


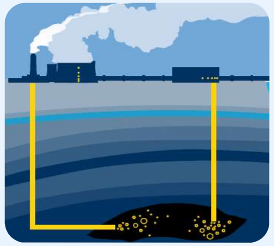



Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget

A study for the

Committee on Climate Change

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elementenergy

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- Richard Halsey, *Energy Systems Catapult*
- Ashley Malster, *Ofgem*
- Chris Nicholls, *Department for Business, Energy and Industrial Strategy*

List of acronyms

Acronym	Meaning	Acronym	Meaning
NZ	Net Zero	IUF	In-Use Factor
CB	Carbon Budget	EST	Energy Savings Trust
LCH	Low Carbon Heating	MCS	Microgeneration Certification Scheme
EE	Energy Efficiency	LCHN	Low Carbon Heat Networks
SC	Space Constrained	HaaS	Heat as a Service
LRVC	Long Run Variable Cost	NEED	National Energy Efficiency Data-Framework
OO	Owner-Occupied	EPC	Energy Performance Certificate
PR	Private Rented	SH	Social Housing
LA	Local Authority	DSM	Demand Side Management
DA	Devolved Administration	CCS	Carbon Capture and Storage
GB	Great Britain	ASHP	Air-Source Heat Pump
ETT	Easy to Treat	GSHP	Ground-Source Heat Pump
HTT	Hard to Treat		
EHTT	Extra Hard to Treat		
IWI	Internal Wall Insulation		
TIWI	Thin Internal Wall Insulation		

Contents

Introduction

The Committee on Climate Change (CCC) have commissioned Element Energy to carry out research on evidence-based pathways and trajectories to achieve full decarbonisation of heat in buildings, to 2050. The resulting analysis will be used to inform the CCC's advice to Government on UK climate action, particularly relating to the 6th Carbon Budget (6CB) period between the years of 2033 and 2037.

Specific aims of the project were to:

1. Assess the most cost-effective and appropriate decarbonisation options for the entire UK housing stock.
2. Provide yearly profiles of measure deployment and costs for all homes to feed into the CCC's modelling to advise on the level of the Sixth Carbon Budget (6CB).

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** reflecting regional national housing survey data for England, Scotland, Wales and Northern Ireland.
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 and develop trajectories of deployment** of technologies and packages.

Overview of approach

- The ultimate aim of the research is to investigate viable pathways to reaching zero emissions from existing buildings in the UK in 2050, with a particular focus on the 6th Carbon Budget period (2033-37).
  - Decarbonisation is achieved via combinations of behaviour change, energy efficiency, and low carbon heating systems; measures are chosen to minimise costs and disruption for households and businesses.
- Starting with several 2050 mixes with varying balances of efficiency and fuel switching (with measure suitability considered), several futures are explored:

Exploratory Scenarios

Widespread Innovation: High innovation occurs in several carbon mitigation technologies and measures. Costs fall faster than central projections. This allows more widespread electrification, a more resource and energy efficient economy, and more cost-effective technologies to mitigate CO_2 emissions.

Widespread Engagement: People and businesses are willing to make more changes to their behaviour. This reduces the demand for the most high-carbon activities and increases the uptake of some climate mitigation measures.

Headwinds: People change their behaviour and new technologies develop, but there are no widespread behavioural shifts or innovations that significantly reduce the cost of low-carbon technologies ahead of current projections. This scenario is more reliant on the use of large hydrogen and Carbon Capture and Storage (CCS) infrastructure to achieve net zero.

