential dwellings when compared with triple glazing [34]. The retrofit scenarios considered in this study are detailed in Table 2.

The post retrofit U-value for wall insulation is set to 0.1 $W/(m^2 \bullet K)$ as the most energy efficient retrofit solution. It exceeds the requirements of the current maximum requirement of UK building regulations, part L1B of 0.3 $W/(m^2 \bullet K)$ [36] and EnerPHit building retrofit standard, which ranges from 0.12 to 0.30 $W/(m^2 \bullet K)$ in the UK [37], but still proved to be feasible for a 1960s housing estate with solid walls [38]. The various measures under consideration are applied to the building stock in such a way that the definition of the measure and the homes to which it could be applied are explicitly programmed. For example, cavity wall insulation is defined as providing a U-value of 0.1 $W/(m^2 \bullet K)$ after installation and is only applied to homes with cavity walls currently without cavity insulation. The National Household Model then searches the stock for suitable homes and applies the measure as defined. Table 3 provides information on the aggregate scope of each scenario when applied to all eligible stock across the nearly 25 m units available to retrofit.

2.3. Modelling operational carbon

2.3.1. National household model

The National Household Model (NHM) is an open-source modelling tool developed for the UK Department of Business Energy and Industrial Strategy [39]. The model (v 7.2.2 used in this study) brings together the standard monthly building energy assessment calculation methods with the representative UK residential building stock. The energy assessment models available are the Standard Assessment Procedure (SAP) and Building Research Establishment Domestic Energy Model (BREDEM), which are closely related in terms of being monthly energy balance methods and SAP having been derived from BREDEM to fulfil the role of the National Calculation Model for the UK to conform to the EU Energy

Table 1

Carbon budgets for the UK and England residential sector – note that only Committee on Climate Change (CCC) values are in carbon equivalent.

Period	CCC UK carbon budget ($MtCO_2e$)	Tyndall UK carbon budget ($MtCO_2$)	Tyndall England carbon budget ($MtCO_2$)	F_e the fraction of England's residential carbon emissions to the UK residential carbon emissions	England residential carbon budget		England residential carbon intensity restriction	
					CCC ($MtCO_2e$)	Tyndall ($MtCO_2$)	CCC ($kgCO_2e/m^2$)	Tyndall ($kgCO_2/m^2$)
2018–2022	2544	1456.9	1175.6	80.7%	500.9	286.8	205.60	145.92
2023–2027	1950	741.0	599.6	80.9%	385.0	146.3	158.04	74.22
2028–2032	1725	366.3	297.3	81.2%	341.6	72.5	140.23	36.69
2033–2037	965	181.3	147.7	81.5%	191.8	36.0	78.74	18.16
2038–2042	/	89.9	73.5	81.8%	/	17.9	/	9.00
2043–2047	/	44.9	36.9	82.2%	/	9.0	/	4.50
2048–2100	/	44.4	36.8	82.9%	/	9.0	/	4.45
2021–2050	4692.6	2008.7	1627.3		1118.8	397.1	459.2	201.2

Table 2
Retrofit scenarios and the description of the interventions modelled for the stock.

Retrofit Scenario	Description
BL	Baseline (BL), no retrofit, the stock stays as it is currently without upgrade.
PV	Add photovoltaic (PV) modules on all buildings with available roof space for PV. The PV modules are assumed to be installed on 30% of all available building roof space, with an efficiency of 20% for electricity generation. All PV has an encumbered view of the sky according to the orientation of the building.
CI	Cavity insulation (CI) applied to all buildings with cavity walls where no previous cavity wall insulation is installed to achieve a post retrofit U-value of 0.1 W/(m^2•K).
EI	External insulation (EI) applied to all buildings with solid walls where no previous external wall insulation is installed, to achieve a post retrofit U-value of 0.1 W/(m^2•K).
II	Internal insulation (II) applied to all buildings of any wall type where no previous internal wall insulation was installed, to achieve a post retrofit U-value of 0.1 W/(m^2•K).
DG	Replace windows in homes where the glazing U-value is greater than 3 W/(m^2•K) to double glazing (DG) with U-value of 1.6 W/(m^2•K).
TG	Replace windows in homes where the glazing U-value is greater than 2 W/(m^2•K) to triple glazing (TG) with U-value of 0.8 W/(m^2•K).
GSHP	Switch to ground source heat pump (GSHP) with seasonal Coefficient of performance (COP) of 3 if outdoor space is available and the current heating system efficiency is less than 100% or uses community heating.
ASHP	Switch to air source heat pump (ASHP) with seasonal COP of 2.5[a] if the current heating system efficiency is less than 100% or uses community heating.
HBHP	Switch to hybrid heat pump (HBHP) with 50:50 split of heating supply between ASHP (COP2.5) and condensing gas boiler, where the current heating system efficiency is less than 100% and the house is connected to the gas network.
AWI	All Walls Insulated (AWI). Apply CI, EI, and II sequentially to all the stock with the same rules as above. No individual home receives more than a single insulation measure to achieve a post retrofit U-value of 0.1 W/(m^2•K) for the treated walls. Many homes which were not classified as simple CI or EI suitable homes and have mixed wall and layout types will result in non-uniform application of insulation measures resulting in a higher than 0.1 W/(m^2•K) for the dwelling.
AWI + DG + ASHP	Combining the all wall insulation, glazing and heating system switch to air source heat pump or hybrid heat pump as per the listed combinations, the measures are applied to the stock as per their individual rules.
AWI + ASHP	
AWI + DG	
DG + ASHP	
AWI + HBHP	
DG + HBHP	
AWI + DG + HBHP	

[a] In practice heat pumps vary significantly in operational performance (seasonal COP of 1.5–4.5 for ASHPs), due to installation quality, product performance and maintenance [35] Lowe R, Summerfield A, Oikonomou E, Love J, Biddulph P, Gleeson C et al. Final report on analysis of heat pump data from the renewable heat premium payment (RHPP) scheme https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/606818/DECC_RHPP_161214_Final_Report_v1-13.pdf; 2017 [35]. This variation in COPs is much greater than the variance in boiler efficiency, resulting in a greater variance in energy demand.

