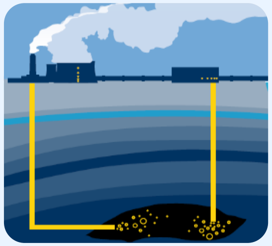

Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets

A study for the
Committee on Climate Change

Final Report (Version 3.4)
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Introduction

The Committee on Climate Change (CCC) have commissioned Element Energy and University College London (UCL) to carry out research on the distribution and characteristics of homes considered 'hard to decarbonise', with regards to possible treatment packages and evidence-based trajectories for decarbonisation. The resulting analysis will be used to inform the CCC's advice to Government on UK climate action, particularly on the date by which the UK can feasibly achieve net zero carbon emissions.

Specific aims of the project were to:

1. *Assess the most cost-effective and appropriate decarbonisation options for the various segments of the hard-to-decarbonise housing stock*
2. *Provide a profile of measure deployment for 'hard to decarbonise' homes that can feed into the CCC's modelling to update the Fifth Carbon Budget (5CB) 'Max' scenario to 2050*

The focus of this analysis is on emissions from **space heating and hot water** demand in **existing buildings** across the UK stock. The CCC undertook separate analysis on heat in new homes, and emissions associated with cooking, lighting and appliance use.

Overview of approach

1. **Develop UK stock model** capturing incidence and coincidence of hard to decarbonise features
2. **Apply packages of energy efficiency measures and low carbon heating systems** based on suitability
3. **Calculate cost effectiveness and carbon savings** of applied measures
4. **Define scenarios for deployment of technologies and packages** across housing stock

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Summary of approach

➢ ***The existing UK domestic building stock has been profiled according to 'hard to decarbonise' features***

The stock was divided into categories according to the primary features identified to constrain the feasibility of deploying energy efficiency measures and/or low carbon heating in these homes:

- **Suitable for DH** contains all homes expected to be suitable for connection to district heating (DH) networks (19%);
- **Heritage** contains all listed buildings and homes in conservation areas not considered suitable for DH (3%);
- **Off gas** contains all non-heritage homes not connected to the gas grid that are not suitable for DH (9%);
- **On gas, space constrained** contains all on gas homes that are non-heritage and not suitable for DH but that are considered to have restrictions on installing efficiency measures or low carbon heating technologies with relatively high space requirements (13%);
- **On gas, no constraints** contains all remaining on gas homes that do not have the above constraints and are not considered suitable for DH (56%).

➢ ***Energy efficiency packages and low carbon heating technologies were applied across the UK stock***

- **Three packages of energy efficiency measures were developed** (Low, Medium and High) that correlate with increasing levels of cost and disruption, and increasing target energy demand reduction (25%, 40% and highest achievable, respectively). Modelled energy efficiency measures included loft insulation (all packages), wall insulation (medium and deep packages), secondary glazing (medium package), double glazing (deep package), and floor insulation (deep package). Ventilation strategies and shading were also included where appropriate to model best practice in addressing potential unintended consequences of retrofit.
- **A range of low carbon technology options were modelled**, including heat pumps (air source, ground source and hybrids), electric heating (resistive and storage heating), district heating, and communal heating (using a shared air source heat pump). Hydrogen and biofuels (in off gas homes) were only used to decarbonise residual fossil fuels in hybrid heat pumps. Additional enabling technologies including solar thermal arrays, small heat batteries and thermal storage for space heating were also modelled.

➢ ***Three decarbonisation scenarios were developed that reflect increasing levels of ambition***

Cost-effective[1] deployment of energy efficiency and low carbon technology was modelled across the UK stock in three scenarios:

- **Core** contains low-cost, low-regret options that align with most strategies to meet the current 2050 target of an 80% reduction in emissions versus 1990. Decarbonisation of gas with hydrogen was not included.
- **Further Ambition** contains all of the options in Core but with the addition of some more challenging and/or more expensive options which are likely to be needed to meet a net-zero target, including decarbonisation of gas with hydrogen.
- **Speculative** includes all of the options in Core and Further Ambition with the addition of options that currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability. A cost threshold was set so that the 10% most costly homes were treated in Speculative.

[1] The combination of energy efficiency package and low carbon heating technology with lowest cost of abatement (£/tCO_2e) was chosen for each building archetype based on annualised cost, emissions savings and technical feasibility criteria

Central case: 95% of direct emissions from existing buildings can be abated by 2050 under the Further Ambition scenario

The **Central** case represents a mix of energy efficiency measures and heating technologies that can feasibly achieve high levels of decarbonisation across the existing UK domestic stock, based upon low reliance on technologies with high non-cost barriers and assumptions of an ambitious but plausible policy environment.

Stock addressed and emissions abatement by scenario

				Direct emissions abatement[†]		Total emissions abatement[†]			
	Existing stock addressed (millions)	Existing stock addressed (%)	Date by which all measures received	$MtCO_2e$	%	$MtCO_2e$	%	Total cost (£m/y)	Average cost effectiveness (£/tCO_2)
Core	22.5	80%	2050	55.7	74%	54.4	72%	9,466	£174
Further Ambition	28.2*	100%	2050	71.8	95%	69.7	92%	13,304	£191
Speculative	28.2*	100%	2060	75.4	100%	73.2	97%	15,299	£209

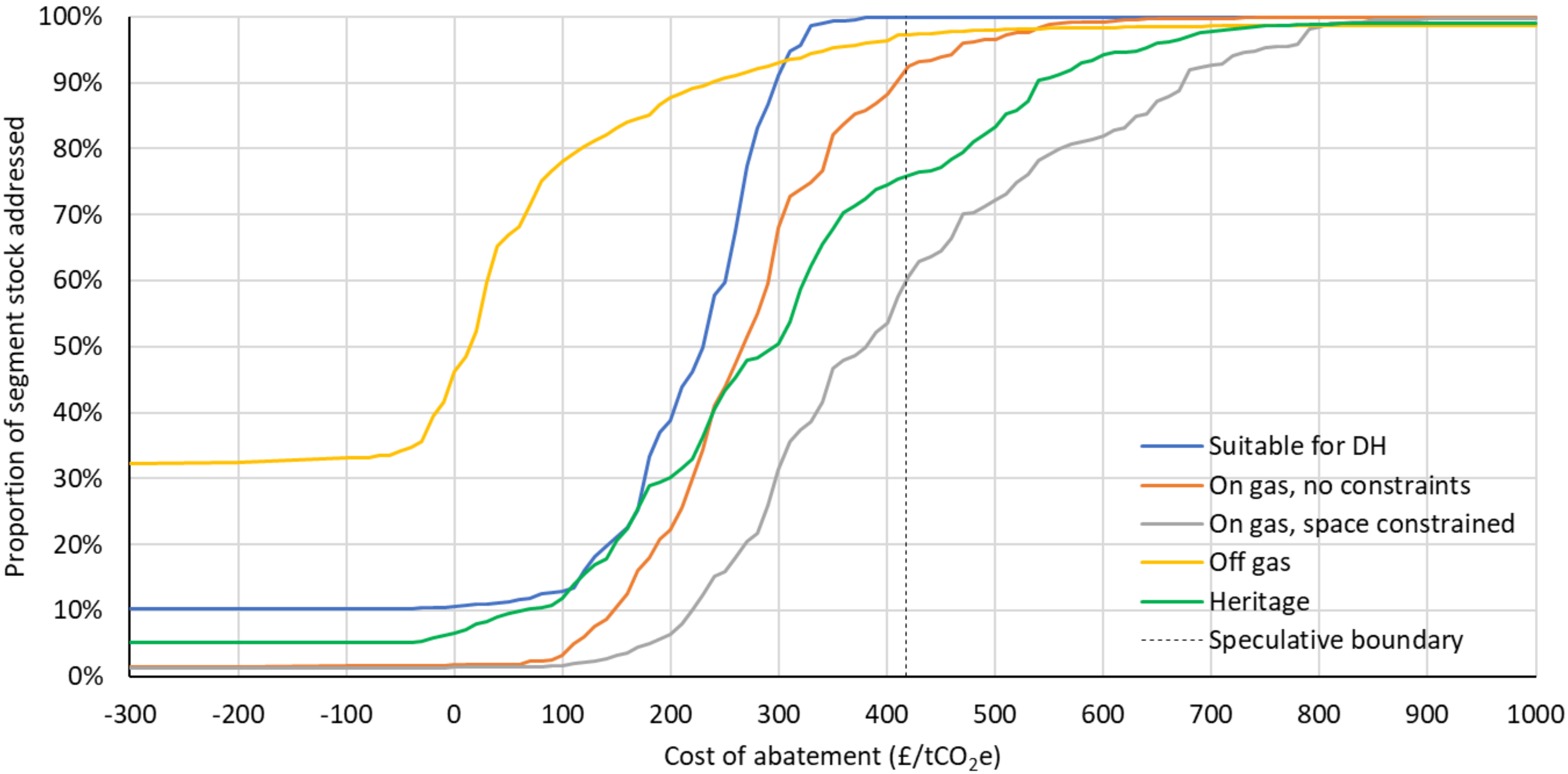
[†] The % emissions abatement given refers to the proportion of baseline emissions avoided in each scenario

*The Further Ambition scenario includes the installation of energy efficiency measures in all homes where part of a cost optimal decarbonisation package. Speculative involves the additional deployment of low carbon heating only in the 10% most costly homes

- 90% of the existing UK stock can be decarbonised with a cost of abatement of under £418/tCO_2e
- Measures are most cost-effective in Off gas homes, where the average abatement cost is negative (-£15/tCO_2e in Speculative). This is due to the high cost of running the counterfactual heating systems and the high emissions savings that are possible in these homes.
- Space constrained homes are the most costly group to decarbonise, with a weighted average abatement cost of £380/tCO_2e in Speculative
- The Devolved Administrations account for 17% of the direct and total emissions abatement in all scenarios, in-line with the proportion of baseline total emissions from each region
- Measures in Northern Ireland have a significantly lower than average cost of abatement (£70/tCO_2e), reflecting the larger proportion of off gas homes in this region

Central case: The abatement cost curves for each stock segment reflects the differing constraints experienced by these homes

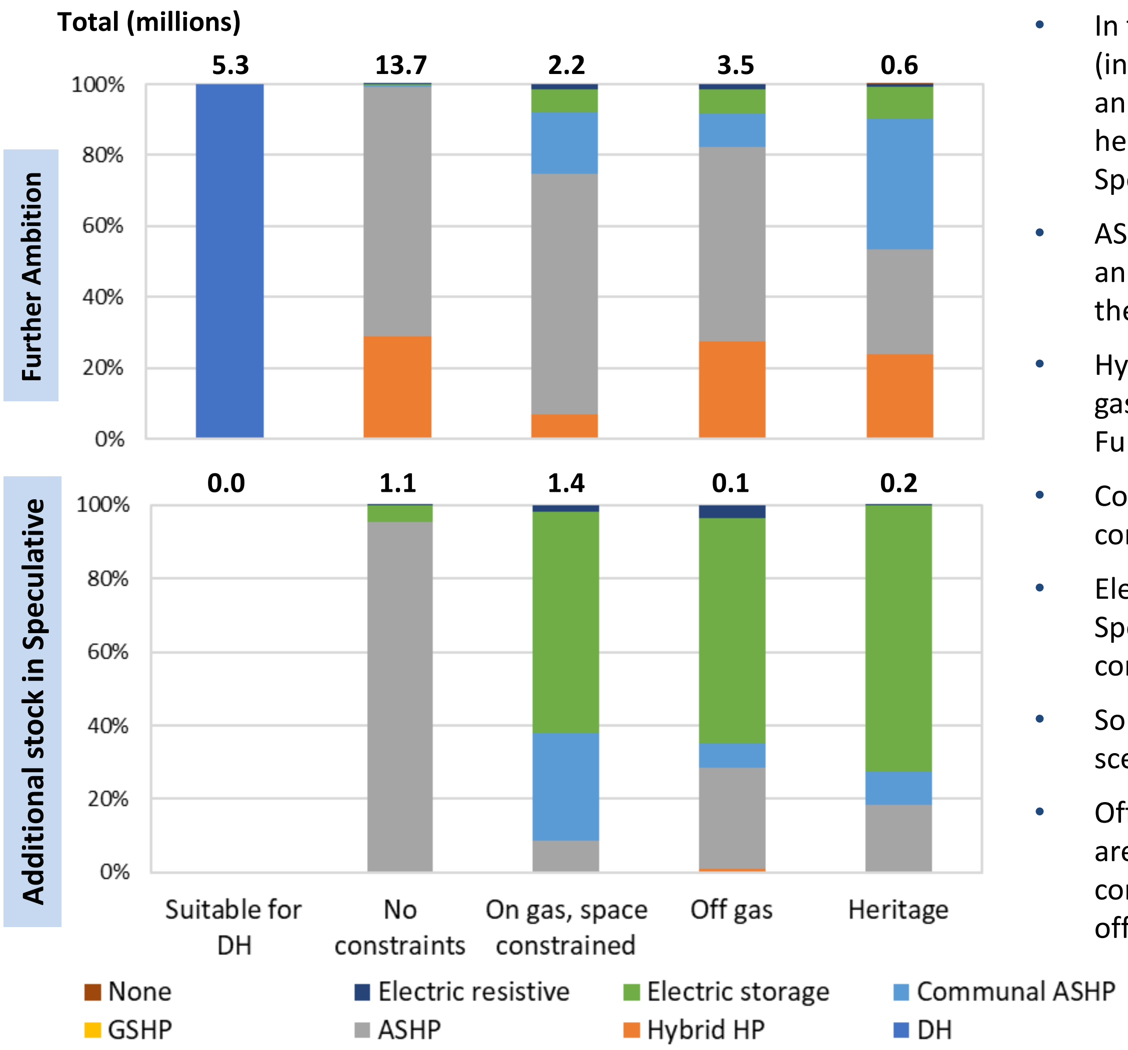
- Stock segments with some off gas homes (including Off gas, Suitable for DH and Heritage) have the highest proportions of stock that can be addressed with negative abatement costs, and the lowest median abatement cost, due to the relatively high cost of the counterfactual in those homes[1]
- The most constrained homes (Heritage and On gas, space constrained) have the largest share of homes with high abatement cost, due to non-suitability for the lower cost low carbon heating options, and/or the higher cost of some technologies in heritage homes



[1] It is noted that the proportion of stock with negative abatement cost does not scale with the proportion of off gas homes in the stock segment, reflecting the more complex interactions between cost and technical feasibility in each segment

Central case: Heat pumps (including hybrids) make up 75% of the heating technologies deployed across the existing stock

Heating systems deployed by stock segment

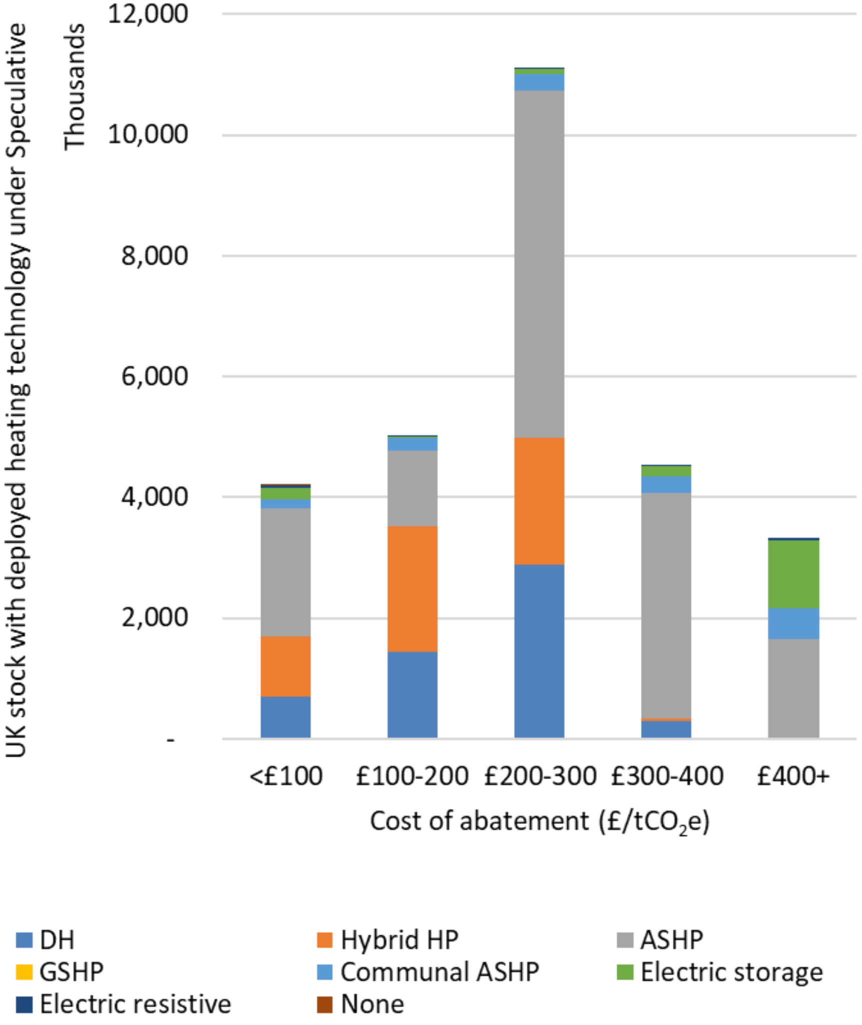


- In the Further Ambition scenario, 18.5m heat pumps (including hybrids) are deployed in existing homes with an additional 1m communal ASHPs. This rises to 19.7m heat pumps and 1.4m homes with communal ASHPs in Speculative.
- ASHPs are the most deployed system at building-level, and are found across all non-DH segments[1] and in both the Further Ambition and Speculative scenarios
- Hybrid heat pumps are taken up across the on and off gas stock, and almost all are deployed under Core and Further Ambition (reflecting the lower cost of hybrids)
- Communal heating is primarily deployed in space constrained homes and heritage homes
- Electric heating options feature most strongly in the Speculative scenario, in homes with some form of constraint
- Solar thermal is available, but not taken up in this scenario
- Off gas hybrid heat pumps and electric heating solutions are overrepresented in all Devolved Administrations compared to the UK stock, in line with the proportion of off gas homes in these regions.

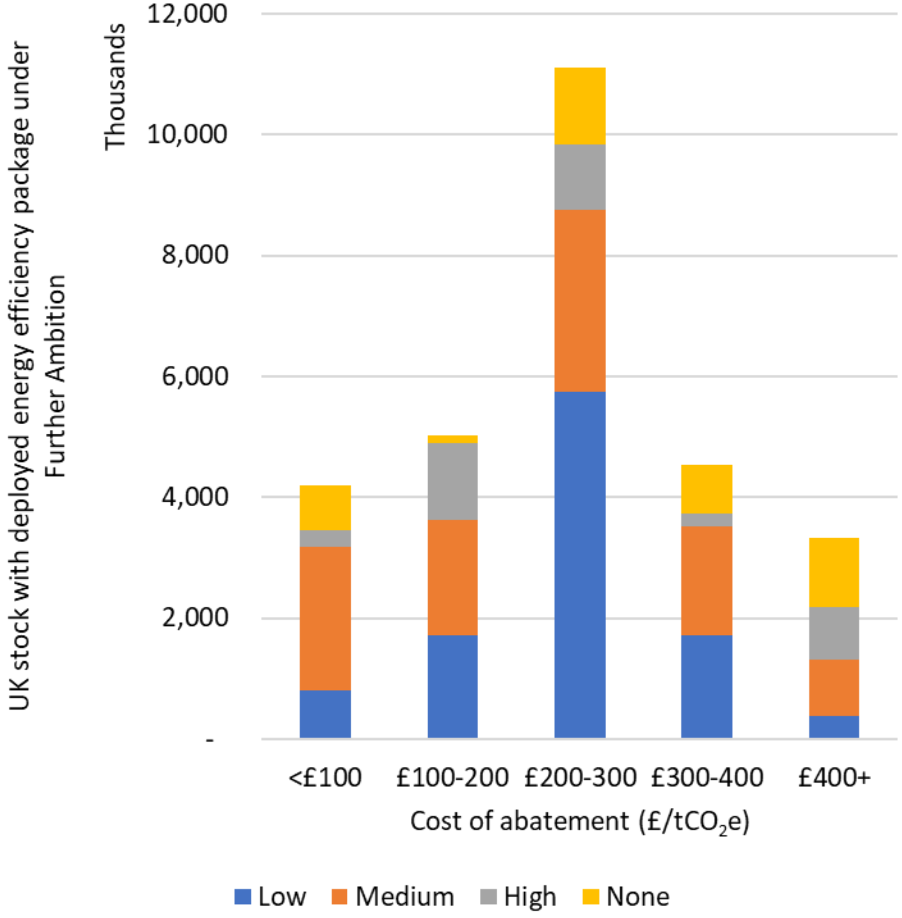
[1] DH also employs heat pumps at a network level

Central: Breakdown of heating technology and energy efficiency package by cost of abatement

Heating technologies by cost effectiveness band



Energy efficiency packages by cost effectiveness band



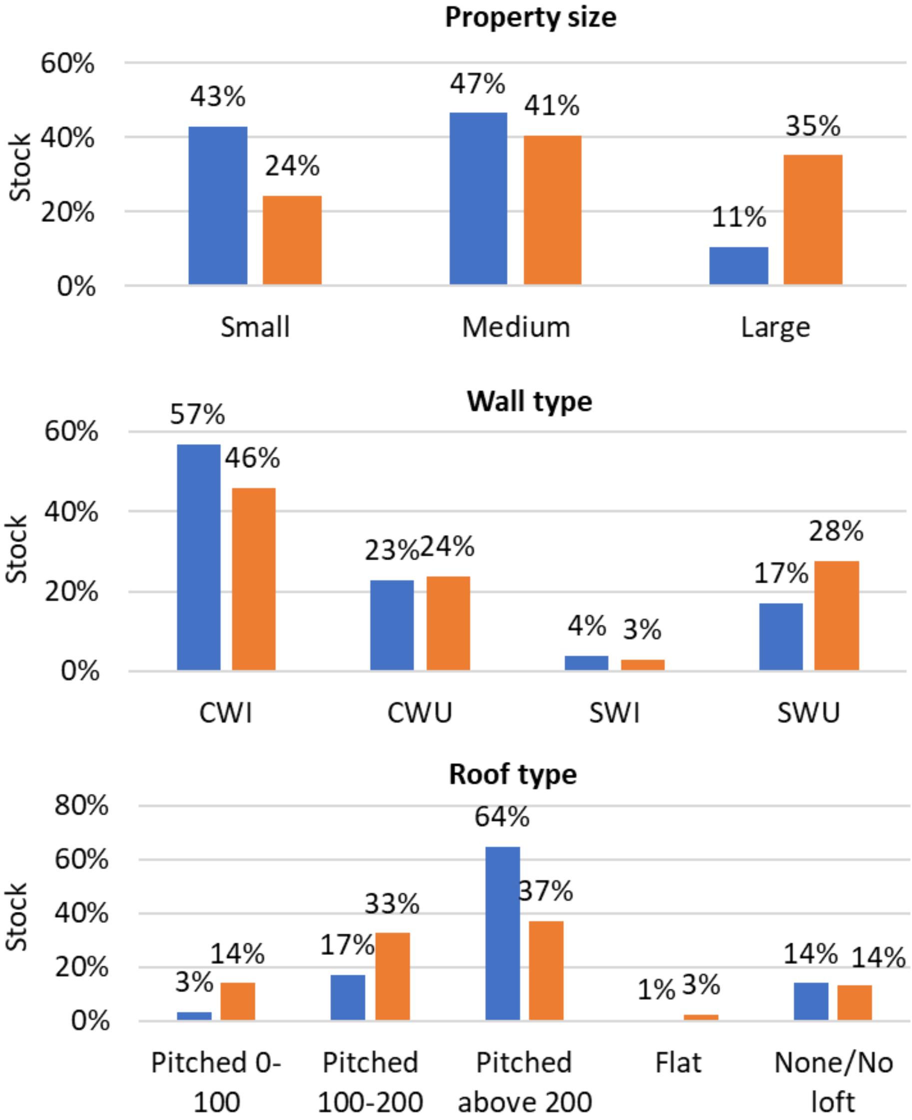
Central case: Nearly 5 million cavity walls, 5 million solid walls and more than 17 million loft top-up measures are deployed

Energy efficiency deployment by scenario

Number deployed (millions)	Core	Further Ambition
Measure		
Loft	17.4	21.4
Cavity wall	4.8	5.7
Solid wall	4.9	5.8
Floor	2.4	3.4
Package		
None	2.4	4.1
Low	8.8	10.4
Medium	8.3	10.0
High	2.6	3.7
Energy demand savings (TWh/y)	78	92
Total heat demand in 2017 (TWh/yr)	365	
Total heat demand in 2050 (TWh/yr)	287	273
Reduction in heat demand as a result of energy efficiency	21%	25%

- Energy efficiency measures account for a 25% reduction in energy demand in Further Ambition.
- At least one measure is installed in 70% of the existing UK stock in the Core scenario, increasing to 85% in Further Ambition.
- Of the solid wall measures, 1 million are in fuel poor homes, which addresses 96% of the potential
- Cavity wall installations address essentially all of the remaining potential in the stock.
- Less than 20% of the estimated potential for floor insulation is addressed, reflecting the relatively low uptake of the High efficiency package (3.7 million High packages including 3.4 million floors).
- Homes in which no efficiency package is taken up are largely those with no remaining potential for wall and loft insulation.
- Higher proportions of Welsh homes receive energy efficiency measures than other devolved administrations, reflecting the lower current levels of insulation measures among homes in Wales

Central case: Majority of the most costly homes to decarbonise are small, energy efficient homes where heating systems have a higher cost per unit of heat supplied



- This analysis shows that homes traditionally thought of as ‘hard to decarbonise’ do not make up the majority of the most costly homes in terms of cost of abatement[1]
- The most costly 10% of homes (with an average cost of abatement of above £418/tCO_2e) are primarily **small or medium** properties, with **insulated** walls and roofs
- That the most efficient homes are the most costly to treat reflects the trade off between the high absolute cost of low carbon heating relative to the resulting carbon abated:
    - Homes with small heat demand have a smaller potential for carbon abatement than homes with larger heat demand
    - The capital cost of the installed heating system per unit of heat delivered is higher for homes with a small heat demand than it is for homes with a high heat demand
    - As a result, **small and/or highly efficient homes tend to have a higher abatement cost**, and are over-represented in Speculative

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[1] Although it should be noted that such homes may experience high absolute (upfront) costs

Alternative cases were modelled to explore the impact of either high or low decarbonisation of gas (Hydrogen-led and No hydrogen, respectively)

					Direct emissions abatement		Total emissions abatement			
		Stock addressed (millions)	Stock addressed (%)	Date by which all measures received	$MtCO_2e$	%	$MtCO_2e$	%	Total cost (£m/y)	Average cost effectiveness (£/tCO_2)
Central	Core	22.5	80%	2050	55.7	74%	54.4	72%	£9,466	£174
	Further Ambition	28.2*	100%	2050	71.8	95%	69.7	92%	£13,304	£191
	Speculative	28.2*	100%	2060	75.4	100%	73.2	97%	£15,299	£209
No hydrogen	Core	22.4	79%	2050	62.5	83%	61.1	81%	£11,167	£183
	Further Ambition	28.2*	100%	2050	71.7	95%	70.0	92%	£13,833	£198
	Speculative	28.2*	100%	2060	75.4	100%	73.5	97%	£15,910	£216
Hydrogen -led	Core	9.9	35%	2050	24.5	32%	24.3	32%	£2,247	*£93***
	Further Ambition	28.2*	100%	2050	72.0	96%	69.5	92%	£11,485	*£165***
	Speculative	28.2*	100%	2060	75.4	100%	72.6	96%	£12,617	*£174***

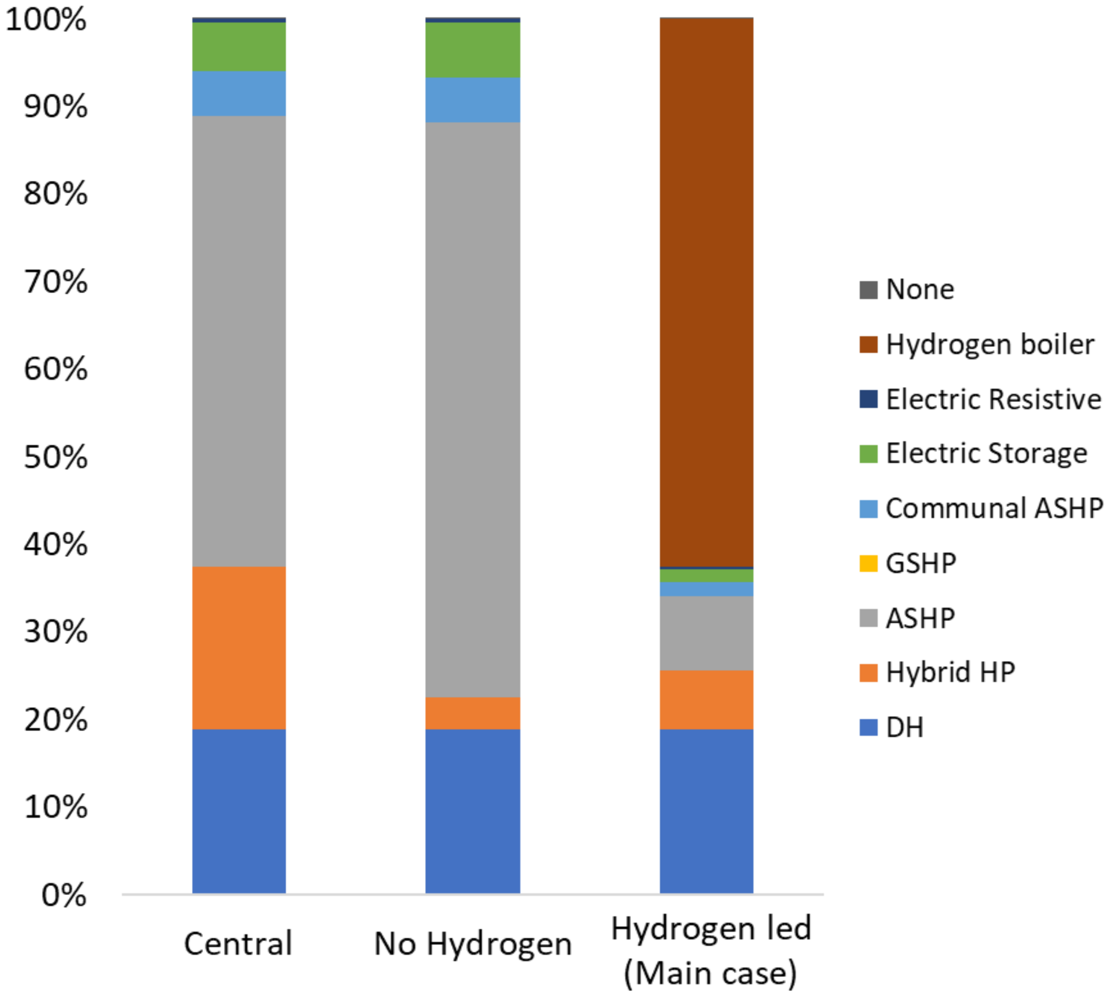
* The Further Ambition scenario includes the installation of energy efficiency measures in all homes where part of a cost optimal decarbonisation package. Speculative involves the additional deployment of low carbon heating only in the 10% most costly homes

- The No hydrogen scenario achieves higher direct and total emissions abatement in Core than Central, due to the removal of gas options from grid-connected homes (since the conversion from gas to hydrogen of homes in Core is only implemented in Further Ambition) – however, this is achieved at a slightly higher cost of abatement.
- The Hydrogen-led scenario, in which hydrogen boilers are allowed, achieves a much lower level of abatement in the Core scenario (since the conversion from gas to hydrogen of homes in Core occurs in Further Ambition) but achieves a similar emissions abatement in Further Ambition and Speculative at a lower cost of abatement than the Central scenario. ****It is important to note that the hydrogen fuel cost applied does not include the cost of large-scale hydrogen storage (such as in salt caverns). In the Hydrogen-led scenario, where hydrogen plays a large role in supplying heat in buildings, this means the costs are likely to be an underestimate. Previous modelling for the CCC by Imperial College suggested that 20TWh of hydrogen storage could be needed to meet peak demand in a winter week in a hydrogen-led scenario, which could add up £6400m/year in costs. Significant uncertainty remains over the costs and required volumes of hydrogen storage.** The CCC's *Hydrogen in a low-carbon economy* report notes that around 90% of this cost is oversizing hydrogen production capacity to provide instantaneous dispatch of large volumes of hydrogen and that alternative approaches to storage could lead to significant cost reductions.
- More generally it should be noted that fuel cost assumptions across scenarios incorporate high-level assumptions on system costs. These remain uncertain and in reality will depend on the scenario and vary as a function of deployment.

Hydrogen in a low-carbon economy, Committee on Climate Change (November 2018); Analysis of Alternative UK Heat Decarbonisation Pathways, Imperial College London (August 2018)

The balance of gas-based technologies (hybrids and hydrogen boilers) and heat pumps varies significantly with the availability of hydrogen

Heating technology mix, Speculative scenario (all stock)



- In the **No hydrogen** option, the deployment of hybrid heat pumps is limited to the off-gas stock, with mainly ASHPs taking the place of hybrids in on gas homes
- In total 18.3m heat pumps are deployed in Further Ambition (19.5m in Speculative) but only 1m are hybrids
- In the **Hydrogen-led** scenario, hydrogen boilers are the mostly widely deployed heating system, covering 63% of the stock (17.6m homes), with heat pumps (including hybrids) taken up in 17% of the stock (4.7m homes).
- The deployment of electric storage heating also falls significantly relative to the Central case.
- This suggests that hydrogen boilers have potential to offer a reduced cost route for decarbonisation for some of the most expensive segments of the stock.

The level of energy efficiency deployment correlates with the deployment of low flow temperature heating systems (heat pumps)

Energy efficiency deployment by scenario

- The table below presents the energy efficiency deployment in existing homes[1].

	No hydrogen		Hydrogen-led		Central	
	Core	Further Ambition	Core	Further Ambition	Core	Further Ambition
Measure						
Loft	18.5	23.5	14.0	19.4	17.4	21.4
Cavity wall	5.2	6.6	4.5	5.3	4.8	5.7
Solid wall	6.2	7.4	4.0	5.8	4.9	5.8
Floor	3.5	4.8	2.2	2.3	2.4	3.4
Package						
None	1.4	1.8	1.9	6.4	2.4	4.1
Low	7.7	9.2	6.5	9.6	8.8	10.4
Medium	9.5	12.1	6.8	9.6	8.3	10.0
High	3.8	5.1	2.5	2.6	2.6	3.7
Energy demand savings (TWh/y)	92	110	76	87	78	92
Total heat demand in 2017 (TWh/yr)	365		365		365	
Total heat demand in 2050 (TWh/yr)	273	255	289	278	287	273
Reduction in emissions through energy efficiency	25%	30%	21%	24%	21%	25%

- A higher level of energy efficiency is taken up in the No hydrogen case, correlated with a higher uptake of low temperature heating systems (ASHP); conversely, a lower uptake of energy efficiency is seen in the Hydrogen-led case

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[1] The CCC separately modelled efficiency in new homes, assuming space heating demand of 15 kWh/m^2/yr from 2025.

Sensitivity analysis was carried out for the Central scenario on seven key model assumptions

Sensitivity	Description
High cost of capital	• Cost of capital is increased to 7.5% (from 3.5% in the Central scenario)
High electricity cost	• On peak and off peak electricity costs are increased by 5.3%, in-line with the difference between the Central and High long-run variable costs for electricity for 2050 given in supporting Table 9 of the HMT Green Book supplementary appraisal guidance[1]
Low energy efficiency	• No application of the 3.25 million additional Medium efficiency packages as applied in the Central scenario to reflect wider benefits of efficiency • Loft insulation is only applied in homes with less than or equal to 200 mm loft insulation present (no low impact top-ups)
Space constraints variation	• The proportion of homes considered to be space constrained is increased to include homes with dwelling floor area per habitable room of up to 18 m^2 (38% of homes)
Low hybrid HP opex	• Reduce Hybrid HP opex by £50/yr relative to the Central scenario • This aligns the opex of natural gas Hybrid HPs with ASHPs at around £100/yr and so assumes no increase in maintenance cost associated with a heat pump and boiler, relative to a heat pump only • Note that a hydrogen Hybrid HP has an additional opex element of £37.50/yr associated with replacement of a catalyst to reduce NOx emissions such that the opex of hydrogen Hybrid HPs is £137.50/yr
Low hybrid HP opex and reduced capex	• As per Low hybrid HP opex above • Additionally, the £500 capex associated with replacement of internal pipework as a result of the conversion of natural gas to hydrogen is removed
Heritage – high costs	• Higher cost uplifts applied to energy efficiency measures and some heating system elements in heritage buildings

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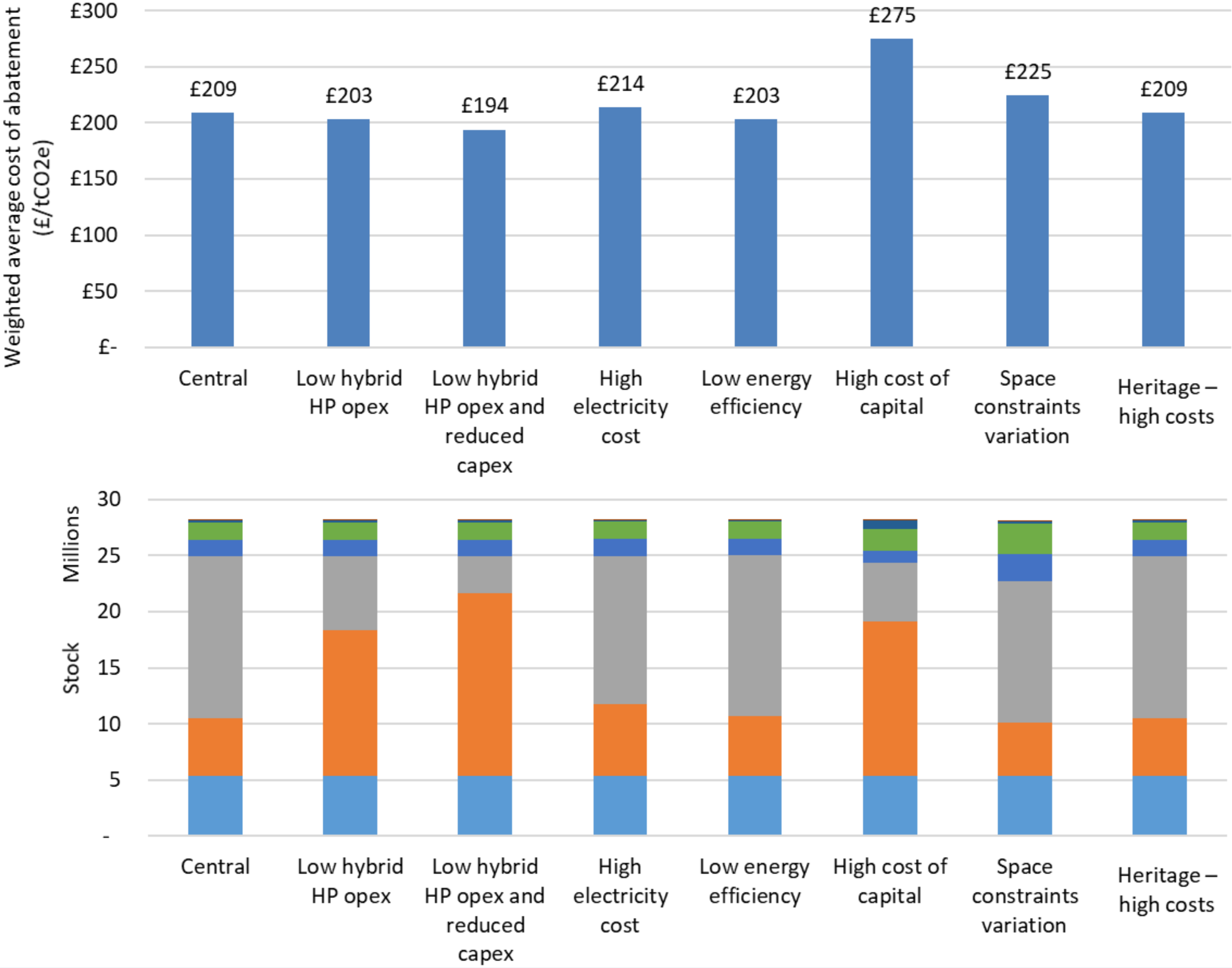
[1] Department for Business, Energy & Industrial Strategy, *Data tables supporting the Treasury Green Book supplementary appraisal guidance on valuing energy use and greenhouse gas (GHG) emissions* (December 2017)

The cost of capital has the largest affect on cost and technology mix, with technology opex and capex also affecting technology mix



- The average abatement cost across the whole UK stock is only significantly affected by the cost of capital
- However, the average cost of abatement for the Heritage segment in the 'Heritage – high costs and constraints' case is increased by 12% relative to Central.
- A greater number of hybrids are deployed in the sensitivity with higher cost of capital, and the sensitivity with reduced hybrid heat pump technology costs

Summary of overarching recommendations for achieving the level of decarbonisation seen in the Central scenarios

Policy recommendations

Overarching

1. **Develop a comprehensive strategy for heat decarbonisation in the UK**, covering energy efficiency and low carbon heating, and including a timeline for decisions on the long term pathway for the UK and the role of electricity, gas and heat networks, as well as bioenergy.
2. **Develop and trial a range of incentives and support mechanisms to replace the RHI**, targeting different segments, consumer groups and technologies, to 'level the playing field' and create a large-scale market for low carbon heating.
3. **Adopt mandatory energy and carbon emissions standards for existing homes**, enforceable at trigger points such as sale and rental (and consider additional trigger points such as renovations requiring planning permission).
4. **Update the energy efficiency policy framework by strengthening the Energy Company Obligation (ECO) and/or implementing additional regulated schemes** to encourage uptake of efficiency across all segments of the stock.
5. **Provide financial assistance, such as low or zero interest loans, and financial incentives** to reduce the upfront cost of retrofits to households (including those targeted particularly at the fuel poor segment).
6. **Design incentives and guidance to encourage whole-house retrofits** combining energy efficiency and low carbon heating, taking advantage of appropriate trigger points such as major renovations, purchase, new tenancies and others.
7. **Support the development of innovative business models** to make energy efficiency and low carbon heat more attractive to consumers.
8. **Provide tailored advice and support** to households on appropriate energy efficiency and low carbon heating measures, on the incentives and other support available, how to access financial assistance and how to identify certified suppliers.
9. Update the **Private Rented Sector (PRS) regulation** to address this sector, with accompanying support (such as low or zero interest loans, replacing the end of Green Deal support) to ensure no adverse impact on tenants and the rental market.
10. Ensure energy standards (and in future carbon emissions standards) in the **Social rented sector** are appropriately set, and that this sector is able to access financial assistance where appropriate.