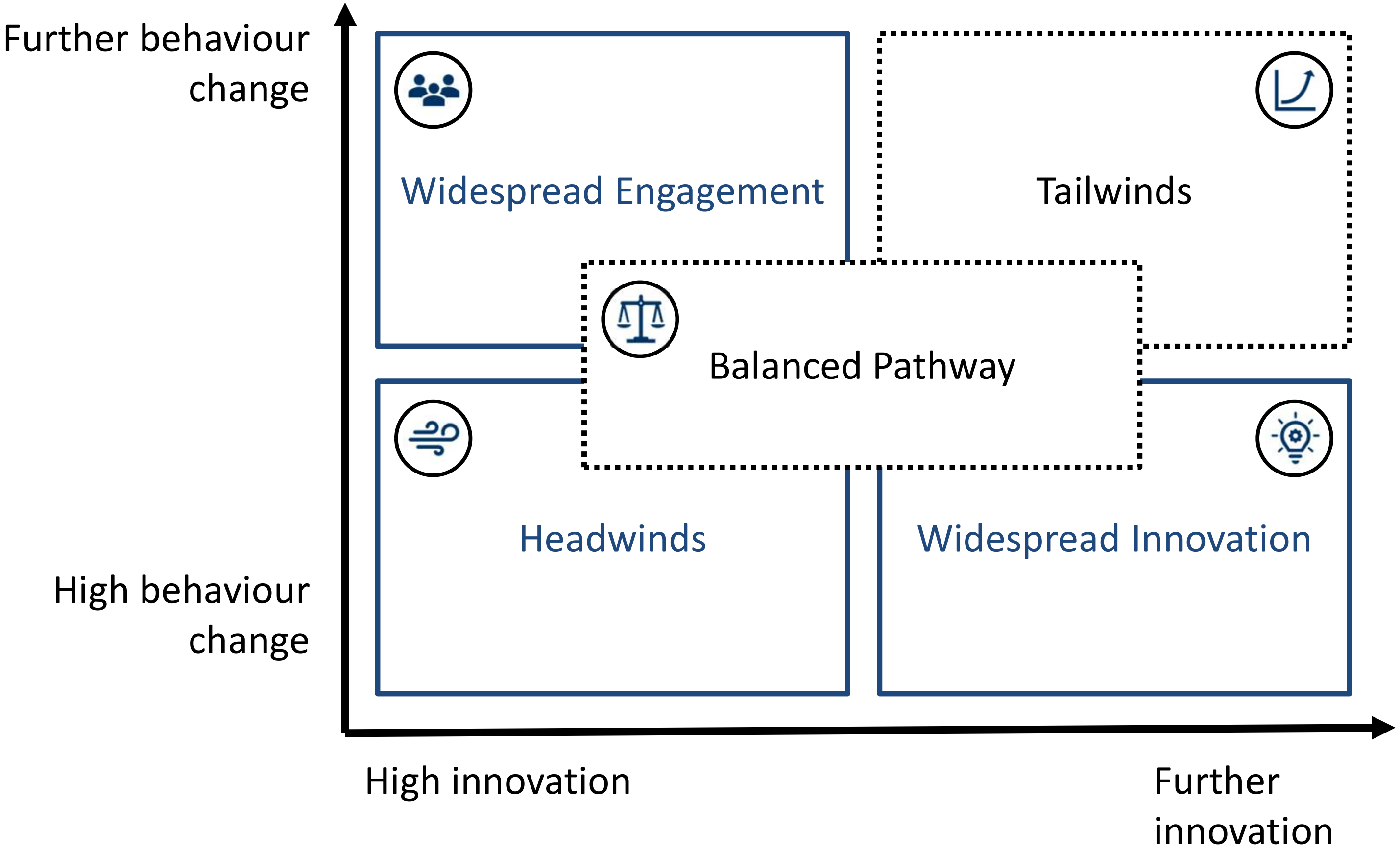
Central Scenarios

Balanced Net Zero Pathway: This scenario, also known as the Balanced Pathway, has a deployment trajectory which makes strong progress towards Net Zero and keeps open alternative states of the world. Reflects a 'fuel poverty first' approach for buildings.

Tailwinds: People pursue significant behaviour change; innovation and heavy infrastructure also succeed on all fronts. This scenario goes beyond the 6th Carbon Budget Pathway to achieve Net Zero before 2050.

Overview of approach – relative representations of scenarios

- The Balanced Pathway aims to keep options open through the 2020s.
- The Tailwinds scenario pursues behaviour change AND innovation AND heavy infrastructure and succeeds on all fronts.



Overview of approach – summary of scenario definitions and drivers

Innovation area	Balanced Pathway	Tailwinds	Widespread Engagement	Headwinds	Widespread Innovation
Behaviour change	Moderate, with some pre-heating and feedback from smart meters.	High, with pre-heating, feedback from smart meters, multi-zone control, and heat as a service model.	High, with pre-heating, feedback from smart meters, and multi-zone control.	Moderate, with some pre-heating and feedback from smart meters.	High, with pre-heating, feedback from smart meters, multi-zone control, and heat as a service model.
Energy efficiency uptake	Moderate, with a focus on fuel poor homes.	Full economic potential.	Moderate-high, with a focus on fuel poor homes.	Lower uptake, with a focus on fuel poor homes.	Lower uptake using lower-end costs and deep retrofit packages, with a focus on fuel poor homes.
Low carbon heating uptake	Hybrid scenario, widely electrified with uptake of H_2 hybrid heat pumps. Heat networks electrified. Limited use of biofuels.	Hybrid scenario, widely electrified with hydrogen pockets around industrial clusters, and more ambitious lifetimes and cost reductions. Heat networks electrified. No biofuels.	Fully electrified (including heat networks). No biofuels.	High hydrogen uptake, with H_2 boilers in the north and H_2 hybrid heat pumps in the south. Heat networks use hydrogen peaking. Limited use of biofuels.	Hybrid scenario, including uptake of high temperature heat pumps and widespread use of flexible technology. More ambitious lifetimes and cost reductions. Heat networks electrified. No biofuels.