Table 3
Retrofit measures deployment scope across the eligible English housing stock.

Retrofit Scenario	PV module area (m^2)	Wall insulation total applied area (m^2)			Glazing replacement total applied area (m^2)		Annual generated thermal energy for domestic space heating from the retrofitted heating system (kWh_t)		
		Cavity	External	Internal	Triple glazing	Double glazing	GSHP	ASHP	Boiler
PV	3.89E+08								
CI		9.52E+08							
EI			6.36E+08						
II				1.65E+09					
TG					4.06E+08				
DG						1.12E+08			
GSHP							1.90E+11		
ASHP								2.07E+11	
HBHP								9.25E+10	9.25E+10
AWI		9.52E+08	6.36E+08	5.90E+07					
AWI + DG + ASHP		9.52E+08	6.36E+08	5.90E+07		1.12E+08		1.37E+11	
AWI + ASHP		9.52E+08	6.36E+08	5.90E+07				1.42E+11	
AWI + DG		9.52E+08	6.36E+08	5.90E+07		1.12E+08			
DG + ASHP						1.12E+08		2.03E+11	
AWI + HBHP		9.52E+08	6.36E+08	5.90E+07				5.46E+09	5.46E+09
DG + HBHP						1.12E+08		9.06E+10	9.06E+10
AWI + DG + HBHP		9.52E+08	6.36E+08	5.90E+07		1.12E+08		4.39E+09	4.39E+09

Performance of Buildings Directive [40,41]. For the purposes of calculating operational carbon, here, we use the BREDEM 2012 energy calculator.

The NHM requires building stock data and has been designed to take English Housing Survey (EHS) data as a primary building stock. For the purposes of this analysis, we use data from the EHS 2012 [32]. Although the NHM has the capability to perform scenario modelling over time, with programmable interventions and changes to the building stock, the operational carbon calculations in this analysis are done over one calendar year with all interventions implemented on the first day of the model run. This is because we are primarily interested in investigating the combined embodied and operational carbon implications of retrofit measures and a deploy-all-first approach represents the most favourable approach in minimizing accumulating operational emissions in the absence of practical constraints. At-the-meter energy consumption of the stock as a whole is modelled before and after intervention measures in

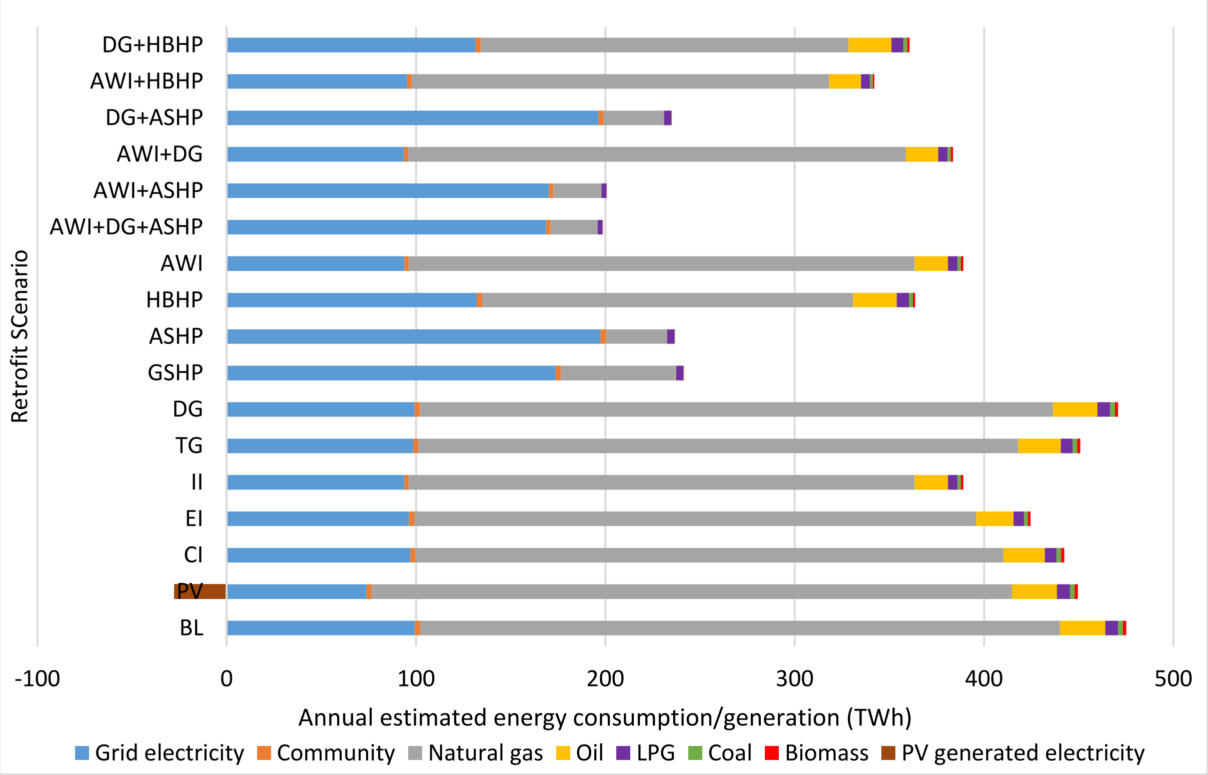

Fig. 1. The energy consumption of the English house stock under different retrofit scenarios.

order to assess the impact of installing each intervention. The detailed NHM energy consumption results of different scenarios and a brief discussion of the results can be found in the SI. The energy demand by fuel from all energy vectors was also collected to gain an accurate picture of the operational carbon resulting from the intervention measure.

The annual energy consumption of the whole English housing stock after undertaking different retrofit measures is presented in Fig. 1. The detailed data can be found in the SI.