Summary of technology/segment-specific recommendations for achieving the level of decarbonisation seen in the Central scenarios (1)

Energy efficiency

11. **Undertake research** to better understand the ‘performance gap’ between predicted and observed energy reductions following retrofit, and take action to close it through higher industry standards

District heating

12. **Continue to provide financial support for low carbon district heating** beyond the end of the period of support via the current Heat Network Investment Project (HNIP) and Renewable Heat Incentive (RHI) (both due to end in 2021).
13. **Use local planning policy** to drive connection to district heating where appropriate.
14. **Provide incentives and/or requirements for sources of waste heat** to be available to heat networks.
15. **Develop competition policy** to protect consumers from issues of natural monopolies.

Off gas homes

16. **Develop policy** to deliver decarbonisation of off gas homes at scale during the 2020s, with a focus on achieving rollout of heat pumps and hybrid heat pumps, as well as heat networks and communal heat pump systems where cost-effective.

Heritage homes

17. **Undertake further research** to better understand the additional challenges and costs of retrofit to heritage homes, and the number and type of homes to which these issues are likely to apply.
18. **Develop the skills base** required to deliver the low carbon retrofit solutions to this segment
19. Consider the ways in which **planning or building consent** represent barriers to decarbonisation

Space constrained homes

20. **Undertake further research to better understand the physical and consumer preference factors** contributing to space constraints, to better characterise this segment of the stock and what solutions will be required to address this issue.
21. **Consider the need for innovation funding to support the development of space saving technologies** such as thin internal solid wall insulation, low temperature heat batteries, low carbon heating systems with innovative space saving designs, small area emitters and other approaches to addressing this constraint.

Summary of technology/segment-specific recommendations for achieving the level of decarbonisation seen in the Central scenarios (2)

Electrification of heat

22. **Ensure deployment at scale of heat pump and hybrid heat pump** technologies can occur as soon as possible in the 2020s to develop a large and skilled supply chain for these technologies in the UK.
23. **Adopt high quality standards for design and installation, and ensure support is available to help the industry meet those standards,** to grow the skills base and supply chain in the UK to facilitate market growth.

Decarbonisation of gas

24. **Continue support and innovation funding for large-scale demonstrations** of hydrogen production.
25. As part of this, **support the development of carbon capture and storage (CCS)** as a key enabler of large-scale production of low carbon hydrogen ('blue' hydrogen).
26. Similarly, **support the development of 'Hyready' boilers**, capable of running on natural gas and hydrogen (with minor modifications), as a potentially cost-effective approach to converting homes to hydrogen.

Contents

Homes can be considered to be ‘hard to decarbonise’ if they are ‘hard to treat’ and/or do not have cost-effective options of low carbon heating (1/2)

Summary of attributes identified in the literature that contribute to a home being ‘hard to decarbonise’[1 – 4]

Physical building attributes	**Wall type**	Solid walls	• Hard to treat wall types do not have low-cost cavity wall insulation options available and/or pose technical difficulties or risks of poor performance • Hard to fill cavities risk poor distribution of filling and resulting thermal bridges • Unfillable cavities must be treated as solid walls, with more expensive external or internal wall insulation
		Hard to fill cavity walls: – Narrow cavity (< 50 mm) – Prefab concrete cavity – Metal frame cavity – Stone cavity – Light weight timber frame – Partially filled cavity – Cavity >4 storeys tall	
	Roof type	No (accessible) loft	• Homes without a loft space, or with an inaccessible loft space (including Mansard roofs) cannot install standard loft insulation
		Flat roof homes	
	Property type	High-rise flats	• High-rise flats (greater than 6 storeys), particularly those built in the 1950s-1970s, are considered hard to treat due to their poor physical condition and, for safety reasons, lack of gas connection • Tenement buildings present difficulties in coordinating works and getting buy-in from all tenants • Listed buildings and homes in conservation areas are subject to restrictions on changes to material and aesthetic characteristics
		Tenement	
		Heritage building	
	Construction	Bespoke features	• Bespoke construction, including bay windows and conservatories, can pose access and technical difficulties in installing energy efficiency measures
		Park home	
		Steel framed (BISF)	
	Size	Space constrained homes	• Limited internal space restricts the choice of heating system to those without large units or hot water storage, and limits installation of internal wall insulation

[1] *A Study of Hard to Treat Homes using the English House Condition Survey* (2008) BRE; [2] *Analysis of hard-to-treat housing in England* (2011) Centre for Sustainable Energy; [3] *Study on hard to fill cavity walls in domestic dwellings in Great Britain* (2010) Inbuilt & Davis Langdon; [4] *Review of the number of cavity walls in Great Britain* (2012) Inbuilt

Homes can be considered to be ‘hard to decarbonise’ if they are ‘hard to treat’ and/or do not have cost-effective options of low carbon heating (2/2)

Summary of attributes that contribute to a home being ‘hard to decarbonise’

Consumer attributes	Tenure type	• Consumer type affects the likelihood of uptake of energy efficiency measures, due to affordability, alignment of tenant and landlord priorities, coordination of works, and ease of regulation (e.g. legislation of standards of private rented homes)
	Household income and socio-economic group	
Location attributes	(Non-)availability of heat network	• Lack of availability of heat network and gas grid connection limits options for decarbonising heat to more expensive, electric heating systems • Homes in conservation areas have greater restrictions on changes to their external appearance, which affects choices and costs of energy efficiency measures and low carbon heating installations • Homes with extreme exposure (e.g. driving rain) may be unsuitable for standard cavity wall insulation measures and may require specialised solutions to improve durability
	(Non-)availability of gas grid	
	Conservation area	
	Location with extreme exposure	

- The above attributes represent the full list of identified factors, from which the attributes to be included in the modelling were selected according to data availability and the tractability of inclusion in the analysis.

Contents

A UK stock model was developed to represent the distribution of hard to decarbonise features across the existing building stock

Overview of approach

1. Define primary building archetypes

- Primary building archetypes were defined based on the building attributes that most strongly determine the current and potential energy performance of the archetype, including: physical attributes, existing heating system and baseline energy demand

2. Calibrate for national stock

- Regional national housing survey data is available for England, Scotland and Wales, providing an estimate of the breakdown of physical attributes and existing heating system across the full GB stock, with an accurate mix of building attributes for each of those Devolved Administrations
- Northern Ireland was included by applying GB stock distribution to the NI stock, with adjustment for the higher proportion of off gas homes in NI

3. Add secondary features

- Secondary features are those that have a weaker influence on energy saving, but which influence the suitability or cost of measures
- Additional physical, consumer and location attributes were included by mapping stock proportions to building archetypes based on geographical data (where available) and/or correlated physical attributes
- EPC data is available for 12m properties in England and Wales, and was used to correlate several of the primary and secondary attributes with location data (postcode level). Scottish and Irish EPC data is currently not publicly available

4. Aggregate to form final archetypes

- Attribute values were reduced to achieve optimum balance between model complexity (number of archetypes) and granularity of detail

The choice of features included in the stock model aimed to capture the range of hard to decarbonise attributes as fully and accurately as possible

	Attribute	Source (s)	Comments	Values
Primary	**Building type**	🟩 • **EPC data** • **English Housing Survey** • **Welsh Housing Condition Survey** • **Scottish Housing Condition Survey**	EPC data provides postcode information which allows secondary features to be mapped to primary features using spatial data **High rise flat data is unavailable** therefore this attribute was not captured in the model	Terraced, Semi-detached, Detached, Flat
	Building size			Small, Medium, Large
	Wall type			15 types with various wall constructions (solid, cavity, pre-fab, timber, stone) and insulation levels
	Floor type			7 types with various construction types and insulation levels
	Roof type			7 types including flat/pitched and insulation levels
	Existing heating system			Gas, Electric resistive, Electric storage, oil boiler, Community
Secondary	**Suitability for heat network**	🟨 • **Sub-national energy demand statistics**	Heat density mapped to archetypes at LSOA[1] level	Suitable/not suitable
	Proximity to gas grid	🟨 • **EPC data** • **Government statistics**	Proximity to gas grid mapped at LSOA level	On/off gas grid and proximity to grid
	Fuel poverty	🟨 • **Government statistics** • **English Housing Survey**	Mapped to archetypes at LSOA level and correlated with wall type, tenure, and heating fuel	Fuel poor/not fuel poor
	Consumer type (tenure)	🟨 • **Government statistics**	Mapped to archetypes at LSOA level	Owner-occupied, private rented, local authority
	Space constraints	🟧 • **EPC data**	Dwelling floor area and number of habitable rooms used as proxy	Constrained, Not constrained
	Heritage status	🟧 • **English Heritage data** • **Published literature**	Proportion of dwellings mapped at LSOA level and correlated with wall type	None, Grade I, Grade II/II*, Conservation area
	Bespoke construction	🟥		Not included in model
	Exposed location	🟥		Not included in model
	Accessibility constraints	🟥		Not included in model

🟩 Strong data, low uncertainty 🟨 Strong data, some uncertainty 🟧 Weaker data, higher uncertainty 🟥 Poor/unavailable data

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[1] LSOA = Lower Layer Super Output Area

Heritage homes – summary of data sources and assumptions

Number of heritage homes and correlation with other attributes

- Heritage homes are defined here as including both Listed buildings (Grade I/II/II*) and homes in Conservation areas[1].

Listed homes

- The number of listed dwellings was based on the Listed Datasets held by Historic England and available in GIS format[2] (no equivalent data for Scotland, Wales or Northern Ireland was identified as available within the timeframe of the project), which gives the numbers of listed buildings as 9,389 Grade I listed and 369,094 Grade II/II* listed

Homes in Conservation areas

- Very little data was identified on the number of homes in Conservation areas
- The number of such homes in this study was taken from a 2005 study[3] which notes that there is high uncertainty over the number of homes in Conservation areas, but develops an estimate of 1.2 million homes in England, Scotland and Wales (i.e. GB)

Overlap of Listed homes with homes in Conservation areas

- No robust evidence could be identified on the overlap between listed homes and Conservation areas. As a provisional estimate, it was assumed that 80% of listed homes are located in Conservation areas
- The total number of heritage homes was therefore assumed to be 1.3 million.

Correlation with other attributes

- The GIS layers of Listed buildings were used to estimate the prevalence of listed homes at an LSOA level, and this attribute combined with the other location-based data (at LSOA level) described above to capture the spatial correlation between these attributes.
- No location-based data was available on homes in Conservation areas, so no spatial correlation was applied in this case
- In order to capture the correlation of heritage status with wall construction, all heritage homes (both listed buildings and homes in Conservation areas) were assigned to archetypes in the stock model as follows:
    - Assign listed homes pro-rata to solid and stone wall building archetypes, at an LSOA level, up to a maximum of the available number of solid and stone wall homes in the relevant LSOA;
    - Assign any remaining listed homes pro-rata across all remaining (non-solid and stone wall) building archetypes;
    - Assign homes in Conservation areas pro-rata to the remaining solid wall building archetypes (which were always sufficient in number to cover the heritage homes).

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[1] Locally-listed buildings have not been included in this analysis. Inclusion of these buildings would increase the number of heritage homes, as not all locally-listed buildings are in conservation areas. [2] https://services.historicengland.org.uk/NMRDataDownload/default.aspx (Accessed February 2019); [3] *Homes in Historic Conservation Areas in Great Britain: Calculating the Proportion of Residential Dwellings in Conservation Areas* (2005) C. Bottrill.

Space-constrained homes – summary of data sources and assumptions

- Space constraints were identified as an important 'hard-to-decarbonise' attribute because several low carbon heating system options have higher space requirements than counterfactual systems including gas boilers and electric heating.
- For example, space constraints (both internal and external to the home) were cited as a barrier to the deployment of heat pumps, in some homes, in a recent evidence gathering exercise[1].
- However, the severity of space constraints is likely to be highly case-specific, and there is very limited data on the number, type and location of homes in which space constraints are most likely to be applicable
- In this analysis, we have developed **a representation of space constraints based on the metric of 'available dwelling floor area per habitable room'.** In the absence of better data addressing the prevalence of space constraints, this metric was deemed to be a useful identifier of homes most likely to value the available space in the home. The metric was deemed a better single identifier than simply total floor area as it better represents the available space per occupant (since the number of habitable rooms will correlate with the number of occupants) and therefore better reflects the space constraints occupants are likely to experience.
- Data on the total dwelling floor area and the number of habitable rooms was available from the EPC database, which allowed us to correlate space constraints with the other building attributes included in the archetype definition.
- Space constrained homes were therefore defined in relation to the following metric:

Dwelling floor area per habitable room = (Total floor area of the dwelling) / (Number of habitable rooms)

- In the Central case, the threshold for a building to be considered space constrained was set at 16 m^2, chosen to capture the 20% 'most space constrained' homes in the stock by this metric. A 'high space constraints' sensitivity was also studied, in which the threshold was raised to 18 m^2, leading to 38% of the stock identified as being space constrained.

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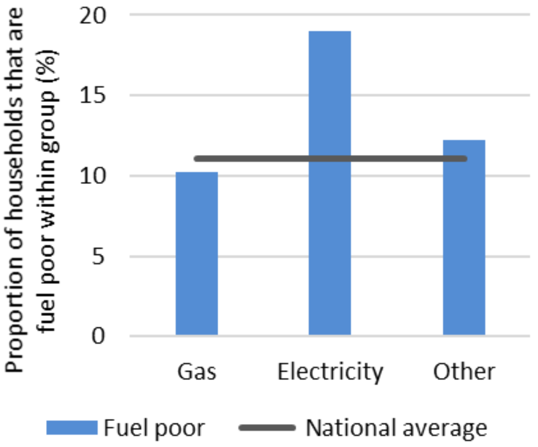
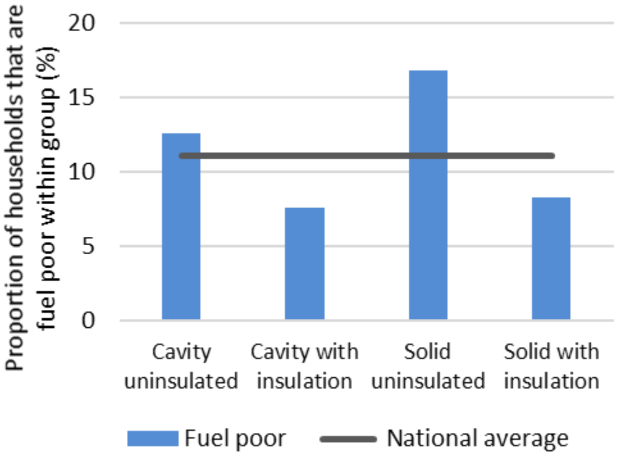
[1] *Evidence Gathering – Low Carbon Heating Technologies: Domestic High Temperature, Hybrid and Gas Driven Heat Pumps: Summary Report*, (2016) The Carbon Trust and Rawlings Support Services report for BEIS

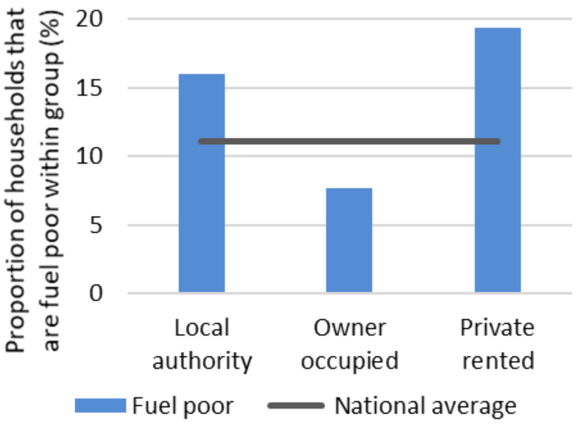
Fuel poor homes – summary of data sources and assumptions

- The government has set out its ambition to tackle fuel poverty in the Clean Growth Strategy[1], with the aim for "*all fuel poor homes to be upgraded to Energy Performance Certificate (EPC) Band C by 2030*"
- To model the appropriate distribution of energy efficiency measures for these wider benefits, the expected proportion of fuel poor homes was defined for each archetype
- The number of fuel poor homes were mapped to the archetypes at LSOA level using fuel poverty statistics[2] to capture the spatial distribution of these homes
- The correlation between fuel poverty and tenure, wall construction, and heating type was then captured by preferentially mapping these properties to the archetypes according to national statistics[3]
  - These correlations aimed to capture the increased prevalence of fuel poor homes among those with electric heating, solid walls and in the rental sector (see charts below)
- The total number of fuel poor homes in the model is **3.2 million**
- It should be noted that the model assumes that the number, distribution and type of fuel poor homes remains static over time, as it stands based on 2017 data; however, in reality, the fuel poor stock is dynamic and the distribution of measures in these homes therefore needs to be interpreted in this context.

Prevalence of fuel poor homes across heating type, wall type and tenure type







[1] The Clean Growth Strategy: Leading the way to a low carbon future, HM Government (2017) [2] Sub-regional fuel poverty data (2016 data) (2018) BEIS; [3] Regional housing surveys

Baseline heat demand is specified for each archetype using EPC data on homes with the relevant combination of primary attributes and calibration to ECUK data

- **Baseline space heating and hot water demand** was derived for each of the archetypes, with distinct energy demand for each combination of primary attributes (Property type, Property size, Wall type, Floor type, Roof type) using:
  - Estimation of space heating and hot water demand for each combination of primary attributes based on the EPC database
  - Calibration to national space heating and hot water fuel demand data for 2017 from the Energy Consumption in the UK[1] (ECUK) database from 2018 (including a weather correction)
- As a modelling simplification step, to manage the number of building archetypes, all homes in the baseline stock model were assigned to one of three heating fuel categories: Gas, Oil or Electric. Heating and hot water demand for other fuels listed in ECUK was assigned to those three fuel categories pro rata, with the calibration preserving the heating fuel demand.
- This approach means that the baseline stock model is calibrated to the space heating and hot water demand of UK homes in 2017 as derived from the ECUK database. However, since the fuel mix is modified as part of the simplification step, there is an approximately 6% overestimate in CO_2e emissions in our 2017 baseline stock model for space heating and hot water relative to the 2017 baseline CO_2e emissions derived from the unmodified ECUK fuel mix for space heating and hot water.
- We also note that the remaining emissions in 2050 in the Core and Further Ambition scenarios (see later) may be slightly overestimated due to the fact that we do not include potential savings due to boiler efficiency improvements versus the baseline in any homes remaining on fossil heating in those scenarios (fabric energy efficiency measures i.e. insulation are accounted for in those homes, but not boiler efficiency improvements).

Baseline stock model: Fuel demand for heating and CO_2e emissions in 2017

Heat fuel	Fuel demand for heating in 2017[2] (TWh)	Baseline Direct emissions in 2017 ($MtCO_2e$)
Gas	352.55	64.86
Oil	42.80	10.56
Electricity	22.41	0
Hydrogen	0	0
BioLPG	0	0
TOTAL	**417.76**	**75.41**

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[1] *Energy Consumption in the UK* (2018) BEIS. [2] Heat delivered through a heat network is presented in terms of the fuel(s) supplying the heat network.

Filtering was carried out to reach the final number of archetypes

- The full list of archetypes resulting from the combination of all primary and secondary attributes was ranked according to the number of homes estimated to be associated with each archetype
- To manage the size of the stock model and streamline model runtime, the list was reduced to capture the smallest number of archetypes required to cover 99% of the stock – this resulted in a final list of **2,925 archetypes**.
- The remaining 1% of homes were allocated pro-rata to the final list of archetypes.

Final archetypes

- **Attributes:** Property type, Property size, Wall type, Floor type, Roof type, Floor area, Space heating demand, Hot water demand Existing heating system
- **Additional information:** Total stock, Proportion of each tenure type, Proportion of fuel poor homes, Proportion in each Devolved Administration

Overview of top 10 archetypes (by stock):

											Fuel poor			Not fuel poor					
ID	Heating system	Property type	Property size	Wall type	Floor type	Roof type	Floor area (m^2)	Annual space heating demand (kWh)	Annual hot water demand (kWh)	Stock	Owner occupied	Private rented	Local authority	Owner occupied	Private rented	Local authority	England	Scotland	Wales	NI
1	Gas boiler	Terrace	Medium	Cavity insulated	Solid uninsulated	Pitched above 200	79	7,038	1,754	685,559	3%	2%	3%	57%	10%	26%	92%	5%	2%	1%
2	Gas boiler	Semi-Detached	Medium	Cavity insulated	Solid uninsulated	Pitched above 200	80	8,027	1,856	671,715	4%	1%	2%	66%	8%	19%	89%	7%	3%	1%
3	Gas boiler	Terrace	Medium	Cavity insulated	Solid uninsulated	Pitched 100-200	79	7,645	1,888	489,260	3%	2%	2%	61%	11%	21%	95%	3%	1%	1%
4	Gas boiler	Detached	Large	Cavity insulated	Solid uninsulated	Pitched above 200	157	14,107	2,267	445,637	5%	1%	0%	90%	5%	0%	86%	9%	3%	1%
5	Gas boiler	Detached	Large	Cavity insulated	Solid uninsulated	Pitched 100-200	157	14,673	2,342	401,779	5%	1%	0%	91%	4%	0%	91%	4%	4%	1%
6	Gas boiler	Terrace	Small	Cavity insulated	Solid uninsulated	Pitched above 200	43	4,558	1,337	382,983	2%	2%	5%	40%	11%	40%	85%	13%	1%	1%
7	Gas boiler	Semi-Detached	Medium	Cavity insulated	Solid uninsulated	Pitched 100-200	80	8,471	1,948	380,859	4%	1%	2%	71%	7%	15%	91%	4%	4%	1%
8	Gas boiler	Semi-Detached	Medium	Cavity insulated	Suspended uninsulated	Pitched above 200	80	9,053	1,891	346,850	4%	1%	2%	66%	8%	19%	89%	7%	3%	1%
9	Gas boiler	Terrace	Medium	Solid uninsulated	Suspended uninsulated	Pitched 100-200	79	11,702	1,842	336,057	7%	6%	2%	61%	18%	6%	92%	2%	5%	1%
10	Gas boiler	Flat	Small	Cavity insulated	Solid uninsulated	None	48	4,526	1,436	327,808	1%	2%	6%	23%	14%	54%	72%	26%	1%	1%

Distribution of final attribute values across the existing UK stock (1/2)

Insulated cavity walls and insulated lofts are very common, whereas the majority of floors are uninsulated

Wall type	Insulation level	UK Stock	%
Cavity	Insulated	12,919,131	46%
	Partially insulated	1,795,795	6%
	Uninsulated	4,871,984	17%
Solid	Insulated	226,443	1%
	Partially insulated	29,058	0%
	Uninsulated	5,565,504	20%
Pre fab	Insulated	238,162	1%
	Partially insulated	27,206	0%
	Uninsulated	507,577	2%
Stone	Insulated	76,553	0%
	Partially insulated	17,288	0%
	Uninsulated	1,365,656	5%
Timber	Insulated	273,769	1%
	Partially insulated	173,325	1%
	Uninsulated	94,381	0%

Roof type	Insulation level	UK Stock	%
Flat	0-100 mm	160,111	1%
	100-200 mm	384,800	1%
	Above 200 mm	161,755	1%
Pitched	0-100 mm	3,970,894	14%
	100-200 mm	9,193,228	33%
	Above 200 mm	10,501,536	37%
None	–	3,809,510	14%

Floor type	Insulation level	UK Stock	%
Solid	Insulated	1,130,732	4%
	Partially insulated	1,094,080	4%
	Uninsulated	14,146,492	50%
Suspended	Insulated	290,018	1%
	Partially insulated	237,418	1%
	Uninsulated	7,776,564	28%
None	–	3,506,530	12%

Distribution of final attribute values across the existing UK stock (2/2)

The majority of dwellings are connected to gas, with relatively even distribution of house type and size

Building size	UK Stock	%
Small	6,827,905	24%
Medium	11,449,284	41%
Large	9,904,645	35%

Building type	UK Stock	%
Flat	9,957,439	35%
Terrace	6,987,187	25%
Semi-Detached	5,163,316	18%
Detached	6,073,891	22%

Heating system	UK Stock	%
Gas boiler	23,393,524	83%
Oil boiler	2,011,506	7%
Electric resistive	562,963	2%
Electric storage	1,731,440	6%
Community	482,402	2%

The majority of UK homes are owner-occupied, but the rental sector is over-represented among fuel poor homes

Tenure	UK Stock	%
Owner occupied	17,803,907	63%
Private rented	5,393,848	19%
Local authority	4,984,079	18%

Tenure	Fuel poor stock	%
Owner occupied	1,316,944	5%
Private rented	1,169,097	4%
Local authority	714,851	3%

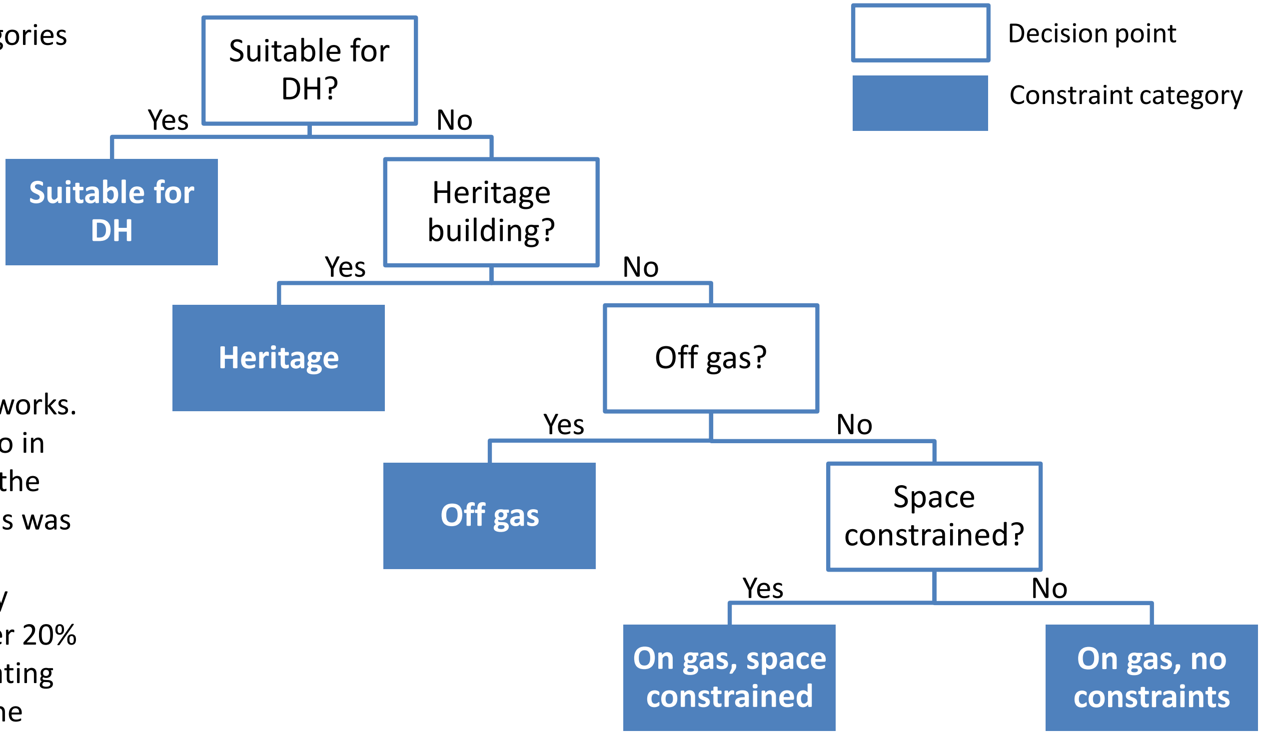
Heritage buildings make up 4% of the national stock

Heritage status	UK Stock	%
None	26,906,138	95%
Grade I	9,389	0%
Grade II	369,094	1%
Conservation area	897,214	3%

Contents

We have defined five categories of homes according to several key features expected to distinguish the 'hard to decarbonise' segments

- The stock has been divided into categories according to several key features and constraints:
  - Suitability for DH
  - Connection to gas grid
  - Space constraints
  - Heritage status
- The 'Suitable for DH' category contains homes expected to be suitable for connection to district heating (DH) networks. Broadly in-line with the Central scenario in the DH modelling for the 5CB[1], 19% of the stock was assigned to this category. This was assumed to correspond to 80% of the dwellings in the areas with heat density greater than 30 kWh/m^2 (with the other 20% assumed not to connect). No other heating systems are allowed in the model for the homes suitable for DH.



Suitable for DH?

Yes

No

Suitable for DH

Heritage building?

Yes

No

Heritage

Off gas?

Yes

No

Off gas

Space constrained?

Yes

No

On gas, space constrained

On gas, no constraints

☐ Decision point

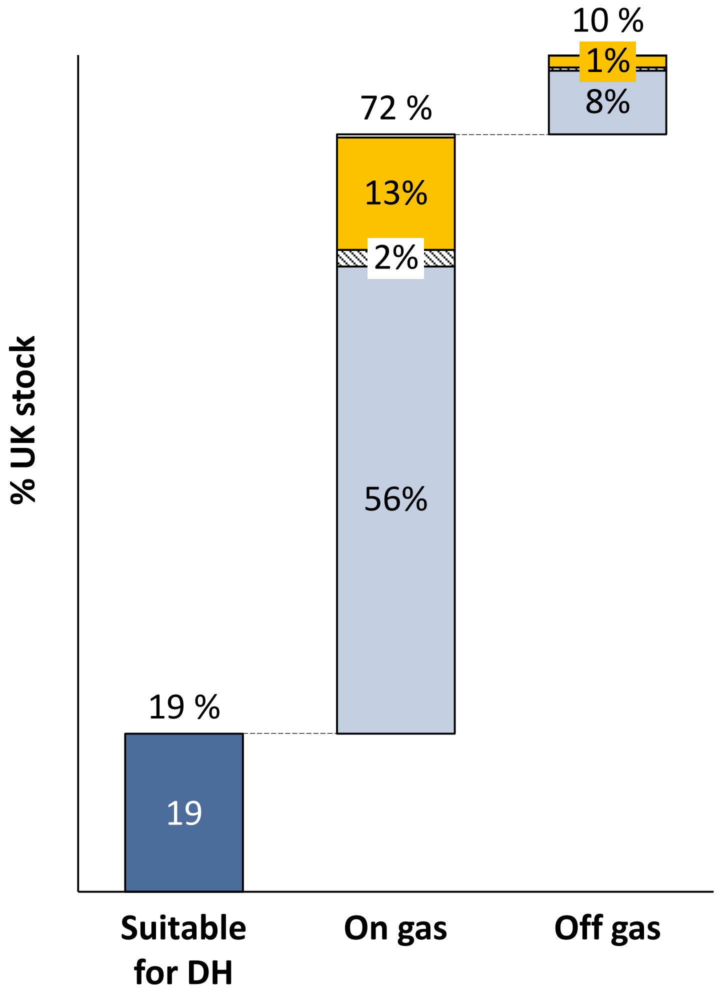
▆ Constraint category

- The remaining stock were allocated to the five categories according to the hierarchy shown above. In each filtering step, the remaining constraints continue to apply (in general) within each group. This means that the Suitable for DH category includes some heritage, off gas and space constrained homes; the Heritage category includes some off gas and space constrained heritage homes, but no homes suitable for DH; the Off gas category includes some space constrained homes, but no homes suitable for DH or heritage homes.

(1) Element Energy and Frontier Economics, *Research on district heating and local approaches to heat decarbonisation*, Report for the CCC (2015)

Coincidence of key constraints across constraint categories

Existing UK stock by key constraints



Coincidence of key constraints

Category	Stock (000's)	Number of homes (000's) in each category that have the following attribute[1] (more than one attribute may apply per dwelling)			
		Suitable for DH	Heritage	Off gas	Space constrained
Suitable for DH	**5,322**	5,322	450	675	1,017
Heritage	**825**	-	825	179	14
Off gas	**3,625**	-	-	3,625	584
On gas, space constrained	**3,591**	-	-	-	3,591
On gas, no constraints	**14,818**	-	-	-	-
TOTAL	**28,181**	**5,322**	**1,276**	**4,479**	**5,207**

⬜ Space constraints, heritage

🟨 Space constraints, not heritage

▨ No space constraints, heritage

🟦 No space constraints, not heritage

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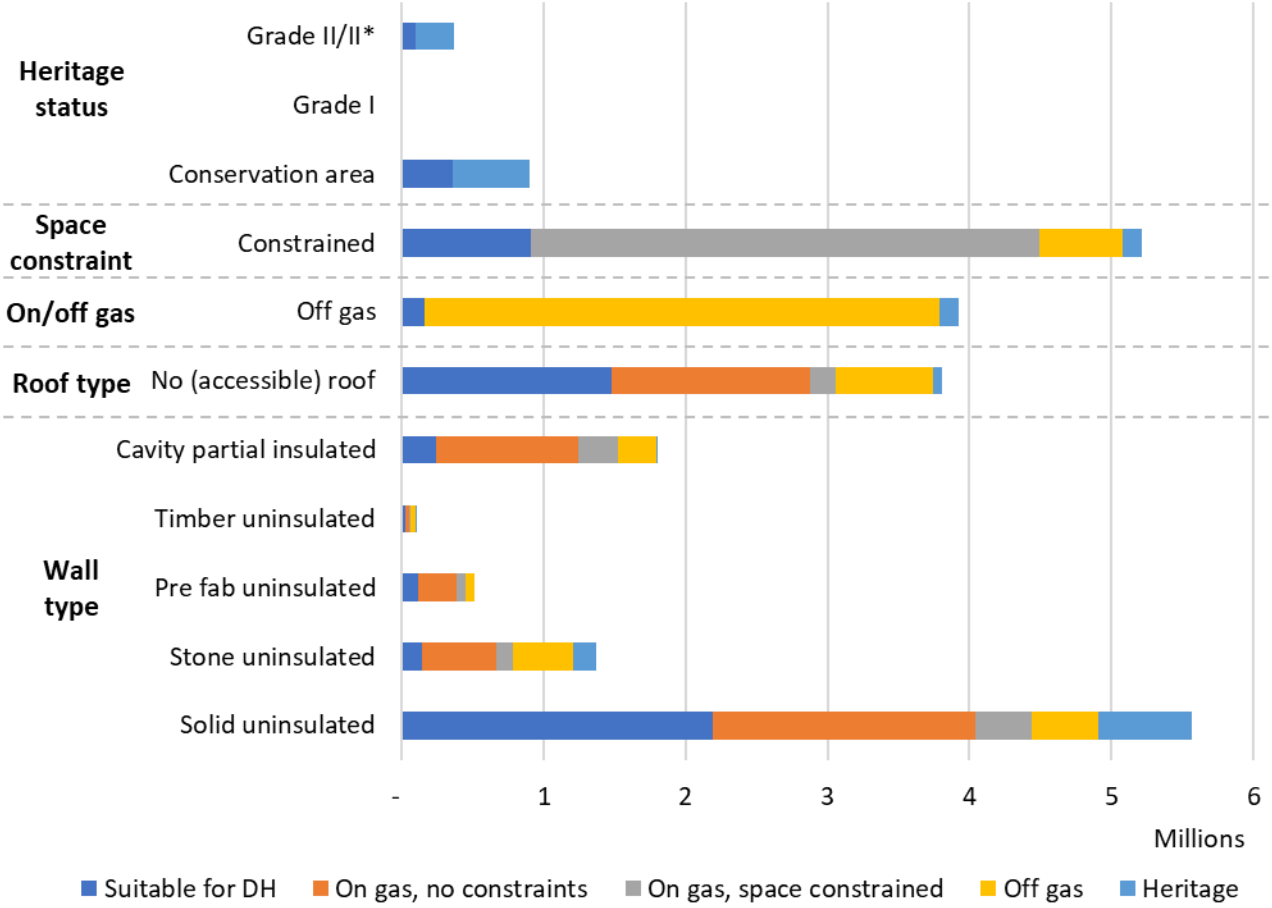
[1] Due to the hierarchy used to define the five categories (see previous slide) there are no homes suitable for DH outside the "Suitable for DH" category, but there are heritage homes outside the "Heritage" category (in the "Suitable for DH" category), and similarly for off-gas and Space-constrained homes, as shown.

Coincidence of other hard to decarbonise features across constraint categories

Modelled coincidence of individual hard to decarbonise attributes



Attribute	% Stock
Grade II/II*	1.3%
Grade I	0.0%
Conservation area	3.2%
Space constrained	18.5%
Off gas	13.9%
No (accessible) roof	13.5%
Cavity partial insulated	6.4%
Timber uninsulated	0.3%
Pre fab uninsulated	1.8%
Stone uninsulated	4.8%
Solid uninsulated	19.7%

Note that while we have not explicitly segmented the stock according to ‘hard-to-treat’ features as was applied in the 5CB work, those hard-to-treat features nonetheless influence the typical costs and savings associated with energy efficiency retrofit measures through the approach described on slide 41 onwards.