Overview of approach – modelling framework to generate scenarios

1. **Develop a UK stock model**, archetypically capturing characteristics and insulation levels of dwellings regionally.
2. **Define assumptions, guidance, and constraints** for behaviour change, energy efficiency, low carbon heating, and overarching scenarios.
3. **Calculate cost effectiveness and carbon savings** of all possible archetype-package combinations.
4. **Apply packages of energy efficiency measures and low carbon heating systems** to stock based on criteria including suitability and lifetime cost.

2050 end-state uptake of low-carbon heating and energy efficiency uptake.

5. **Apply trajectories of energy efficiency and low carbon heating systems** based on regulatory levers and supply chain considerations.

iterative process

6. **Check in-year deployment numbers against deployment constraints** and amend uptake trajectories, as necessary.
7. **Determine yearly cost and deployment characteristics** including investment, abatement, operating costs, cost effectiveness, etc.

2020-2050 yearly uptake scenarios of low carbon heating and energy efficiency.

Summary of advancements relative to Net Zero work

- This work included several major advancements relative to the Net Zero work, including:
  - Trajectory modelling capability, which allowed detailed modelling of uptake trajectories for both energy efficiency measures and low carbon technologies.
  - Extensive updates to assumptions:
    - Heating demand baseline accounts for a warming climate and is more closely calibrated to real life consumption based on data from the National Energy Efficiency Data-Framework (NEED).
    - Fuel costs and emissions updated, with a refined representation of the effect of flexibility on electricity costs (five different electricity costs modelled, reflecting different profiles of use).
    - Incorporated latest evidence on energy efficiency: technical potential, cost data, including on hard to treat, and savings data from NEED.
    - Low carbon heat costs updated
    - Low carbon heat technology sizing updated (via updated load factors) based on latest evidence.
    - Yearly deployment constraints for heating technologies and energy efficiency measures accounted for in trajectory modelling.
    - Hydrogen trajectory aligned against trajectories developed in industry.
  - Wider range of technologies and technology variations modelled, including improved representation of Ground Source Heat Pumps and Solar Thermal.
  - High-level examination of relevant accompanying adaptation costs.
- As with the Net Zero analysis, hard to decarbonise attributes such as heritage value and space constraints were represented in the modelling. In some cases, representation was on a simplified basis relative to previous work (which focused specifically on hard to decarbonise homes), to accommodate greater levels of complexity elsewhere.

NEED: National Energy Efficiency Data Framework

Overview of approach – behaviour change

- Behavioural measures are applied first in the modelling to reduce a household's energy demand (prior to energy efficiency or low carbon heating).
- Unless otherwise stated (e.g. pre-heating), behavioural measures applied in a scenario are applicable to the whole domestic stock.
- The process by which the behavioural measures, in the table below, were selected and applied is shown in the high-level process flow to the right.

1. **Conduct literature review of known behavioural measures** to develop a list of potential measures.
2. **Add additional novel behavioural measures** to the list, and check feasibility with relevant expert stakeholders.
3. **Select and model a few applicable measures** that are feasible for wide-scale uptake.
4. **Apply selected measures to scenarios** that align with the scenario narrative.

Innovation area	Balanced Pathway	Tailwinds	Widespread Engagement	Headwinds	Widespread Innovation
Pre-heating	25% of post-1952 homes.	50% of post-1952 homes	50% of post-1952 homes	25% of post 1952 homes.	50% of post-1952 homes
Heat as a service	No	Yes [a]	No	No	Yes [a]
Smart metering & control	Standard smart meter [b]	Smart meter with zonal control [c]	Smart meter with zonal control [c]	Standard smart meter [b]	Smart meter with zonal control [c]
Reduced water temperature	No	No	Yes, 50 °C [d]	No	No
Low flow shower head	Yes				

[a] *Heat as a service modelled using: 7.5% cost of capital, 5% increase in heat demand, 3% financial savings, 15% increase in heat pump efficiency.*
[b] *Heat demand reduction based on actions including turning thermostat down and changing operating times.*
[c] *Heat demand reduction based on implementation of automated multizone control.*
[d] *50 degrees only applicable in dwellings which uptake a HP; allowance for daily legionella cycle of 1hr duration included.*

Overview of approach – energy efficiency

1 **Determine the cost (£) and demand savings (%/kWh)** per measure for different property types and sizes based on relevant studies

→ 2 **Apply a savings uplift factor for partial closure of a measure's performance gap** based on a measure type's in-use factor

→ 3 **Create three energy efficiency packages,** putting measures into low, medium, and high packages based on their cost effectiveness and levels of disruption

→ 4 **Determine the annualised cost (£) and savings (£)** of each package for each archetype including capex and fuel savings.