2.3.2. Grid emissions and decarbonisation scenarios

To arrive at emissions related to residential consumption we need to assume a carbon intensity for the national grid in the period 2021–2050. From 2008 to 2019, the carbon emissions from the power sector fell by 67% with the decarbonisation of the power sector dominating the UK carbon emissions fall for the last decade [30]. However, the power sector needs to be further decarbonised to achieve the net zero carbon emissions target. In this study, the effect of grid decarbonisation on the carbon emission factor of electricity is explored by initially considering six future grid decarbonisation scenarios based on the analysis of Committee on Climate Change and that of the national grid:

S1: In 2019, the electricity carbon emissions for the UK were 200 gCO_2/kWh [42]. According to the analysis and targets set by the CCC [3], the grid carbon emissions are assumed as 50gCO₂/kWh in 2030 and 10gCO₂/kWh in 2050. Interpolation is used to calculate the grid carbon emissions of other years in-between, with a constant decarbonisation pace assumed between 2019-2030 and 2030–2050.

S2 to S5: The national grid [43] has developed a set of four future energy scenarios with different CO_2 intensities of electricity generation, namely consumer transformation (S2), system transformation (S3), leading the way (S4) and steady progression (S5). The three scenarios, S2–S4, all rely on bioenergy with carbon capture and storage (CCS) and achieve negative emissions prior to 2050.

S6: In the Committee on Climate Change's sixth carbon budget [31], a balanced net zero pathway for electricity generation was developed, which very largely decarbonises electricity generation by 2030, and decarbonises it completely by 2035. Actions thereafter focus on meeting rising demand with low-carbon generation.

These grid carbon emissions scenarios only account for direct CO_2 emissions. In this paper, we make adjustments to include all GHG emission in the grid emissions. By assuming the ratio between grid emitted GHG and CO_2 remains constant at its 2017 value of 1.008 [44], the emission factor of electricity accounting for all GHG is calculated following:

$$OC_{e,y} = G_{CO_2,y}*1.008 \tag{3}$$

$OC_{e,y}$ is the carbon emission factor of electricity in year y in gCO_2e/kWh; $G_{CO_2,y}$ is the grid carbon emissions considering only CO_2 in year y measured in gCO_2/KWh. The grid carbon emissions of all scenarios from 2019 to 2050 are presented in Fig. 2. The grid carbon emissions in 2019 are lower for national grid scenarios (S2 to S5) as the analysis of the national grid ignores network and operability constraints on the transmission or lower voltage networks [45].

Since a successful and scalable deployment of CCS before 2050 could ensure a net zero transition almost independently from other available interventions, we will only use scenarios S1, S5 and S6 in our grid emissions results moving forward. Results from the other three future grid carbon emissions scenarios can be accessed in the supplementary material. It is also worth considering, given current progress on CCS scalability and deployment, that CCS mass deployment is an unlikely scenario before 2050 [46].

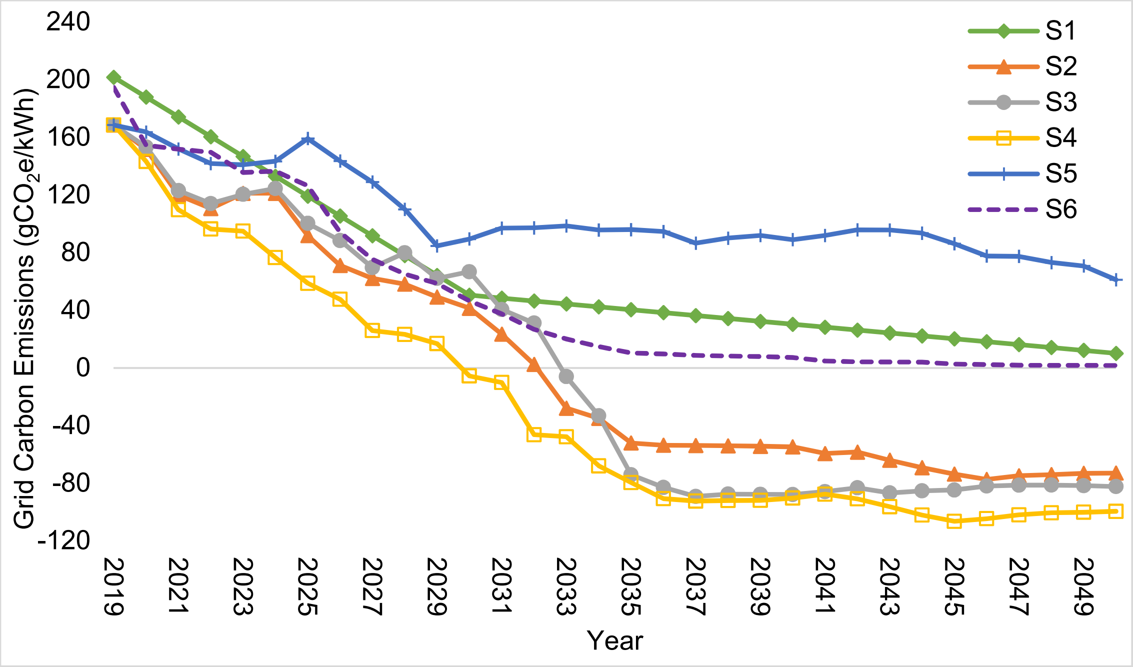

Fig. 2. Future grid carbon emissions for all scenarios.

2.3.3. *Operational carbon*

Finally, the total annual operational carbon emissions for 2021–2050, O, is then calculated based on the operational energy consumption after:

$$O = \sum_{2021}^{2050} O_y = \sum_{2021}^{2050} \left[(M_e + P) \times OC_{e,y} + M_g \times OC_g + M_o \times OC_o + M_l \times OC_l + M_c \times OC_c + M_m \times OC_m + M_b \times OC_b \right] \tag{4}$$

where M is the annual consumption of a specific fuel in kWh; P is the annual photovoltaic electricity generation fed back to grid in kWh; OC is the carbon emission factor of a specific fuel in gCO_2e/kWh, with the subscript e, g, o, l, c, m, and b standing for electricity, natural gas, oil, LPG, coal, community, and biomass, respectively. The values for OC are taken as $OC_g = 184$, $OC_o = 247$, $OC_l = 214$, $Oc = 345$, $OC_m = 50$, $OC_b = 16$ [44,47]. Although in the future, more sustainable fuels, e.g. biogas, hydrogen might be able to replace some portion of the carbon intensive fossil fuels currently consumed within residential stock, the approach taken in this study, using the NHM model is based on SAP methodology, which utilises present-day energy vectors and does not take direct account of innovative fuels such as biogas and hydrogen. As such, the implications of these fuels are excluded from the analysis, both in terms of residential demand, as well as, implications such as additional grid generation for fuel production. Therefore, constant carbon emission factors are assumed for natural gas, oil, LPG, coal, community and biomass between 2021 and 2050.