Contents

Overview of technoeconomic modelling approach

INPUTS	MODEL STEPS	*Further details in relevant section*
Energy efficiency package cost and energy savings	**1. Calculate costs and energy demand savings** from packages of energy efficiency measures for each archetype	*Energy efficiency modelling*
Heating technology cost + efficiency **Fuel costs and CO_2e intensity**	**2. Calculate total costs, fuel consumption and emissions** for all possible combinations of energy efficiency package + low carbon heating technology	*Cost calculation methodology*
Technical suitability of efficiency packages and heating technologies	**3. Choose most appropriate combination of energy efficiency package and heating system** for each archetype based on suitability, carbon savings and cost effectiveness	*Cost calculation methodology*
	4. Calculate key output metrics for decarbonisation for whole stock, including **cost of abatement**, direct and indirect **emissions**, heating technology **deployment in 2050**	*Outputs*

Contents

Energy savings and costs for packages of energy efficiency measures were determined using a 'data derived' approach

General Principles

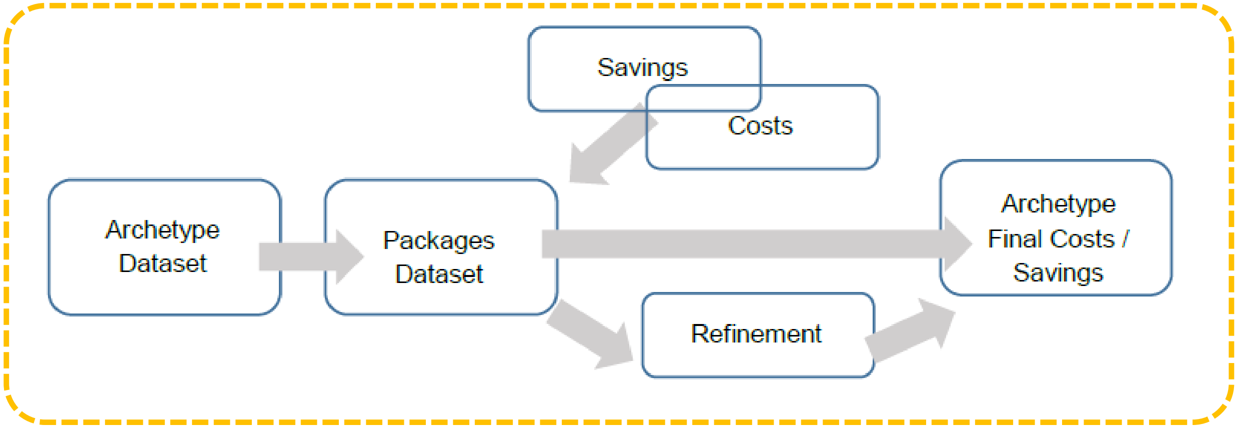
- The 'data derived' method incorporates the best-available data on the cost and performance of retrofit packages in a range of building types from UCL's prior research and the recent literature
- Based in Excel, the model applies a rule-based methodology to derive estimated costs and savings arising from application of each energy efficiency package to the individual archetypes based on compiled datasets
- The key strengths of this approach are that it is based on the most up-to-date and sound evidence base using assumptions derive from real-life case studies as well as modelling exercises
- The proposed approach was selected and developed based on the following factors:
    - **Appropriateness:** Utilises a methodology that is feasible within time/budget available
    - **Flexibility:** Allows exploration of impact of different measures
    - **Robustness**: Incorporates best-available/evidence-based datasets from research/literature
    - **Applicability:** Supports the large archetype variant dataset and allows 'soft-linking' to various modelling platforms for future analysis
- In addition to the above requirements, the model development process also adheres to the Government Social Research (GSR) code
- To extend the robustness of the data derived approach, dynamic modelling was implemented to introduce a number of refinement and verification processes to ensure the validity of results

Energy savings and costs for packages of energy efficiency measures were determined using a ‘data derived’ approach

Methodology

The derived data-based approach involved the general following steps:

1. The model starts with the stock model of building archetypes described in the previous section, defined according to the primary and secondary feature categorisation
2. An initial energy savings and cost assessment was undertaken using best-available datasets
3. The predesigned retrofit packages (low-medium-high) were then applied to each of the archetypes, accounting for the suitability (described later). The packages were defined in a detailed database that includes costings and energy saving potential estimates for applied measures based on current evidence and previous work.
4. Where applicable a series of refinement factors were applied to represent the impact of factors such as scale of implementation or single measure versus whole house installation on the costs and energy savings. These were applied as estimated percentage increase or decrease to the initial estimates to calculate the final refined cost and energy savings estimates



A broad range of sources were used to inform the costs and emissions savings of package components

- Key sources were used to gather data for the package components themselves and their suitability for the hard-to-decarbonise archetypes, the associated costs and estimated energy savings.
- The data sources used to inform the targeted levels of estimated savings from each of the designed packages included a number of studies that looked at both modelling desk based research as well as housing retrofit case studies.
- As such, the combination of data sources aimed to ensure that the flexibility offered by modelling was grounded in observed data from real life case studies, while also addressing some of the key limitations associated with case study research such as generalisability and observer or subject bias.

Summary of key sources

Retrofit for the Future: The programme, sponsored by UK government's Technology Strategy Board (TSB) from 2009 to 2013, demonstrated innovative approaches to High retrofitting of social housing, using a whole-house approach for achieving an 80% CO_2 reduction target. Information regarding the measured fuel use and a description of measures for a sub-sample of the over 100 properties which were include is available on the Low Energy Building Database repository.[1, 2] An overview of costs is generally available for each project with some specific information available for a subset of London projects.[3]

What does it cost to retrofit homes? : This report and associated dataset presents indicative costs for retrofitting a number of different dwelling types with a range of energy efficiency measures. Measures such as boilers, lighting and insulation are discussed alongside other factors that can influence costs.[4]

Building supply chains for retrofit projects : The project funded by the ETI aimed to develop solutions for retrofitting UK homes at mass scale through designing a supply chain solution to improve the energy efficiency of the vast majority of UK homes. The work included an in-depth modelling study of individualised improvement scenarios tailored to the customer segments and house types which calculated the energy savings (in terms of CO_2, heat energy consumption and fuel costs) pre and post retrofit. The modelling tool used incorporated a take-back factor algorithm developed by UCL to account for comfort taking that often impacts estimated reductions post retrofit. A range of cost data was available for installed measures.[5]

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[1] *Building Research & Information* 43, 435-451 (2015) R. Gupta *et al.*; [2] *Retrofit Revealed* (2013) Technology Strategy Board; [3] *Retrofit delivery – Key Findings* (2012) UCL for Institute for Sustainability; [4] *What does it cost to retrofit homes?* (2017) BEIS; [5] *Single dwelling implementation plan* (2013) ETI

A broad range of sources were used to inform the costs and emissions savings of package components

Summary of key sources, continued

Assessment of the Energiesprong Model: This project aimed to evaluate a mass retrofit approach to assess its transferability to the London market in practice through analysing the potential energy savings achievable via retrofit packages applied to key London archetype homes. The analysis included evaluating cost effectiveness of options and the development of finance models/business cases.[1]

Understanding best practice in deploying external solid-wall insulation in UK (2017) BEIS: This project aimed to gather evidence of EWI best-practice in the UK by considering case-studies, and research and innovation work, and undertaking interviews with practitioners, researchers and other stakeholders. The work included the provision of cost estimates associated with EWI and an analysis to cost determinants.

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[1] *London Energiesprong Transferability Assessment* (2016) UCL and Frontier Economics

An options appraisal was carried out to define three broad packages of measures

- The most suitable energy performance improvement package for a building is one that comprehensively addresses building performance issues and is compatible as a set of measures when applied.
- To develop these packages an options appraisal was carried out that considered a range of advantages and disadvantages of various products and how they fit into retrofit packages, with the following principles:
  - Preferred package options are those that are applicable to a wide range of properties, and a combination easily replicable and scalable to enable wider roll out maximise potential impact
  - In targeting levels of savings, at about 50% to 60% savings, the emissions reduction curve shows a steep increase in cost

Package levels and measures

Three packages of measures were defined, based on differing levels of disruption/intervention, cost and estimated improvement in energy efficiency:

- **Low intervention package:** This combination of measures aimed to target an estimated 25% improvement in energy efficiency (emissions and energy cost), while minimising disruption and cost.
- **Medium intervention package:** This combination of measures aimed to target an estimated 40% improvement in energy efficiency (emissions and energy cost), with some disruption and cost
- **High intervention package:** This combination of measures aimed to target what was regarded the be the highest achievable improvement in energy efficiency (emissions and energy cost), regardless of disruption and associated costs

All costs were initially estimated for individual, standalone measures. To account for the cost savings that can be achieved through whole package installation, **an average 30% reduction** in cost was applied to the combined cost of single measures. This reflects the average economies of scale reported in an recent report, that reflect the reduction of some aspects of installation costs.[1]

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[1] *Retrofit delivery – Key Findings* (2012) UCL for the Institute for Sustainability

Additional measures were included in packages to address unintended consequences of energy efficiency installation (1/2)

- While domestic retrofit strategies generally concentrate on measures to reduce energy use and carbon emissions through minimising heat loss through the building fabric, various studies have highlighted that, if these interventions are not well thought through, they can lead to undesirable impacts.[1]
    - For example, unintended consequences of increased insulation and air tightness levels may result in a rise in indoor airborne pollutant levels, condensation risk, associated mould growth, and internal overheating during the summer period.[2]
- In addressing these potential issues in the formulation of the packages, measures for addressing overheating risk as well as ensuring adequate ventilation strategies were included

Overheating mitigation

- The building archetypes with the highest risk of overheating and the energy efficiency measures that should in particular be considered in regards to overheating risk were identified through consultation with the CCC and with reference to guidance provided by the Chartered Institution of Building Service Engineers (CIBSE)[3] and DECC[4]
- This mainly included bungalows and flats, in particular smaller properties where IWI was included as part of the upgrade package
- Shading was deemed the most suitable approach to mitigating overheating, therefore this was applied to flats within the model, with costs of around £2,000, £3,000 and £4,000 for small, medium and large flats, respectively.[5]

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[1] *International Journal of Disaster Resilience in the Built Environment* 4, 269-286 (2013) L. Shao; [2] *The Unintended consequences of energy efficient retrofit on indoor pollution and overheating risk in a typical Edwardian Mid-terrace* (2013) A. Mavrogianni *et al.*;[3] *The Limits of Thermal Comfort: Avoiding overheating in European Buildings*(2013) CIBSE; [4] *Guidance on preventing overheating in the home* (2015) DECC; [5] Source: CCC

Additional measures were included in packages to address unintended consequences of energy efficiency installation (2/2)

Ventilation strategies

- Maintaining adequate ventilation post-installation is an important aspect to mitigating the unintended consequences of retrofit connected to such aspects as the deterioration of air quality within homes.[1]
- Options for ventilation systems and strategies that can be used when retrofitting properties include:
  - **Purge ventilation**: Opening windows during/ after showering, cooking and trickle vents on windows
  - **Extract ventilation**: Installation of extractor fans in kitchens and bathrooms
  - **Mechanical extract ventilation (MEV)**: Constant low level extraction from bathroom and kitchen combined with trickle vents in windows in living rooms and bedrooms, which can be boosted when cooking or showering
  - **Mechanical ventilation with heat recovery (MVHR):** For homes with very high levels of airtightness and energy efficiency
- For houses that are renovated to very high (airtight) standards, MVHR should be used to maintain the balance between efficiency and airtightness.
- However, studies have suggested that MHVR is only cost effective/viable with a fabric airtightness near Passivhaus standard levels (1 $m^3/hr/m^2$)[2 – 4]
  - Air tightness in itself is not considered an energy efficiency measure, since heat loss occurs through the building fabric by conduction; however, improvements in air tightness can be complimentary to fabric upgrades in ensuring targeted savings are achieved
  - As the hard to decarbonise stock is in general considered to be leaky, the levels of airtightness that would necessitate the use of MVHR are not expected to be reached even with the highest package level.[5]
  - Furthermore, due to issues with limitations on the installation of ducting, purge ventilation and extract ventilation were considered to be the most suitable ventilation options and were therefore specified and costed in the energy efficiency packages, where applicable

[1] *Building and Environment* 122, 126–133 (2017) A. Broderick *et al.*; [2] *What air-tightness required for MVHR?* (2007) C. Cole [3] *Building and Environment* 95, 227–239 (2016) M. Gillott *et al.* [4] For new build properties, the EST 'Good practice' air permeability is 5 $m^3/hr/m^2$ and ‘Best practice’ is 3 $m^3/hr/m^2$; [5] *Refurbishing the UK's `hard to treat' dwelling stock: understanding challenges and constraints.* (2011) D. Loveday *et al.*

The derived costs and energy savings were refined with more detailed modelling for one case study

Energy Modelling: Refinement and Validation

- In addition to the data derived approach, the packages were refined and validated using the EnergyPlus Generator 2 (EpGen-2) modelling tool.
- The case study building chosen for analysis was a pre-1919 terraced house as terraced homes were the most common occurring type in the stock (37%) and the Pre-1919, solid wall variant was deemed to be the most relevant to the Hard-to-decarbonise segment.
- In total, 512 simulations were run for each of the single measures as well as the combined packages for the Pre 1919 solid wall variant to assess the impact on energy savings (as a percentage change from the baseline performance). In addition, various exploratory scenarios were also run to help inform model assumptions, these included :
    - Occupant Energy Use Scenarios: Different thermostat set points of 18°C and 21°C were modelled to account for different occupant energy user types (conservative use vs high use)
    - Regulatory relaxation Scenarios: Trickle vents were excluded for window replacement to assess the impact of relaxing regulatory requirements on energy savings

Final model assumptions

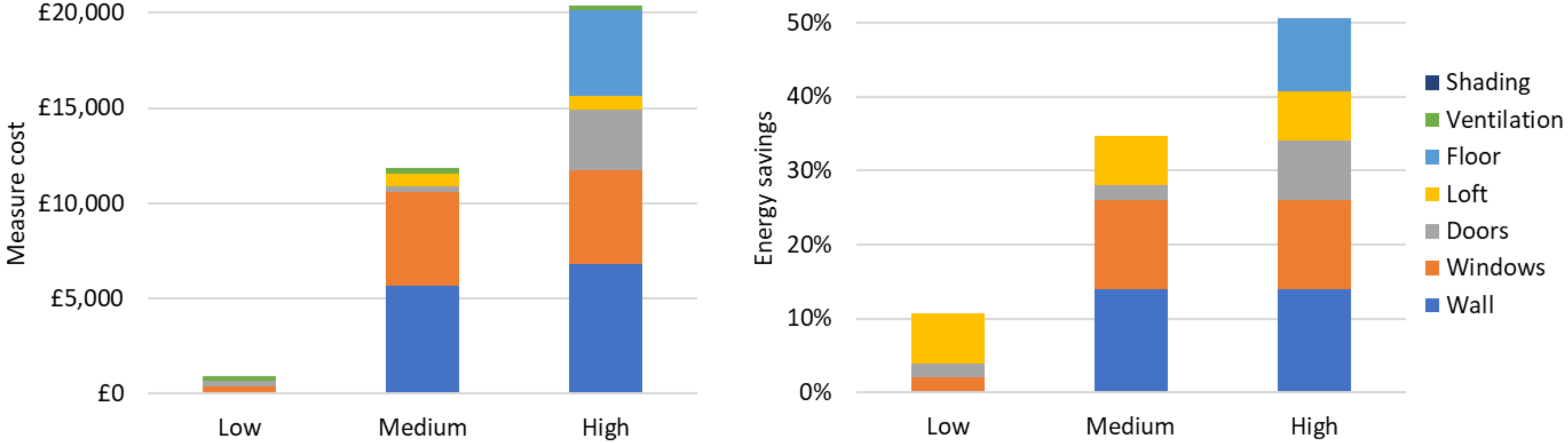
- In the final modelling, it was assumed that the energy saving achieved post-retrofit (post installation of packages) includes a move towards 'informed' average use for occupants such as adequate window opening for ventilation/ avoidance of moisture build-up, using temperature set points of 18°C and 21°C for bedrooms and livings areas, respectively

- Trickle vents are assumed for all window replacements

Summary of measures included in the final packages

	Wall			Windows	Doors	Loft[1]	Floor	Ventilation measures	Shading (overheating)
	Insulation	**Location**	**Insulation to reveals?**						
Low	None	None	No	Proofing	Proofing	Install to 300mm	No intervention	HR Extract Fans kitchen/bathrooms	None
Medium	High performance IWI + EWI	IWI - Front EWI - Extensions	No	Secondary glazing	Proofing	Install to 300mm	No intervention	HR Extract Fans kitchen/bathrooms	None
High	High performance IWI + EWI	IWI - Front façade, EWI - Extensions	Yes	Replace with double-glazed	Replacement	Install to 300mm	Thermal bridges, Underlay insulation	HR Extract Fans kitchen/bathrooms	Yes (flats only)

Example individual measure costs and energy savings for a Pre-1919, medium, terraced house (costs in 2018 prices, not including 30% cost reduction for whole package approach)



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[1] Where insulation is already present, additional insulation to top up to 300mm is modelled

Energy efficiency savings applied are based on real observed data, and we have applied an ‘uplift’ in savings reflective of a closure of the ‘performance gap’

Assumptions on energy efficiency savings and impact of closure of the performance gap

- The energy savings estimates used in our analysis are based on real observed case studies as well as modelling exercises, and reflect **typically observed savings.**
- It is known that there is a **‘performance gap’** between energy savings that are typically observed upon the installation of energy efficiency measures and the ‘potentially deliverable’ energy savings (here we refer to the retrofit context, although an analogous gap is known to exist for new buildings).
- This gap is caused by a variety of factors, including quality of construction and materials, as well as the way the occupant interacts with, operates and maintains the dwelling and the way that they use energy – such as correct operation of installed systems; appropriate ventilation strategy; and avoidance of damage to insulation layers.
- The performance gap referred to here is distinct from the gap between observed and *modelled* savings (e.g. in SAP) which, in addition to the factors listed above, relates to differences between modelling assumptions and reality (such as on occupancy profiles, internal temperatures and other factors).
- In line with the recommendations of the CCC’s 2019 report, *UK housing: Fit for the future?*[1], bridging the performance gap is an important part of the ambition to realise the value of energy efficiency.
- However, there is limited evidence regarding the size of this gap and the degree to which it can realistically be closed
- A study by the Carbon Trust identified an average performance gap of 16% between observed and predicted savings in best practice construction, even when more detailed modelling and benchmarking underpinned the predicted savings[2]
- This scale of performance gap is supported by longitudinal studies of domestic energy efficiency, which showed gaps of 18-24% between observed savings and full technical potential.[3, 4]
- Based on the available evidence, **an uplift in energy savings of 16% was assumed** relative to the data derived from real observed case studies, to represent closure of the performance gap through improvements in design and construction, as well as informed occupant use of installed technologies and appropriate heating and ventilation strategies.
- However, we note that this is an area of significant uncertainty, and further work is recommended to generate more robust evidence on the potential improvement in energy savings through closure of the performance gap in the retrofit context.
- This assumption is also contingent on appropriate policy being put in place to close the gap.[1]

[1] *UK Housing: Fit for the future?* (2019) CCC; [2] *Closing the Performance Gap* (2011) Carbon Trust; [3] *Energy Policy* 84, 35-43 (2015) P. Webber *et al.*; [4] *Energy and Buildings* 130, 578-591 (2016) J. Bros-Williamson *et al.*

The modelled technical suitability of energy efficiency packages was determined according to the dwelling's heritage status

- The technical suitability of energy efficiency measures depends on a range of building characteristics in addition to the physical characteristics of the building (e.g. location, space constraints, planning constraints); in this study, suitability was defined primarily by heritage status
- **Heritage buildings** are subject to tighter restrictions on changes to their material and aesthetic characteristics, which can limit their suitability for some types of retrofit.
- Listed buildings have special protection and require consent for changes in materials, details and finishes, both internally and externally, whereas buildings in conservation areas may require permission to make changes to the external appearance of the building.
- These restrictions greatly restrict the use of external wall insulation in these homes and can either limit the use of internal wall insulation and the replacement of external fixtures such as windows, or make them more costly.
- To reflect the additional barriers to retrofit experienced by these homes, suitability criteria and cost uplifts were applied to heritage homes.
- The suitability criteria were formulated using the 'Responsible retrofit wheel' developed by the Sustainable Traditional Buildings Alliance[1] and local council planning guidance documents,[2, 3] and were confirmed and refined through consultation with experts from organisations including Historic England, Welsh Government Historic Environment Service (Cadw) and Historic Environment Scotland.
- The suitability was considered for individual measures (see next slide for table), but suitability was applied on a package-level basis – where one component of a package was deemed unsuitable, the building was considered unsuitable for that package.
- Due to the variability in planning guidance across the UK, there will be variations in cases where planning or consent will or will not be granted; however, conservative assumptions were made with regards to the likely technical suitability of measures (for example, with regards to their aesthetic impact) in order to be as representative as possible of the general case
- Nevertheless there remains uncertainty over the suitability of different measures for heritage buildings.
- Where the suitability of measures was considered ambiguous or planning or buildings consent is likely to vary on a case-by-case basis (see box, below), the measures were deemed to be suitable for 50% of the relevant building type
- This assumption was necessarily simplistic, given the available time and practical modelling constraints, and a variation on the suitability assumptions was derived. This is shown on a later slide but is not applied in any of the scenarios shown in this report.
- **Homes with space constraints** may also be restricted in their use of internal wall insulation; however, this aspect was not included in this study.

Where firm guidelines are not specified for measures, consent for installation is subjective and can vary based on local area and property. For example, acceptability of slim profile double glazing amongst conservation professionals was found to vary across the UK.[4] This lack of certainty can be a deterrent to undertaking energy efficiency measures and may encourage planners and owners to rely on the exemptions contained in the Building Regulations when carrying out renovations. There is significant potential to increase applicability of measures where planning restrictions are either revised or planners are included in a more informed decision-making process

[1] http://responsible-retrofit.org/wheel/; [2] *Retrofitting Historic Buildings for Sustainability* (2013) City of Westminster; [3]*Energy Efficiency & Renewable Energy Guidance For Listed Buildings and Undesignated Buildings* (2013) Bath & North East Somerset Council; [4] Buildings and Energy 149, 391-399 (2017) N. Ginks and B. Painter

Summary of basis for technical suitability of energy efficiency measures (1/2)

Measure	Factors affecting technical suitability
Loft insulation	• Building regulations do not apply to loft insulation and permission is not normally required unless it alters the external appearance of the roof, or (for listed buildings) requires modification of the structure of the roof • However, measures are considered harder to implement in Grade I listed buildings and therefore only 50% of these buildings were considered suitable
Ventilation measures	• Guidelines do not specify suitability of damp treatment (fitting of extractor fans) and it is expected to be case specific • Since proper ventilation is required for high performance of energy efficiency measures, damp treatment was allowed in all buildings, with other measures as the driver for package suitability
Internal wall insulation	• Planning permission is not required for homes in conservation areas but consent is required for listed buildings and any special architectural details, materials or finishes must be preserved
Cavity wall insulation	• Planning permission is not required for homes in conservation areas but consent is required for listed buildings and any special architectural details, materials or finishes must be preserved
External wall insulation	• Planning permission is required for all types of heritage homes and listed building consent is required for listed homes • Permission may be granted for rear facades in conservation area homes but, although it may be granted in some cases, external wall insulation (EWI) is generally considered inappropriate for listed buildings.
Windows	• Double glazing is assumed to be uPVC for non-heritage buildings but it is assumed that alternative frames (e.g. timber) will be required for homes in conservation areas with an associated additional cost • Listed buildings are unlikely to be granted permission to replace windows with double glazing • Fewer restrictions apply to secondary glazing, but special requirements on materials and installation may apply

Summary of basis for technical suitability of energy efficiency measures (2/2)

Measure	Factors affecting technical suitability
Doors	• Draught-proofing does not require permission or consent but advice is likely to be required for listed buildings with especially important features (more likely in Grade I) • Permission is not required to replace doors in conservation area homes, but is more difficult in listed buildings and less likely to be approved unless like-for-like
Floor insulation	• Planning permission is not required for homes in conservation areas but consent may be required for listed buildings, particularly since the work is highly disruptive and risks material damage
Overheating treatment	• Guidelines do not specify suitability of overheating measures (shading) and it is expected to be case specific • It is assumed that measures are allowed in all buildings, with other, more disruptive, measures driving the suitability of the package

Overview of suitability criteria applied in the model for energy efficiency measures

🟩 Suitable for all dwellings
🟧 Suitable for some dwellings
🟥 Unsuitable for all dwellings

Package	**Efficiency measures**		**Heritage status**[1]			
			Conservation area	**Grade I**	**Grade II***	**Grade II**
Low	**Loft Insulation**	Top-up to 300mm where partial insulation present	🟩	🟧 50% of dwellings suitable	🟩	🟩
		Replacement	🟩	🟧 50% of dwellings suitable	🟩	🟩
	Doors	Proofing	🟩	🟧 50% of dwellings suitable	🟩	🟩
	Ventilation	Extractor fans (Kitchens and Bathrooms)	🟩	🟧 Case-specific[2]	🟧 Case-specific[2]	🟧 Case-specific[2]
Medium	**External Wall**	Internal Wall Insulation	🟩	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable
		Cavity Wall insulation	🟩	🟧 50% of dwellings suitable	🟩	🟩
		External Wall Insulation	🟧 Rear facades only	🟥	🟧 Rear facades only	🟧 Rear facades only
	Windows	Secondary glazing	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable
High	**Ground floor insulation**	Under floor insulation	🟩	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable
	Windows	Replace with double-glazed	🟧 50% of dwellings suitable	🟥	🟥	🟥
	Doors	Replacement	🟩	🟥	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable
	Overheating treatment	Installing shading devices	🟧 Case-specific[2]	🟧 Case-specific[2]	🟧 Case-specific[2]	🟧 Case-specific[2]

The assumptions set out here were developed to reflect current perspectives for the purposes of modelling only. They should not be used as a guide to suitability of energy efficiency measures in real buildings. For guidance on suitability in real buildings, we suggest that the Sustainable Traditional Buildings Alliance's *Responsible Retrofit Wheel*[3] is a good starting point.

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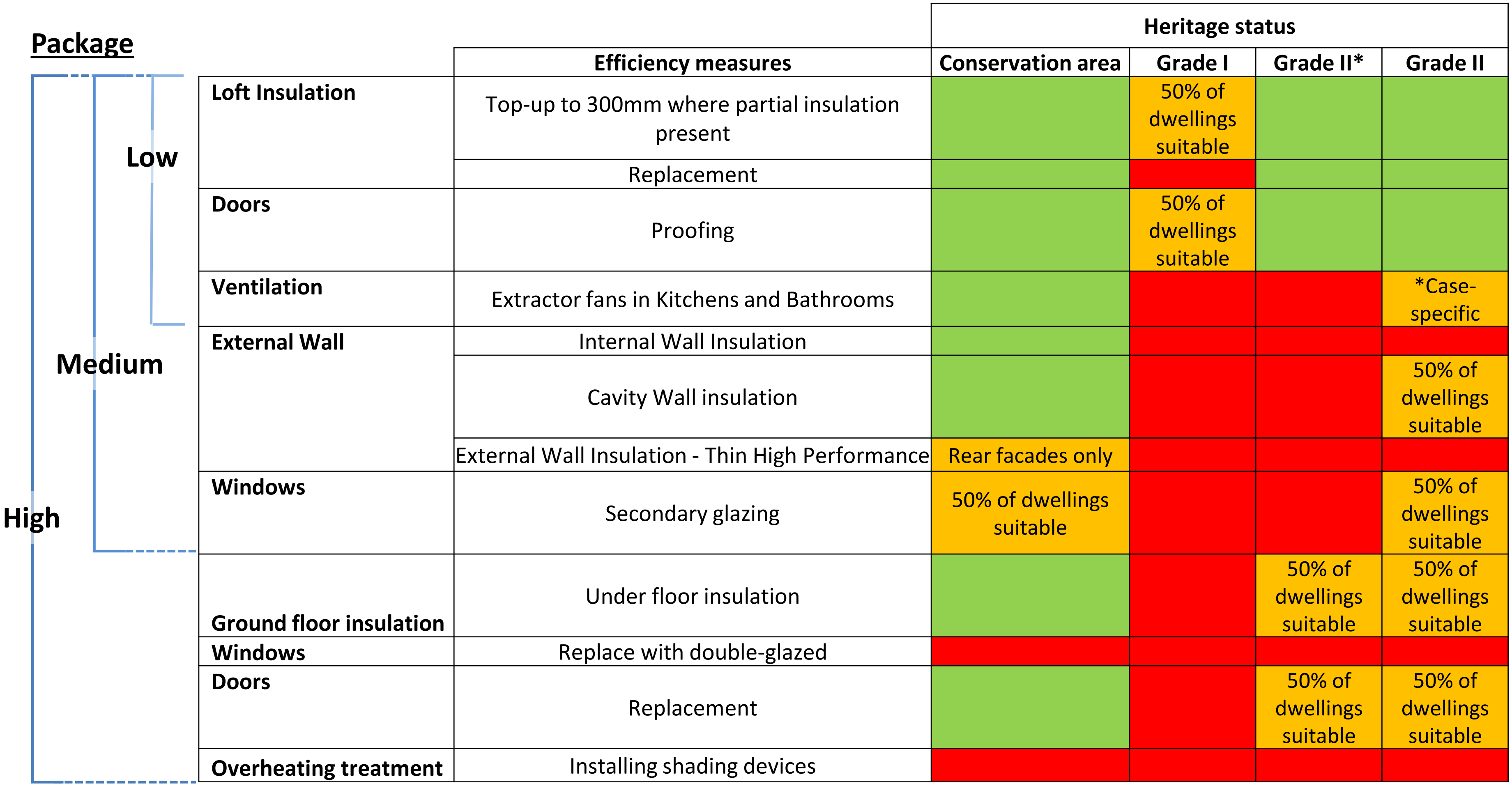
[1] Grade in itself is not a determinant of suitability but some measures are expected to be less commonly applicable in Grade I homes than Grade II or II*, which is reflected in the suitability criteria. [2] Measures that are considered case-specific are allowed in the model for all buildings but it is understood that this will not be true of all real world applications. [3] http://responsible-retrofit.org/wheel/

A ‘pessimistic’ view of energy efficiency suitability in heritage homes was derived – however, these assumptions were not applied in scenarios shown in this report

Pessimistic energy efficiency suitability assumptions

N.B. Not applied in any scenarios shown in this report



Package			**Heritage status**			
		Efficiency measures	**Conservation area**	**Grade I**	**Grade II***	**Grade II**
Low	**Loft Insulation**	Top-up to 300mm where partial insulation present	🟩	🟧 50% of dwellings suitable	🟩	🟩
		Replacement	🟩	🟥	🟩	🟩
	Doors	Proofing	🟩	🟧 50% of dwellings suitable	🟩	🟩
	Ventilation	Extractor fans in Kitchens and Bathrooms	🟩	🟥	🟥	🟧 *Case-specific
Medium	**External Wall**	Internal Wall Insulation	🟩	🟥	🟥	🟥
		Cavity Wall insulation	🟩	🟥	🟥	🟧 50% of dwellings suitable
		External Wall Insulation - Thin High Performance	🟧 Rear facades only	🟥	🟥	🟥
	Windows	Secondary glazing	🟧 50% of dwellings suitable	🟥	🟥	🟧 50% of dwellings suitable
High	**Ground floor insulation**	Under floor insulation	🟩	🟥	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable
	Windows	Replace with double-glazed	🟥	🟥	🟥	🟥
	Doors	Replacement	🟩	🟥	🟧 50% of dwellings suitable	🟧 50% of dwellings suitable
	Overheating treatment	Installing shading devices	🟥	🟥	🟥	🟥

- This alternative view of the suitability of energy efficiency measures was developed as a ‘worst case’
- These assumptions were not applied in any scenario shown in this report, but demonstrate the uncertainty over this aspect of the modelling

🟩 Suitable for all dwellings
🟧 Suitable for some dwellings
🟥 Unsuitable for all dwellings

Cost uplifts are applied in heritage homes to reflect higher costs of materials, labour and design (1/2)

- Planning restrictions and the need to work around and preserve period features can result in higher costs of labour and materials in retrofitting heritage buildings.
- The exact nature of the solutions required to insulate heritage homes are varied and typically more specialised than for modern homes, and the costs reported in the few case studies available for these homes span a wide range.
- To capture the additional costs experienced by these homes, cost uplifts were defined for each individual component based on available case studies and literature data,[1] and further refined by consultation with heritage retrofit experts[2] (see table below). There is a high level of uncertainty associated with the cost uplifts due to a dearth of robust evidence in the literature.
- The individual component uplifts were then converted into a package-level cost uplift that was applied in the model
- No cost uplifts were assumed for internal works in Conservation area homes, since planning and building regulations do not require specialised materials or processes in these homes; this is a conservative assumption since additional costs may be incurred in installing measures in these homes where occupants wish to retain period features.

Summary of range and basis for cost uplifts applied in the model

Measure	Cost uplift[3]			Factors affecting cost in heritage buildings
	Low	Medium	High	
Loft insulation	4%	15%	80%	• For listed homes, higher costs (80% uplift) are typically associated with use of natural or specialised materials; however, there is no requirement for use of these materials and therefore it is not expected that they would be widely deployed in large scale rollout of measures • For the Central case, only an increase in labour costs (estimated at 50%) is expected
Wall insulation	30%	150%	300%	• Higher costs are associated with the use of specialised insulation materials or techniques (blown cavity wall insulation) and increased cost of labour to restore or accommodate period features such as coving and bay windows
Windows	50%	80%	300%	• Double glazing costs are based on replacement with uPVC windows in the wider stock, but alternative (more costly) frame materials such as timber are likely to be required in conservation area homes – a central uplift value of 80% was chosen to reflect this • The majority of case studies available employed secondary glazing, with the wide range of costs resulting from typically larger windows in period homes combined with specialised requirements of frame materials and finishes and additional design and labour costs • A central cost uplift value of 100% was applied to secondary glazing

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[1] See next slide for full details. [2] Consultation was held with Historic Environment Scotland, PDP London, Gannochy Trust and the PassivHaus Trust. [3] Uplifts are the increase in cost as a proportion of the standard cost – a 50% cost uplift means a total cost of 1.5 times the standard cost.

Cost uplifts are applied in heritage homes to reflect higher costs of materials, labour and design (2/2)

Measure	**Cost uplift**			**Factors affecting cost in heritage buildings**
	Low	**Medium**	**High**	
Floor insulation	40%	100%	200%	• Installation of floor insulation is highly disruptive and cost uplifts are expected to primarily be associated with additional labour and design costs to ensure protection of internal features and/or like-for-like replacement
Other measures	None identified			• While some additional costs may be expected for measures such as fitting of extractor fans or draughtproofing, no cost data was available for these components • As such, no cost uplift was applied to these components in the model, with the assumption that the main drivers of cost in heritage homes are already captured in the insulation measures

Summary of Central cost uplifts applied in the model

Component	Contribution to package cost			Component cost uplift	
	Low package	Medium package	High package	Conservation area	Listed building
Loft insulation	8%	6%	5%	–	15%
Wall insulation	–	19%	13%	–	150%
Secondary glazing	–	59%	35%	–	100%
Double glazing	–	–	35%	80%	–
Floor insulation	–	–	25%	–	100%
Other	92%	17%	22%	–	–

Package type	Overall Package cost uplifts	
	Conservation area	Listed building
Low	0%	1%
Medium	0%	88%
High	28%	81%

Sources for cost uplift values:

[1] Historic Scotland Refurbishment Case Studies 1, 8, 16 and 20; [2] *Retrofit for the Future: Analysis of Cost Data* (2014) Sweett Group; [3] *Residential Retrofit: 20 Case Studies* (2013) M. Baeli; [4] *What does it cost to retrofit homes?* (2017) BEIS

Contents

A range of low carbon heating technologies have been modelled

- The range of low carbon heating technologies included in the model were chosen on the basis that they were feasible, deliverable, certain (demonstrated) technology and aligned with UK competitiveness.
- These included electric, hybrid and shared heating options, as well as a number of additional technologies to reduce or decarbonise demand or enable the use of heating systems in homes that would otherwise experience constraints (see tables below)

Summary of low carbon heating systems included in the model

Renewable heating technologies

Electric heating	• **Heat pumps**, both air source and ground source • **Storage heating** • **Resistive heating**, using panel heaters
Hybrid heating	• **Hybrid heat pumps**, using (decarbonised) gas, biofuels or resistive heating to meet peak demand
Shared heating	• Connection to large-scale **district heating (DH)** networks • **Communal heating** from a shared air source heat pump

Additional modelled options

- **Solar thermal** – for meeting part of the hot water demand in electrically heated homes
- **Small heat batteries** – for providing hot water storage in space constrained homes
- **Additional thermal storage** – to allow a proportion of the space heating demand to be shifted to off-peak times
- **Hydrogen and BioLPG** – for decarbonising homes with residual gas demand
  - In hybrid heat pumps
  - In boilers (in sensitivities only)

Costs of heating systems have been applied using a bottom-up approach to tailor each system to the building archetype

- For each technology, the required size of the system was determined by the peak heat demand (in kW), calculated by applying a load factor to the annual space heating demand of the building archetype
- The base capital cost of the system (capex) was derived from fixed (£/unit) and marginal (£/kW) components, and represents the minimum cost of the system (including unit and installation) that is applicable to all archetypes
- Additional costs were then applied to each archetype as appropriate, as determined by both the existing and newly assigned heating system, and the archetype attributes
- Full costs are set out in the Assumptions log accompanying this report; all costs given in this report are in 2018 prices

Assumptions for existing heating systems

- Hot water tanks were assumed to be installed in all homes with electric heating (both storage and resistive) but not installed in homes with gas or oil boilers; this is a simplification as a number of homes with gas boilers are known to have hot water tanks
- It is assumed that a number of homes connected to the gas grid require the replacement of gas cooking appliances (either hob and/or oven) with electric counterparts on switching to low carbon heating. An average cost of £315 was applied to all on gas homes, assuming a cost of £500 for the replacement and that 62% of gas homes require replacement of one or more appliances.[1]
- It is assumed that homes with existing electric storage heating have electrical wiring systems that are sufficient to switch to resistive heating without upgrade, whereas the switch from resistive heating to storage heating would likely require upgrade of the existing wiring

Summary of assumptions for existing heating systems

Existing heating system	Wet heating system	Communal distribution system	Wiring suitable for storage heaters	Wiring suitable for resistive heaters	Hot water tank	Non-gas cooker/hob
Gas	🟩	⬜	⬜	⬜	⬜	🟨
Oil	🟩	⬜	⬜	⬜	⬜	🟩
Electric resistive	⬜	⬜	⬜	🟩	🟩	🟩
Electric storage	⬜	⬜	🟩	🟩	🟩	🟩
Community	⬜	🟩	⬜	⬜	⬜	🟩

🟩	Assumed present for all dwellings
🟨	Assumed present for some dwellings
⬜	Assumed absent for all dwellings

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[1] In line with assumptions in *Analysis of Alternative UK Heat decarbonisation Pathways* (2018) Imperial College, based on data from *Energy Consumption in the UK* (2017) BEIS; all households with a gas oven were assumed to also have a gas hob

Costs of heating systems have been applied using a bottom-up approach to tailor each system to the building archetype

Additional cost	**Description**	**Applicable existing heating systems**	**Applicable low carbon heating systems**	**Cost (2018 prices)**	**Source and assumptions**
Installation of wet heating system	The cost of pipework and standard radiators	• Electric heaters (storage and resistive)	• All heat pumps (including hybrids) • DH • Hydrogen boiler (sensitivities only)	£1,273	[1]
Removal of wet heating system	The cost of decommissioning pipework and radiators where no longer required	• Gas boiler • Oil boiler	• Electric heaters (storage and resistive)	£204	[1]
Communal heating	The cost of pipework and in-building heat meter	• Gas boiler • Oil boiler • Electric heaters (storage and resistive)	• Communal ASHP	£3,364 (flats) £6,157 (terraced houses)	[2] Assumes communal heating shared between 6 dwellings *See later slide for details*
Electrical wiring	The cost of new ring circuits for electric heaters. For storage heaters, an Economy 7 control panel is also included.	• Gas boiler • Oil boiler • Community • Electric resistive heating (where switching to storage heating)	• Electric heating (storage and resistive)	£89 plus £135/kW (resistive heating) £509 plus £178/kW (storage heating)	[1] One ring circuit per heater

[1] *Evidence gathering for electric options in off-gas grid homes* (2019) Element Energy for BEIS; [2] Element Energy in-house modelling for private client (2018)

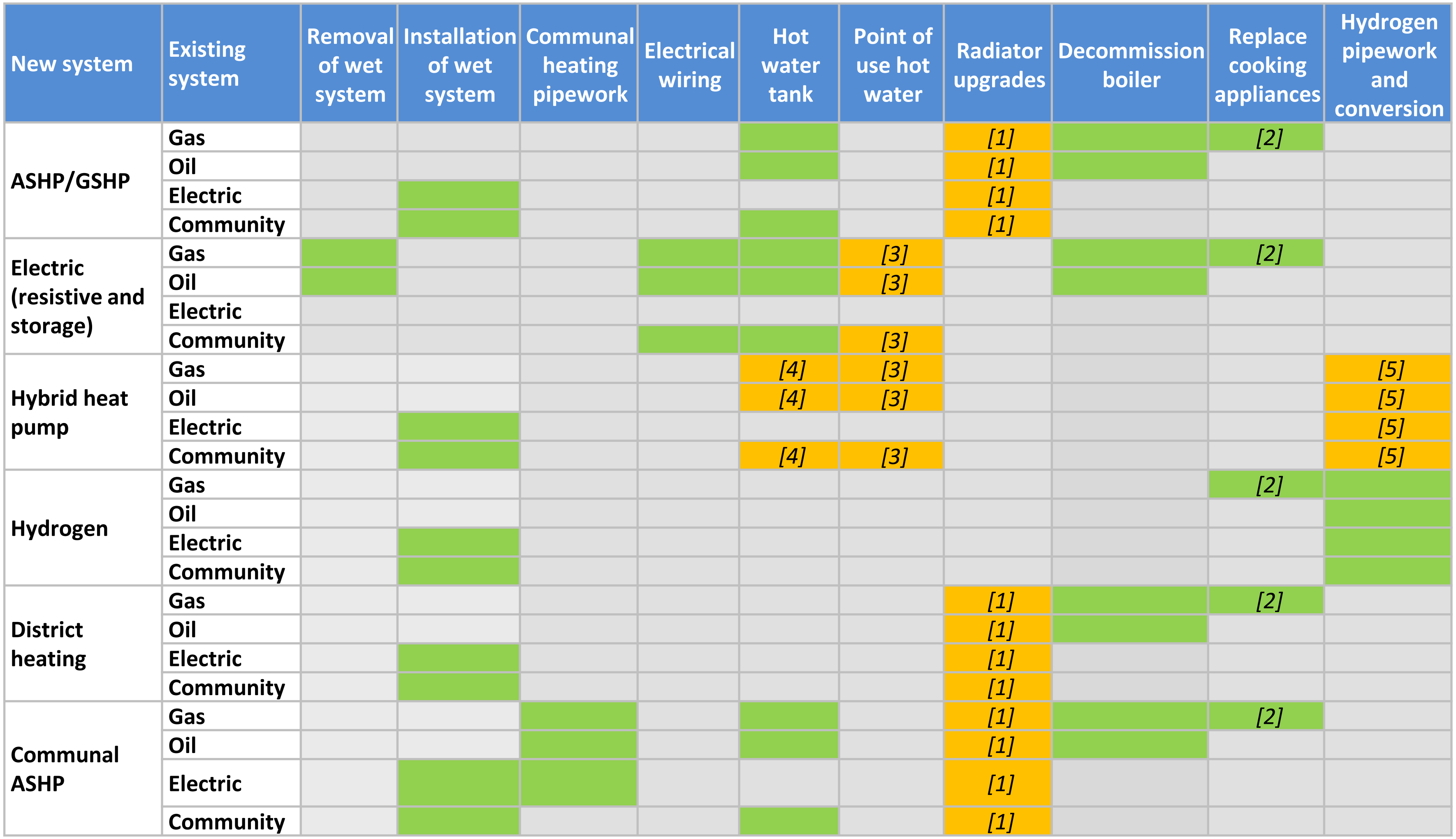
Costs of heating systems have been applied using a bottom-up approach to tailor each system to the building archetype