→ **2050 end-state energy efficiency packages** based on suitability and lifetime cost

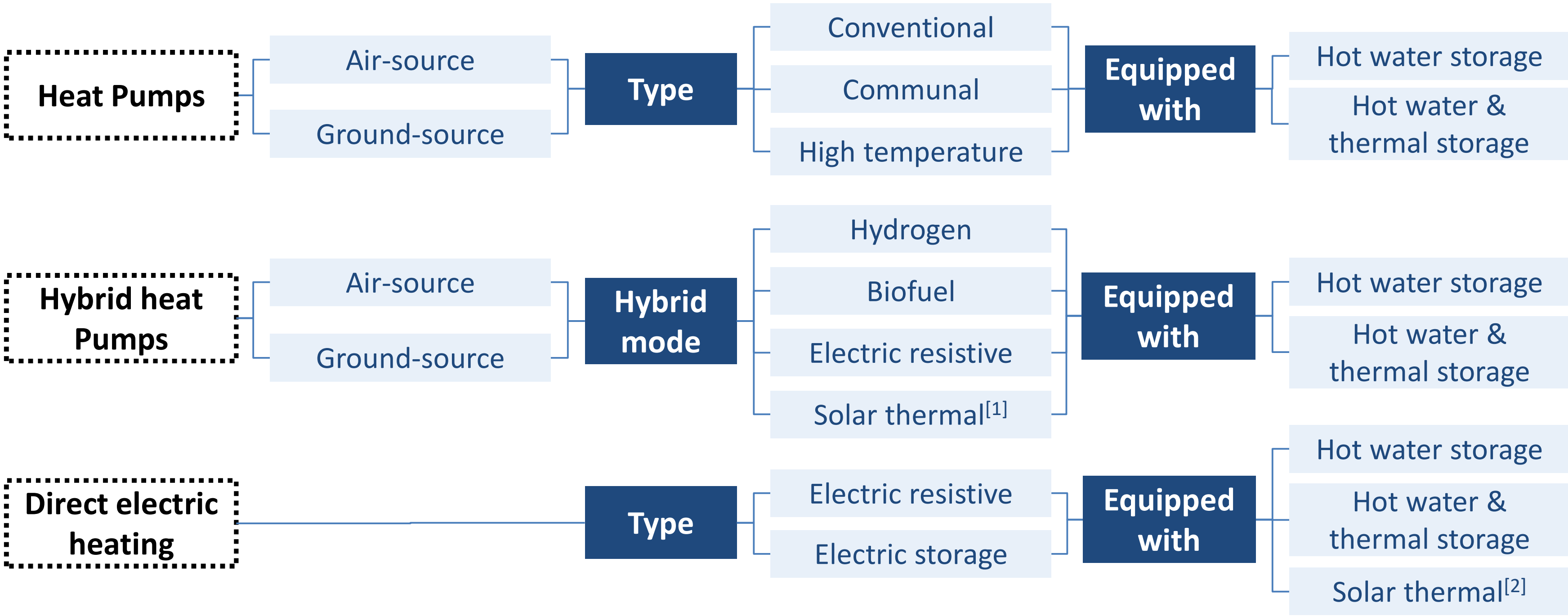
- Three main energy efficiency packages were modelled, each made up of different sets of building fabric and behavioural measures.
  - **Low:** Contains only the least cost, least disruptive measures.
  - **Medium:** Contains more measures than the low package, providing higher savings.
  - **High:** Contains all measures falling under economic potential, to achieve the higher energy demand savings at a higher cost.
- An additional, more extensive, 'deep retrofit' package was modelled particularly for the Widespread Innovation scenario. It is modelled as a whole-house, integrated retrofit approach which delivers an increased level of heat demand savings at higher cost.