2.4. *Embodied carbon calculation*

Embodied carbon measures greenhouse gas emissions during the non-operational phase and as such includes emissions released through extraction, manufacture, transportation, assembly, maintenance, replacement, deconstruction, disposal, and end-of-life aspects of the materials and systems that make up a building [48]. The scope of embodied emissions in this study covers cradle-to-gate, i.e., A1-A3 embodied carbon [49]. This essentially covers the supply-chain up to the point that construction products are ready for use at the factory gate.

2.4.1. *Retrofit embodied carbon*

Insulation: We consider three types of wall insulation in this study. These are solid wall external insulation, internal insulation and cavity wall insulation. Thirteen different insulation materials have been considered in this study to estimate mean embodied emissions across available options. (See SI for the characteristics of the individual insulation materials used.) The thickness of insulation material to meet the required U-value specified in Table 2 is calculated using

$$\delta = \lambda \times (1 / U_b - 1 / U_a) \tag{5}$$

where U_b and U_a are the thermal transmittance of the wall before and after the retrofit in $W/(m^2 \cdot K)$; δ is the thickness of chosen insulation material in meters; and λ is the thermal conductivity of chosen insulation material in $W/(m \cdot K)$. The embodied carbon of wall insulation, E_w, can then be calculated following

$$E_w = \delta \times A_w \times D \times EC_w \tag{6}$$

where A_w is the total area of retrofitted wall in m^2, see Table 3; D is the density of the chosen insulation material in kg/m^3; and EC_w is the cradle-to-gate embodied carbon intensities of the insulation measured in $kgCO_2e/kg$.

Glazing: We consider double and triple glazing as the two types of market available retrofit measures for openings. The embodied carbon of window replacement, E_d, is calculated following

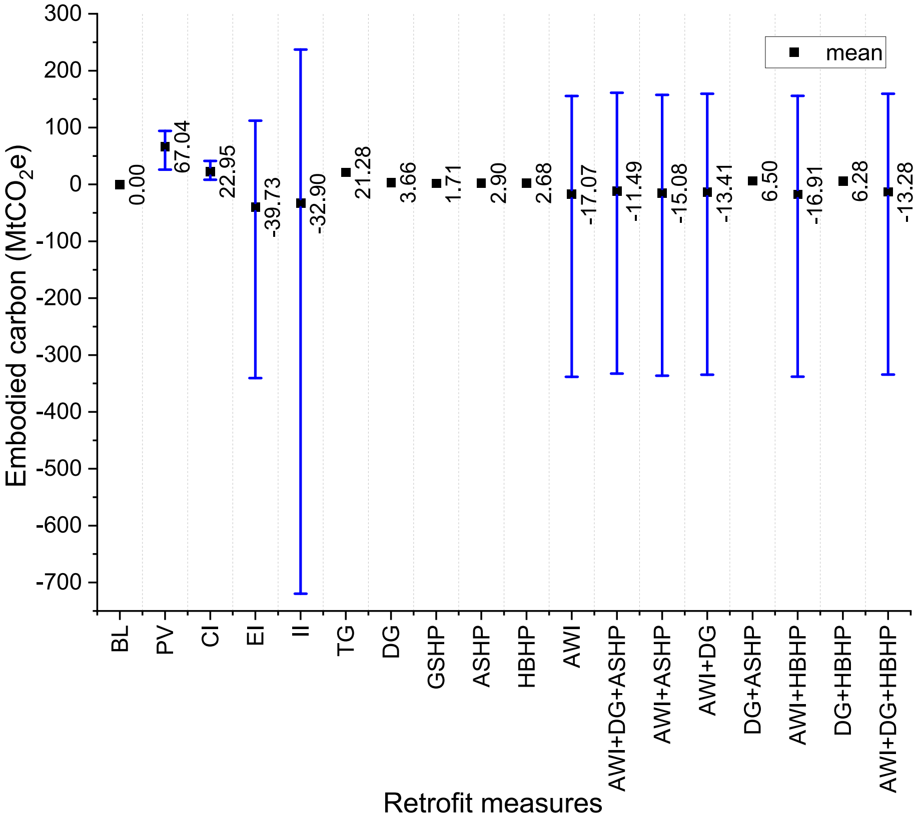

Fig. 3. Embodied carbon emissions of different retrofit scenarios.

$$E_d = EC_d \times A_d \tag{7}$$

where A_d is the retrofitted window area in m^2 and EC_d is the cradle-to-gate embodied carbon intensities of the replaced window taken as 32.5 kgCO$_2$e/m^2 for double glazing and 52.4 kgCO$_2$e/m^2 for triple glazing, respectively [50].

Heat pump and boiler: In the UK, governmental renewable heat schemes like Domestic Renewable Heat Incentive (RHI) have historically promoted the deployment of heat pumps [51]. Air source, ground source, and hybrid heat pumps, i.e., combined air source heat pump and condensing gas boiler, are considered to replace existing boilers in eligible stocks. The embodied carbon of heating system replacement, E_h, is calculated through

$$E_h = EC_h \times T_h + EC_b \times T_b \tag{8}$$

where EC_h is the cradle-to-gate embodied carbon intensities of heat pump in kgCO$_2$e/kWht; T_h is the thermal energy generated by heat pumps for residential space heating and hot water in kWht; EC_b is the cradle-to-gate embodied carbon intensities of condensing gas boilers in kgCO$_2$e/kWht; and T_b is the thermal energy generated by boilers for residential space heating and hot water measured in kWh$_t$. Based on a study by Greening and Azapagic [52], assuming that 95% of global warming potential (GWP) impact is from the operational energy consumption, the life cycle embodied carbon intensities of air source heat pumps, ground source heat pumps and condensing gas boilers are taken as 0.014kgCO$_2$e/kWh$_t$, 0.009kgCO$_2$e/kWh$_t$, and 0.015kgCO$_2$e/kWh$_t$, respectively. Including extraction and processing of fuels and raw materials; system manufacture; installation; maintenance; decommissioning and transportation for heat pumps, as well as extraction and processing of fuels and raw materials; boiler manufacture; decommissioning and transportation for boiler. Given that these values include emissions beyond cradle-to-gate, such as installation and disassembly, our values for these components are likely to lead to a slight overestimation of their cradle-to-gate embodied carbon.