Additional cost	Description	Applicable existing heating systems	Applicable low carbon heating systems	Cost (2018 prices)	Source and assumptions
Hot water tank	The cost of installing a hot water tank	• Gas boiler • Oil boiler	• ASHP, GSHP, communal ASHP • Hybrid HPs where the heat pump provides hot water	£1,059	[1] 180 L hot water cylinder is assumed
Point of use hot water systems	Electric, on-demand water heating (taps and showers) for providing hot water where a standard cylinder can't be accommodated	• Gas boiler • Oil boiler • Community	• Electric heaters (storage and resistive) • Hybrid heat pumps with resistive heating	£2,060	[1] Assumes three taps and one shower per household
Radiator upgrades	The cost of large area emitters for low flow temperature systems, where standard radiators are insufficient	• All	• ASHP, GSHP, communal ASHP • DH	Dependent on property size: £1,100 (small) £1,833 (medium) £2,567 (large)	[2] Applied dependent on suitability calculation
Boiler decommissioning	Removal of a boiler system and (for on gas homes) any other non-cooking gas appliances	• Gas boiler • Oil boiler	• ASHP, GSHP, communal ASHP • Electric heaters (storage and resistive)	£509	[3]
Hydrogen pipework and conversion	Additional in-house pipework and labour cost of conversion to hydrogen	• All	• Hydrogen boilers (sensitivities only) • On gas hybrid HPs	£560	[3, 4] £500 for pipework, plus 1h labour for Hyready boiler switchover

[1] *Evidence gathering for electric options in off-gas grid homes* (2019) Element Energy for BEIS; [2] *Hybrid Heat Pumps* (2017), Element Energy for BEIS; [3] *Analysis of Alternative UK Heat Decarbonisation Pathways (2018) Imperial College for CCC*; [4] *Hydrogen supply chain evidence base* (2018) Element Energy for BEIS

Summary of applied additional costs

🟩 Cost applied for all relevant dwellings
🟧 Cost applied for some dwellings
⬜ Cost not applied for any dwellings

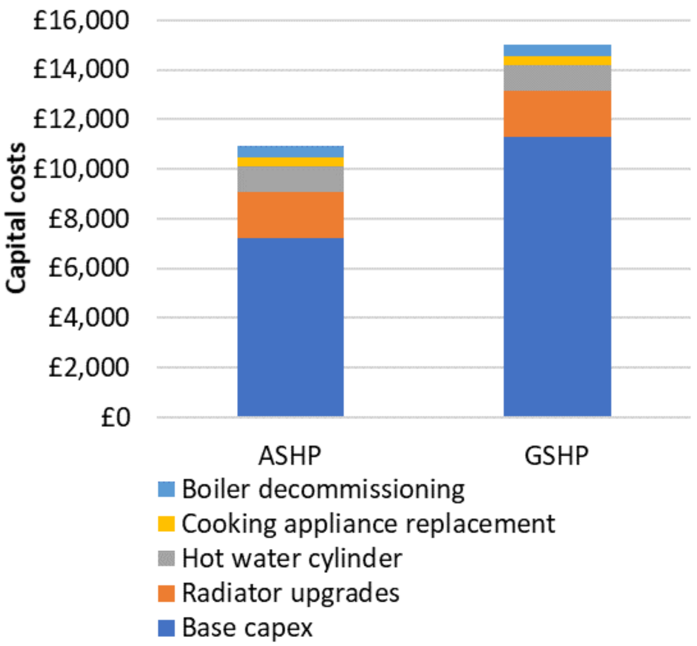


New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Electrical wiring	Hot water tank	Point of use hot water	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
ASHP/GSHP	**Gas**	⬜	⬜	⬜	⬜	🟩	⬜	🟧 *[1]*	🟩	🟩 *[2]*	⬜
	Oil	⬜	⬜	⬜	⬜	🟩	⬜	🟧 *[1]*	🟩	⬜	⬜
	Electric	⬜	🟩	⬜	⬜	⬜	⬜	🟧 *[1]*	⬜	⬜	⬜
	Community	⬜	🟩	⬜	⬜	🟩	⬜	🟧 *[1]*	⬜	⬜	⬜
Electric (resistive and storage)	**Gas**	🟩	⬜	⬜	🟩	🟩	🟧 *[3]*	⬜	🟩	🟩 *[2]*	⬜
	Oil	🟩	⬜	⬜	🟩	🟩	🟧 *[3]*	⬜	🟩	⬜	⬜
	Electric	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
	Community	⬜	⬜	⬜	🟩	🟩	🟧 *[3]*	⬜	⬜	⬜	⬜
Hybrid heat pump	**Gas**	⬜	⬜	⬜	⬜	🟧 *[4]*	🟧 *[3]*	⬜	⬜	⬜	🟧 *[5]*
	Oil	⬜	⬜	⬜	⬜	🟧 *[4]*	🟧 *[3]*	⬜	⬜	⬜	🟧 *[5]*
	Electric	⬜	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧 *[5]*
	Community	⬜	🟩	⬜	⬜	🟧 *[4]*	🟧 *[3]*	⬜	⬜	⬜	🟧 *[5]*
Hydrogen	**Gas**	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩 *[2]*	🟩
	Oil	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩
	Electric	⬜	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩
	Community	⬜	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩
District heating	**Gas**	⬜	⬜	⬜	⬜	⬜	⬜	🟧 *[1]*	🟩	🟩 *[2]*	⬜
	Oil	⬜	⬜	⬜	⬜	⬜	⬜	🟧 *[1]*	🟩	⬜	⬜
	Electric	⬜	🟩	⬜	⬜	⬜	⬜	🟧 *[1]*	⬜	⬜	⬜
	Community	⬜	🟩	⬜	⬜	⬜	⬜	🟧 *[1]*	⬜	⬜	⬜
Communal ASHP	**Gas**	⬜	⬜	🟩	⬜	🟩	⬜	🟧 *[1]*	🟩	🟩 *[2]*	⬜
	Oil	⬜	⬜	🟩	⬜	🟩	⬜	🟧 *[1]*	🟩	⬜	⬜
	Electric	⬜	🟩	🟩	⬜	⬜	⬜	🟧 *[1]*	⬜	⬜	⬜
	Community	⬜	🟩	⬜	⬜	🟩	⬜	🟧 *[1]*	⬜	⬜	⬜

[1] Applied when standard radiators are deemed to be inefficient (see later slides); [2] Weighted average cost applied assuming that 62% of gas households require replacement (23.9m gas households in 2017, 14.8m with gas hob and 8.4m with gas oven; all homes with gas oven are assumed to also have gas hob); [3] Only applicable for space constrained homes where a hot water solution is required (for hybrids, only applied where the heat pump is supported by resistive heating); [4] Only applicable in options where the heat pump is meeting the hot water demand (where the boiler is meeting hot water demand then on-demand hot water from a combi boiler is assumed); [5] Applicable in on-gas hybrids only.

Heat pumps – Summary of costs

- Both air source heat pumps (ASHP) and ground source heat pumps (GSHP) are assumed to operate using a wet heating system (air-to-water and ground-to-water heat exchange, respectively) and to require a hot water solution
- For both technologies, one heat pump per building is assumed but, for GSHP, the ground loop is assumed to be shared between two buildings; a shared ground loop is assumed to represent most cost-effective configuration.[1]
- Base capex costs include the heat pump unit and installation; for GSHPs, the cost of groundworks is also included
- For a home with an annual space heating demand of 11,000 kWh[2], base capex in 2020 is £7,200 for an ASHP and £11,300 for a GSHP (see plot, right)
- A reduction in the base capex of 20% is assumed between 2020 and 2030 to reflect technology advancement and wider scale deployment, in line with 5CB assumptions
- Additional costs of conversion (see matrix, below) can bring the total installation cost up to over £10,000 for an ASHP and close to £15,000 for a GSHP, although for many homes the total cost will be lower
- Opex was set at around £100 per year for both technologies, in line with 5CB assumptions



Illustrative capital costs in 2020 of ASHP and GSHP for a dwelling with an existing gas boiler and an annual space heating demand of 11,000 kWh (8 kW heat pump)

Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Electrical wiring	Hot water tank	Point of use hot water	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
ASHP/GSHP	**Gas**					🟩		🟨	🟩	🟩	
	Oil					🟩		🟨	🟩		
	Electric		🟩					🟨			
	Community		🟩			🟩		🟨			

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[1] Based on discussions with the Heat Pump Association and Kensa Heat Pumps. Two homes represents minimum number ground loop may be shared between, however in reality there remains scope for a larger number of homes to share a single ground loop, which could potentially lead to further reduction in costs due to economies of scale; [2] 11,000 kWh is the average space heating demand of the building archetypes in the model

Heat pumps – efficiency and performance

🟥 Unsuitable
🟩 Suitable

		Specific heat demand (W/m^2)						ASHP Space heating SPF		ASHP - Hot water SPF		GSHP Space heating SPF		GSHP - Hot water SPF	
Flow temperature (°C)	Oversize factor	0-30	30-50	50-80	80-100	100-120	120-150	2020	2030	2020	2030	2020	2030	2020	2030
35	6.8	🟩	🟩	🟩	🟥	🟥	🟥	3.6	4.1	2.1	2.6	3.8	4.2	2.5	3.0
40	4.3	🟩	🟩	🟩	🟩	🟥	🟥	3.4	3.9			3.6	4.1		
45	3.1	🟩	🟩	🟩	🟩	🟩	🟥	3.0	3.5			3.2	3.7		
50	2.4	🟩	🟩	🟩	🟩	🟩	🟩	2.7	3.2			3.0	3.5		
55	1.9	🟩	🟩	🟩	🟩	🟩	🟩	2.4	2.9			2.7	3.2		
60	1.6	🟩	🟩	🟩	🟩	🟩	🟩	2.1	2.6			2.5	3.0		

- Heat pumps are assumed to meet 100% of the building’s space heating and hot water demand
- Efficiency was defined by the Seasonal Performance Factor (SPF) which accounts for variation in performance over the year, and which varies with the flow temperature of the system (where flow temperature is defined as the difference in temperature between the output and return flow)
- ASHP SPF values in 2020 were based on reported modelled values which are broadly in line with those used in the 5CB;[1] GSHP SPF values were set to be in line with those used in the 5CB, assuming that the 5CB combined space heating and hot water SPF value (2.84) assumed a flow temperature of 50°C and that flow temperature dependence varied as for modelled values.[1]
- The SPF for hot water is assumed to be equal to the space heating SPF at the highest flow temperature
- An improvement in the combined space heating and hot water SPF of 0.5 was assumed between 2020 and 2030
- The flow temperature of the system was assigned in the model by choosing the lowest flow temperature suitable to meet the specific heat demand[2] (see table, above)
- An oversize factor was specified for each flow temperature (see table above), which is the required rated heat output of the radiators at a mean air to water temperature difference of 50°C divided by the heat loss of the room
- Radiator upgrades were deemed necessary (and the additional cost applied) if the baseline heat demand multiplied by 1.3[3] was less than the new energy demand of the building after energy efficiency measures multiplied by the respective oversize factor (see table above)
- Heat pumps were assumed to have an operational lifetime of 18 years (ASHP) and 20 years (GSHP)

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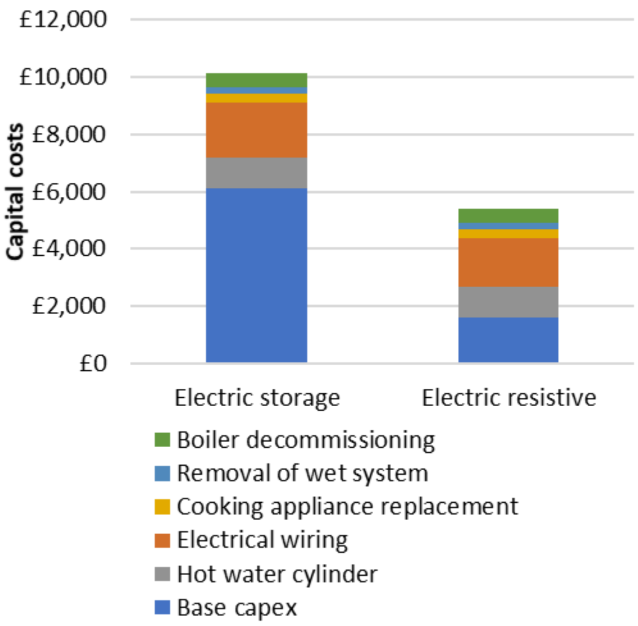
[1] Microgeneration Certification Scheme *Heat Emitter Guide for Domestic Heat Pumps*; [2] Based on average floor area and number of rooms for each archetype; [3] A typical oversize factor of 1.3 is assumed for standard radiators

Electric heating – costs and assumptions

- Costs for electric heating systems are based on modern panel heaters or storage heaters[1]
- Resistive heating systems are sized in increments based on a typical panel heater capacity of 1.5 kW; whereas Storage heating systems are sized in increments based on a typical storage heater capacity of 15 kWh, with 15 kWh of storage capacity assumed to be required per 1 kW peak heat demand (based on prior analysis by Element Energy)[2]
- Base capex for both systems includes heaters and installation, equivalent to the cost incurred from replacement of heaters in a home with existing electric heating
- For a home with an annual space heating demand of 11,000 kWh, base capex is £6,100 for storage heaters and £1,600 for panel heaters (see plot, right), and it is assumed that there is no change in cost over time
- Additional wiring costs of approximately £2,000 apply for installation of heaters in homes that are switching from an alternative counterfactual; for storage heating, this additional cost includes the cost of an Economy 7 distribution board
- Additional costs can bring the total cost of conversion up to just over £10,000 for storage heating and £5,400 for resistive heating
- Opex is set to around £100/year for both storage and resistive heating in line with the 5CB
- Electric heating systems are assumed to meet 100% of space heating and hot water demand, and are assumed to be 100% efficient
- Electric systems were assumed to have an operational lifetime of 15 years



Illustrative example of capital costs of electric heating for a dwelling with an existing gas boiler and an annual space heating demand of 11,000 kWh (12 kWe resistive heating and 8 x 15 kWh storage heaters)

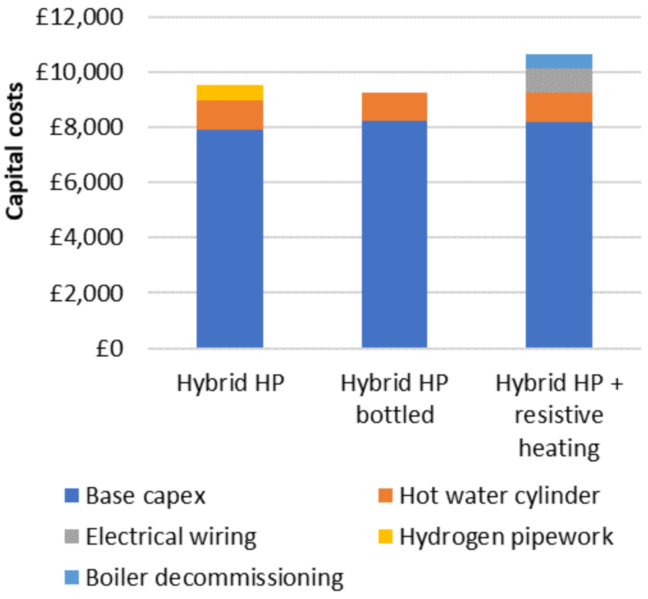
Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Electrical wiring	Hot water tank	Point of use hot water	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Electric (resistive and storage)	**Gas**	🟩			🟩	🟩	🟨		🟩	🟩	
	Oil	🟩			🟩	🟩	🟨		🟩		
	Electric										
	Community				🟩	🟩	🟨				

[1] *Evidence gathering for electric options in off-gas grid homes* (2019) Element Energy for BEIS; [2] Average size assigned to homes in [1]

Hybrid heat pumps – costs

- Hybrid heat pumps (HHPs) are assumed to comprise an ASHP with either a boiler or resistive heating
- In all cases, the capex includes the ASHP, control unit, the additional heating system and installation:[1]
    - For gas HHPs, a Hyready boiler is assumed to enable the switch to a hydrogen distribution network in a high decarbonisation scenario
    - For HHPs running on bottled gas (in off-gas homes), the boiler cost has been adjusted to reflect installation of an LPG boiler[2]
    - For HHPs with resistive heating, a cost was derived based on a modelled $kW_{\text{resistive heating}}$ per $kW_{\text{installed heat pump}}$
    - For all HHPs, the system was sized based on the heat pump component
- For a home with an annual space heating demand of 11,000 kWh, base capex in 2020 is £7,900 for an on gas HHP, and £8,200 for an off gas HHP and £8,200 for HHP with resistive heating (see plot, right)
- Additional costs bring the total cost to £9,550 for on gas HHPs, £9,300 for off gas HHPs and £11,000 for HHP with resistive heating (although the conversion of a home from gas boiler to HHP with resistive heating is unlikely, therefore this is the upper bound cost)



Illustrative example of capital costs of HHPs for a dwelling with an existing gas boiler and an annual space heating demand of 11,000 kWh (6 kW heat pump plus boiler or resistive heating)

Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Electrical wiring	Hot water tank	Point of use hot water	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Hybrid heat pump	**Gas**					🟨	🟨				🟨
	Oil					🟨	🟨				🟨
	Electric		🟩								🟨
	Community		🟩			🟨	🟨				🟨

[1] EE Hybrid Heat Pump analysis for BEIS (2017); [2] the cost of the boiler was adjusted by the average ratio of oil boiler to gas boiler cost in the fifth carbon budget (1.54), assuming the cost of an LPG boiler is equivalent to that of an oil boiler

Hybrid heat pumps – operational costs and efficiencies

Opex

- Opex costs were assumed to be £50 lower than the opex of the two individual components (around £100 per component but around £150 for the hybrid system)
    - For on gas HHPs, an additional uplift of 50% in the component of the opex associated with the hydrogen boiler (an additional £38) was applied on conversion of the gas network to hydrogen due to the need to replace catalyst to reduce NOx (total opex of £190)[1]
    - For off gas HHPs, an additional £66 was added to cover the cost of LPG delivery

Operation and efficiency

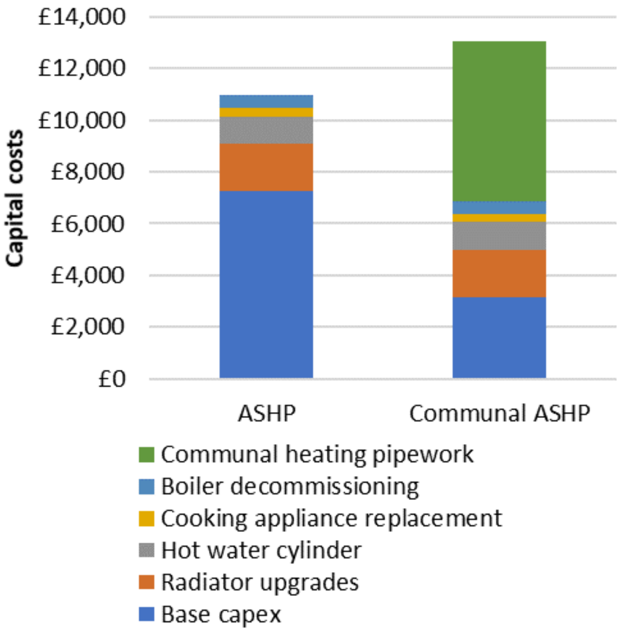
- The heat pump component is assumed to meet 80% of the space heating demand, with the additional heating system meeting 20% (only peak heating periods)
- Two options for hot water heating are considered in the model:
    - 100% of the hot water demand is met by the boiler (no hot water storage solution required)
    - 80% of the hot water demand is met by the heat pump (hot water cylinder required) with 20% met by the additional heating system[2]
- Efficiencies were set to those of the individual components:
    - The heat pump component SPF is set assuming a flow temperature of 40°C – space heating SPF of 3.4 (efficiency of 340%) in 2020 and hot water SPF of 2.1 in 2020, in line with a standard ASHP[3]
    - Hyready boilers are assumed to be 87% efficient in both gas and hydrogen mode
    - LPG boilers for off gas homes are assumed to be 89% efficient
    - Resistive heating is assumed to be 100% efficient
- HHPs are assumed to have an operational lifetime of 15 years, limited by the boiler or electric heating system; this is a simplification that could overestimate the costs of the hybrid option on replacement of the heating system

[1] *Hydrogen supply chain evidence base* (2018) Element Energy for BEIS; [2] CCC calculations based on *Analysis of alternative heat decarbonisation pathway* (2018) Imperial College (Hybrid heat pump 10 Mt scenario); [3] A fixed flow temperature is assumed for all HHPs, assuming that the lowest flow temperature (highest efficiency) will be used

Communal ASHP

Key assumptions

- Communal ASHP costs are calculated assuming a network shared between 6 homes[1]
- The opex and the fixed capital cost of a standard ASHP is divided between the homes but the marginal costs (£/kW) of the heat pump remain the same, assuming that the shared ASHP will be sized according to the needs of all houses on the network
- For a home with an annual space heating demand of 11,000 kWh, the base capex is reduced to £3,200, compared to a standard ASHP of £7,200 (see plot, right)
- Additional costs are incurred for installing the communal network, and these costs differ for houses and flats to reflect the differences in the amount of external trenching and pipework required in each case[2]
  - **For terraced houses**: the model assumes homes have individual connections to the network, with 30m external pipeline per communal heating system and 2.5m service pipe per house.
  - **For flats:** the model assumes 2.5m service pipe per flat, 10m lateral pipe and 3.1m heat riser per floor, and a building pump for heat distribution.
- For a terraced house, additional costs bring the total cost per dwelling to £13,000



Illustrative example of capital costs of communal vs. standard ASHP for a dwelling with an existing gas boiler and an annual space heating demand of 11,000 kWh (8 kW heat pump demand per home)

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Electrical wiring	Hot water tank	Point of use hot water	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Communal ASHP	**Gas**			🟩		🟩		🟨	🟩	🟩 *[2]*	
	Oil			🟩		🟩		🟨	🟩		
	Electric		🟩	🟩				🟨			
	Community		🟩			🟩		🟨			

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[1] Average length of terrace is 6 homes, derived from numbers of end- and mid-terraced homes reported in the *English Housing Survey*

District heating

District heating

- The cost of district heating is taken from Element Energy’s analysis for the 5CB.[1]
- Using outputs from that work, the cost of heat to the consumer was derived, including the cost of the district heating energy centre and fuel costs, the heat network infrastructure, connection to individual homes and the heat interface unit (HIU) and heat meter.
- As a result of these cost elements being included in the cost of heat, there is no ‘base capex’. However, several household conversion elements were applied in addition including, where appropriate, the installation or replacement of emitters with low temperature emitters, decommissioning of the boiler and replacement of cooking appliances.
- Additional costs can add up to £3,800 to the cost of conversion
- In the Central scenario and Hydrogen-led scenario (see later) the source of heat for the heat networks is a mix of heat pumps (including waste heat-source and water-source, as in the 5CB Central scenario) and hydrogen for peaking; in the No hydrogen scenario, additional thermal storage capacity is included and all heat demand is met by heat pumps.

Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Electrical wiring	Hot water tank	Point of use hot water	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
District heating	**Gas**							🟧	🟩	🟩	
	Oil							🟧	🟩		
	Electric		🟩					🟧			
	Community		🟩					🟧			

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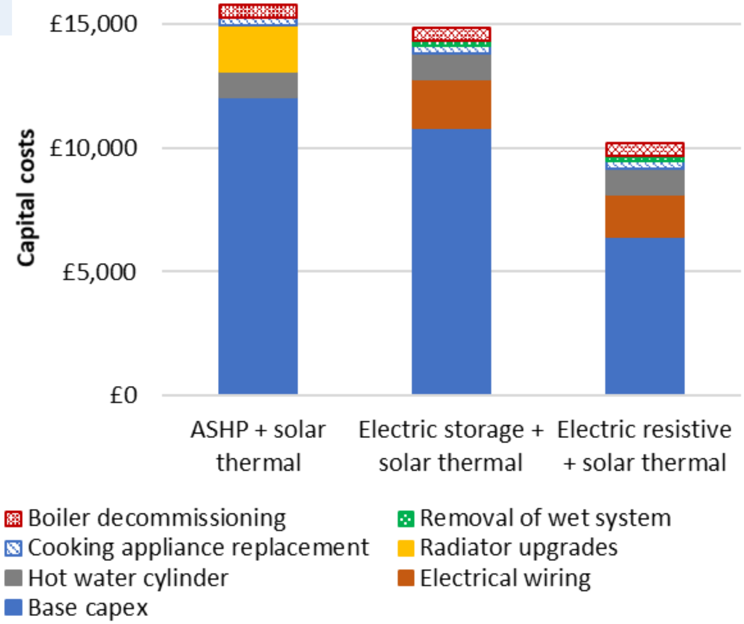
[1] *District heating and local approaches to heat decarbonisation* (2015) Element Energy for the CCC

Additional modelled options

Solar thermal

- Solar thermal water heating was assumed to meet 60% of a dwelling's hot water demand[1]
- The size and cost of the solar thermal system was dependent on the size of the primary heating system:
    - The cost of solar thermal arrays (£/kW) was converted to £/kWh heat supplied, assuming a maximum of 643 kWh/kW[1]
    - The size of the solar thermal array required was calculated by deriving the $kWh_{solar\ thermal}$ per $kW_{heating\ technology}$, assuming a ratio of space heating demand to hot water demand of 3.5[2]
    - The cost of solar thermal per $kW_{heating\ technology}$ was then added to the base cost of the heating technology to give the total base capex
- For a home with an annual space heat demand of 11,000 kWh, costs range from £10,000 - £15,000 (see plot, right)
- Opex for the joint system was assumed to be £50 lower than for the two individual components (£100 per component, £150 for the joint system)
- Solar thermal arrays were tested in combination with air source heat pumps and electric heating



Illustrative example of capital costs of heating systems with additional solar thermal for a dwelling with an existing gas boiler and an annual space heating demand of 11,000 kWh

Thermal storage options

Small heat batteries

- Small heat batteries (6 kWh) were modelled as alternative hot water solutions in space constrained homes, and were applied in place of hot water cylinders in applicable homes/technologies
- The batteries were assumed to become cost competitive with a hot water cylinder by 2030 (cost of £2,050 in 2020, £1,059 in 2030)

Thermal storage for space heating

- For heat pumps, the option of shifting some of the space heating demand to off peak times was modelled by applying the cost of an additional hot water cylinder (£1,800 for two cylinders, assuming no additional installation cost for the second cylinder)
- The additional thermal storage was assumed to allow 29% of the annual space heating demand to be moved to off peak times

[1] *The UK Supply Curve for Renewable Heat* (2009) NERA and AEA; [2] *Energy consumption in the UK* (2017) BEIS

Boilers and fuel costs

Boiler costs

- Costs for gas and oil boilers were defined with only fixed costs for discrete system sizes, in line with costs modelled in the 5CB. The same cost assumptions were used for oil boilers, and boilers fuelled by Bio-LPG. Biomass boilers were not deployed in our scenarios.
- In the model, the minimum discreet size to meet the peak demand was assigned to the archetype
- **Hydrogen boiler** costs for the Central scenario (installed as part of a Hybrid heat pump system) were based on installation of a Hyready boiler, derived by adding £150 to the cost of an equivalent gas boiler.[1] For the Hydrogen-led alternative scenario (Main case), the replacement of natural gas boilers with hydrogen boilers at the time of conversion of the local gas grid to hydrogen was considered (in this scenario we consider the deployment of stand-alone hydrogen boilers as well as hydrogen boilers as part of hybrid heat pump systems). In this case, hydrogen boiler costs were also derived by adding £150 to the cost of an equivalent gas boiler (N.B. the additional associated costs of labour for conversion were excluded). A sensitivity to the Hydrogen-led scenario was also undertaken, in which widespread hydrogen deployment is achieved through the rollout of Hyready boilers, with boiler cost assumptions the same as those in the Central case.
- Opex costs for all boilers were set at £100 per year, with an additional £50 for hydrogen boilers for the additional cost of a catalyst to reduce NOx emissions[1]
- Boilers were assumed to have an operational lifetime of 15 years

Fuel costs and carbon emissions

- For the purposes of this modelling, the CCC provided Long Run Variable Costs (LRVCs) and carbon emissions for natural gas, oil, electricity and hydrogen
- The LRVCs of electricity were differentiated by end use and by diurnal peak/off-peak use, as electricity demand during peak periods can incur significant costs, particularly for networks. The costs used incorporated a representation of the additional network and generation costs incurred at peak.
- For heat pumps with additional thermal storage, a mixed on-peak/off-peak electricity price was derived from the LRVCs assuming that 29% of the space heating demand can be shifted to off peak times[2]
- LPG and bioLPG prices were estimated using the ratio of retail price of propane and biopropane to gas[3]

[1] *Hydrogen supply chain evidence base* (2018) Element Energy for BEIS; [2] Based on analysis of ASHP demand load profiles; [3] *Biopropane for the off-grid sector* (2016) Energy and Utilities Alliance

Contents

Summary of factors affecting viability of decarbonisation options

Factor	Affect on viability	Technologies affected
Heritage status	• Listed buildings have special protection and require consent for changes in materials, details and finishes, both internally and externally • Buildings in conservation areas may require permission to make changes to the external appearance of the building	• Heat pumps and hybrid heat pumps • Solar thermal water heating
Heat demand	• Technical suitability of a heating system relies on the ability of the system to meet required comfort levels • Where the average room heat loss rate is high (>150 W/m^2) , the efficiency of heat pumps will be compromised in meeting this demand, and the required electrical demand from all electric heating systems may exceed the fuse limit of a typical building	• Heat pumps • Storage heaters • Panel heaters
Dwelling type	• Communal heating systems that supply heat from a shared heating technology are most suitable for homes located close to each other, such as terraces and flats	• Communal ASHP
Space constraints	• Heating systems that comprise large units or require large cylinders for hot water or thermal storage will be unsuitable in houses where space is limited	• Heat pumps and hybrid heat pumps • Systems with thermal storage for hot water and/or space heating
Gas grid connection	• Heating technologies that require gaseous fuel (natural gas or, in future, hydrogen) require either a grid connection or a more expensive fuel supply (e.g. bottled gas)	• Hybrid heat pumps • Hydrogen boiler (sensitivities only)

Technical feasibility of electric heating and technologies in space constrained homes is case-dependent

Electric heating

- High peak space heating demands compromise the efficiency of heat pumps, but also generate a large electrical power draw in storage and electric heating systems and may exceed the fuse limit of the building (rendering the building unsuitable for electric heating)
- Most dwellings typically have an 80A fuse, but upgrade to 100A is assumed to be the maximum possible fuse rating without incurring additional costs[1]
- To determine whether the fuse limit was breached, buffers that are representative of wider household electricity use during the daytime (for resisitive heating and heat pumps) or night time (for storage heaters) were added to the peak heat demand (kW) and compared to the maximum power draw possible with a 100A fuse (see table, below)

House type	Peak time buffer (kW)	Peak time Power draw limit (kW)	Night time buffer (kW)	Night time Power draw limit (kW)
Flat	5.5	17.5	1.8	21.2
Terrace	5.5	17.5	1.8	21.2
Semi-Detached	6.3	16.7	2.1	20.9
Detached	6.6	16.4	2.2	20.8

Space constrained homes

- Space constrained homes were assumed to be unable to accommodate technologies that require hot water cylinders
- The ability to accommodate a small heat battery and/or a heat pump unit itself (either ASHP, GSHP or hybrid HP) is likely to be case-specific
- To capture this variation, heat pumps with small heat batteries, and hybrid heat pumps without hot water storage, were assumed to be suitable for 50% of space constrained homes; other forms of heat pump and hybrids were assumed to be unsuitable.

[1] *Evidence gathering for electric options in off-gas grid homes* Element Energy for BEIS (2019)

Technical feasibility and costs of technologies in heritage homes are more restricted

Heritage homes

- Technical feasibility was determined based on available planning guidance documents and targeted consultation with a small group of industry experts (broader consultation was limited by the available timeframes for the study)
- Generally, low carbon heating technologies were deemed more feasible in heritage buildings than energy efficiency measures, since lower disruption and material change is required
- For heat pumps (including hybrids), the primary restriction is acceptability in placement of the unit such that it does not alter the external appearance; however, it is likely that many buildings can accommodate heat pumps in a discreet (acceptable) location
- For solar thermal arrays, the primary restrictions are visibility and the roof type; for example, where the material is protected itself (e.g. Welsh slate) then solar thermal would not be acceptable but more standard roof types would not cause restrictions
- Less visible or more standard technologies (communal heating or boilers) are considered to be feasible in all buildings
- To reflect the variability of feasibility, heat pumps and hybrid heat pumps were considered suitable in 50% of heritage homes, whereas solar thermal was considered suitable for 50% of conservation area and Grade II listed homes only
- This assignment is necessarily highly simplified and does not fully reflect the complexity and case-by-case nature of retrofit in heritage homes
- Cost uplifts were only considered applicable in listed homes where there is an additional need to install the technology in a sympathetic way, in-keeping with the period home:
    - For technologies with specialised emitters, an increase in cost in the range of 25-75% was considered likely
    - A central cost uplift of 50% was therefore applied to the cost of radiator upgrades in ASHP, GSHP, communal ASHP and DH, and to the capex for electric heating (storage and resistive)
- This treatment of cost is intended to be reflective of more restrictive planning regimes, as in some areas; where planning rules are (or become) less restrictive, the cost of addressing these homes would be expected to reduce.

[1] *Evidence gathering for electric options in off-gas grid homes* (2019) Element Energy for BEIS

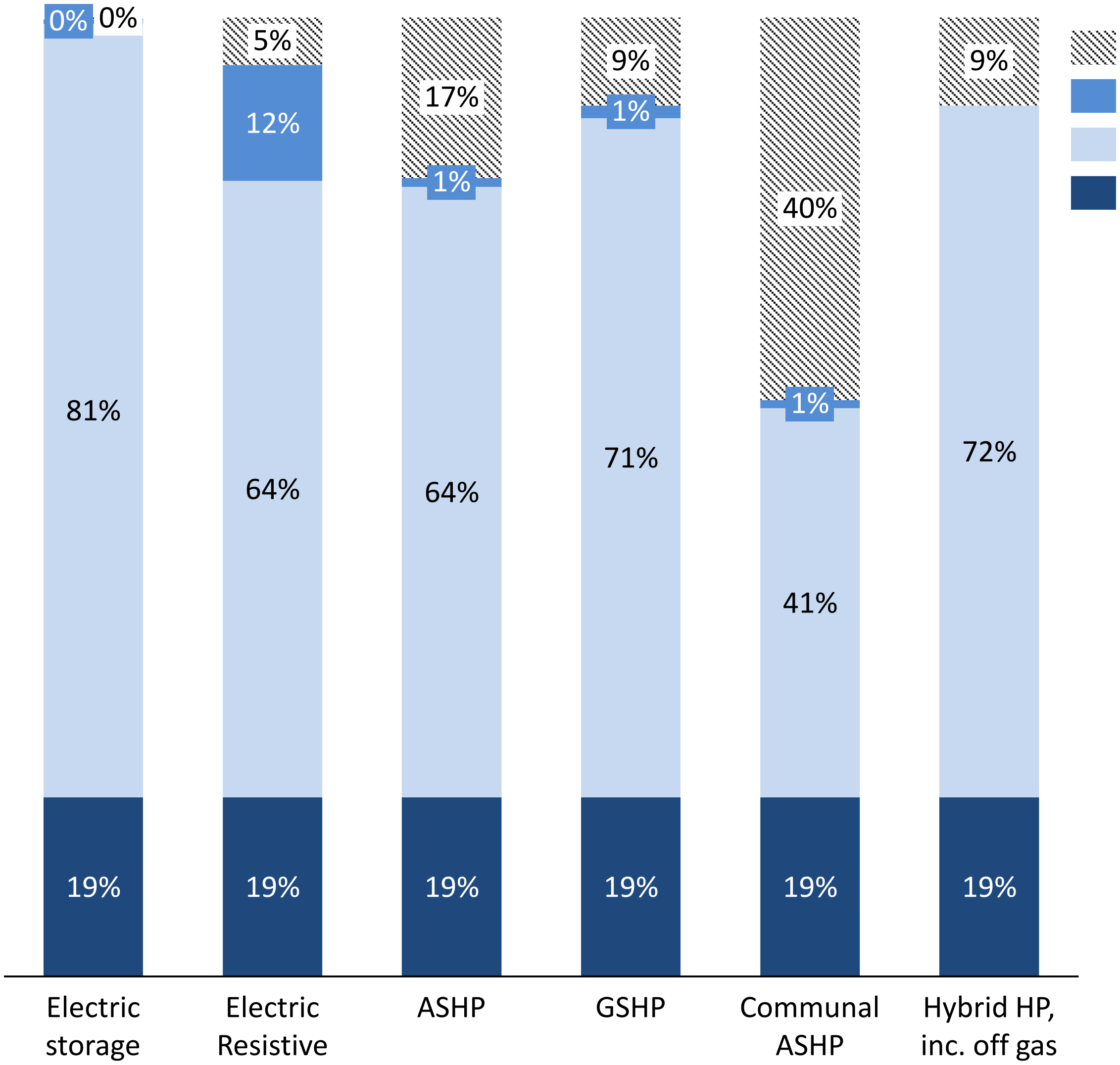
Overview of suitability criteria used in the model

🟩 Suitable for all dwellings
🟨 Suitable for some dwellings
🟥 Unsuitable for all dwellings

		Heat demand	Dwelling type			Space constraint	Gas grid connection		Heat density	Heritage status		
Heating system			**Detached/ Semi-detached**	**Terrace**	**Flat**	**Total dwelling floor area divide by no. habitable rooms < $16m^2$**	**Yes**	**No**	**<30 kWh/m^2**	**Conservation area**	**Grade I**	**Grade II/Grade II***
ASHP	With hot water cylinder	🟨 Up to 150 W/m^2 peak demand or fuse limit	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟨 50% of Detached, Semi-detached and Terraces suitable, no Flats suitable		
	With small heat battery		🟩	🟩	🟩	🟨 50% of dwellings suitable	🟩	🟩	🟩			
	With thermal store for space heating		🟩	🟩	🟩	🟥	🟩	🟩	🟩			
GSHP	With hot water cylinder		🟩	🟩	🟩	🟥	🟩	🟩	🟩			
	With small heat battery		🟩	🟩	🟩	🟨 50% of dwellings suitable	🟩	🟩	🟩			
	With thermal store for space heating		🟩	🟩	🟩	🟥	🟩	🟩	🟩			
Hybrid HP	No hot water storage	🟩	🟩	🟩	🟩	🟨 50% of dwellings suitable	🟩	🟥	🟩			
	With hot water cylinder	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩			
Hybrid HP (off-gas)	No hot water storage	🟩	🟩	🟩	🟩	🟨 50% of dwellings suitable	🟥	🟩	🟩			
	With hot water cylinder	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩			
Hybrid HP with resistive heating		🟩	🟩	🟩	🟩	🟨 Point-of-use hot water solution required	🟩	🟩	🟩			
Communal ASHP		🟨 Up to 150 W/m^2 peak demand or fuse limit	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Electric heating			🟩	🟩	🟩	🟨 Point-of-use hot water solution required	🟩	🟩	🟩	🟩	🟩	🟩
Storage heating			🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩
Heat network		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩
Hydrogen boiler		🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩
Solar thermal		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨 50% of dwellings suitable	🟥	🟨 50% of dwellings suitable

All of the UK stock has technical feasibility for one or more technology

Technical feasibility of heating technologies across the UK stock



▨ Technically unfeasible

■ Additional technically feasible after energy efficiency

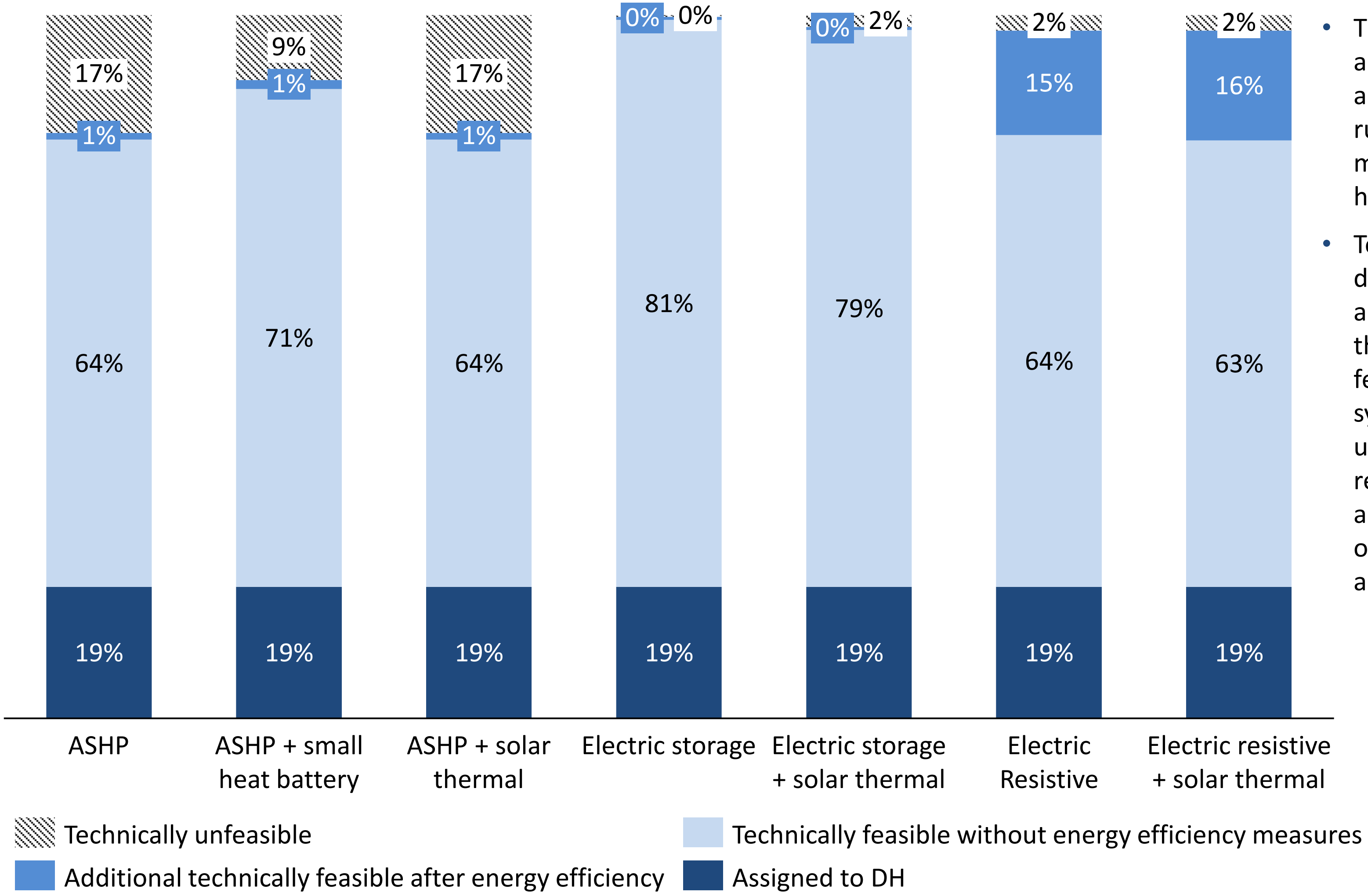
■ Technically feasible without energy efficiency measures

■ Assigned to DH

- The plots shown on the left indicates technical feasibility as determined by the suitability criteria applied in the model
- Technical feasibility does not imply cost-effectiveness, since capital and running costs of the systems may not be feasible for all homes
- There is only a small increase in technical suitability for heat pumps when energy efficiency is applied because high flow temperature systems (60°C) are allowed by the model – meaning that there are few homes unsuitable for heat pumps in the base case. However, these systems will operate with a low SPF and will be less cost-effective to run; energy efficiency measures significantly improve the running cost of those heat pumps
- A small number (231) of homes were found to not be suitable for any technology as they exceeded the fuse limit for electric heating, even with applied energy efficiency measures

Smaller hot water storage options increase the number of dwellings for which heat pumps are technically feasible

Suitability of heating technologies across the UK stock



- The primary effect of adding a solar thermal array is to reduce running costs through meeting some of the hot water demand
- Technical feasibility does not take into account costs, therefore the feasibility for the joint systems is either unaffected or slightly reduced (due to additional restrictions on solar thermal arrays)

Contents

All suitable combinations of energy efficiency and low carbon heating technologies are compared in terms of annualised cost and abatement cost

Calculation steps

- The cost of low carbon heating is calculated for each building archetype for each scenario as follows
- For each archetype in the model, all combinations of the available low carbon heating technologies (see list in previous section) and energy efficiency packages (including None, Low, Medium and High) are considered
- For each suitable combined package per archetype, given the technical suitability constraints described in the previous section, the following key metrics are calculated for the year in question (usually 2050 but also in 2030 – see next slide) as shown below:
  - *Annualised cost (£/yr) of the low carbon option and the counterfactual*. Costs are calculated as resource costs. The total annualised cost of the low carbon option is the sum of the annualised capital cost plus the in-year operating cost of the low carbon heating system. This includes all equipment and installation costs at the building-level, as well as costs incurred relating to supporting infrastructure, such as network upgrades (in the case of electrical heating) or conversions (in the case of hydrogen). The total annualised cost of the counterfactual option – defined as replacement of the incumbent heating system with one of the same type, with no energy efficiency retrofit – is calculated in a similar way.
  - *Carbon emissions abatement (tCO$_2$e) of the option versus the counterfactual (direct and indirect emissions)*.
  - *Abatement cost (£/tCO$_2$e) of the option versus the counterfactual (where abatement includes direct and indirect savings)*.

Annualised cost

$$Annualised\ cost\ (£) = \frac{c}{1 - \frac{1}{(1+c)^n}} \times Present\ value\ of\ Capital\ cost\ (£) + Annual\ operating\ cost\ (£) + Annual\ fuel\ cost\ (£)$$

n = Lifetime of technology (in years)

c = Cost of capital (taken as 3.5% in all scenarios unless otherwise stated)

Abatement cost

$$Abatement\ cost\ (£/tCO_2e) = \frac{(Annualised\ cost\ of\ EE\ and\ LCH\ (£) - Annualised\ cost\ of\ Counterfactual\ (£))}{(Annual\ emissions\ from\ Counterfactual\ (tCO_2e) - \ Annual\ emissions\ from\ EE\ and\ LCH\ (tCO_2e))}$$

The cost-optimal low carbon heating technology is selected for each archetype in 2050, following selection of the cost-optimal energy efficiency level in 2030

Default approach in the model for selection of Energy efficiency + Heating system package

- **In a given scenario, one 'cost-optimal' energy efficiency + low carbon heating system package is selected to be deployed in each archetype** according to the following procedure:
    1. Cost calculations are performed for **2030**, and for each archetype the energy efficiency + low carbon heating system package with the lowest abatement cost (£/tCO_2e) versus the counterfactual is selected[1]
    2. From this 2030 analysis, the **energy efficiency package** to be deployed in each archetype **is fixed** (except where additional energy efficiency packages are deployed for wider benefits – see next slide)
    3. Cost calculations are then performed for **2050**, and for each archetype the low carbon heating system package with the lowest abatement cost (£/tCO_2e) versus the counterfactual, when combined with the energy efficiency package chosen as above, is selected[1]
- This analysis results in the deployment of a single energy efficiency + low carbon heating system package across the stock of buildings associated with each archetype over time
- **The selection of energy efficiency package deployment is undertaken for 2030 so that the emissions benefits of efficiency over the period between now and 2050 are more fully captured**. Since the emissions from all low carbon heating technologies are very low in 2050 (as the electricity grid is decarbonised), energy efficiency deployed alongside a low carbon heating technology in 2050 does not result in significant emissions savings. In 2030, before full decarbonisation of the grid, emissions savings due to energy efficiency are greater, and better reflect the emissions reduction benefit of energy efficiency in the intervening period. This timeframe also aligns with government aspirations for energy efficiency deployment by 2030-2035.[2]
- **The selection of low carbon heating system deployment is undertaken for 2050, to reflect the long-term 'cost-optimal' solution**.

[1] Where abatement cost is negative, the option with the lowest annualised cost is selected; [2] *Clean Growth Strategy* (2017) BEIS

Additional Energy efficiency deployment is specified, above and beyond the cost-optimal level, to provide wider benefits in line with the CCC's 5CB analysis

Additional Energy efficiency deployment for wider benefits

- In line with the CCC's 5CB analysis, some additional energy efficiency is assumed to be deployed beyond the level found to be cost-optimal according to the definition set out on the previous slide (in which the benefits of efficiency are limited to the reduction in fuel costs).
- In view of the wider benefits of energy efficiency, such as reduction in fuel poverty, improved health and well-being, 3.25 million additional solid wall measures are therefore deployed in the model
- This is achieved through the application of 3.25 million additional medium packages in suitable, solid wall archetypes.
- The packages are deployed in the model in a way that favours archetypes more likely to be associated with fuel poor homes:
  - Based on the data on the share of homes in fuel poverty described in section 3, the archetypes are ranked by proportion of fuel poor homes, and the additional medium packages applied to archetypes in this priority order until all 3.25 million have been deployed (or no further potential for solid wall insulation remains – though this constraint was never reached in the scenarios studied)
  - It should be noted that the additional medium packages cannot be applied only to the fuel poor share of the archetype since archetypes are not differentiated by tenure [1] and the model selects a single energy efficiency + low carbon heating package to be applied to each archetype
- These additional energy efficiency packages were applied in all scenarios, unless otherwise stated.

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[1] As set out in Section 3, archetypes are defined by physical features, with fuel poverty information retained as a proportion (%) of stock

Contents

Central scenarios: Summary of assumptions

Key assumptions

- The Central set of scenarios represents a mix of energy efficiency measures and heating technologies that can feasibly achieve high levels of decarbonisation across the existing UK domestic stock, based upon **low reliance on technologies with high non-cost barriers** and **assumptions of an ambitious but plausible policy environment.** This scenario is intended to act as an update to the ‘Max’ scenario set out in the 5CB.

Low carbon technology

- All low carbon technologies described in Section 4 except hydrogen boilers are considered, including:
  - All heat pumps (ASHP, GSHP, hybrid HP, communal ASHP)
  - Electric heating (storage and resistive)
  - District heating (DH; using a mix of heat pumps, waste heat and hydrogen for peaking)
  - Additional options (heat batteries, solar thermal, additional storage)

Decarbonised gas

- Hydrogen is only used with hybrid heat pumps in on gas homes and to decarbonise residual gas peaking plant used in heat networks
- Biofuels are used with hybrid heat pumps in off gas homes, modelled as bioLPG

Three scenarios are considered, with increasing levels of ambition

CORE	• Core contains low-cost, low-regret options that align with most strategies to meet the current 2050 target of an 80% reduction in emissions versus 1990 • For most of these options, Government has already made commitments or begun to develop policies (although in many cases these need to be strengthened) • No hydrogen deployment is assumed, but all hybrid heat pumps deployed in off gas homes are decarbonised using biofuels, modelled as BioLPG
FURTHER AMBITION	• Further Ambition contains all of the options in Core but with the addition of some more challenging and/or more expensive options which are likely to be needed to meet a net-zero target • Includes decarbonisation of all hybrid heat pumps deployed in on gas homes using hydrogen, and decarbonisation of residual gas peaking plant in DH using hydrogen
SPECULATIVE	• Speculative includes all of the options in Core and Further Ambition with the addition of options that currently have very low levels of technology readiness, very high costs, or significant barriers to public acceptability • It is unlikely that all speculative options will be deliverable; however, some options would be required to reach net-zero GHG emissions in the domestic sector

- The Baseline energy demand and emissions profile was constructed to represent the building stock as it stands in 2017, assuming no further energy efficiency or change in heating technology to 2060.
- For all scenarios, it is assumed that only the relevant, defined portions of the stock will deploy energy efficiency measures and/or low carbon heating, with the remainder of the stock continuing to follow the baseline.

Stock has been assigned to each scenario according to constraint category and cost effectiveness of decarbonisation

- **A cost-effectiveness threshold was set** such that the most costly 10% of the stock[1] was allocated to the Speculative scenario.
- **Below the threshold**, homes in the On gas, no constraints and Off gas categories were allocated to Core, since these represent low cost, low regrets options that align with most strategies and/or commitments to achieve decarbonisation.[2] On gas, space constrained homes and Heritage homes were allocated to Further Ambition, as these were considered to be likely to be more costly and/or difficult to treat.
- Homes in the Suitable for DH category are assigned to Core both above and below the cost threshold, as the level of DH deployment is based on the 5CB Central scenario and deemed part of the cost-effective pathway to meeting the existing decarbonisation target of 80% reduction by 2050
- All energy efficiency packages in homes above the threshold were allocated the Core or Further Ambition scenario (as shown below), leaving only the low carbon heating deployment of the remaining 10% of homes in Speculative.

Summary of allocation of archetype groups to Scenarios

Constraint category	Cost-effectiveness	Scenario (Energy efficiency)	Scenario (Heating system)
Suitable for DH	Below £/t threshold	Core	Core
On gas, no constraints	Below £/t threshold	Core	Core
On gas, space constrained	Below £/t threshold	Further Ambition	Further Ambition
Off gas	Below £/t threshold	Core	Core[3]
Heritage	Below £/t threshold	Further Ambition	Further Ambition
Suitable for DH	Above £/t threshold	Core	Core
On gas, no constraints	Above £/t threshold	Further Ambition	Speculative
On gas, space constrained	Above £/t threshold	Further Ambition	Speculative
Off gas	Above £/t threshold	Further Ambition	Speculative
Heritage	Above £/t threshold	Further Ambition	Speculative
Residual Gas -> H_2 (associated with gas peaking for DH)		N/A	Further Ambition
Residual Gas -> H_2 (associated with on gas homes addressed in Core + Further Ambition)		N/A	Further Ambition
Residual Gas -> H_2 (associated with homes addressed in Speculative)		N/A	Speculative

[1] When considering combined costs of energy efficiency and low carbon heating; [2] Off gas homes were assigned to Core since they are targeted for early decarbonisation in the Clean Growth Strategy; [3] All hybrid heat pumps in off gas homes in Core are decarbonised with biofuels (bioLPG)

Simplified trajectories for deployment of heating technologies and energy efficiency measures have been used (1/2)

- This analysis does not include a detailed assessment of the most appropriate deployment trajectory for the energy efficiency and low carbon heating systems taken up in the scenario, but rather focuses on specifying an appropriate date by which these measures could be applied across all homes in the stock segment in question.
- The uptake of measures and technologies has therefore been defined in a simplified way by specifying a date of full deployment chosen to represent a reasonable date by which uptake could be achieved across all relevant stock.
- For **Core and Further Ambition**, it is assumed that energy efficiency and low carbon heating measures can be deployed by **2050**, with combined packages of measures ramping up to reach a peak annual deployment rate after the first 10-15 years (note that there are opportunities and benefits to deploy energy efficiency measures more rapidly).
  - For the majority of the stock in the Further Ambition scenario, 2050 is assumed to be a realistic timeframe for full rollout of energy efficiency and low-carbon heating. The rollout of energy efficiency measures, low carbon heat networks and technologies such as heat pumps constitute a major programme of work which is contingent on development of markets and skilled supply chains. Where a 'hybrid first' scenario is pursued (as is assumed for Further Ambition), the CCC has previously advised that decisions be made from 2025 on how to decarbonise on-gas buildings fully. Where hydrogen is deployed it is assumed conversion could only commence by 2030 at the earliest, due to dependence on CCS, the need for large-scale hydrogen production capacity and the need for a skilled workforce to undertake the conversion. Infrastructure conversion is then assumed to take around 20 years. Whilst there may be scope to achieve this more quickly (e.g. it may be possible to reduce it to 15 years), the uncertainties and risks are such that this was not judged to be a prudent central assumption for the purposes of setting legally binding emissions targets at this stage. There may be scope for this view to be revised in the future.
  - For off gas homes, it is assumed that energy efficiency and low carbon heating measures in the Further Ambition scenario can be deployed by 2045. This is a function of the opportunities for highly cost effective carbon savings in this sector[1], the lower infrastructure challenges, and existing Government commitments around phasing out installation of high carbon fossil fuel heating in off-gas homes. Energy efficiency is assumed to be in place in these homes before or at the same time as low carbon heating systems to minimise the required size of the system.

Simplified trajectories for deployment of heating technologies and energy efficiency measures have been used (2/2)

- For the most costly 10% of the stock that receive low carbon heating only in the **Speculative scenario** that there is no uptake before 2045 and full deployment by **2060**.
    - For these homes, there is a greater level of uncertainty over appropriate low carbon heating solutions and, due to the high abatement cost, it is assumed that uptake will be more challenging/slower. The defined timeframe for deployment assumes that these systems are only taken up once supply chains and markets are established and low carbon heating technologies are the primary choice for consumers
    - Where these homes are on the gas grid in areas which are converted to hydrogen, hybrid heat pumps with hydrogen boilers are likely to prove a straightforward and cost-effective solution. However, where off the gas grid, or in areas not converted to hydrogen, these homes can be expected to remain the most expensive to decarbonise, therefore remaining on fossil fuel heating for the longest
    - Energy efficiency measures for these homes are assumed to be easier to deploy, in line with government aspirations for energy efficiency improvements. These measures are treated in Further Ambition, full deployment by 2050.

Although simplified, the rates of deployment are reasonable considering underlying factors

- For heating technologies, the minimum deployment period for maximum uptake of low carbon heating is 15 years, which assumes heating systems are taken up as fossil fuel-based heating systems are replaced, assuming a lifetime of 15 years (6% of the stock replaced per year)
  - This assumption is supported by the reported UK sales of gas boilers of 1.6m per year,[1] which, accounting for new build sales,[2] gives an average stock turnover of ~16 years (6% of stock, based on 80% of total UK stock with existing gas boiler)
- For energy efficiency measures, the rates of deployment depend on a variety of factors including trigger points (such as moving house and planned renovations) and consumer willingness to retrofit. These factors vary depending on the type of tenure residents have:
  - The **social rented sector** faces the fewest restrictions on timings with regard to retrofits, as they are not dependent on the end of tenancies or other trigger points. The Government's former CESP programme targeted social housing, with the majority of measures delivered in the final six months of the scheme at a rate equivalent to 340,000 homes per year, or 9% of the social rented stock.[3, 4] This implies that the social rented stock could plausibly be retrofitted within a timeframe of 10-11 years. This sector is also well suited to early action, given regulatory levers, large housing portfolios, and wider benefits for low-income tenants.
  - The **private rented sector** experiences a higher number of opportunities for retrofit, since 25% of private renters move each year, compared to 3% of owner occupiers and 5% of social renters.[5] Shorter tenancies in this segment of the stock imply that the timeframe for implementation could be faster than for owner-occupiers. Landlords are generally less willing to install measures where the return in rental income is not apparent;[6] however, this sector is subject to regulatory levers such as Minimum Energy Efficiency Standards which can be used to drive uptake.
  - For **owner occupied homes**, just over half have carried out renovations over the past ten years, with 11% planning renovation in the next year.[7] At current rates, and with ambitious and effective policy, this implies energy efficiency measures could be installed as part of house renovations over the next two decades, provided strong policy is put in place with incentives to drive uptake and green finance. However, evidence also suggests that owner occupiers are more likely to renovate in stages, implying that deeper retrofits may take longer.[6] The feasibility of these timeframes will also relate to the ease and convenience of retrofit, which will in part be a function of technology advancements.

[1] BSRIA research and HHIC findings, both webpages last accessed 15/03/2018; [2] 192,090 new builds in 2017-2018, Ministry of Housing, Communities & Local Government; [3] *The final report of CESP* 2009-2012, Ofgem; [4] Analysis of data in *Green Deal and Energy Company Obligation* (2016) DECC National Audit Office; [5] English Housing Survey Annex Table 1.20; [6] *Trigger Points* (2011) EST; [7] Hiscox Renovations and Extensions Report (2018)

Central: 95% of direct emissions from existing homes can be abated by 2050 under the Further Ambition scenario

Stock addressed and emissions abatement by scenario

				Direct emissions abatement†		Total emissions abatement†			
	Stock addressed (millions)	Stock addressed (%)	Date by which all measures received	$MtCO_2e$	%	$MtCO_2e$	%	Total cost[1] (£m/y)	Average cost effectiveness (£/tCO_2)
Core	22.5	80%	2050	55.7	74%	54.4	72%	9,466	£174
Further Ambition	28.2*	100%	2050	71.8	95%	69.7	92%	13,304	£191
Speculative	28.2*	100%	2060	75.4	100%	73.2	97%	15,299	£209

†The % emissions abatement given refers to the proportion of baseline emissions avoided at each scenario

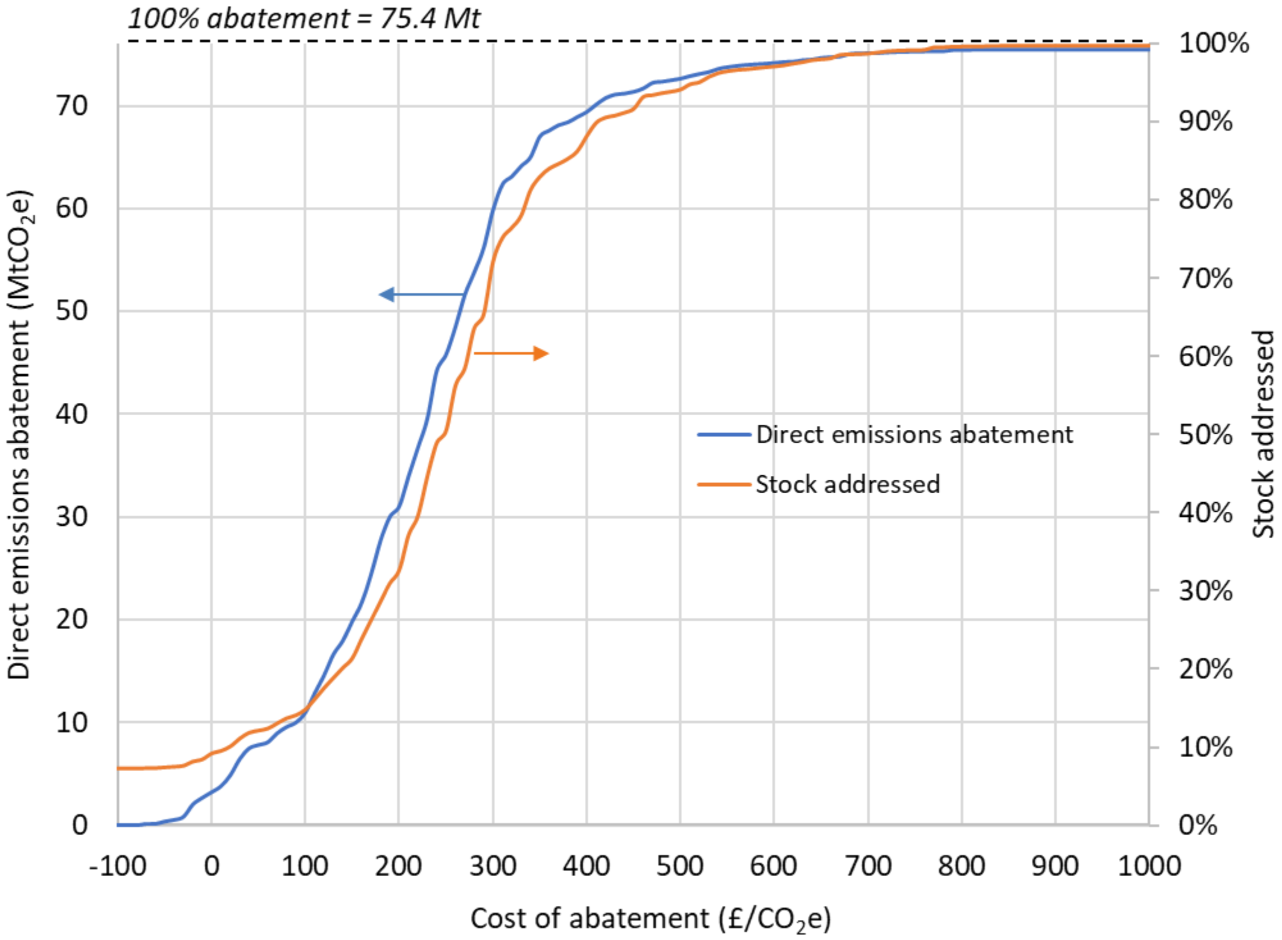
*The Further Ambition scenario includes the installation of energy efficiency measures in all homes where part of a cost optimal decarbonisation package. Speculative involves the additional deployment of low carbon heating only in the 10% most costly homes

- Direct emissions are those emitted through the direct combustion of a fuel for heat; total emissions include both direct and indirect emissions, where indirect emissions are those emitted through the production of electricity and hydrogen
- Direct emissions abatement results from displacement of gas or oil consumption for heating in the counterfactual
- Indirect emissions abatement results from the displacement of or reduction in (through energy efficiency) electricity consumption in the counterfactual
- An increase in indirect emissions results from additional electricity and hydrogen consumption for heating, and leads to a lower total abatement compared to the direct emissions abatement
- Total annualised energy efficiency capex in Further Ambition in 2050 is estimated at £3.7 bn with zero cost of capital. This is annualised over a 30 year lifetime, giving a cumulative cost of £110 bn to install all efficiency measures. This can be compared to BEIS's estimate of the capital investment required to bring homes to EPC Band C by 2035 of £35-65 bn[2].

[1] Total cost (£m/yr) is the annualised cost relative to the baseline (i.e. counterfactual heating system and no energy efficiency). [2] Statement by Claire Perry MP, BEIS Committee Session, 24th April. https://www.parliamentlive.tv/Event/Index/134952d2-3c04-4bda-b699-506cbe9e452b

Central: 90% of the existing UK stock and direct emissions are addressed with an abatement cost of under £418/tCO_2e

Direct CO_2 emissions abatement and stock addressed as a function of abatement cost



- In the Central scenario, the threshold for Speculative was set at £418/tCO_2e
- The remaining emissions after Core and Further Ambition are 19.7 and 3.7 $MtCO_2e$, respectively
- 9% of the stock and 4% of the emissions abatement are addressed with negative cost of abatement, indicating that measures in these homes result in lower lifetime cost of heating than the counterfactual, in addition to providing emissions reduction
- Note that the residual emissions presented here do not include the impact of further carbon savings which might be achieved through injection of biomethane into the gas grid.

Central: Summary of abatement cost

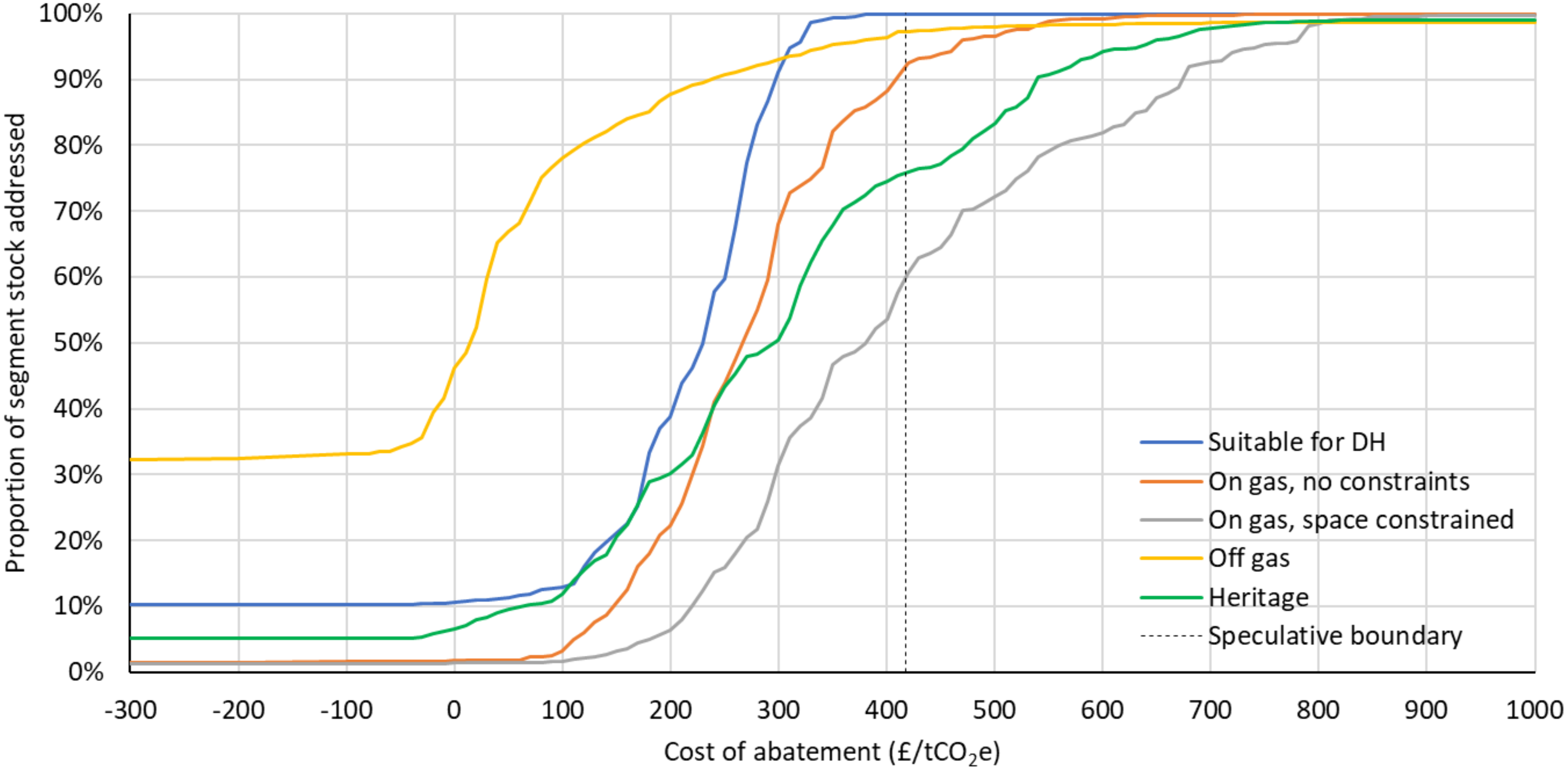
Weighted average abatement cost (£/t) by constraint category and scenario

Weighted average £/t abatement cost	Core	Further Ambition	Speculative
Suitable for DH	£195	£195	£195
On gas, no constraints	£223	£223	£232
On gas, space constrained		£311	£380
Off gas	-£19	-£18	-£15
Heritage		£196	£280
Residual LPG decarbonisation to bioLPG	£41	£47	£47
Residual gas decarbonisation to H_2		£215	£215

- The table above gives the weighted average abatement cost for each stock segment across the scenarios.
- Measures are most cost-effective in off gas homes where the counterfactual systems are costly to run and emissions savings are high.
- Space constrained homes are the most costly group to decarbonise.

Central: Abatement curves across stock segments

- Stock segments with some off gas homes (including Off gas, Suitable for DH and Heritage; see Section 3) have the highest proportions of stock that can be addressed with negative abatement costs, and the lowest median abatement cost, due to the relatively high cost of the counterfactual in those homes[1]
- The most constrained homes (Heritage and On gas, space constrained) have the largest share of homes with high abatement cost, due to non-suitability for the lower cost low carbon heating options, and/or the higher cost of some technologies in heritage homes
- These trends are discussed in more detail in a later slide.



[1] It is noted that the proportion of stock with negative abatement cost does not scale with the proportion of off gas homes in the stock segment, reflecting the more complex interactions between cost and technical feasibility in each segment

Central: Heat pumps (including hybrids) make up 75% of the heating technologies deployed across the existing stock

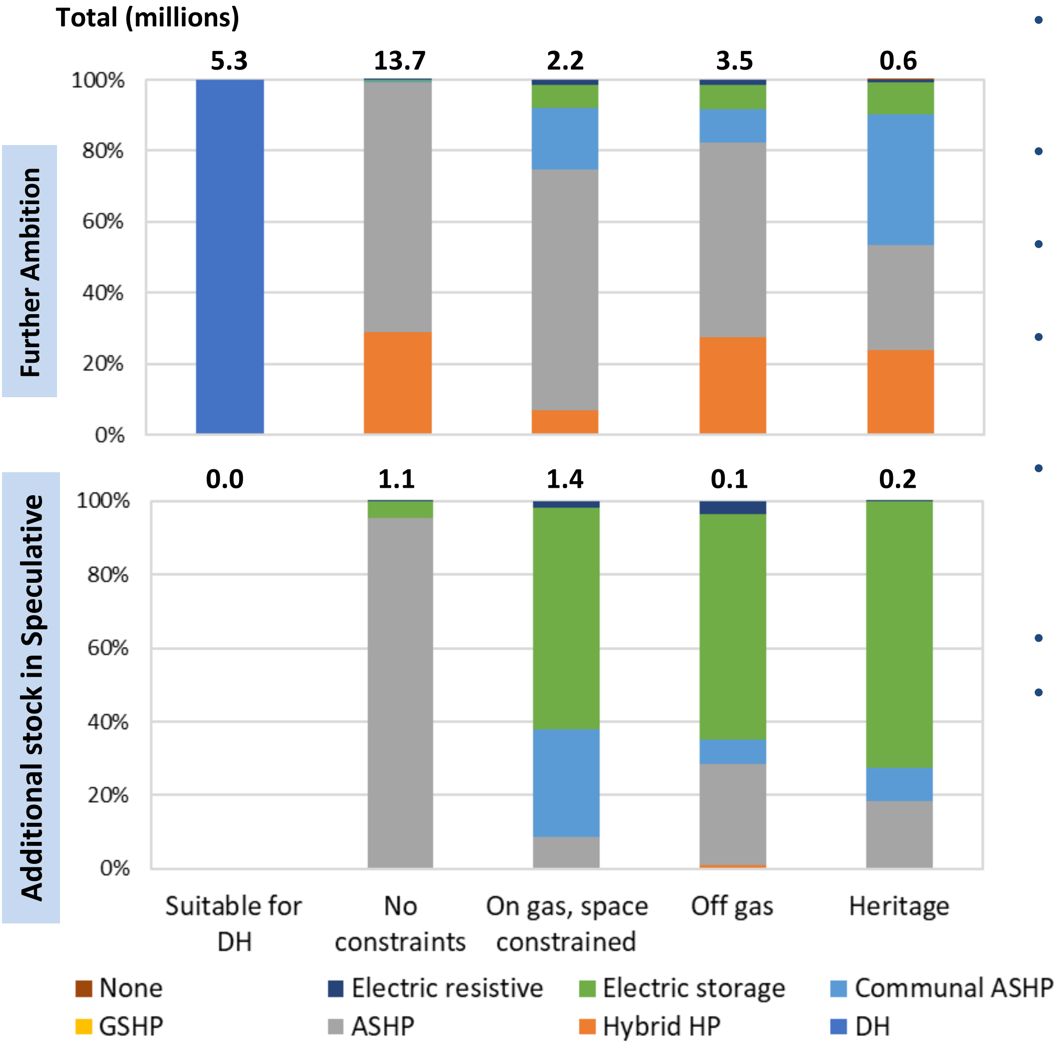
Heating systems deployed across the UK stock by scenario

Heating technology	Core	Further Ambition	Speculative
DH	**5,321,947**	**5,321,947**	**5,321,947**
Electric storage	**260,854**	**458,310**	**1,569,521**
Electric resistive	**57,646**	**93,385**	**124,216**
All ASHP	**11,579,000**	**13,242,545**	**14,501,756**
Standard ASHP	*11,205,143*	*11,367,149*	*12,494,432*
with small heat battery for DHW	*171,003*	*1,672,493*	*1,804,416*
with additional thermal storage for SH	*202,854*	*202,902*	*202,908*
All GSHP	**38**	**67**	**67**
Standard GSHP	–	–	–
with small heat battery for DHW	*38*	*67*	*67*
with additional thermal storage for SH	–	–	–
All hybrid heat pumps	**4,919,066**	**5,216,470**	**5,217,410**
On gas grid	*3,954,307*	*4,215,186*	*4,215,186*
Off gas grid	*964,758*	*1,001,284*	*1,002,224*
without storage for DHW	*4,919,066*	*5,216,470*	*5,217,410*
with storage for DHW	–	–	–
with resistive heating	–	–	–
Solar thermal	–	–	–
Communal ASHP	**406,085**	**1,010,847**	**1,446,687**
None	–	**231**	**231**
Total	**22,544,635**	**25,343,802**	**28,181,834**

The new build stock, modelled by the CCC, is expected to add another 500,000 homes on district heating, with around 7m new build homes relying on heat pumps under the Core, Further Ambition and Speculative scenarios.