Photovoltaics: We calculate the embodied carbon of the PV modules, E_p, following

$$E_p = EC_p \times A_p \tag{9}$$

where A_p is the area of PV modules installed in m^2 and EC_p is the cradle-to-gate embodied carbon intensities of PV modules taken as 242 kgCO$_2$/m^2 for monocrystalline PV modules, 208 kgCO$_2$/m^2 for polycrystalline PV modules, and 67 kgCO$_2$/m^2 for thin-film PV modules [50]. The embodied carbon intensities of PV modules only accounts for CO$_2$ instead of all GHG meaning the overall embodied carbon of PV modules are generally underestimated.

3. Results and discussion

3.1. Whole-life carbon emissions from retrofit

The embodied carbon emissions of applying the aforementioned retrofit measures for all suitable residential buildings in the English housing stock is presented in Fig. 3. The error bars for embodied emissions account for the variation in material for insulation and PVs, as more than one material and one type of PV module are considered. It is clear that retrofit scenarios which include installation of insulation, especially external and internal insulation, can have a wide range of embodied emissions highlighting the importance of material selection. For example, when using wood fibre as insulating material, real-terms emission saving can be achieved as a result of the overall sequestration of carbon within the product.

Fig. 4, shows the corresponding operational carbon emissions over a 30-year period up to 2050 and how these operational emissions relate to the Tyndall and CCC carbon budgets, assuming that all the measures

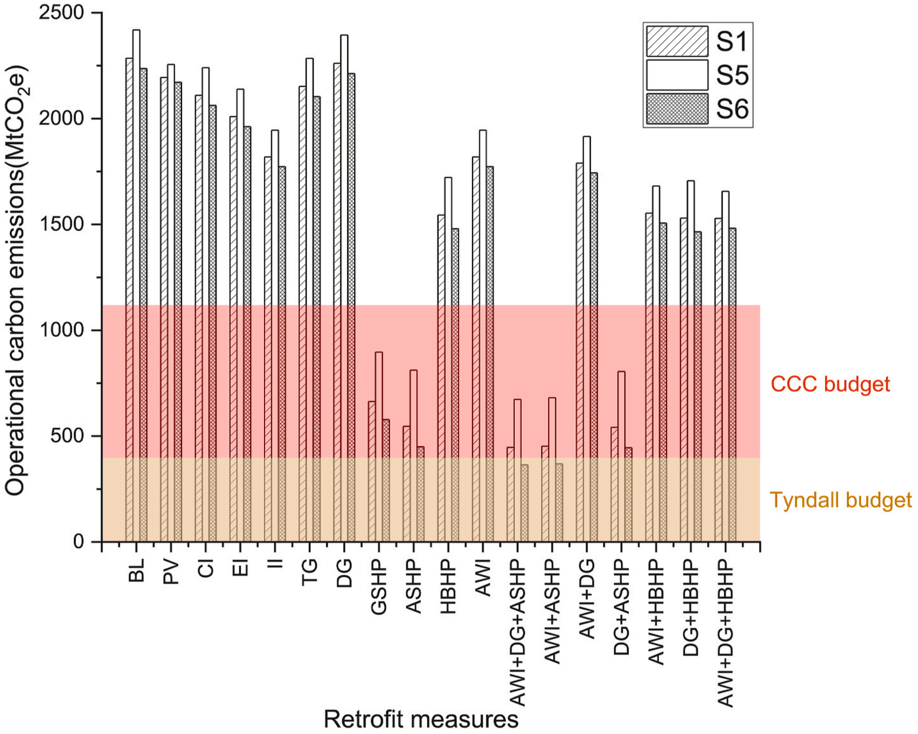

Fig. 4. 30 years (2021–2050) operational carbon emissions of different retrofit scenarios – highlighted regions show the CCC and Tyndall budgets between 2021 and 2050.

Table 4
The carbon payback time [unit: year(s)].

Retrofit scenario	S1	S5	S6
PV	13	10	>30
CI	4	4	4
EI	1	1	1
II	1	1	1
TG	5	5	5
DG	5	5	5
GSHP	1	1	1
ASHP	1	1	1
HBHP	1	1	1
AWI	1	1	1
AWI + DG + ASHP	1	1	1
AWI + ASHP	1	1	1
AWI + DG	1	1	1
DG + ASHP	1	1	1
AWI + HBHP	1	1	1
DG + HBHP	1	1	1
AWI + DG + HBHP	1	1	1

were undertaken at the beginning of 2021 and that the grid decarbonises at three different rates/scenarios. The measure that has the biggest impact on operational carbon emissions, while applied on its own, is the ASHP. However, this has to be combined with insulation measures, AWI + DG + ASHP and AWI + ASHP under S6, to meet the strictest Tyndall carbon budget. When compared with the baseline of undertaking no retrofit at all, the operational carbon emissions savings of all retrofit scenarios considered range from 1% for DG to 81% for AWI + DG + ASHP under S1 grid decarbonisation scenario, 1%–72% under scenario S5, and 1%–84% under scenario S6. What is crucial to note, is that, without a mass deployment of air or ground source heat pumps, the 30-year operational carbon emissions from any of the retrofit scenarios would exceed both CCC and Tyndall carbon budgets.

Compared with the 30 years of post-retrofit operational carbon emissions, however, the mean embodied carbon emissions from retrofit measures are almost negligible. Under S1, S5 and S6, the carbon payback of applying various retrofit measures is presented in Table 4, apart from PV, all scenarios achieved carbon reduction through retrofit within 5 years, while many of them emit less carbon compared to the baseline from the first year. The carbon payback for PV modules is over 10 years, and it is not able to payback at the end of our study period (30 years from 2021 to 2050) under the S6 grid decarbonisation scenario. It is of interest to note that both double glazing and triple glazing can achieve carbon payback within 5 years when applied alone. Although the cradle-to-gate embodied carbon intensities for triple glazing are 1.6 times that of double glazing, the triple glazing achieved bigger energy savings as more properties can accommodate this upgrade.