Central: Heat pumps are deployed across all non-DH stock segments, with storage heating and communal heating prevalent where heat pumps are constrained

Heating systems deployed by stock segment



- ASHPs are the most deployed system at building-level, and are found across all non-DH segments[1] and in both the Further Ambition and Speculative scenarios
- DH and Hybrid heat pumps are also deployed in a large share of the stock, almost all in Further Ambition
- Hybrid heat pumps are taken up across the on and off gas stock, with a lower share in space constrained homes
- Electric heating options feature most strongly in the Speculative scenario, in homes with some form of constraint
- Communal heating is deployed across several segments, primarily in space constrained homes (only half of which are assumed suitable for heat pumps or hybrids) and heritage homes
- Solar thermal is available, but not taken up in this scenario
- Very few GSHPs are taken up in this scenario due to the higher capital cost relative to ASHPs, despite the higher efficiency assumed. However, different shares of HPs may result with variations in the input assumptions on cost and efficiency. In addition, consideration of a longer timeframe could benefit GSHPs, since the difference in replacement cost between the two technologies is lower than the difference in first time installation cost, as the GSHP ground array can have a long lifetime.[2]

[1] DH also deploys heat pumps (network level heating); [2] GSHPs have a higher base cost of first time installation than ASHPs due to required groundworks but this cost is not repeated as the technology is replaced

Central: Nearly 5 million cavity walls, 5 million solid walls and more than 17 million loft top-up measures are deployed

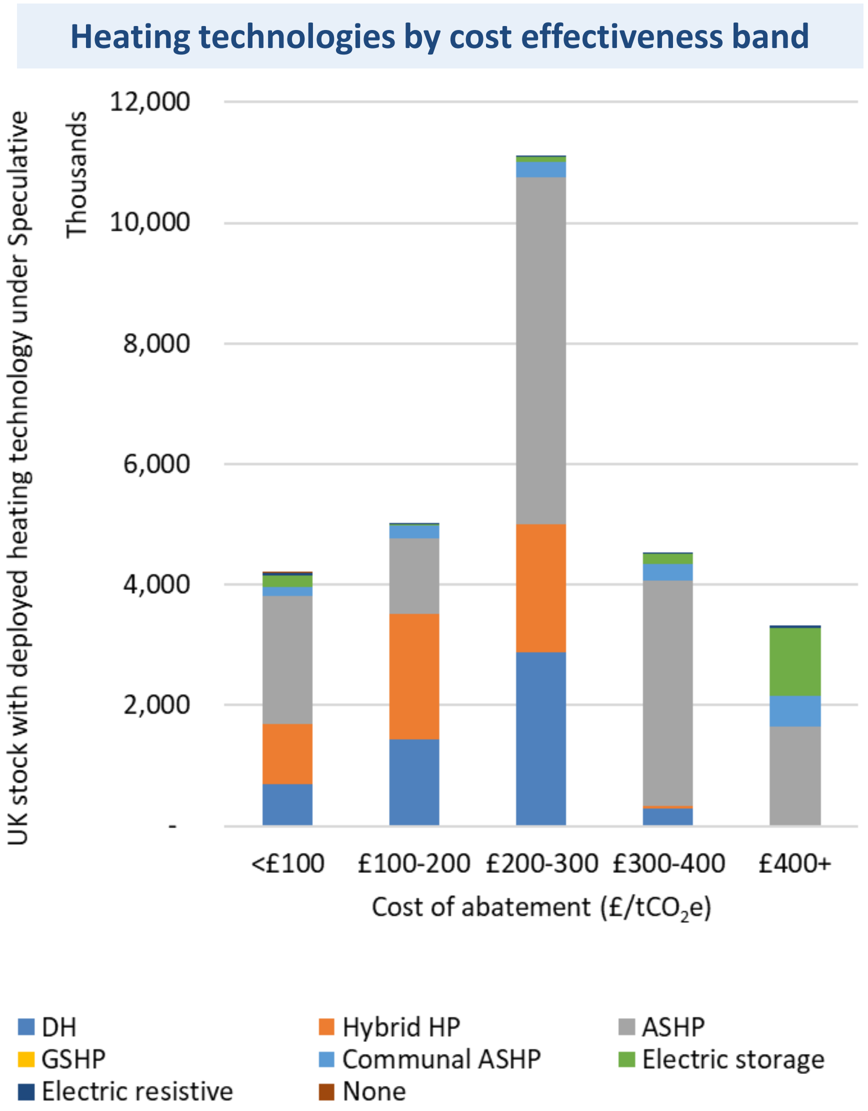
Energy efficiency deployment by scenario

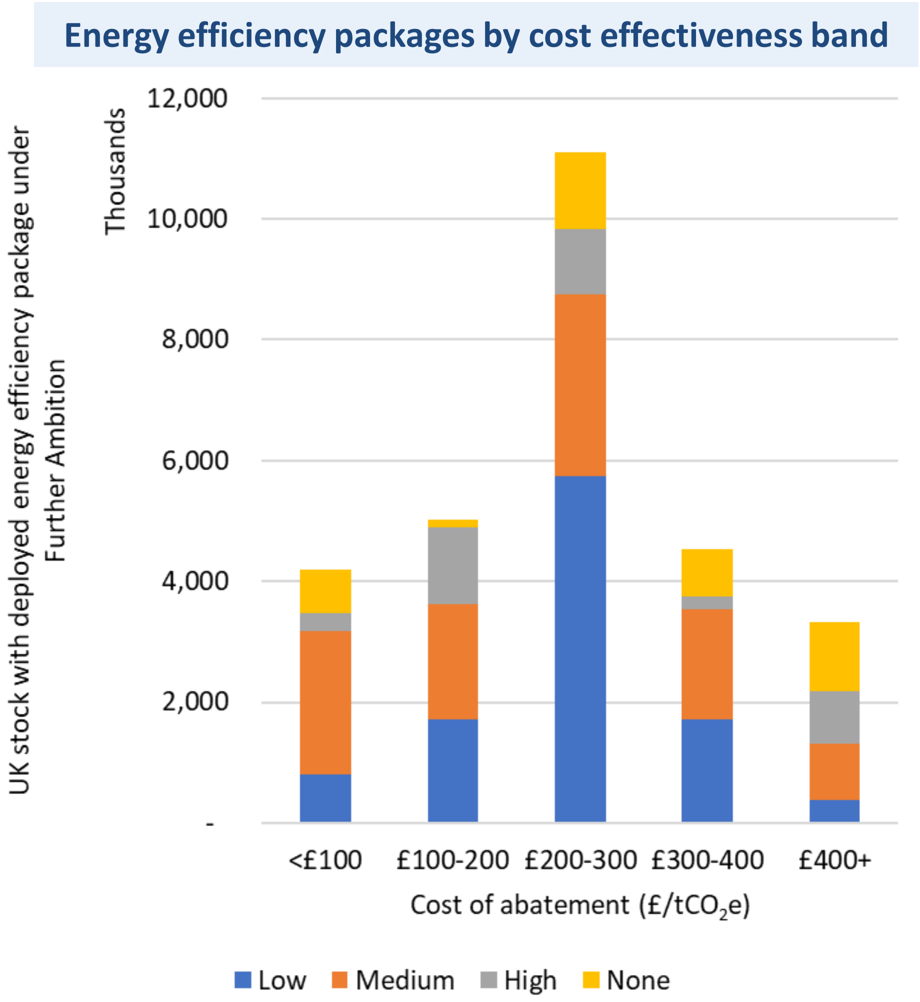
Number deployed (millions)	Core	Further Ambition
Measure		
Loft	17.4	21.4
Cavity wall	4.8	5.7
Solid wall	4.9	5.8
Floor	2.4	3.4
Package		
None	2.4	4.1
Low	8.8	10.4
Medium	8.3	10.0
High	2.6	3.7
Energy demand savings (TWh/y)	78	92.4
Total heat demand in 2017 (TWh/yr)	365	
Total heat demand in 2050 (TWh/yr)	287	273
Reduction in heat demand as a result of energy efficiency	21%	25%

- The Further Ambition scenario includes a reduction of the heat demand in the UK's existing stock by 25% through the installation of energy efficiency.
- At least one measure is installed in 70% of the UK stock in the Core scenario, increasing to 85% in Further Ambition.
- For comparison, analysis for the 5CB[1] in 2013 identified a remaining potential of 7.2 million solid walls and 5.8 million cavity walls (2.5 million easy-to-treat and 3.3 million hard-to-treat) and 20.2 million uninsulated floors (of which 8.2m were insulated by 2050 in that work).
- Just under 6 million solid wall insulation measures are deployed under Further Ambition; comparison with the 5CB figures suggest that roughly 80% of the potential for solid wall insulation is addressed.
- Of the solid wall measures, 1 million are in fuel poor homes, which addresses 96% of the potential (noting that additional solid wall measures were deployed explicitly to that segment).
- Comparison of the cavity wall figures suggest that essentially all the remaining potential is addressed.
- The 5CB analysis identified potential for nearly 11 million loft insulation top-ups; the number of loft insulation measures deployed in this scenario is greater (21.4 million) due mainly to the inclusion of loft top-ups in cases with existing insulation of 200mm and above, which were excluded in the 5CB analysis.
- Less than 20% of the estimated potential for floor insulation is addressed, reflecting the relatively low uptake of the High efficiency package (3.7 million High packages including 3.4 million floors)[2].
- Homes in which no efficiency package is taken up are largely those with no remaining potential for wall and loft insulation.

[1] *Review of potential for carbon savings from residential energy efficiency*, (2013) Element Energy and Energy Saving Trust for the CCC. [2] The floor insulation deployment is below the level deemed cost-effective in the 5CB work. Here, a cautious view has been taken in view of the level of disruption associated with this intervention. A greater potential for floor insulation may be realised where innovative solutions can be applied to address this barrier.

Central: Breakdown of heating technology and energy efficiency package by cost of abatement





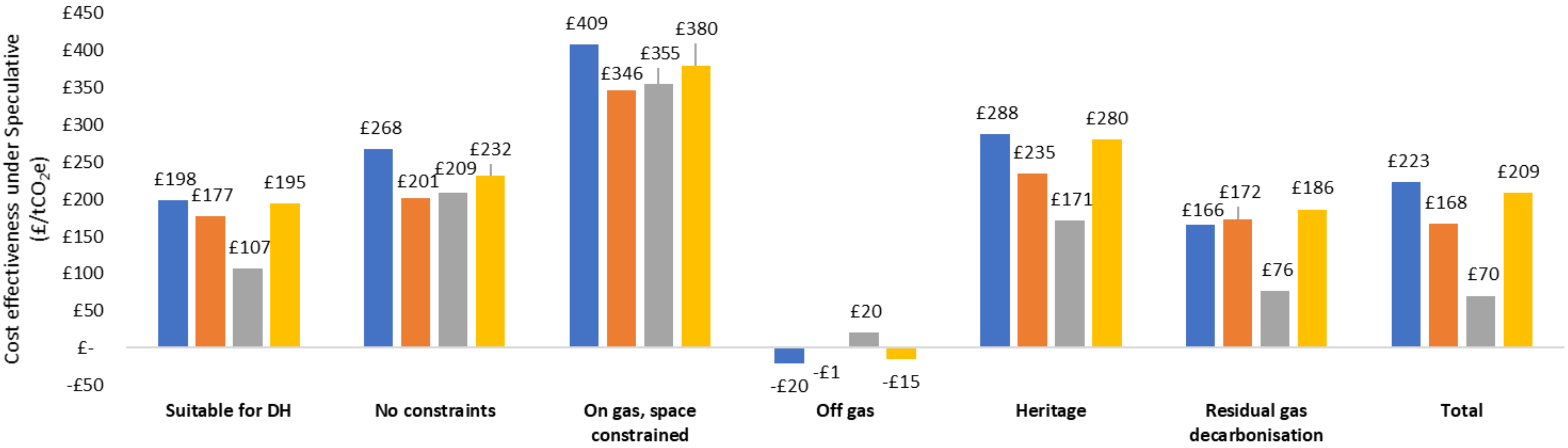
Central: Summary of stock addressed and emissions abatement by Devolved Administration

				Direct emissions abatement		Total emissions abatement			
		Stock addressed (millions)	Proportion of Regional Stock addressed (%)	$MtCO_2e$	Proportion of UK direct emissions abatement %	$MtCO_2e$	Proportion of UK total emissions abatement %	Total cost (£m/y)	Average cost effectiveness (£/tCO_2)
Scotland	Core	1.8	76%	3.8	7%	3.7	7%	£656	£175
	Further Ambition	2.4	100%*	4.9	7%	4.8	7%	£922	£194
	Speculative	2.4	100%	5.3	7%	5.2	7%	£1,152	£223
Wales	Core	1.0	83%	3.2	6%	3.1	6%	£429	£136
	Further Ambition	1.3	100%*	4.1	6%	4.0	6%	£622	£156
	Speculative	1.3	100%	4.2	6%	4.1	6%	£684	£168
Northern Ireland	Core	0.7	90%	2.6	5%	2.5	5%	£122	£48
	Further Ambition	0.8	100%*	2.9	4%	2.9	4%	£187	£65
	Speculative	0.8	100%	3.0	4%	2.9	4%	£204	£70

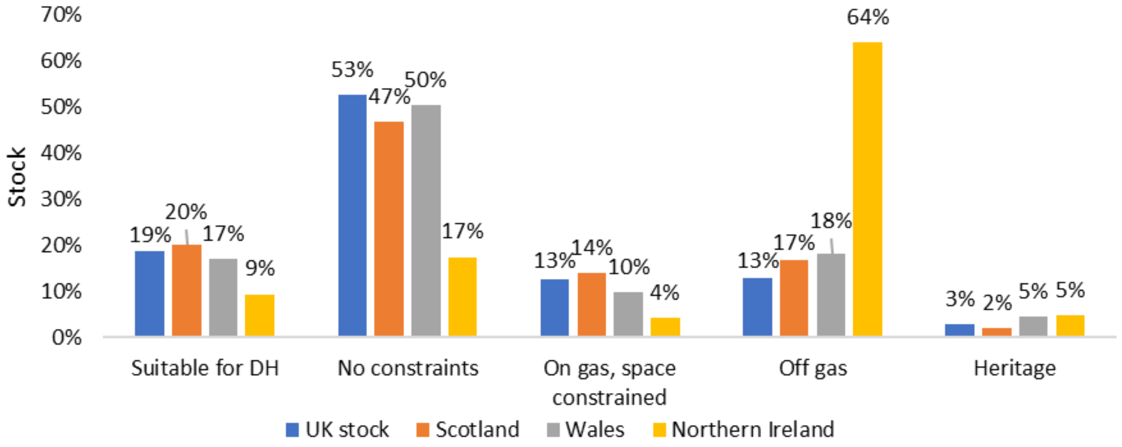
- The devolved administrations account for 17% of the direct and total emissions abatement in all scenarios, in-line with the proportion of baseline total emissions from each region
- Measures in Scotland have a higher than average cost of abatement, whereas measures in Northern Ireland have a significantly lower than average cost of abatement, reflecting the larger proportion of off gas homes in Northern Ireland
- Cost of abatement across stock segment is included in the Appendix

* The Further Ambition scenario includes the installation of energy efficiency measures in all homes where part of a cost optimal decarbonisation package. Speculative involves the additional deployment of low carbon heating only in the 10% most costly homes

Central: Summary of cost effectiveness by Devolved Administration

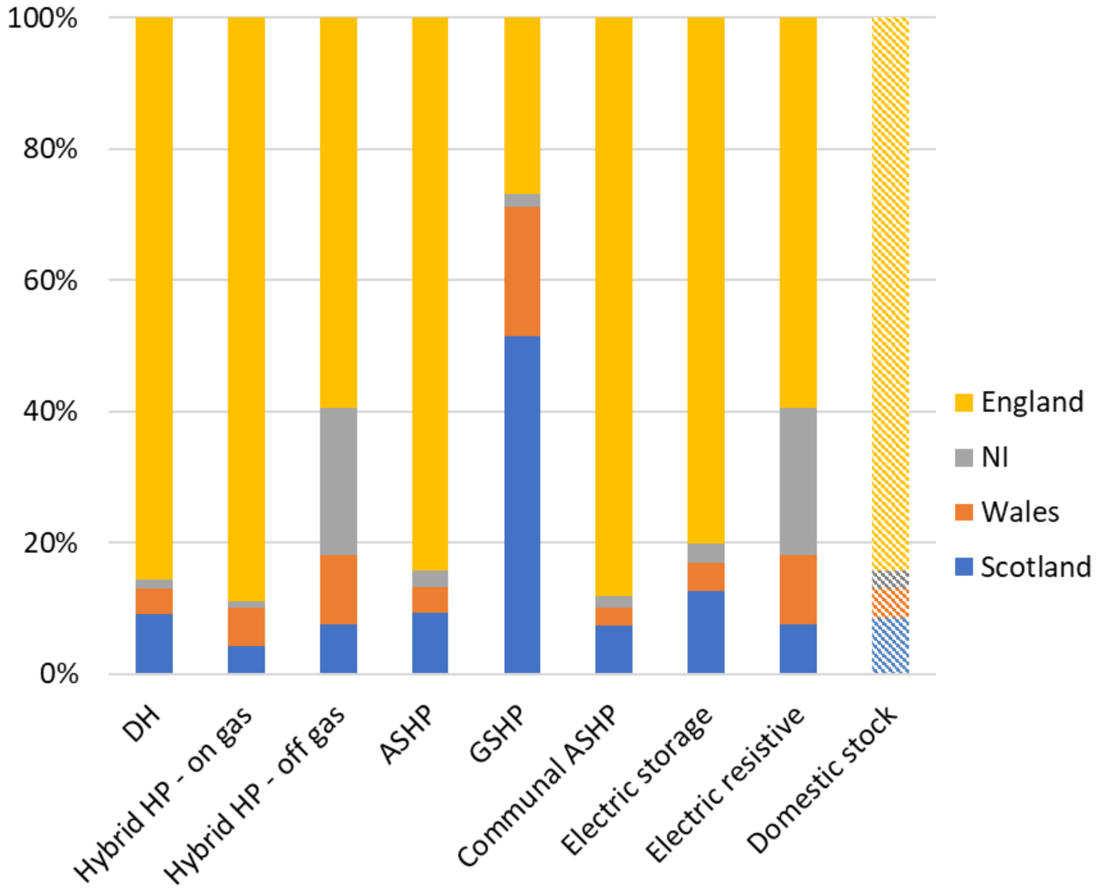


Proportion of regional stock by constraint category



Central: Summary of heating system deployment by region

Heating systems deployed by region



- DH and ASHPs are distributed fairly evenly across the UK stock, with slight underrepresentation in Northern Ireland
- On gas hybrid heat pumps are underrepresented in Scotland and Northern Ireland while off gas hybrid heat pumps are overrepresented in all devolved administrations compared to the UK stock. This overrepresentation is in-line with the proportion of off gas homes in these regions.
- Similarly, electric resistive heating – and, to a lesser extent, storage heating – is overrepresented in the devolved administrations where a higher proportion of off gas options are deployed.
- GSHPs are largely deployed in Scotland and Wales,[1] although the absolute number of GSHPs is very small (67 total across the whole stock) and the correlation may not be meaningful.

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[1] In the model, GSHPs are deployed in homes with electric storage heaters as the counterfactual. In these homes, the difference in CO_2 content of off peak to on peak electricity results in negative carbon savings on switching to ASHP but the higher SPF of GSHPs results in positive carbon savings. Aside from these cases, the higher costs assumed for GSHPs relative to ASHPs mean GSHPs are not taken up.

Central: Summary of energy efficiency deployment across Devolved Administrations

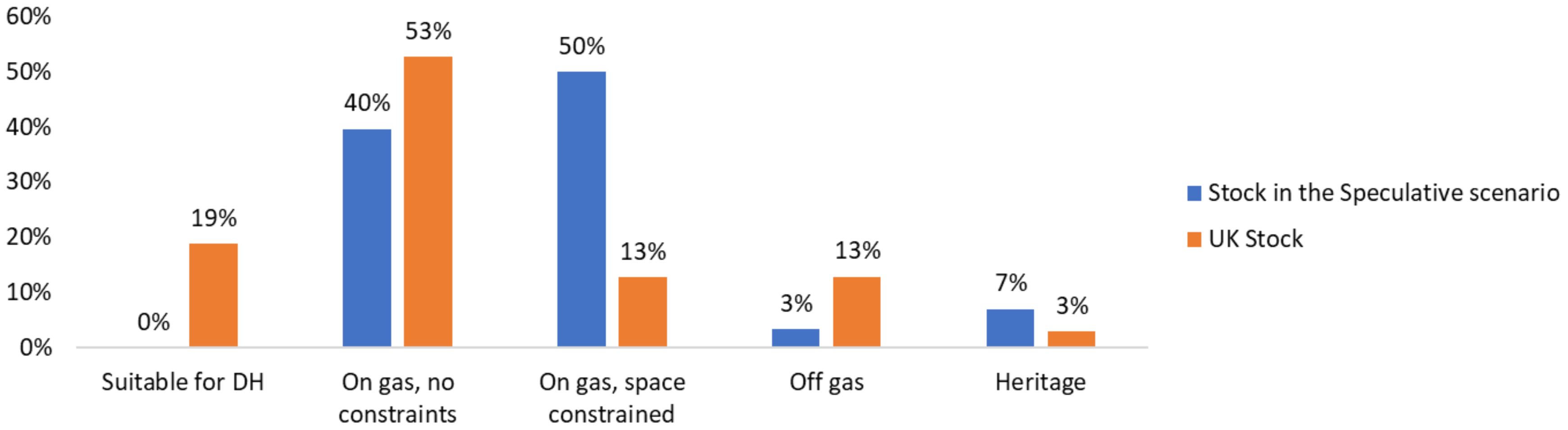
Energy efficiency deployment by scenario

	Core			Further Ambition		
	Scotland	Wales	Northern Ireland	Scotland	Wales	Northern Ireland
Measure						
Loft	1,097,251	902,791	541,732	1,431,915	1,072,141	607,236
Cavity wall	377,280	273,668	130,416	474,147	318,286	139,022
Solid wall	375,747	308,363	208,635	445,295	353,238	231,161
Floor	95,018	169,753	49,152	186,957	215,912	58,498
Package						
None	492,550	353,909	210,439	594,383	419,240	239,747
Low	900,959	427,433	309,396	1,105,618	492,223	339,320
Medium	110,003	177,025	53,558	203,839	223,966	63,117
High	318,739	91,432	117,019	497,383	123,661	128,967
Total stock	**1,822,251**	**1,049,798**	**690,411**	**2,401,223**	**1,259,090**	**771,151**

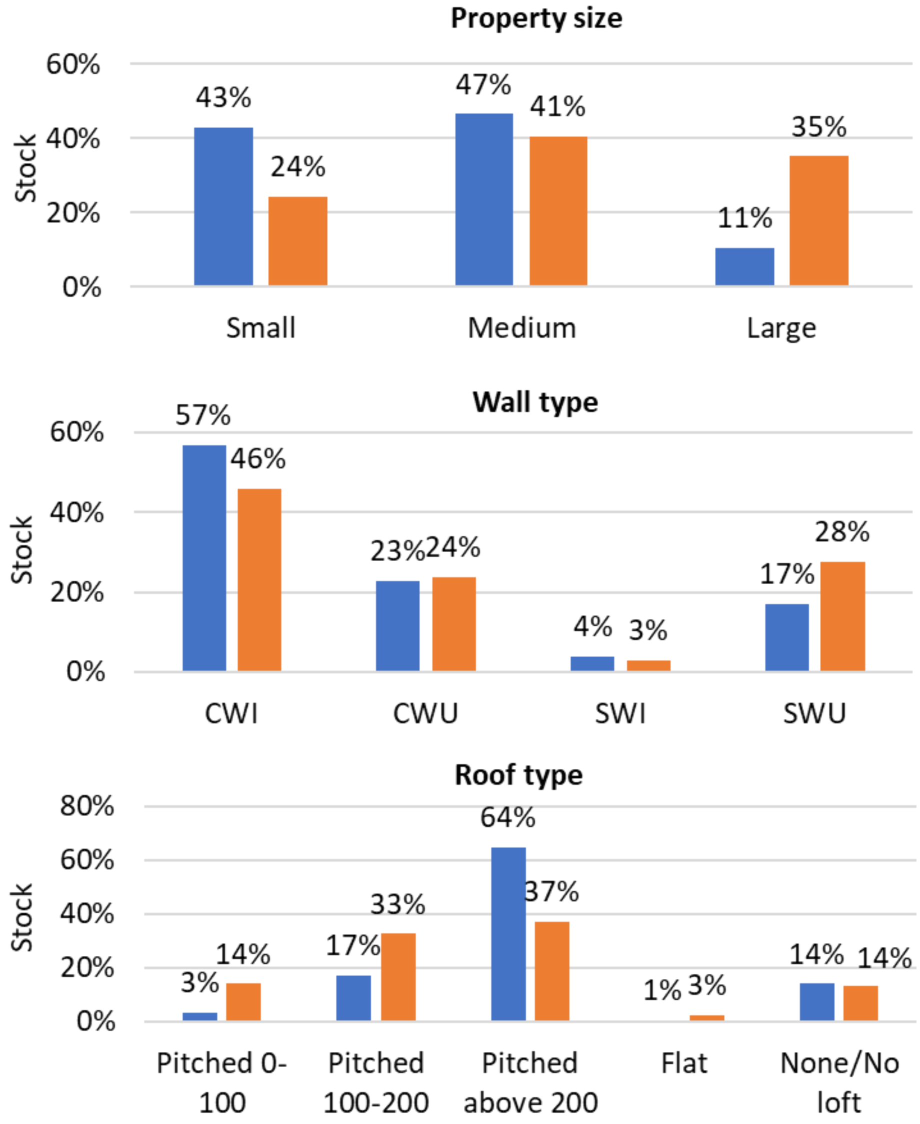
- A high proportion of Welsh homes (90%) receive at least one measure under Further Ambition, with 85% of lofts and 53% of walls receiving insulation, reflecting the lower degree of existing insulation in homes in this region (in the model, 69% of Welsh walls are uninsulated compared to 51% in the wider stock); Similarly, a higher than average number of Welsh homes receive High packages (18% compared to 8% in Scotland and Northern Ireland, and 13% for the UK overall)
- In Northern Ireland, 79% of lofts and 48% of walls receive insulation, compared to 60% of lofts and 38% of walls in Scotland, reflecting the differences in existing insulation in these regions (59% of walls are uninsulated in NI compared to 46% in Scotland)
- 1m solid wall insulation measures are deployed across the devolved regions, accounting for 18% of all wall insulation measures
- As noted in Section 2, the modelling does not take into account certain factors, in particular exposed locations, which may render some homes less suitable for some types of wall insulation; these factors would benefit from further consideration

Central: The majority of existing UK homes decarbonised only in the Speculative scenario are connected to the gas grid, but Heritage homes are over-represented

- The chart below shows the share of the whole UK stock, and the share of the building stock in the Speculative group, associated with each of the ‘Constraint categories’ .
- This shows that **certain categories are over-represented in the Speculative stock**, and others are under-represented.
- The **most over-represented category is the On gas, space-constrained category**, which make up approximately 50% of all homes in the Speculative group, but only 13% of the wider stock. This is a result of the technology suitability constraints, which mean that 50% of these homes are unsuitable for ASHPs, GSHPs and Hybrid HPs, and are therefore forced to take up Electric storage heating, Resistive heating or Communal ASHP, which are more costly.
- **Also highly over-represented are the Heritage homes**, where the suitability constraints and cost-uplifts described in an earlier section combine to mean that more of these homes are pushed towards higher costs. While Heritage homes represent 3% of the wider stock, they make up 7% of the Speculative homes.
- The **most under-represented groups in Speculative are the Suitable for DH** category, as defined by the scenario allocation criteria, **and the Off-gas homes**, which make up 13% of the stock but only 3% of the Speculative homes.
- The **On gas, no constraints category is also under-represented** in the Speculative group relative to the UK stock as a whole, **but still makes up 40% of the Speculative homes**. Further explanation of this is provided on the following slides.



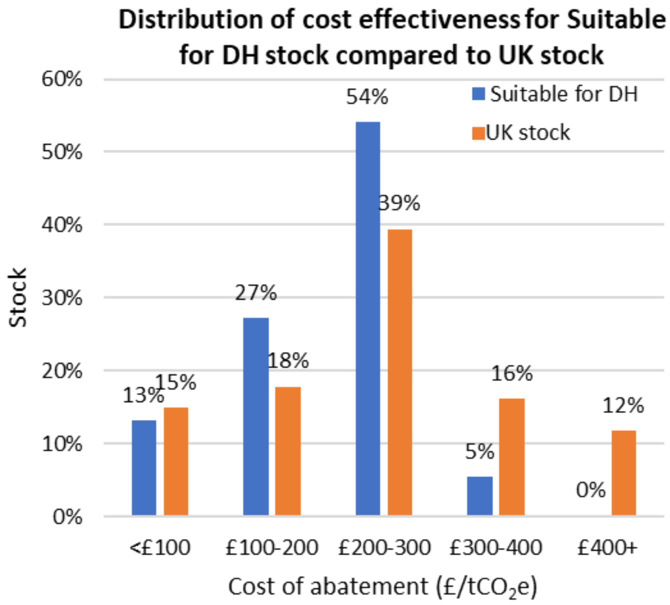
Central: The majority of the most costly homes are small, well-insulated homes for which heating systems have a higher cost per unit of heat delivered

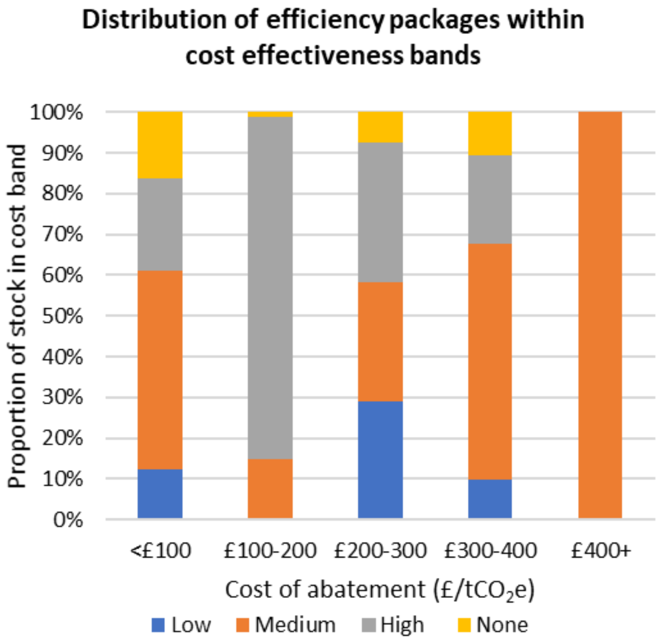


- Homes with an average cost effectiveness of above £418/tCO_2e (i.e. assigned to Speculative) are primarily **small or medium** properties, with **insulated** walls and roofs
- The fact that the most efficient homes are the most costly to treat reflects the balance between the cost of the heating system and the resulting carbon abated:
  - Homes with small heat demand have a smaller potential for carbon abatement than homes with larger heat demand
  - Since most low carbon heating systems have a **fixed cost component** as well as a marginal £/kW component, and a **minimum size**, the capital cost of the heating system per unit of heat delivered is higher for homes with a small heat demand than it is for homes with a high heat demand
  - As a result, **small and/or highly efficient homes tend to have a higher abatement cost**, and are over-represented in the Speculative group
- These trends suggest that homes conventionally thought of as 'hard to treat' are not necessarily the most costly in terms of cost of abatement, although such homes may experience the highest upfront costs in absolute terms.

Central: Suitable for DH

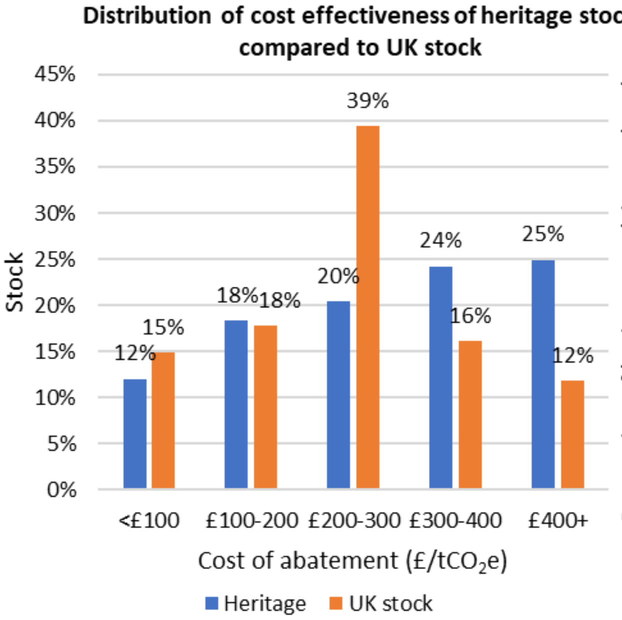
- The majority (94%) of homes in the Suitable for DH category, as shown in the first chart below, have an abatement cost of below £300/t, with 40% below £200/tCO$_2$e
- Only 6% of the Suitable for DH stock has an abatement cost of over £300/tCO$_2$e compared with 28% across the whole stock
- A mix of energy efficiency packages are deployed, with a significant share of Medium and High packages; although there is generally less need for improving energy efficiency to meet comfort levels in homes connected to heat networks than for homes with heat pumps (since heat from DH can be supplied at high temperatures), infrastructure costs are included in the modelled fuel costs for DH, which incentivises improved energy efficiency (to minimise running costs)
- This supports the notion that the level of heat network deployment presented in the Central scenario (19% of the stock) is cost-effective, and homes suitable for DH aren't part of the 'hard-to-decarbonise' stock



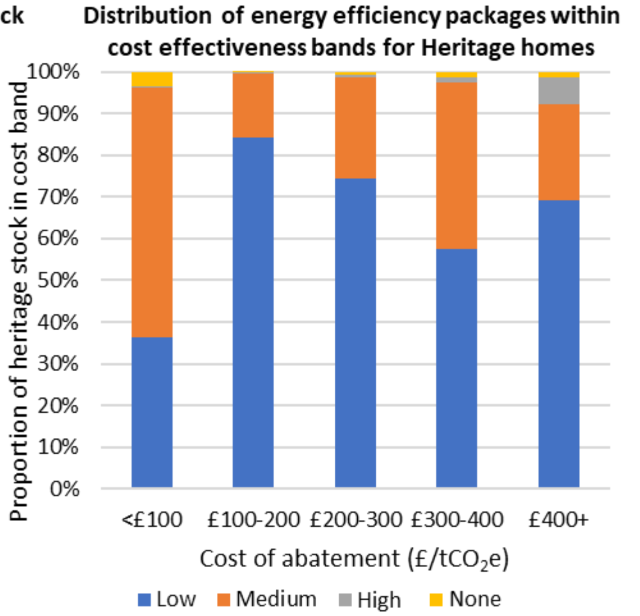


Central: Heritage

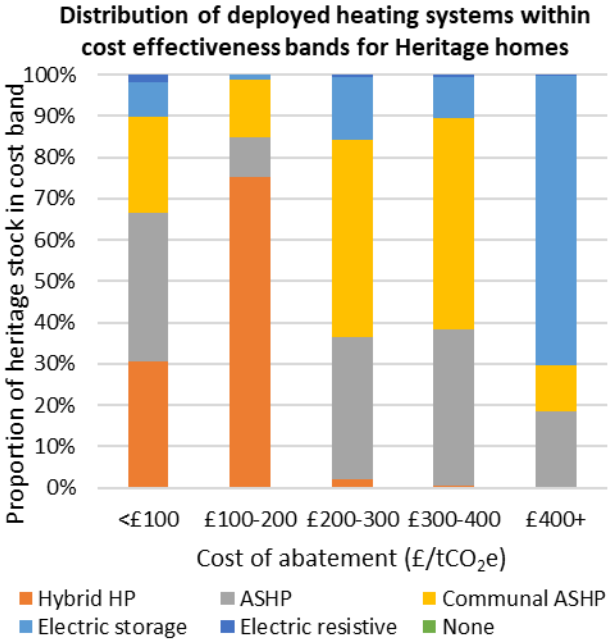
- Heritage homes have a higher abatement cost profile than the stock as a whole.
- Nearly 50% of the Heritage stock has an abatement cost above £300/tCO_2e, compared with 28% across the whole stock.
- The majority of heritage homes in the Central scenario take up a Low efficiency package, with very few taking up a High package. This is partly related to the suitability constraints – all listed buildings and 50% of buildings in conservation areas are deemed unsuitable for the High package due to the unsuitability of double glazing (secondary glazing is in the Medium package) – and partly to the cost uplifts applied to efficiency measures.
- A large share of the homes in the higher abatement cost bands above £200/tCO_2e are those where the suitability constraints preclude the deployment of ASHPs and Hybrid HP, and the homes instead take up the more costly options of Electric storage heating and Communal ASHP.



Distribution of cost effectiveness of heritage stock compared to UK stock



Distribution of energy efficiency packages within cost effectiveness bands for Heritage homes

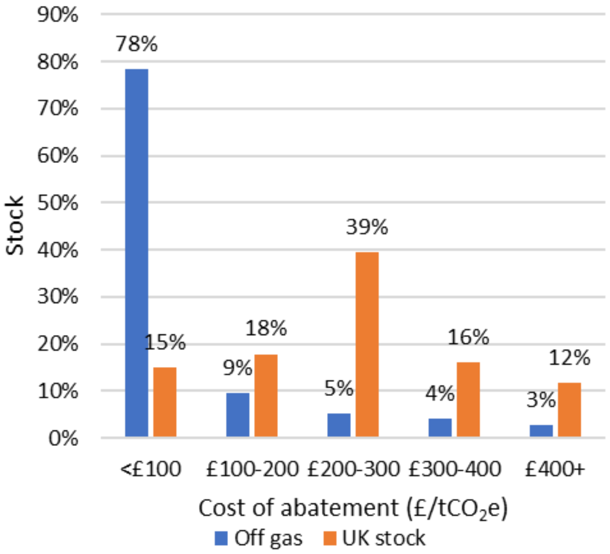


Distribution of deployed heating systems within cost effectiveness bands for Heritage homes

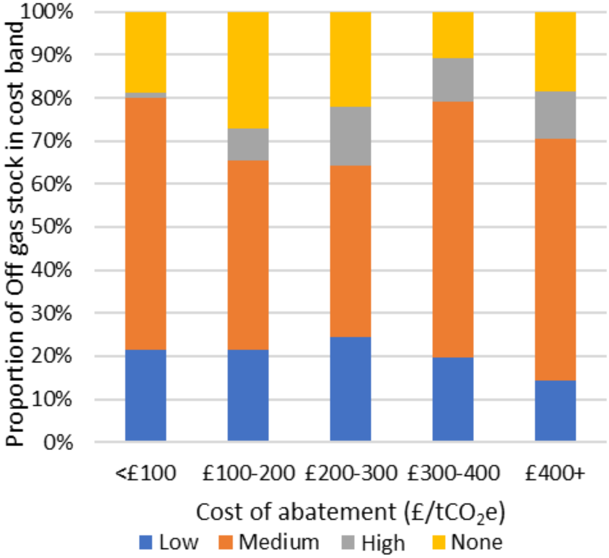
Central: Off gas

- A significantly smaller share of the Off gas stock is found in the higher abatement cost bands, compared with the UK stock as a whole.
- 78% of the Off gas homes have an abatement cost less than £100/tCO_2e, compared with 15% across the whole stock
- The comparatively low cost of abatement is largely a result of the higher cost counterfactual in the Off gas category than in the wider stock, since the cost of electric and oil heating is substantially higher than the cost of gas heating.
- A mix of energy efficiency packages are taken up, but this is not strongly correlated with the abatement cost.
- The higher abatement cost homes are those correlated with the deployment of Electric storage heating – this includes Off gas homes that are space-constrained and so unable to take up ASHPs or Hybrid HPs.