As mentioned, the selection of low environmental impact materials and systems in retrofit can significantly reduce embodied carbon emissions, as is the case with the external and internal wall insulation. Considering total whole-life carbon emissions, as shown in Fig. 5, careful selection of materials and systems used in retrofit provides a greater chance to meet stricter carbon budgets. However, there must also be a focus on ensuring the materials perform well in situ, i.e. to reduce the performance gap [53].

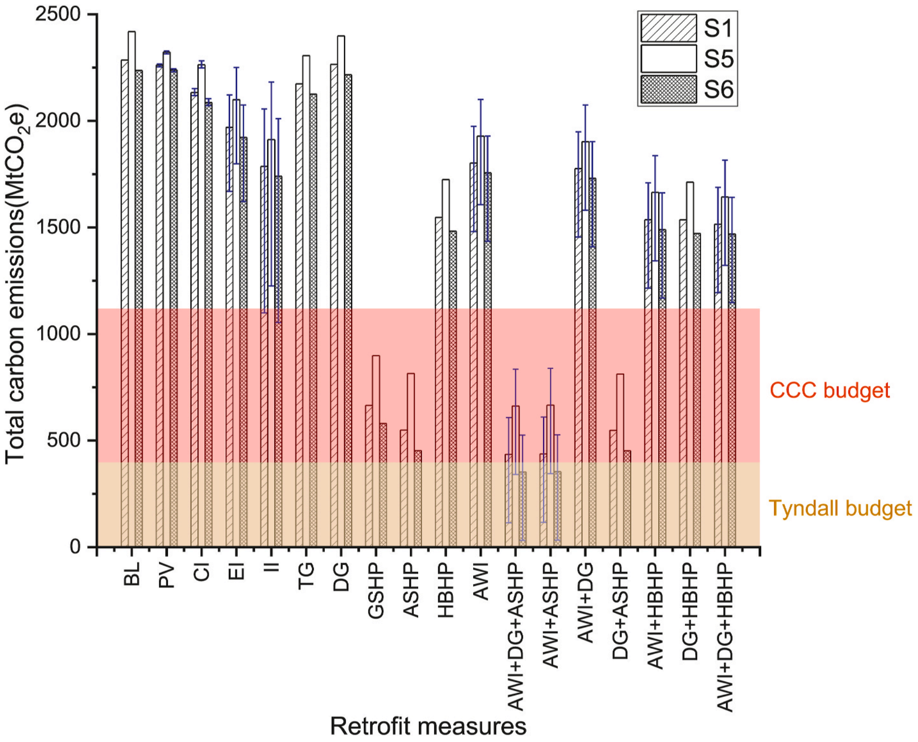

Fig. 5. 30 years (2021–2050) total embodied and operational carbon emissions when considering different retrofit measures and grid decarbonisation scenarios for English residential stock – note that heat pumps are the only way that the budgets can be met with the Tyndall budget requiring careful selection of insulation material across the entirety of the stock.

3.2. *England's house stock carbon emissions in 2050*

The English housing stock will play a key role on whether net zero emissions can be achieved in the UK by 2050. The operational carbon emissions per annum in 2050 for different grid decarbonisation scenarios and retrofit combinations are presented in Fig. 6, by using electricity carbon emission factors in 2050. Based on the stock operational energy prediction results from NHM, the English housing stock is not likely to achieve net zero carbon emissions by 2050 through building retrofit measures alone, even when considering non-transformational grid decarbonisation. Achieving net zero in 2050 therefore likely requires both retrofit, complete electrification of cooking, successful deployment of CCS technologies and a massive increase in renewables capacity, likely to be wind, by 2050.

3.3. *Additional wind capacity to meet carbon budget*

UK wind capacity has continuously increased from 5.4 GW in 2010 to 24 GW in 2019. By 2019, wind made up the UK's second largest source of electricity [54]. Current ambitious plans to power all UK homes with wind by 2030 could theoretically provide carbon reduction benefits as well [55]. According to Smoucha and Fitzpatrick [56], an onshore 2 MW turbine with annual electricity generation of 4520 MWh has 787 tCO_2e of embodied carbon emissions from the manufacturing stage. Under S1, S5 and S6 grid scenarios, a 2 MW turbine achieves net carbon reduction at the end of the 2nd year. Whilst a 30-year operation provides for an emissions offset of 6929 tCO_2e, 13007 tCO_2e and 4721 tCO_2e, respectively, when compared with the grid electricity. This we use to estimate the wind capacity required to meet Tyndall carbon budget targets.

For all the retrofit scenarios considered in this study, among those failing to meet the Tyndall carbon target, DG + ASHP has the lowest total carbon emissions. After the retrofit interventions, the 30-year total carbon emissions from the English housing stock (from 2021 to 2050) are 150.88 $MtCO_2e$, 414.79 $MtCO_2e$ and 54.99 $MtCO_2e$ over the Tyndall carbon target under S1, S5 and S6 scenarios, respectively. To help meet the Tyndall carbon target, 21,776, 31,890 and 11,650 2 MW turbines need to be installed in 2021 depending on the grid scenario. The accumulated carbon emissions from the stock after DG + ASHP retrofit and accumulated carbon reductions from the wind turbines from 2021 to 2050 are presented in Fig. 7.

With the installation of enough wind turbines, the Tyndall carbon target can be achieved. However, deploying the equivalent capacity of up to nearly 32 thousand 2 MW wind turbines would pose practical challenges to load management in the national grid, and construction challenges to deliver this level of capacity. More generally, our results highlight mass deployment of heat pumps to be fundamental when trying to meet carbon targets for the residential stock in England. This on its own means that the electrification of residential demand is crucial in meeting targets. The increase of electricity demand for space heating ranges from 1.76 TWh to 82.72 TWh in 9 out of 18 retrofit scenarios utilizing heat pumps, i. e 0.5%–23.9% of the total UK electricity demand in 2019 [57], which is in itself a challenge to grid supply balance and grid decarbonisation in the UK [58].

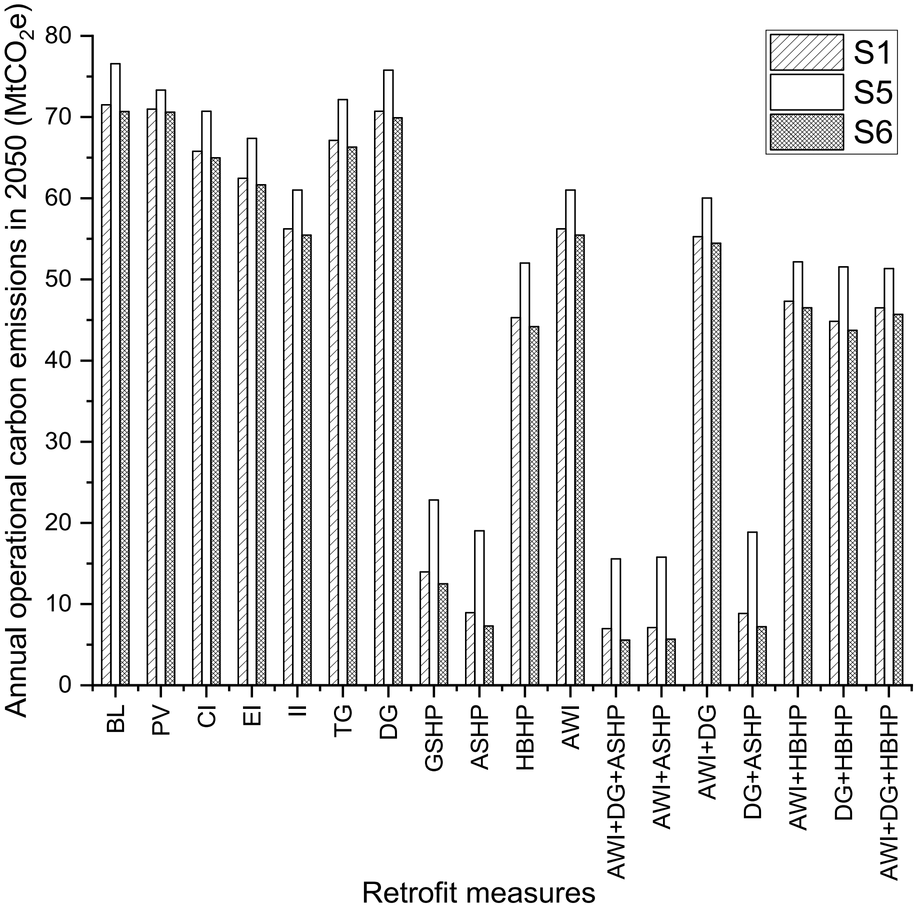

Fig. 6. Operational carbon emissions in 2050 (one year) for different grid decarbonisation and retrofit scenarios.

3.4. Limitations

The embodied carbon calculated here covers only cradle-to-site (A1-A3) unless otherwise specified. This means our embodied carbon estimates, while low, do not include the emissions associated with the construction process stage (A4-A5), use stage (B1–B7), and end of life stage (C1–C4) of the retrofit interventions [59]. Moreover, we have not considered circumstances under which retrofit interventions might require replacement during the 30-year study period of 2021–2050. Depending on the working environment and the service life of the specific retrofit materials and PV modules used, they may need to be replaced. The embodied carbon emissions of retrofit materials and PV modules in this study are, as such, likely to be underestimated.

During the NHM simulations, fixed regionally specific weather profiles were used to calculate the annual energy consumption of the English housing stock without considering the potential impacts of climate change. The monthly climatic conditions are taken from the SAP2012 (Appendix U) regional values and were considered not to change from year to year. With the progress of global warming, the residential energy consumption structure will switch from space heating to space cooling, leading to higher space cooling loads and lower space heating loads compared to SAP2012 weather data. We have utilized a constant annual operational energy consumption for 30 years, although the energy saving efficiency of retrofit interventions tends to decrease over time due to factors such as system degradation and occupant behaviour [60]. These would potentially lead to stricter requirements for building retrofit carbon efficiency in order to meet the carbon budgets.

The NHM model also makes in-built assumptions regarding the types of PV modules which result in an electricity generation efficiency of 20%. In reality, the efficiency of different modules as deployed may differ, with the efficiencies of monocrystalline, polycrystalline and thin-film PV panels ranging between 10% and 22% [61]. The embodied carbon emissions of the PV retrofit scenario is likely to be underestimated as we only accounted for PV modules, while a house-integrated PV system have other components, such as invertor and batteries.

For all retrofit scenarios including wall insulation measures, a U-value of 0.1 W/(m^2•K) is assumed to have been achieved after retrofit, which as stated in section 2.2 is stricter compared to the current standard requirement. Such low U-values may not be feasible to achieve due to their high cost and the space they would physically require to be installed. This would lead to a higher post retrofit U-value and a smaller operational carbon reduction compared to our estimates.

The above-mentioned limitations are likely to result in an underestimation of whole life carbon emissions of the building stock, which in turn makes meeting the carbon targets even more challenging in practice. As the results of the study show, even immediate residential stock retrofit deployment requires combined retrofit actions to meet carbon budgets. The retrofit challenge will increase exponentially with delays in deployment.