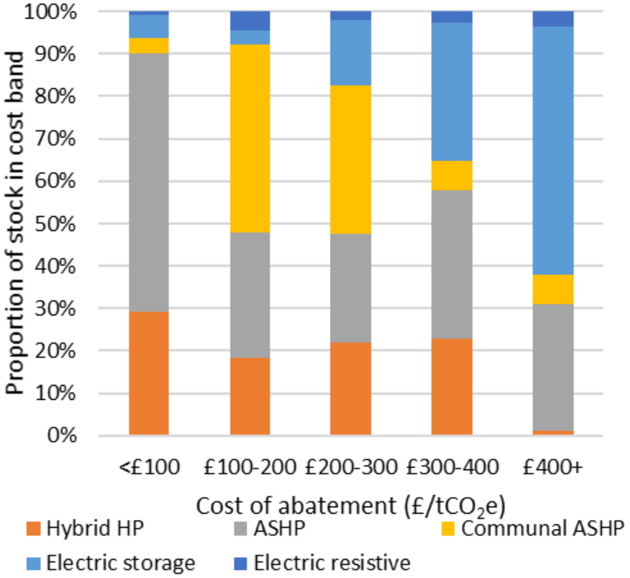
Distribution of cost effectiveness of Off gas stock compared to UK stock



Distribution of energy efficiency packages within cost effectiveness bands for Off gas homes



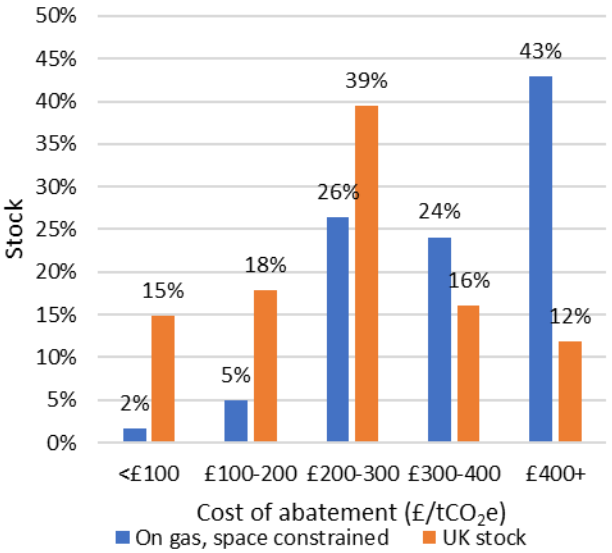
Distribution of deployed heating systems within cost effectiveness bands for Off gas homes



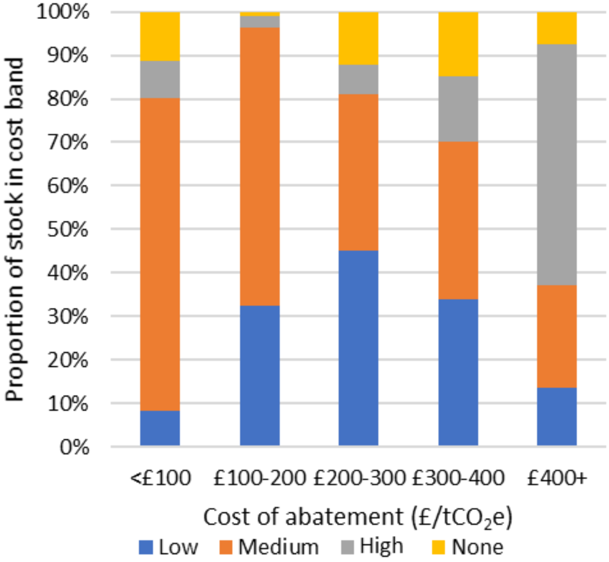
Central: On gas, space constrained

- On gas, space constrained homes show a high abatement cost profile compared with the wider stock.
- Only 7% of these homes have an abatement cost less than £200/tCO_2e, compared with 33% of the stock as a whole; and 43% have an abatement cost over £400/tCO_2e, compared with 12% of the wider stock.
- This is primarily due to the fact that Hybrid HPs and ASHPs of any type are deemed unsuitable across 50% of homes in this group, in which only the higher cost heating options such as Communal ASHP, Electric storage and Electric resistive heating can be deployed.
- A large share of those homes in the highest abatement cost band above £400/tCO_2e take up a High package

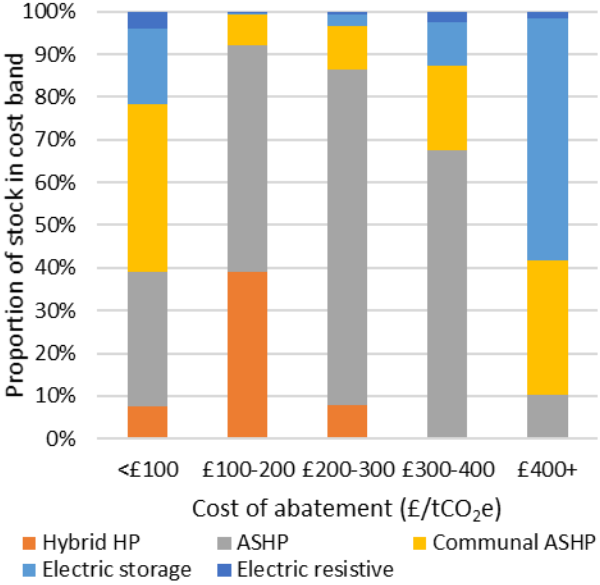
Distribution of cost effectiveness of On gas, space constrained stock compared to UK stock



Distribution of energy efficiency packages within cost effectiveness bands for On gas, space constrained homes

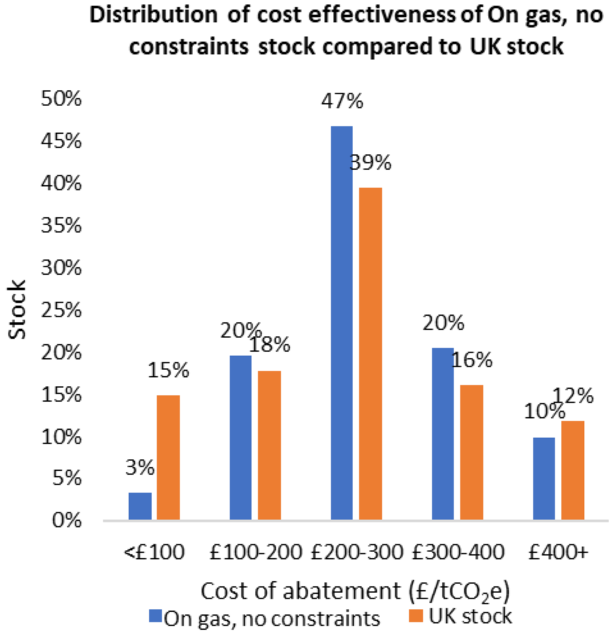


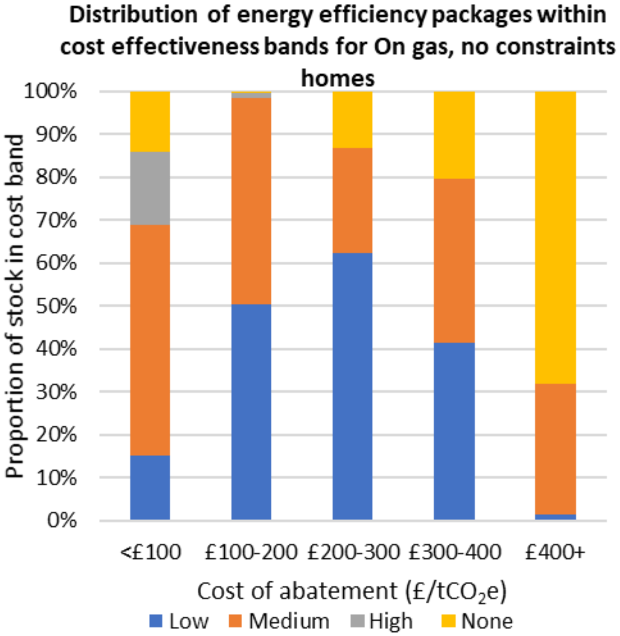
Distribution of deployed heating systems within cost effectiveness bands for On gas, space constrained homes

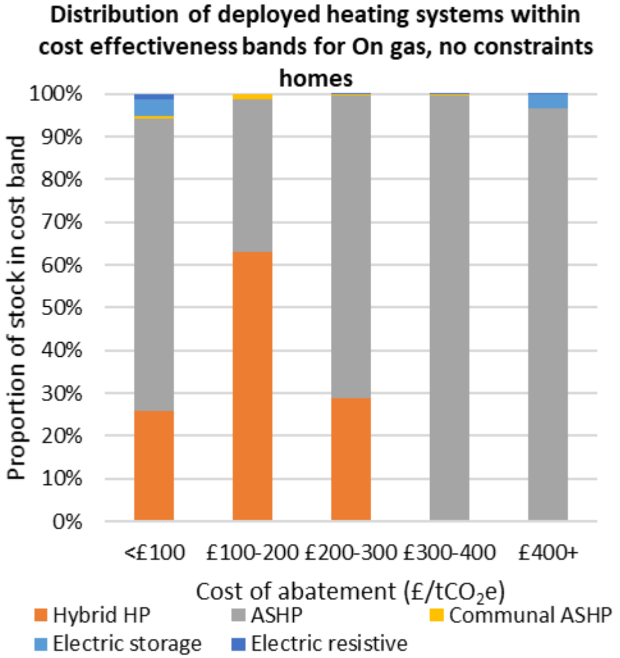


Central: On gas, no constraints

- The abatement cost profile of the On gas, no constraints category, which makes up 53% of the whole stock, is broadly similar to that of the whole stock, but with lower representation in the lowest (less than £100/tCO_2e) and highest (more than £400/tCO_2e) cost bands.
- It is notable that this category has a significant share in the high abatement cost bands, since this is the most common category and, more than any other category, represents the typical gas-heated home in the UK.
- The under-representation of On gas, no constraints homes in the lowest abatement cost band reflects the absence of off gas homes (the Non constraints category is all on gas) and to a lesser extent the homes suitable for DH.
- The higher abatement cost bands contain a high share of homes where no energy efficiency is deployed – this is consistent with the evidence presented on an earlier slide showing that the higher abatement costs contain a higher share of homes which are already energy efficient (already have wall and loft insulation), and so the energy efficiency packages do not provide significant (or any) savings.
- The relatively large share of high abatement costs is therefore attributable to the high cost of low carbon heating relative to a gas counterfactual, particularly in small and relatively energy-efficient homes where, as described on a previous slide, the cost of the low carbon heating system per unit of delivered heat is high.


Distribution of cost effectiveness of On gas, no constraints stock compared to UK stock


Distribution of energy efficiency packages within cost effectiveness bands for On gas, no constraints homes


Distribution of deployed heating systems within cost effectiveness bands for On gas, no constraints homes

Contents

Two alternative options to the Central scenario have been studied, to assess the impact of no hydrogen deployment and more widespread hydrogen deployment

Option	Description	Available technologies
No Hydrogen	• Explores the mix of heating technologies required for decarbonisation in a scenario where hydrogen is not deployed in the gas grid • Hydrogen faces uncertainty with regards to technical challenges of delivery and production at scale, particularly with carbon capture and storage (CCS) which is crucial to hydrogen becoming a low carbon fuel • This option represents a case where hydrogen cannot be used to decarbonise gas technologies	• No hydrogen-using technologies allowed: • No hybrid heat pumps using hydrogen (only hybrids using bioLPG in off gas homes) • No hydrogen boilers • No hydrogen used to decarbonise gas peaking plant in heat networks – further heat pumps and thermal storage used to replace the peaking hydrogen plant • No other differences from the Central case
Hydrogen-led (Main case)	• Explores the mix of heating technologies that could be taken up if hydrogen was widely available throughout the existing gas grid and homes able to use hydrogen boilers as main heating system • This option represents a "least action" view at the building-level, where hydrogen is widely relied upon for decarbonisation • In the main Hydrogen-led case, the situation modelled is the replacement of natural gas boilers with hydrogen boilers at the time of conversion of the local gas grid to hydrogen (better aligning with assumptions made for the equivalent scenario in the CCC's 2018 report 'Hydrogen in a low-carbon economy'). We assume that the gas boilers are on average halfway through their lifetimes at the time of replacement, and so half of the value of the gas boiler remains to be paid at the point in time the hydrogen boiler is installed.[1]	• All technologies allowed, including hydrogen boilers (as well as hybrid heat pumps with hydrogen and peaking hydrogen for DH, as included in the Central scenario) • Hydrogen only available to on gas homes (bioLPG available to off gas homes) • No other differences from the Central case
Hydrogen-led (Hyready boiler rollout sensitivity)	• Sensitivity on the Hydrogen-led scenario in which rollout of hydrogen boilers occurs through deployment of 'Hyready' boilers, capable of running on both natural gas and hydrogen, at the natural replacement rate (i.e. at end of life) • This approach avoids the cost of early replacement that occurs in the main Hydrogen-led case, as described above • An additional (smaller) cost is applied for the switchover of the Hyready boilers from gas to hydrogen (reflecting one hour of a gas engineer's labour – see Assumptions log for details) • This is an alternative, more cost-effective, possible approach to widespread rollout of H_2 boilers	• As for Hydrogen-led (Main case)

[1] This is accounted for in the modelling by including in the 2050 cost of the hydrogen boiler half the cost of the counterfactual gas boiler (with both costs annualised over the lifetime of 15 years). The 2050 annualised cost for the hydrogen boiler therefore represents that during the first generation of hydrogen boiler rollout – in subsequent generations there would be no 'early replacement' and the effective cost would be lower.

Alternative options: Summary of stock addressed and emissions abatement in Central, No hydrogen and Hydrogen-led scenarios

					Direct emissions abatement		Total emissions abatement			
		Stock addressed (millions)	Stock addressed (%)	Date by which all measures received	MtCO$_2$e	%	MtCO$_2$e	%	Total cost (£m/y)	Average cost effectiveness (£/tCO$_2$)
Central	Core	22.5	80%	2050	55.7	74%	54.4	72%	£9,466	£174
	Further Ambition	28.2*	100%	2050	71.8	95%	69.7	92%	£13,304	£191
	Speculative	28.2*	100%	2060	75.4	100%	73.2	97%	£15,299	£209
No hydrogen	Core	22.4	79%	2050	62.5	83%	61.1	81%	£11,167	£183
	Further Ambition	28.2*	100%	2050	71.7	95%	70.0	92%	£13,833	£198
	Speculative	28.2*	100%	2060	75.4	100%	73.5	97%	£15,910	£216
Hydrogen -led (Main)	Core	9.9	35%	2050	24.5	32%	24.3	32%	£2,247	£93**
	Further Ambition	28.2*	100%	2050	72.0	96%	69.5	92%	£11,485	£165**
	Speculative	28.2*	100%	2060	75.4	100%	72.6	96%	£12,617	£174**

* The Further Ambition scenario includes the installation of energy efficiency measures in all homes where part of a cost optimal decarbonisation package. Speculative involves the additional deployment of low carbon heating only in the 10% most costly homes

- The No hydrogen scenario achieves higher direct and total emissions abatement in Core than Central, due to the removal of gas options from grid-connected homes (since the conversion from gas to hydrogen of homes in Core is only implemented in Further Ambition) – however, this is achieved at a slightly higher cost of abatement.
- The Hydrogen-led scenario, in which hydrogen boilers are allowed, achieves a much lower level of abatement in the Core scenario (since the conversion from gas to hydrogen of homes in Core occurs in Further Ambition) but achieves a similar emissions abatement in Further Ambition and Speculative at a lower cost of abatement than the Central scenario. ****It is important to note that the hydrogen fuel cost applied does not include the cost of large-scale hydrogen storage (such as in salt caverns). In the Hydrogen-led scenario, where hydrogen plays a large role in supplying heat in buildings, this means the costs are likely to be an underestimate. Previous modelling for the CCC by Imperial College suggested that 20TWh of hydrogen storage could be needed to meet peak demand in a winter week in a hydrogen-led scenario, which could add up £6400m/year in costs. Significant uncertainty remains over the costs and required volumes of hydrogen storage.** The CCC's *Hydrogen in a low-carbon economy* report notes that around 90% of this cost is oversizing hydrogen production capacity to provide instantaneous dispatch of large volumes of hydrogen and that alternative approaches to storage could lead to significant cost reductions.
- More generally it should be noted that fuel cost assumptions across scenarios incorporate high-level assumptions on system costs. These remain uncertain and in reality will depend on the scenario and vary as a function of deployment.

Hydrogen in a low-carbon economy, Committee on Climate Change (November 2018); Analysis of Alternative UK Heat Decarbonisation Pathways, Imperial College London (August 2018)

Alternative options: Summary of fuel demand and direct emissions abatement in Central, No hydrogen and Hydrogen-led scenarios

Fuel demand and direct emissions in Central, No hydrogen and Hydrogen-led scenarios (Further Ambition)

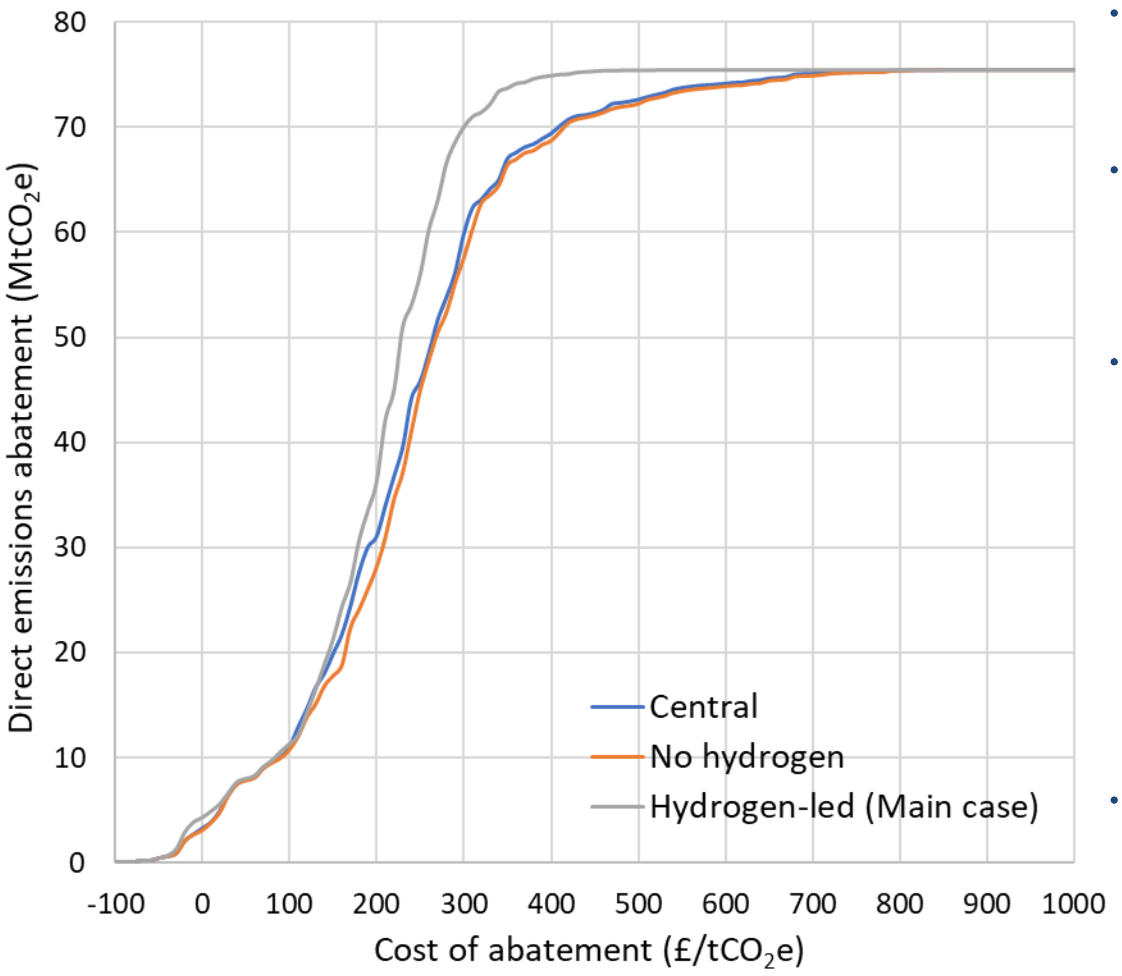
	Fuel demand for heating in 2050[1] (TWh)				Direct emissions in 2050 in Further Ambition scenario ($MtCO_2e$)			
Heat fuel	**Baseline (No EE)**	**Central**	**No Hydrogen**	**Hydrogen-led (Main case)**	**Baseline (No EE)**	**Central**	**No Hydrogen**	**Hydrogen-led (Main case)**
Gas	352.6	19.8	20.3	17.5	64.9	3.7	3.7	3.2
Oil	42.8	0.0	0.0	0.67	10.6	0.0	0.0	0.2
Electricity	22.4	68.4	76.0	27.0	-	-	-	-
Hydrogen	-	40.3	-	203.3	-	-	-	-
BioLPG	-	6.5	6.4	7.0	-	-	-	-
TOTAL	**417.8**	**135.0**	**102.8**	**255.5**	**75.4**	**3.7**	**3.7**	**3.4**

- All three cases achieve at least 95% reduction in direct CO_2 emissions by 2050, with remaining emissions of 3.7 $MtCO_2e$ or less
- This is achieved in all cases through the almost total eradication of gas and oil demand for heating, but with widely varying fuel mixes for heating in 2050
- The electricity demand for heating in 2050 increases to between 27 and 76 TWh compared with 22 TWh in the Baseline
- The hydrogen demand is (unsurprisingly) largest in the Hydrogen-led case, at more than 200 TWh in 2050; in the Central case, the hydrogen demand is 40 TWh
- Demand for BioLPG in off-gas homes ranges between 6-7 TWh in the three cases

[1] Heat delivered through heat networks is presented in terms of the fuel(s) supplying the heat network.

Alternative scenario options: Comparison of cost abatement curves

Direct CO_2 emissions abatement as a function of abatement cost



- For the No hydrogen case, the threshold for Speculative, corresponding to the cost below which approximately 90% of the stock (by number, not emissions) can be addressed, is £418/tCO_2e, as for the Central scenario.
- Under the cost assumptions applied here, widespread uptake of hydrogen boilers allows the majority of the UK stock to be decarbonised at a lower cost of abatement, with the threshold for Speculative set at £316/tCO_2e.
- The lower cost of abatement for the Hydrogen-led option is partly attributable to the lower capital costs of hydrogen boilers compared to heat pumps and hybrids after accounting for the household conversion costs, under the assumptions made here (which we acknowledge carry significant uncertainty). We also reiterate that the hydrogen fuel costs applied here do not include the cost of large-scale hydrogen storage (such as salt caverns) which could lead to significantly higher abatement costs than shown here, particularly in the Hydrogen-led case, as described further on slide 112.
- The similar operation of hydrogen boilers to gas boilers means that fewer energy efficiency measures are required to meet the technical feasibility requirements of the technology, further reducing the cost of deployment – see discussion in following slides.

No hydrogen option: Hybrid heat pumps are only taken up in off gas homes with ASHPs taking their place in most on gas homes

Heating systems deployed by ambition level – No hydrogen scenario

Heating technology	Core	Further Ambition	Speculative
DH	**5,321,947**	**5,321,947**	**5,321,947**
Electric storage	**262,141**	**459,327**	**1,773,201**
Electric resistive	**61,952**	**97,582**	**134,773**
All ASHP	**15,338,464**	**17,222,629**	**18,475,007**
Standard ASHP	*14,904,136*	*15,157,563*	*16,273,002*
with small heat battery for DHW	*171,414*	*1,791,289*	*1,928,221*
with additional thermal storage for SH	*262,914*	*273,777*	*273,783*
All GSHP	**38**	**38**	**38**
Standard GSHP	–	–	–
with small heat battery for DHW	*38*	*38*	***38***
with additional thermal storage for SH	–	–	–
All hybrid heat pumps	**993,201**	**1,028,412**	**1,030,299**
On gas grid	–	–	–
Off gas grid	*993,201*	*1,028,412*	*1,030,299*
without storage for DHW	*993,201*	*1,028,412*	*1,030,299*
with storage for DHW	–	–	–
with resistive heating	–	–	–
Solar thermal	–	–	–
Communal ASHP	**405,729**	**1,010,482**	**1,446,339**
None	–	**231**	**231**
Total	**22,383,472**	**25,140,648**	**28,181,834**

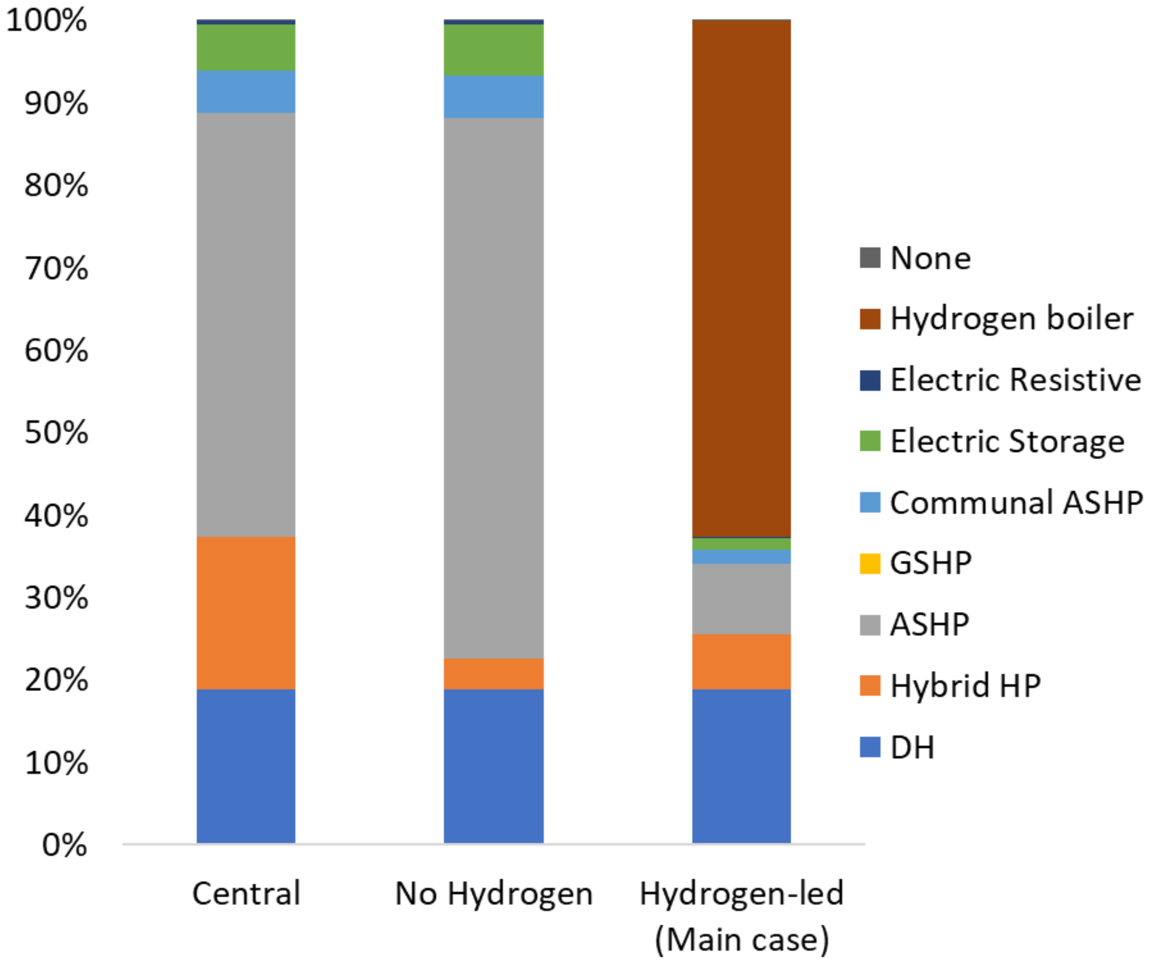
Hydrogen-led option: hydrogen boilers are widely adopted and there is a much lower deployment of electric heating

Heating systems deployed by ambition level – Hydrogen-led (Main case) scenario

Heating technology	Core	Further Ambition	Speculative
DH	**5,321,947**	**5,321,947**	**5,321,947**
Electric storage	**189,739**	**227,052**	**405,110**
Electric resistive	**50,401**	**54,156**	**66,578**
All ASHP	**2,194,917**	**2,267,475**	**2,394,361**
Standard ASHP	*1,888,530*	*1,937,229*	*2,062,671*
with small heat battery for DHW	*70,861*	*85,426*	*85,597*
with additional thermal storage for SH	*235,526*	*244,820*	*246,092*
All GSHP	**38**	**751**	**752**
Standard GSHP	-	-	-
with small heat battery for DHW	*38*	*751*	*752*
with additional thermal storage for SH	-	-	-
All hybrid heat pumps	**1,669,964**	**1,819,124**	**1,873,086**
On gas grid	*747,144*	*859,759*	*860,398*
Off gas grid	*922,820*	*959,365*	*1,012,688*
without storage for DHW	*1,669,964*	*1,819,124*	*1,873,086*
with storage for DHW	–	–	–
with resistive heating	–	–	–
Solar thermal	–	–	**–**
Communal ASHP	**370,791**	**431,556**	**481,414**
Hydrogen boiler	**7,934,264**	**9,895,807**	**17,638,490**
None	–	**96**	**96**
Total	**21,495,662**	**25,123,691**	**28,181,834**

Alternative scenario options: Comparison of heating technology mix

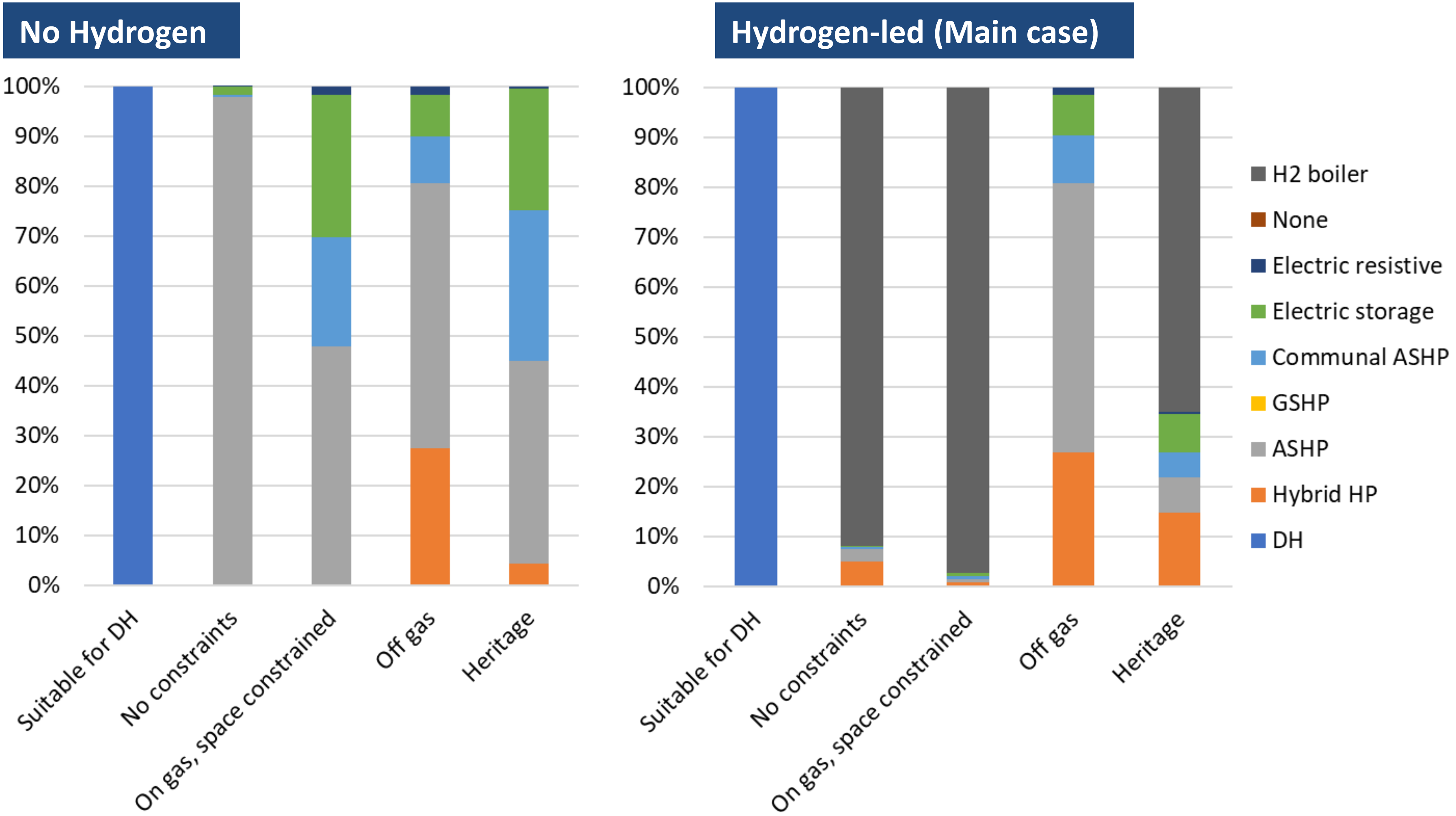
Heating technology mix, Speculative scenario (all stock)



- In the **No hydrogen** scenario, the deployment of Hybrid HPs is limited to the off-gas stock, with mainly ASHPs taking the place of Hybrids in on gas homes
- There is also a small increase in the deployment of Electric storage heating
- In the **Hydrogen-led** scenario, hydrogen boilers are the mostly widely deployed heating system, covering 63% of the stock, with ASHPs (including Communal systems) and Hybrid HPs only taken up in 17% of homes
- The deployment of electric storage heating also falls significantly relative to the Central case
- This implies that even in a system where hydrogen plays a niche role (as in the Central scenario), hydrogen boilers have potential to offer a reduced cost route for decarbonisation for some of the most expensive segments of the stock.

Alternative scenario options: The heating technology mix is unchanged for off gas homes across the options, while on gas homes show large variations

Heating systems deployed by stock segment, Speculative scenario (all stock)



Summary of energy efficiency deployment and heat demand savings

Energy efficiency deployment by scenario

- The table below presents the energy efficiency deployment in existing homes[1].

	No hydrogen		Hydrogen-led (Main case)		Central	
	Core	Further Ambition	Core	Further Ambition	Core	Further Ambition
Measure						
Loft	18.5	23.5	14.0	19.4	17.4	21.4
Cavity wall	5.2	6.6	4.5	5.3	4.8	5.7
Solid wall	6.2	7.4	4.0	5.8	4.9	5.8
Floor	3.5	4.8	2.2	2.3	2.4	3.4
Package						
None	1.4	1.8	1.9	6.4	2.4	4.1
Low	7.7	9.2	6.5	9.6	8.8	10.4
Medium	9.5	12.1	6.8	9.6	8.3	10.0
High	3.8	5.1	2.5	2.6	2.6	3.7
Energy demand savings (TWh/y)	92	110	76	87	78	92
Total heat demand in 2017 (TWh/yr)	365		365		365	
Total heat demand in 2050 (TWh/yr)	273	255	289	278	287	273
Reduction in emissions through energy efficiency	25%	30%	21%	24%	21%	25%

- The No hydrogen option requires higher levels of insulation deployment than Central, to accommodate a higher number of low temperature heating systems (ASHP)
- Conversely, the large reliance on hydrogen boiler technology in the Hydrogen-led case results in lower overall rollout of efficiency measures since optimised energy demand is not required by the heating technology

[1] The CCC separately modelled efficiency in new homes, assuming space heating demand of 15 kWh/m^2/yr from 2025.

The Hyready boiler sensitivity presents a potentially more cost-effective approach to widespread hydrogen deployment

Comparison of Hydrogen-led cases: Main case versus Hyready boiler sensitivity

					Direct emissions abatement		Total emissions abatement			
		Stock addressed (millions)	Stock addressed (%)	Date by which all measures received	$MtCO_2e$	%	$MtCO_2e$	%	Total cost (£m/y)	Average cost effectiveness (£/tCO_2)
Hydrogen-led (Main case)	Core	9.9	35%	2050	24.5	32%	24.3	32%	£2,247	£93
	Further Ambition	28.2*	100%	2050	72.0	96%	69.5	92%	£11,485	£165
	Speculative	28.2*	100%	2060	75.4	100%	72.6	96%	£12,617	£174
Hydrogen-led (Hyready sensitivity)	Core	21.2	75%	2050	28.9	38%	28.7	38%	£3,362	£117
	Further Ambition	28.2*	100%	2050	71.0	94%	68.4	91%	£9,808	£143
	Speculative	28.2*	100%	2060	75.4	100%	72.6	96%	£10,969	£151

- The Hyready boiler sensitivity considers a case in which the rollout of hydrogen boilers occurs through deployment of boilers capable of running on both natural gas and hydrogen
- The potential advantage of this approach is that it could allow the deployment of hydrogen-capable boilers at the natural replacement rate (i.e. at end of life) avoiding the cost of early replacement that occurs in the Hydrogen-led Main case
- In the Hyready case, an additional cost is applied for the switchover of the Hyready boilers from gas to hydrogen, reflecting one hour of a gas engineer’s labour at the point of conversion – however, this cost is much smaller than the effective cost of the early replacement in the Main case
- The table above shows that this results in a reduction in the average abatement cost of more than £20/tCO2 versus the Main case (see Further Ambition and Speculative rows where a comparable level of decarbonisation is achieved in each case)
- The Hyready case represents a potentially more cost-effective option for the widespread deployment of hydrogen heating. This could be viable where the conversion to hydrogen is planned and coordinated far enough in advance that consumers in areas designated as hydrogen conversion areas could be encouraged (or perhaps required) to take up Hyready boilers such that most or all boilers are compatible with hydrogen ahead of the grid conversion.
- The analysis presented here is relatively high-level and does not account, for example, for a reduced efficiency of Hyready boilers versus single-fuel boilers, but highlights that this option merits further consideration.

Contents

Sensitivity analysis was carried out for the Central scenario on six key model assumptions

Sensitivity	Description
High cost of capital	• Cost of capital is increased to 7.5% (from 3.5% in the Central scenario)
High electricity cost	• On peak and off peak electricity costs are increased by 5.3%, in-line with the difference between the Central and High long-run variable costs for electricity for 2050 given in supporting Table 9 of the HMT Green Book supplementary appraisal guidance[1]
Low energy efficiency	• No application of the 3.25 million additional Medium efficiency packages as applied in the Central scenario to reflect wider benefits of efficiency • Loft insulation is only applied in homes with less than or equal to 200 mm loft insulation present (no low impact top-ups)
Space constraints variation	• The proportion of homes considered to be space constrained is increased to include homes with dwelling floor area per habitable room of up to 18 m^2 (38% of homes)
Low hybrid HP opex	• Reduce Hybrid HP opex by £50/yr relative to the Central scenario • This aligns the opex of natural gas Hybrid HPs with ASHPs at around £100/yr and so assumes no increase in maintenance cost associated with a heat pump and boiler, relative to a heat pump only • Note that a hydrogen Hybrid HP has an additional opex element of £37.50/yr associated with replacement of a catalyst to reduce NOx emissions such that the opex of hydrogen Hybrid HPs is £137.50/yr
Low hybrid HP opex and reduced capex	• As per Low hybrid HP opex above • Additionally, the £500 capex associated with replacement of internal pipework as a result of the conversion of natural gas to hydrogen is removed
Heritage – high costs	• Higher cost uplifts applied to energy efficiency measures and some heating system elements in heritage buildings

[1] Department for Business, Energy & Industrial Strategy, *Data tables supporting the Treasury Green Book supplementary appraisal guidance on valuing energy use and greenhouse gas (GHG) emissions* (December 2017)

The *Heritage – high costs* sensitivity studies the impact of higher cost uplifts for energy efficiency and for some heating systems

Summary of cost uplifts applied

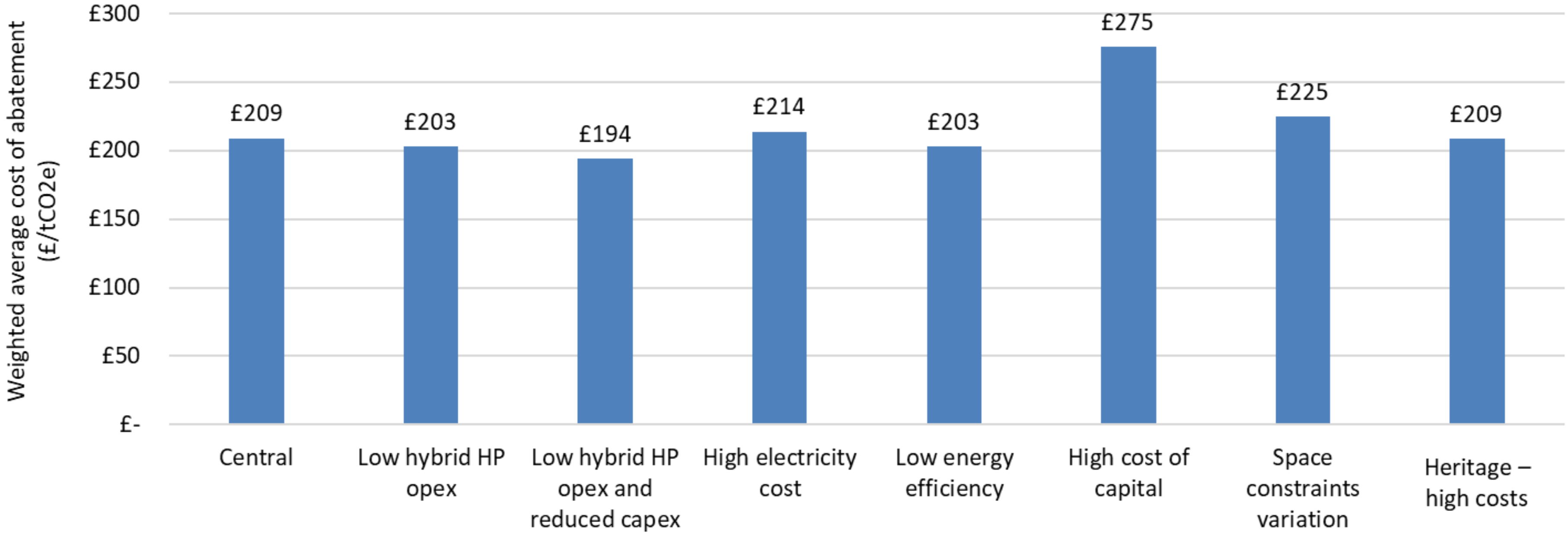
- 75% uplift in cost of radiator upgrades applied for ASHP, GSHP, communal ASHP, and DH
- 75% cost uplift was applied for electric heating (storage and resistive) to reflect the need for more sympathetic heater design
- The high range of cost uplifts were applied to energy efficiency measures (see Section 3)

Cost uplifts applied to single energy efficiency measures and the resulting overall package uplifts

Component	Contribution to package cost			Component cost uplift	
	Low package	Medium package	High package	Conservation area	Listed building
Loft insulation	8%	6%	5%	–	80%
Wall insulation	–	19%	13%	–	300%
Secondary glazing	–	59%	35%	–	300%
Double glazing	–	–	35%	300%	–
Floor insulation	–	–	25%	–	200%
Other	92%	17%	22%	–	–

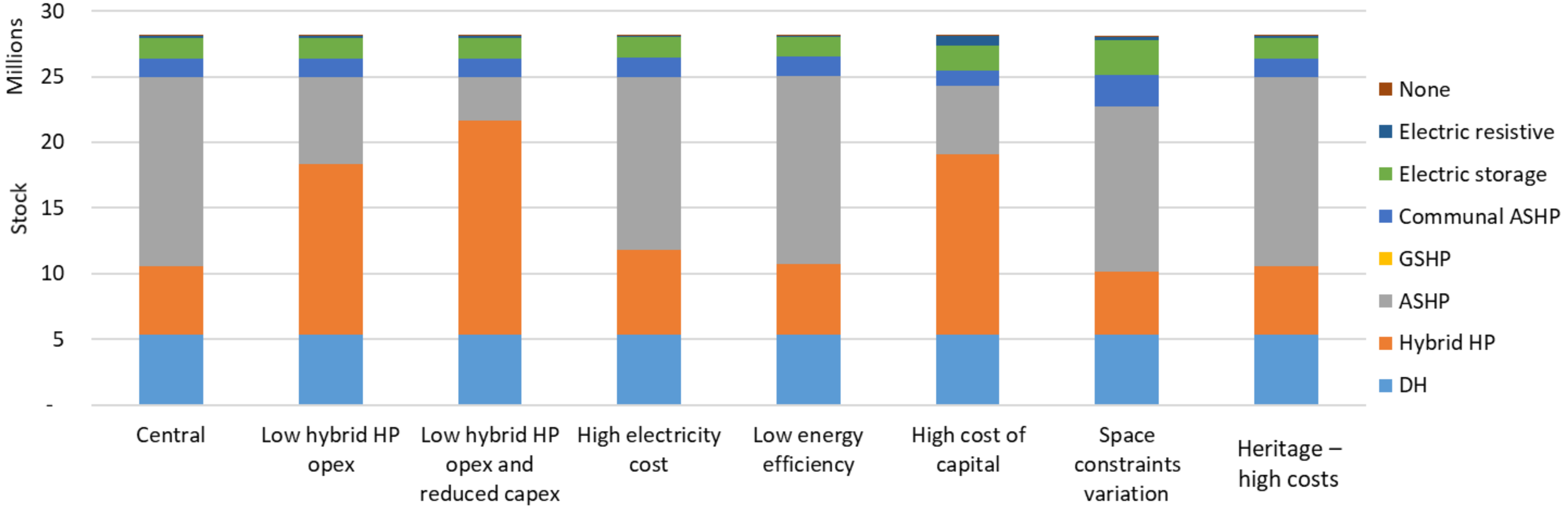
	Cost uplift	
Package type	Conservation area	Listed building
Low	0%	6%
Medium	0%	237%
Deep	106%	199%

Summary of abatement cost across sensitivities



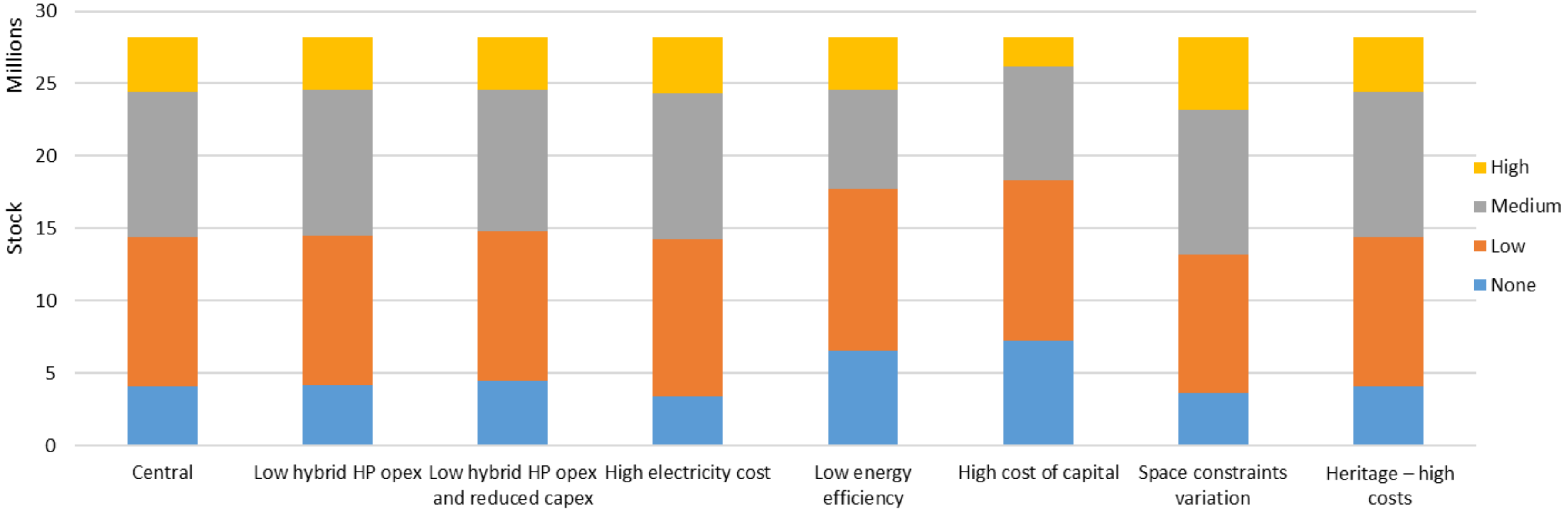
- The average abatement cost is within the range £194-225/tCO_2e for all sensitivities except the High cost of capital, for which the average abatement cost is significantly increased to £275/tCO_2e.
- The factors driving the variation in cost across the sensitivities is explained further in the following slides.

Summary of heating technology deployment across sensitivities



- Heating technology mix varies across the sensitivities, with the main variation being the mix of ASHPs and Hybrid HPs. The sensitivities examining the impact of relatively small reductions in the opex and capex of Hybrid HPs show a large increase in deployment of Hybrids, and a small associated reduction in average abatement cost. Hybrids are also favoured relative to the Central scenario in the High cost of capital sensitivity (since Hybrids are impacted slightly less than ASHPs in this case).
- In the Low energy efficiency sensitivity (see next slide for the change in efficiency package deployment), ASHPs are slightly favoured relative to Hybrids, but the impact is relatively small. The High cost of capital sensitivity results in an increase in the deployment of Hybrids relative to ASHPs, reflecting the lower capital cost of Hybrids relative to ASHPs on average, once the household conversion costs (such as emitter upgrades and hot water cylinders, which are more commonly required in the case of heat pumps than hybrids) are included. This sensitivity also results in a small increase in the deployment of Electric resistive heating, as a low capital cost (but high ongoing cost) technology option.
- In the Space constraints variation sensitivity, in which more homes are assumed to be space constrained, there is a substantial increase in the deployment of Electric storage and Communal ASHPs, mainly at the expense of a reduction in deployment of ASHPs.
- The Heritage – high costs sensitivity is described in more detail on a later slide.

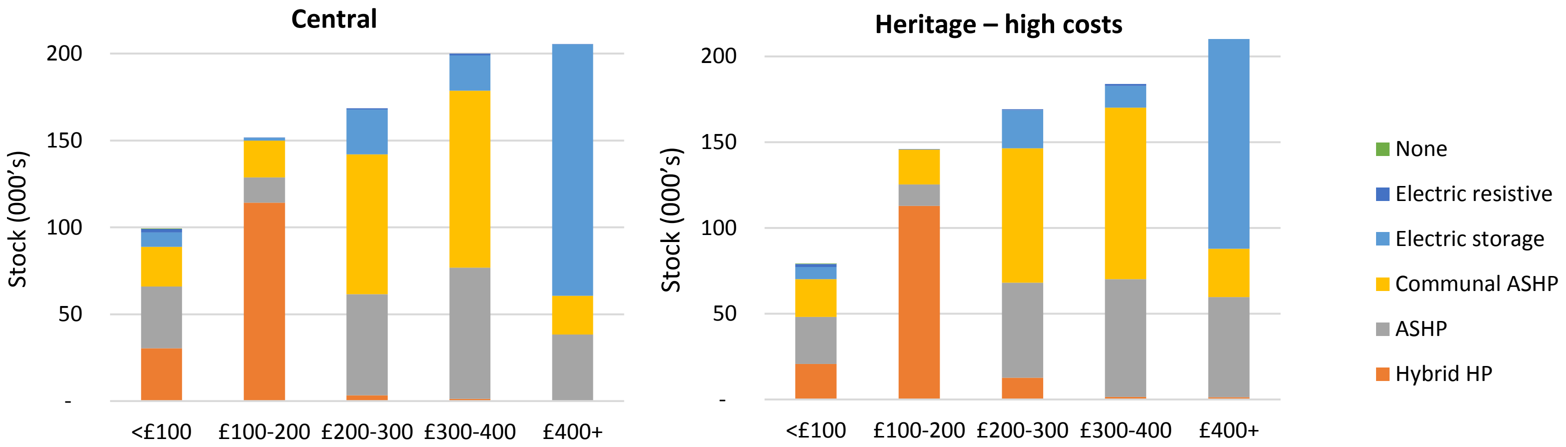
Summary of energy efficiency package deployment across sensitivities



- The Energy efficiency mix is only substantially different from the Central case in several of the sensitivities.
- In the Low energy efficiency case, the deployment of solid wall insulation measures for ‘wider benefits’ is removed as an input assumption, and ‘low impact’ loft insulation top-ups are not allowed; this is reflected mainly as a lower deployment of Medium packages. The average abatement cost in this scenario is slightly lower than in the Central case, in line with the fact that the additional solid wall measures are not cost-effective within the limits of this analysis (i.e. not accounting for the wider benefits).
- In the High cost of capital sensitivity, the deployment of High packages in particular is reduced, with an increase in Medium packages and None (i.e. no efficiency package taken up).
- In the Space constraints sensitivity, in which there is a higher deployment of Electric storage heating, with relatively high ongoing fuel costs, the deployment of efficiency is high, with the largest uptake of High packages across the sensitivities
- The energy efficiency package mix for the Heritage – high costs sensitivity was set in the model to be the same as that in the Central scenario to ensure that the impact of the cost uplifts on abatement cost could be observed clearly

Heritage – high costs sensitivity

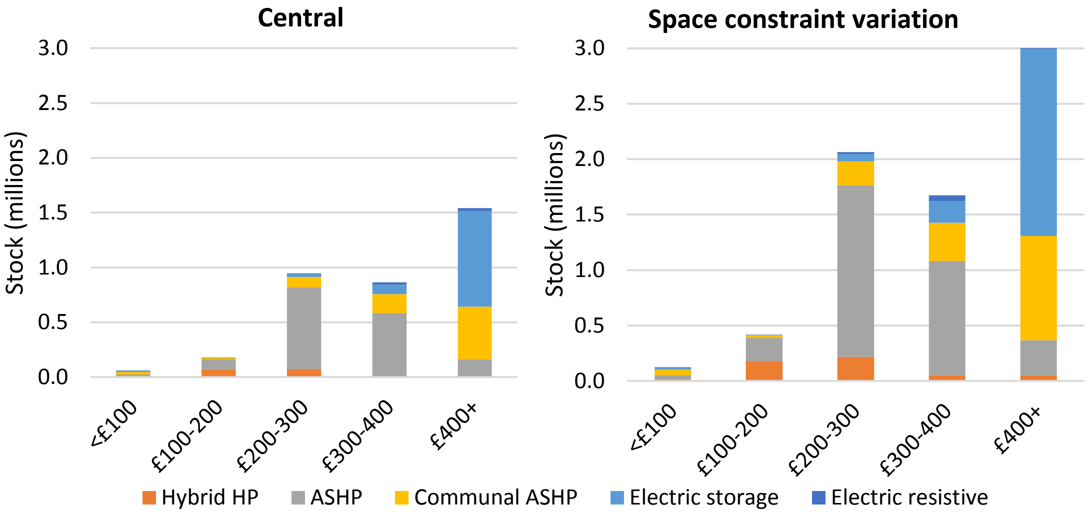
Heating technologies by cost effectiveness band



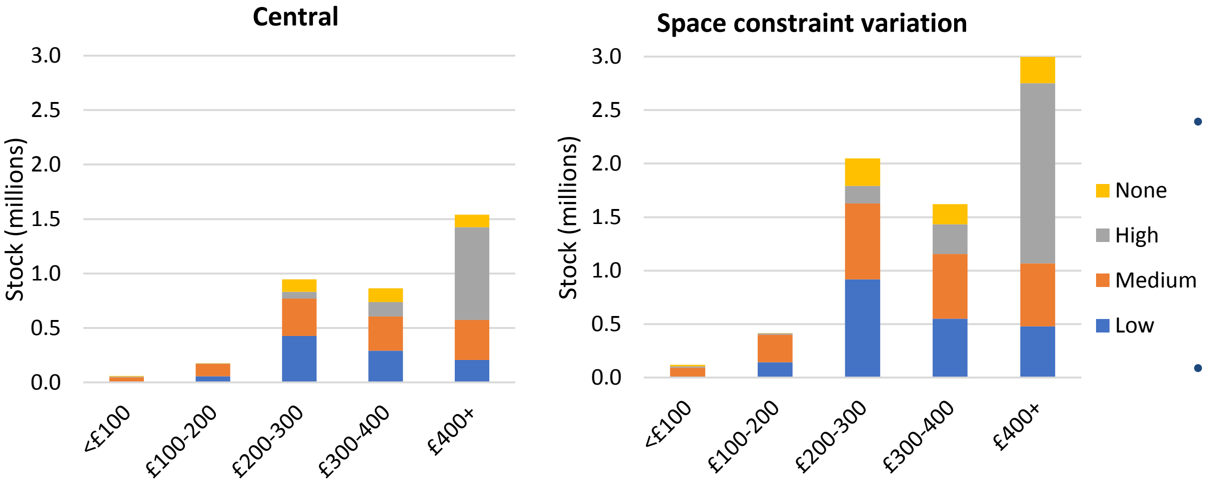
- In the Heritage – high costs sensitivity, the overall average abatement cost across the whole stock is only slightly higher than for the Central scenario, at £210/tCO$_2$e
- However, for the Heritage stock segment, the average abatement cost increases by 12% (from £275/tCO$_2$e in the Central scenario to £310/tCO$_2$e in the sensitivity, in Speculative)
- In line with the higher cost uplifts, the charts show that there is a decrease in the share of heritage homes in the lowest cost band (<£400/tCO$_2$e), and a slight increase in the share of homes in the highest cost band >£400/tCO$_2$e
- The relatively modest impact on the abatement cost of the more stringent suitability constraints and cost uplifts is due to the fact that a high proportion of heritage homes are those that are in conservation areas but not listed (given that these face only very limited cost uplifts)
- In addition, the efficiency package mix in the Heritage segments is dominated by Low packages and cost uplifts to the Low package are small even in this sensitivity

Space constraint variation sensitivity

Heating technologies by cost effectiveness band



Efficiency packages by cost band



- In the Space constraints sensitivity, the total number of homes in the 'On gas, space constrained' segment increases from 3.6 million to 7.2 million
- The distribution of abatement cost in homes in this now-larger On gas, space constrained segment of the stock broadly follows that of the On gas, space constrained segment in the Central scenario, with a high proportion of homes in the highest cost band of >£400/tCO_2e
- Since the share of homes in this segment above £400/tCO_2e is larger than for the wider stock, this drives the increase in abatement cost in this sensitivity versus the Central case
- The mix of heating technology is similar to that in the Central scenario, with a high share of Electric storage and Communal ASHPs
- Small changes in the heating mix, including a slight increase in the share of Hybrid HPs in the higher cost bands, reflect the changing mix of underlying building types and on/off gas share as further homes are introduced into the space-constrained segment)
- There is similarly little impact on the energy efficiency package mix

Contents

Limitations of the modelling (1/3)

Summary of limitations of the modelling and suggestions for further work

- The analysis described in this report has made use of the **latest and best-available evidence base** on the characteristics of UK homes, and on the cost and performance of the technologies that could be applied to decarbonise heat across the housing stock.
- Our assessment of the incidence and coincidence of key attributes influencing the cost and challenges associated with various segments of the stock – that is, how 'hard to decarbonise' they are likely to be – **uses a range of spatial datasets recently made available and incorporates a large volume of new research** on energy efficiency and low carbon heat undertaken in recent years.
- Nonetheless, as with all modelling exercises, assumptions and simplifications have been made, commensurate with the time available and the limitations of the modelling framework. Below, we summarise the **key modelling limitations and gaps in the evidence base** identified, and suggest areas where further work would be valuable.

- **Heritage homes**. This analysis made use of data on listed buildings, and academic literature on the prevalence of homes in conservation areas. Targeted consultation with a small group of industry experts was also undertaken to understand the additional challenges and costs of decarbonising heat in heritage homes (with broader consultation limited by the timeframes available). However, few case studies with quantitative information on the costs and constraints presented to retrofit in these properties were available. In addition, there is significant uncertainty around the number and types of homes for which these additional costs and challenges apply – these issues are likely to also apply to a greater or lesser extent to many homes built before 1919, even where they are not listed and are located outside of conservation areas. The number of heritage homes considered in the model is relatively small (4.5%), however the severity of these constraints and their potential wider applicability will impact the cost of deep decarbonisation consistent with a net zero target and further work to better understand these constraints is recommended.
- **Space constrained homes**. Space constraints in homes are likely to be a key barrier to the deployment of several low carbon heating technologies and enabling technologies, such as heat pumps and hybrid heat pumps, hot water storage, internal wall insulation and large area emitters. However, there is a lack of evidence on this topic, particularly with regards to the size of home that can be considered constrained and consumer behaviour influencing installation of energy efficiency and/or low carbon heating in these homes. As such, the size of this segment is uncertain and the strength of this barrier is not well understood. As explored in the sensitivity analysis, this factor strongly influences the cost of deep emissions reduction and the mix of suitable technologies. Further work to better characterise space constraints as a barrier to heat decarbonisation is recommended, alongside further analysis on the technologies that may be suitable in these homes (e.g. thin internal wall insulation[1]).

[1] Leeds Beckett University is currently conducting research in this area on behalf of BEIS. It is expected to be available at lower cost and with lower associated energy savings relative to conventional insulation. For preliminary findings see: https://www.leedsbeckett.ac.uk/-/media/files/LSI/TIWI-Preliminary-Findings-Leeds-Beckett

Limitations of the modelling (2/3)

Summary of limitations of the modelling and suggestions for further work (continued)

- **Further ‘hard-to-decarbonise’ attributes.** Several further attributes were identified in our literature review as contributing to a home being hard to decarbonise, including exposure to severe climate conditions, constraints on accessibility, specific issues associated with high rise buildings, and bespoke construction approaches. It was not possible to include these in the analysis due to a lack of data and/or a tractable modelling approach. Further work could consider how to incorporate these features into a similar analysis.
- **Suitability constraints**. The application of suitability constraints on energy efficiency measures and low carbon heating technologies was highly simplified, with suitability factors limited to binary ‘suitable’ or ‘unsuitable’ or, in some cases, applying a 50% suitability factor. This was a necessary limitation to ensure tractability of the modelling in the time available. The reality is of course much more nuanced. Sensitivities on several key constraints were tested in order to assess the impact of varying these assumptions, and the results of any one scenario should be viewed in the context of this uncertainty. There are further sources of uncertainty over the suitability (or acceptability) of different solutions relating to consumer preference as well as technical and planning-related factors that are not considered in detail here; for example we have not restricted deployment of heat pumps in flats, which may not in reality be acceptable in all cases.
- **Performance gap**. Our analysis assumes an uplift in energy savings of 16% relative to the data derived from real observed case studies, to represent closure of the performance gap through improvements in design and construction, as well as informed occupant use of installed technologies and appropriate heating and ventilation strategies. The size of the performance gap, and hence the achievable savings, are however identified as an area of significant uncertainty, and further work is recommended to generate more robust evidence on the potential improvement in energy savings through closure of the performance gap in the retrofit context.
- **Methodology to derive cost and savings assumptions for energy efficiency measures.** To enable a more realistic estimation of savings, a number of real-world case studies were reviewed as part of the data collection process. However, due to the inherent nature of case study-based research, a significant limitation that affects the robustness of the approach is the ability to generalise findings arising from what can be unique cases. The data derived approach is a simplified method that is based on best available data to inform the model. Unlike a dynamic modelling approach this limits the ability of the model to calculate interactions between various aspects impacting the performance of the building fabric, instead relying on evidence-based estimations and rules of thumb to account for complex interactions. This introduces limitations on the flexibility of the model.

Limitations of the modelling (3/3)

Summary of limitations of the modelling and suggestions for further work (continued)

- **Availability of data on costs and savings of energy efficiency measures.** A wide range of data sources were reviewed as part of this project. However, key limitations associated with the availability and consistency of data in regards to costings and performance improvements was found. In particular, cost data was based on self-reported information from contractors. To address this, more consistent and up to date information needs to be systematically collected and made available for government funded retrofit projects to enable long term analysis.
- **Further permutations of technologies and packages, including further applications of solar thermal**. A wide range of technology options were considered in the analysis. However, in reality further options would be available, in particular combinations of technologies which were not studied here in order to ensure tractability in the scope of the analysis. For example, there is potential for solar thermal to contribute to space heating (as well as hot water demand) and to be deployed in larger, communal heating systems, in scales from several dwellings up to heat network level – which were not studied here (but which industry experts have suggested could offer substantial economies of scale). Similar possibilities could apply to other technologies and combinations not studied here, such as micro combined heat and power (microCHP).
- **More detailed assessment of the local/spatial infrastructure impacts**. A key strength of this analysis is that it incorporates a range of spatial datasets to account for the coincidence of many of the hard-to-decarbonise attributes. The level of spatial detail in the modelling approach was the best achievable in the relatively short timeframe available. Inclusion of further detail in spatial treatment is a direction we suggest would bring substantial benefits in future modelling exercises. This could include, for example, more detailed treatment of local electricity infrastructure constraints; regional suitability for hydrogen production; and local availability of bioenergy (e.g. bioLPG). Greater spatial resolution of building attributes could also be achieved by development of a similar model in more powerful modelling platforms than that used here (Excel).
- **Deployment trajectories**. This analysis does not include a detailed assessment of the most appropriate deployment trajectory for the energy efficiency and low carbon heating systems taken up in the scenarios, but rather focuses on specifying an appropriate date by which these measures could be applied across all homes in the stock segment in question. Further work considering the most appropriate deployment trajectory and tipping points for grid conversion would be beneficial to understand whether this introduces additional challenges or constraints to achieving the scenarios set out here.

Contents

Behaviour change among consumers will be an important component of the level of decarbonisation envisaged in these scenarios (1/3)

Key areas in which behaviour change is likely to be required

In a number of areas, achieving the level of carbon emissions reduction set out in the scenarios studied will be contingent on changes in occupant behaviour. The key areas in which we envisage behaviour change will need to play a role are described below.

Delivery of targeted energy efficiency savings, including closure of the performance gap

- A number of studies have found that occupant behaviour can significantly impact energy demand reductions in homes, accounting for variations in achieved energy savings ranging from 25% to 50%. Improper use of installed measures can also result in unintended consequences, such as condensation, mould growth and overheating (as discussed in Section 3). Consequently, actions to encourage households to implement changes in the way they use their homes once measures are installed are an essential component of any retrofit strategy.[1, 2]
- In modelling the energy savings in this study, a number of key assumptions relating to the behaviour of occupants post-retrofit were made, informed by relevant literature on the role of users and their observed post-retrofit behaviour in achieving targeted energy savings: [1, 3–5]
  - A shift from pre-retrofit ‘standard use’ patterns to post-retrofit ‘informed use’ behaviour is assumed, in which householders understand how to benefit from improved building fabric and energy efficient technologies, and at the same time are encouraged to think differently about energy use. This includes correct operation of installed systems and technologies, maintaining the integrity and avoiding damage of insulation layers, appropriate ventilation behaviours such as opening windows to allow for adequate ventilation and mitigation of moisture build up by avoiding indoor drying of clothes (where possible).[6] Reasonable thermostat set temperatures are also assumed (18°C in bedrooms and 21°C in living areas).
  - To enable this change, strategies such as occupant engagement, and wider schemes to increase awareness of proper use will need to be implemented alongside retrofit.
  - Any risks concerning occupant interaction with the installation and use of measures and technologies need to be understood and mitigated.[7] These may include such aspects as inaccessibility and/or difficulty in using controls, and lack of occupant training to operate or maintain the system adequately, or to spot poor technical performance and damage to insulation layers.[8]

[1*] The Missing Quarter: Integrating Behaviour Change in Low Carbon Housing Retrofit. Low Carbon Housing Retrof*it (2011) GMC; [2*] International Journal of Energy Research*. 41, 1150–1163 (2017) C. V. Jansson-Boyd et al.[3] *Engineering Sustaibility* 163, 197–207 (2010) C. Ainger et al. [4] *Sustainable Cities* 41, 611-624 (2018) F. Papadopoulos et al.;[5] *The delivery and communication challenges of retrofit (*2016) A. Willey; [6] *Building Research & Information* 42, 574-590 (2014) L. F. Chiu et al.; [7] *Managing behavioral risks in large scale social housing sustainable retrofit projects in the UK* (2013) W. Swan et al.; [8] *Occupant-centred retrofit: engagement and communication Key Findings: Analysis of a selection of Retrofit for the Future projects* (2012) R. Lowe et al

Behaviour change among consumers will be an important component of the level of decarbonisation envisaged in these scenarios (2/3)

Key areas in which behaviour change is likely to be required

Delivery of targeted energy efficiency savings, including closure of the performance gap (continued)

- Assumptions on ‘informed use’ behaviour are also relevant to our treatment of the ‘performance gap’ – defined here as the difference between energy savings that are typically observed upon installation of energy efficiency measures and the ‘potentially deliverable’ energy savings. As described in Section 3, it is understood that this gap is caused by a variety of factors, including quality of construction and materials, as well as the way the occupant interacts with, operates and maintains the dwelling and uses energy.
- In our analysis, we assume that the performance gap can be closed, leading to a 16% uplift in energy savings relative to the typically observed savings derived from real world case studies. Closure of the performance gap is dependent, in part, on informed occupant use of installed technologies and deployment of appropriate heating and ventilation strategies.

Use of low carbon heating technologies to achieve targeted emissions reduction

- In order to achieve high efficiency, heat pumps (and potentially hybrid heat pumps depending on the operational model) deliver heat at lower flow temperatures than are typically seen in most homes using fossil fuel boilers. This requires a change in the way the system is operated by the user, as the lower flow temperature means that the heating is less responsive and needs to be ‘on’ for longer periods of time than a typical boiler to achieve equivalent levels of comfort. Achieving high efficiency while maintaining comfort is therefore dependent on ‘informed use’ of the heat pump by the occupant – and not, for example, using additional heating, such as low efficiency electric fan heaters, to achieve a faster temperature response (which would incur higher costs).

- Delivering the targeted emissions savings using hybrid heat pumps, particularly when the boiler is still using natural gas, requires homeowners and tenants not to overuse the boiler, only deploying it during peak periods. This may require the application of cost signals to guide dispatch (such as time-of-use tariffs and/or carbon taxation), but even then the outcome depends ultimately on informed occupant behaviour to achieve the desired outcome.

Behaviour change among consumers will be an important component of the level of decarbonisation envisaged in these scenarios (2/3)

Key areas in which behaviour change is likely to be required

Tools to increase interaction of consumers with their heating systems

- Changing the way that households use their heating systems is challenging and requires a combination of education and engagement. Information may in part come from Government but in large part is an opportunity for suppliers of energy and heating technology.[1] Studies with Home Energy Management Systems (HEMS) have shown that users understood their energy needs better after using the system and enjoyed better control over their heating experience, although misuse still occurred among a minority.[1, 2] Developing systems such as HEMS and other tools for monitoring energy use, as well as new ways of selling heat have been suggested as areas for innovation that can achieve behaviour change.[1]

Consumer purchasing behaviour in response to policy and incentives

- Our analysis specifies the heating systems deployed in each type of home on the basis of the most cost-optimal option to achieve deep decarbonisation – it does not attempt to reflect actual consumer purchasing behaviour. All scenarios studied are dependent on the implementation of policy, and fiscal and regulatory frameworks to drive deployment of energy efficiency and low carbon heating, whether by making those options attractive to consumers, or removing the option of not decarbonising through forms of mandation. Understanding and guiding consumer behaviour is therefore central to achieving net zero emissions.
- Changing consumer purchasing behaviour also requires wider awareness of technologies – one study finds that 40% of consumers are open to low carbon technologies but few are aware of the options and 90% still choose gas boilers.[1] Building awareness and education around low carbon heating technologies will need to accompany incentives and regulations to drive uptake.

[1] *How can people get the heat they want at home without the carbon?* (2018) ETI; [2] *HEMSv1 2016-2017 Winter Analysis – Trial of a consumer orientated Home Energy Management System* (2018) ETI

Contents

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (1)

Introduction

- The level of decarbonisation of heat, and the associated mix of energy efficiency measures and heating technologies deployed in the scenarios studied, is based on a number of assumptions regarding the **policy and regulatory framework**, **advances and innovations in technology** cost and performance, and **changes in consumer behaviour**.
- Government has already committed to action to reduce the carbon intensity of heating in targeted areas of the domestic building stock – particularly the off gas and fuel poor segments[1] – but a greater level of policy ambition extended to all segments of the stock is required to achieve the level of carbon emissions reduction represented by the Further Ambition scenario. These policy gaps are described further below.
- Although this analysis is based on the best available evidence, limited data is available to support the underlying assumptions made in some key areas. We also set out below the areas where we find that further research will be required to better characterise the available heat decarbonisation options and the likely cost and associated challenges across some key segments of the stock.

Overarching recommendations (see below for segment and technology-specific recommendations)

Recommended actions:

- ➢ **Develop a comprehensive strategy for heat decarbonisation in the UK**, covering energy efficiency and low carbon heating, and including a timeline for decisions on the long term pathway for the UK and the role of electricity, gas and heat networks, as well as bioenergy. Stable policy signals are critical to providing the market with the certainty required to invest in developing and deploying the technologies, and to build consumer awareness of the need for heat decarbonisation and of the options available.
- ➢ **Develop and trial a range of incentives and support mechanisms to replace the RHI**, targeting different segments, consumer groups and technologies, to 'level the playing field' and create a large-scale market for low carbon heating. This analysis demonstrates that, for most homes, the cost of low carbon heating is likely to be substantially higher than the counterfactual (particularly gas heating) and sustained financial support targeted at upfront costs is highly likely to be required to create this market outside certain niches.
- ➢ Over the longer term, adopt **mandatory energy and carbon emissions standards for existing homes**, enforceable at trigger points such as sale and rental (and consider additional trigger points such as renovations requiring planning permission), ensuring support is available where necessary.

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[1] *The Clean Growth Strategy: Leading the way to a low carbon future* (2018) HM Government

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (2)

Overarching recommendations (continued)

Recommended actions:

- **Update the energy efficiency policy framework by strengthening the Energy Company Obligation (ECO) and/or implementing additional regulated schemes** to encourage uptake of efficiency across all segments of the stock.
- **Provide financial assistance, such as low or zero interest loans, and financial incentives** to reduce the upfront cost of retrofits to households (including those targeted particularly at the fuel poor segment).
- **Design incentives and guidance to encourage whole-house retrofits** combining energy efficiency and low carbon heating, taking advantage of appropriate trigger points such as major renovations, purchase, new tenancies and others.
- **Support the development of innovative business models** (considering the need for innovation funding or other support mechanisms) to make energy efficiency and low carbon heat more attractive to consumers (such as heat-as-a-service, pay-as-you-save models and so on), exploring the potential role for a wide variety of delivery agents, including energy suppliers, energy service companies, local and national public sector delivery bodies, as well as ‘traditional’ technology providers and others.
- **Provide tailored advice and support** to households on appropriate energy efficiency and low carbon heating measures, on the incentives and other support available, how to access financial assistance and how to identify certified suppliers.
- Update **Private Rented Sector (PRS) regulation** to address this sector, with accompanying support (such as low or zero interest loans, replacing the end of Green Deal support) to ensure no adverse impact on tenants and the rental market.
- Ensure energy standards (and in future carbon emissions standards) in the **Social rented sector** are appropriately set, and that this sector is able to access financial assistance where appropriate.

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (3)

Energy efficiency and closure for the performance gap

- The Further Ambition scenario requires that at least one energy efficiency measure is installed in 85% of the existing domestic building stock, even where the cost of abatement is high and the payback period is long (and in some cases, never realised).
- Ambitious rates of installation must also be met to achieve the target deployment by 2050. The table below shows the indicative installation rate required to roll out all 24.1m efficiency packages in the Further Ambition scenario within 20 years (as assumed in the analysis). Faster installation rates may be relevant where there is initiative to roll out measures in social housing and private rented homes more quickly.
- While clearly ambitious, particularly in the case of solid wall and floor insulation, these rates are considered feasible as the required annual installation rate to 2050 has been exceeded in the case of cavity wall and loft insulation at peak periods during previous regulated schemes (the Carbon Emissions Reduction Target, CERT, and the Community Energy Saving Programme, CESP).
- We note, however, that installation rates have since declined substantially under the Energy Company Obligation (ECO), particularly for loft insulation.

Insulation measure[1]	Installation rate (thousands per year)		
	Peak rate required under Further Ambition	Peak rate achieved under CERT and CESP	Peak rate achieved under ECO (to 2015)
Solid wall	290	80	70
Cavity Wall	285	650	320
Loft	1070	1600	180
Floor	170	–	–

Closure of the performance gap

- The energy savings resulting from the energy efficiency packages modelled here assume that installation quality and consumer behaviour is sufficient to achieve the full ‘potentially deliverable’ energy savings – that is, closing the ‘performance gap’ between the potential savings and the typically observed savings in real case studies to date. Measures are likely to be needed to support the supply chain required to deliver the large-scale rollout of measures and ensure high standards of design and installation are achieved.
- We find, however, that the evidence base in relation to the size of the performance gap is limited and, therefore, that there is significant uncertainty in the realistically achievable performance of energy efficiency in real installations.

Recommended actions:

- ➢ **Undertake research** to better understand the performance gap and take action to close it through higher industry standards

[1] This refers to additional measures installed from 2019, though in the case of loft insulation the majority are top-ups.

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (4)

District heating

- The deployment of heat networks in the scenarios studied here, based on detailed analysis undertaken as part of the 5CB work,[1] demonstrates that low carbon district heating can provide substantial cost-effective potential for heat decarbonisation across nearly 20% of the residential building stock
- The scenarios presented assume a high connection rate to heat networks in areas with suitable heat density. Policy therefore needs to be in place to support rollout of networks and to ensure that consumers connect to district heating in these areas, where viable and cost-effective in comparison with other low carbon heating options.
- Policies should ensure that heat networks are at least as low carbon as other viable options for heating the same homes.

Recommended actions:

- **Continue to provide financial support for low carbon district heating** beyond the end of the period of support via the current Heat Network Investment Project (HNIP) and Renewable Heat Incentive (RHI) (both due to end in 2021).
- **Use local planning policy** to drive connection to district heating where appropriate; in the longer term, this should extend to the use of planning policy to require connection of existing homes to heat networks at suitable trigger points, where appropriate. Approaches based on local heat zoning should be considered, combining planning instruments with financial incentives where required. This should be accompanied by appropriate carbon emissions standards for heat networks, for example indexed against alternative heating options such as heat pumps or hybrid heat pumps.
- **Incentives and/or requirements for sources of waste heat** to be available to heat networks.
- **Competition policy** to protect consumers from issues of natural monopolies.

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[1] *District heating and local approaches to heat decarbonisation* (2015) Element Energy for the CCC

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (5)

Off gas homes

- Off gas homes are targeted under the Clean Growth Strategy, which sets out the Government's ambition "to phase out the installation of high carbon fossil fuel heating in new and existing off gas grid residential buildings…during the 2020s". However, policy measures to achieve this have not yet been set out in any detail.
- This analysis strongly supports the decarbonisation of heat in off gas homes as a near term priority, showing that this can be achieved with a negative average abatement cost across the entire off gas stock. Early deployment of low carbon heating options, particularly heat pumps and hybrid heat pumps, across the more than 2 million homes in this segment during the 2020s will provide a large early market for these technologies. This early market will help to develop the supply chain, and provide an opportunity to drive reductions in cost and learn what works to help inform the longer term pathway.

Recommended actions:

- ➢ **Develop policy** to deliver decarbonisation of off gas homes at scale during the 2020s, with a focus on achieving rollout of heat pumps and hybrid heat pumps, as well as heat networks and communal heat pump systems where cost-effective.

Heritage homes

- Heritage homes, defined in this study to include listed buildings and homes in conservation areas, are expected to present particular challenges to retrofit with energy efficiency and low carbon heating, due to more onerous planning restrictions and/or more costly approaches to retrofit in order to preserve the character of the property and area.
- As previously stated, however, a limited evidence base regarding the costs and challenges to retrofit in heritage homes, with relatively little published data from case studies.

Recommended actions:

- ➢ **Undertake further research** to better understand the additional challenges and costs of retrofit to heritage homes, and the number and type of homes to which these issues are likely to apply.
- ➢ **Develop the skills base** required to deliver the low carbon retrofit solutions to this segment, such as through training programmes and other initiatives, for example as part of the Construction Sector Deal.
- ➢ Consider the ways in which **planning or building consent** represent barriers to decarbonisation, and to what extent relaxation of these restrictions could be permissible in the context of deep decarbonisation targets. Better funding of Local Authorities, local planning and building control to support the skills base in these areas would also be beneficial.

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (6)

Space constrained homes

- This analysis identifies space-constrained homes as a key hard-to-decarbonise segment with high associated abatement costs. These high costs are due to the restricted low carbon heating system options available (with heat pumps and hybrid heating systems, as well as conventional hot water cylinders, less likely to be feasible or attractive to consumers), and the higher costs associated with some space saving technologies (such as point-of-use hot water systems or heat batteries as replacements for conventional hot water cylinders).
- As previously stated, the number and type of homes to which these space constraints are likely to apply is highly uncertain, and likely to be very case-specific. Whether these constraints apply is expected to relate to a complex interplay of the dwelling size and layout, the number and type of occupants, and consumer preference – determining factors that have not been possible to model in detail in this study. Due to the lack of evidence on this topic, the size of this segment is uncertain, and this may have a significant influence on the eventual technology mix across the wider stock, and the policies required to deliver heat decarbonisation.

Recommended actions:

- ➢ **Undertake further research to better understand the physical and consumer preference factors** contributing to space constraints, to better characterise this segment of the stock and what solutions will be required to address this issue.
- ➢ **Consider the need for innovation funding to support the development of space saving technologies** such as thin internal solid wall insulation, heat batteries, low carbon heating systems with innovative space saving designs, small area emitters and other approaches to addressing this constraint. Specific areas for development include:
    - ***Low temperature heat batteries****:* heat batteries currently operate at high infeed temperatures (58°C)[1] which is not compatible with the most efficient mode of heat pump operation. Our modelling assumes that heat batteries compatible with heat pumps will be available in the near term. However, costs of abatement will be higher if heat batteries cannot enable heat pumps in the space constrained stock.
    - ***Large-scale hybrid heat pump trials:*** large scale trials have not yet been carried out to demonstrate decarbonisation of both space heating and hot water demand in homes retrofitted with hybrid heat pumps. Although industry indicate that this approach is possible, it needs to be demonstrated at scale and the required hot water storage capacity to support it needs to be determined; in turn, these findings will influence the suitability of hybrid heat pumps for space constrained homes.

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[1] Design and installation manual for the UniQ range of heat batteries, Sunamp (link)

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (7)

Electrification of heat (Heat pumps and Hybrid heat pumps)

- The heating technology mix in most scenarios studied in this analysis comprises a large number of heat pumps and hybrid heat pumps, with around 20 million of these systems deployed by 2050 in the Central scenario, and all other scenarios and sensitivities except the Hydrogen-led case, in which case nearly 4 million heat pumps and hybrids are still deployed.
- Although heat pumps have an established supply chain in Europe (particularly in France, Italy and Sweden), the UK currently has a limited supply chain and skills base. The scale of rollout of heat pumps and hybrids under Further Ambition is ambitious (800,000 per year on average to 2050, compared to current UK sales of only 20,000 per year, and EU-wide sales of all types of heat pump of 1 million in 2016). The shortage of skilled labour in the UK presents a risk to the required scale of rollout, and it is imperative that early markets are created for these technologies to build up this capability – such as in the off gas segment as described above, as well as in new homes.
- The scenarios presented here also assume that heat pump seasonal performance factors (SPFs) improve over time; failure to achieve this improvement will result in higher cost of abatement, and potentially lower levels of deployment. High efficiency standards should be promoted, and support to develop the appropriate installation skills base is also likely to be required.

Recommended actions:

- ➢ **Ensure deployment at scale of heat pump and hybrid heat pump** technologies can occur as soon as possible in the 2020s to develop a large and skilled supply chain for these technologies in the UK. In the early stages this market may be focused on the off gas and new build segments, but should not be limited to those homes.
- ➢ **Adopt high quality standards for design and installation, and ensure support is available to help the industry meet those standards,** to grow the skills base and supply chain in the UK to facilitate market growth.

Achieving the level of deployment seen in the Central set of scenarios will require concerted Government intervention (8)

Decarbonisation of gas

- Reaching net zero in the Central scenario, and all other scenarios studied except for the ‘No hydrogen’ case, requires decarbonisation of hybrid heat pumps via decarbonisation of the gas grid using hydrogen, as well as through the use of bioLPG (or other biofuel) to off gas homes. This is consistent with the CCC’s 2018 *Hydrogen in a low carbon economy* report, which presented evidence on the benefits of hydrogen in supporting decarbonisation through electrification.
- For hydrogen in particular, there is still considerable uncertainty over the commercial and technical viability of various approaches to its production and application for heating.

Recommended actions:

- ➢ **Continue support and innovation funding for large-scale demonstrations** of hydrogen production. Initially, uses for hydrogen are likely to include applications requiring little conversion of infrastructure, such as blending into the gas grid and use in transport, certain industrial applications and power generation. This should be accompanied or followed by use for heating in communities and industrial clusters requiring conversion of the gas network and heating appliances, in order to test the viability of these aspects. This is necessary to reduce uncertainty over commercial and technical feasibility to inform a decision during the 2020s on the long-term role for hydrogen.
- ➢ As part of this, **support the development of carbon capture and storage (CCS)** as a key enabler of large-scale production of low carbon hydrogen (‘blue’ hydrogen) will be required.
- ➢ Similarly, **support the development of ‘Hyready’ boilers**, capable of running on natural gas and hydrogen (with minor modifications) as a potentially cost-effective approach to converting homes to hydrogen.