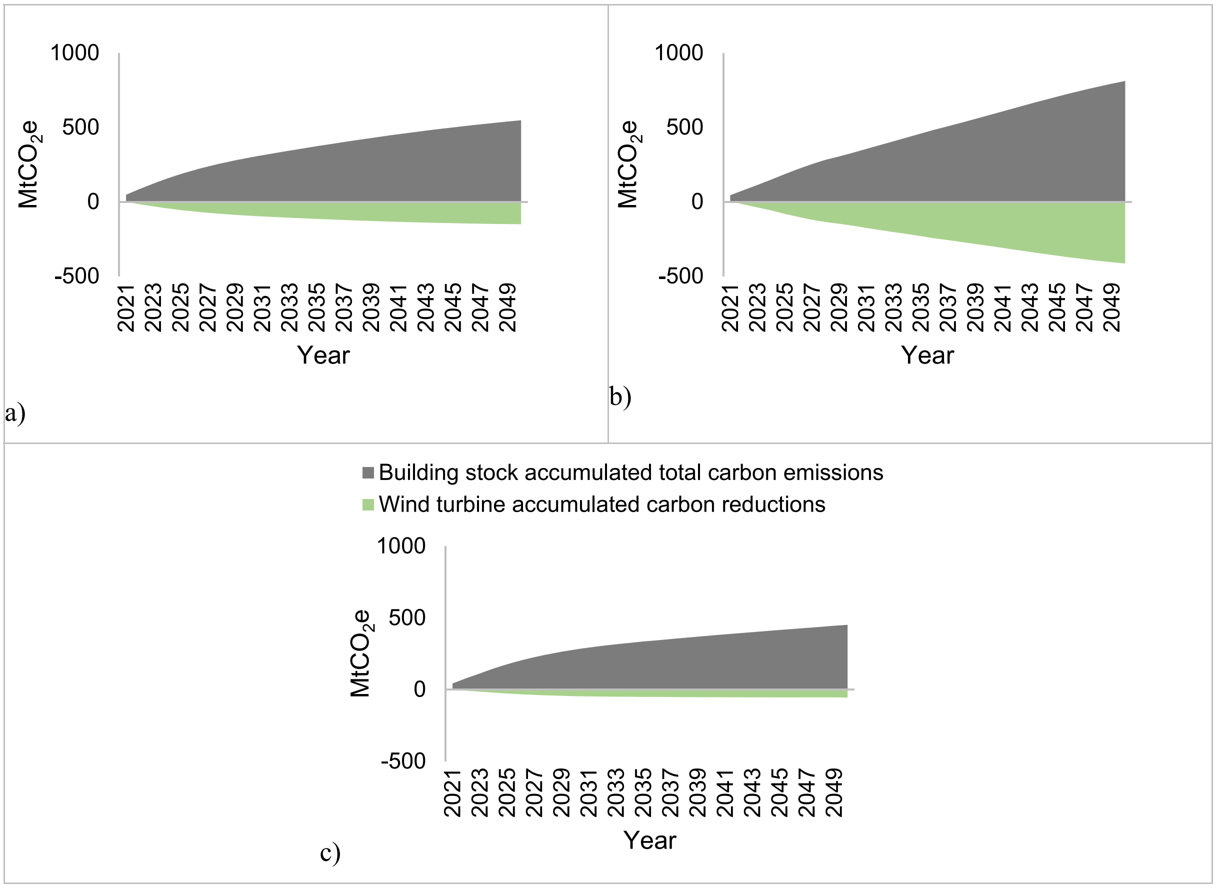

Fig. 7. The carbon emissions from English house stock after DG + ASHP retrofit and carbon reduction from wind turbines between 2021 and 2050 under S1 (a), S5 (b) and S6 (c)– the accumulated carbon reduction from wind turbines are assigned with negative values to offset the accumulated carbon emissions from the stock.

Finally, the carbon budget projection in this study is based on the historical proportions of carbon emissions from residential stock. Depending on the difficulty of carbon reduction in different sectors, the carbon budget assigned to residential stock might be higher or lower than what is estimated here.

4. Conclusions and policy implications

By combining the operational carbon calculated and cradle-to-gate embodied carbon of retrofit materials and systems in this study, we have investigated the whole-life carbon performance of retrofit measures in the whole English house stock. The results are compared with carbon targets to support retrofit policy making in achieving net zero emissions without overspending the emissions budget. At our current emissions rate, we have shown England's homes to have produced somewhere over 2200 MtCO$_2$e by 2050. This leads to surpassing the CCC and Tyndall carbon budget by over 1100 MtCO$_2$e and over 1800 MtCO$_2$e respectively under S1, S5 and S6. We have also shown that even under large-scale residential retrofit scenarios, total emissions consistently overshoot the 2050 carbon budget, except for those aggressively deploying heat pumps and thus electrifying heating. Given our implicit assumption that all retrofit measures have already been implemented at the start of 2021, the following policy recommendations are critical to achieve net zero by 2050 within the residential sector:

1. Rapidly increased heat pump deployment, without the current planned delays until 2028. Given nearly 20 million homes in England alone are eligible for heat-pumps, installing at the pace of current targets, i.e., achieving a deployment rate of only 600 thousand heat pumps annually by 2028, will require an additional 25 years after 2028 before every home is converted.
2. Carefully select materials to retrofit building envelopes to drive down the embodied carbon emissions from retrofit, whilst reducing the heating demand to maintain a comfortable indoor environment. Thus, leading to less electricity consumption during operation and lower electricity bills for heating when switched to heat pump systems.
3 Current targets for offshore wind are insufficient to achieve net zero carbon by 2050 and need to be made more ambitious. Our estimates suggest deployment of over 11 thousand additional 2 MW wind turbines in the beginning of 2021 is required in tandem with the nationwide installation of heat pumps and double glazing in order to meet the Tyndall carbon budget for the English house stock.

Measures 1 and 2 need to be deployed across all homes, creating challenges in financing, and incentivising what can be disruptive retrofits. Thus, there is a need to increase awareness about the potential energy/carbon/cost savings, from residential retrofit, in addition to the thermal comfort benefits. Attractive financing options will need to be provided to enable all homeowners to undertake retrofits given their key role in delivering widespread decarbonisation, and these need to be made available near immediately given the pace of change we have shown is required to meet carbon budgets. Measure 3 is in some respects simpler in that it is not at the mercy of millions of individual homeowners, but the need is no less urgent and requires significant government investment and leadership.

Credit author statement

Li, X: Methodology, Investigation, Writing – original draft, Writing – review & editing.; **Arbabi, H**: Methodology, Investigation, Writing – original draft, Writing – review & editing.; **Bennett, G**: Methodology, Investigation, Writing – original draft.; **Oreszczyn, T**: Conceptualization, Methodology, Writing – review & editing.; **Densley Tingley, D.**: Conceptualization, Methodology, Writing – review & editing.

Data accessibility

The data used for the analysis presented in this paper is available at the online supplementary materials for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112384.

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