Measure	Cost Effectiveness (£/tCO2)	Low	Medium	High
Loft insulation, easy to treat (0-99 mm ETT)	-109	✔	✔	✔
Easy to treat cavity wall insulation (ETT CWI)	-82	✔	✔	✔
Loft insulation, hard to treat (0-99 mm HTT)	-39	✔	✔	✔
Hot water tank insulation	-34	✔	✔	✔
Loft insulation, easy to treat (100-199 mm ETT)	154	✔	✔	✔
Draught proofing (draught stripping)	176	✔	✔	✔
Suspended timber floor insulation	292		✔	✔
Hard to treat cavities wall insulation (HTT CWI)	293		✔	✔
Loft insulation, hard to treat (100-199 mm HTT)	473		✔	✔
Thin internal (solid) wall insulation	556		[1]	[1]
Internal (solid) wall insulation	661		✔	✔
Solid floor insulation	691			✔
External (solid) wall insulation	1039			✔
Double glazing (from single glazed)	2285			[2]
Double glazing (from double glazed pre 2002)	5935			
Triple glazing (from double glazed pre 2002)	4500			

[1] Thin internal (solid) wall insulation replaces standard internal (solid) wall insulation in the Widespread Innovation scenario.
[2] Glazing is present as part of the deep retrofit, which replaces the standard high package, in the Widespread Innovation scenario.

Overview of approach – low carbon heating

- 3 groups of low carbon heating technologies were modelled, with numerous configurations:



- **Hydrogen boilers** and **low carbon heat networks** were also modelled.
- Solar thermal was modelled in two different configurations, providing either (i) a portion of hot water demand, or (ii) a portion of hot water and space heating demand.
- Certain configurations were also split further, depending on the type of electricity used (e.g. flexibility of electricity demand of the technology configuration).

In total, **53** technology configurations were modelled. The list of suitable technologies and assumptions (e.g. costs, lifetimes), were varied between scenarios.

[1] Only air source heat pumps were modelled in the solar thermal hybrid configuration
[2] Includes configurations with added hot water storage and thermal storage

Overview of approach – trajectory development

- Deployment trajectories were developed based on an energy efficiency first approach, with the aim of readying the stock for uptake of low carbon heating technologies ahead of fossil fuel phase-out.
- The building stock was broken down by gas grid connection status (on- or off-grid), fuel poverty (fuel poor or not fuel poor) and tenure (local authority, private rented and owner occupied).[1]
- Each stock segment was then assigned a deployment trajectory representing a regulatory approach (on a UK-wide basis), based on levers for delivery which were deemed realistic:
  – A backstop approach (100% deployment by the backstop date) was used for energy efficiency deployment in the fuel poor, local authority, and private rented segments as those were considered easier to regulate (and in some cases already have government targets for energy efficiency).
  – For energy efficiency deployment in owner occupied homes, which were considered more difficult to regulate, an approach based on incentives for lenders and regulations at Point of Sale (PoS) was used.
  – For most low carbon heating technology deployment, an approach based on setting phase-out dates for fossil heating technologies was used, with the phase out date for off-grid homes set earlier than that for on-grid homes. This approach aims to work with replacement cycles and minimize scrappage costs.
  – For the deployment of hydrogen technologies and low carbon heat networks, trajectories were developed based on geographical conversion profiles e.g. hydrogen technologies being deployed in homes as they gain access to a converted gas grid.
- The regulatory approach used to develop deployment trajectories for this study is meant to be representative of a range of ambition that could be delivered in different ways.
- In total, an average of **28** [2] distinct trajectories were developed per scenario.

Early years (2020 – 2025): Trajectories primarily based on specific measure deployment constraints, developed via input from external stakeholders.

→

Later years:
Trajectories modelled to reflect various policies, and to reflect four approaches.

Backstop dates

Incentives and PoS regulations

Phase-out dates

Geographical conversion

[1] Building stock was broken down further but only the 3 categories mentioned were used to define trajectories
[2] The exact number of curves per scenario varies based on the scenario definition

Overview of approach – key dates for trajectories

	Stock segment	Headwinds	Widespread Innovation	Widespread Engagement	Balanced Pathway	Tailwinds
Backstop date by which sufficient[1] energy efficiency required across all eligible homes	*Private rented sector:*	2030	2028	2027	2028	2027
	Social homes:	2030	2028	2027	2028	2027
	Fuel poor homes:	2030	2030	2030	2030	2030
Period over which incentives for lenders assumed to drive retrofits	*Owner occupiers (mortgagors):*	2025 - 2035	2025 - 2035	2025 - 2030	2025 - 2033	2025 - 2030
Date by which regulations at trigger points are implemented	*Owner occupiers (outright owners):*	2030	2030	2025	2028	2025
Date by which all new heating systems must be low carbon	*Off gas grid:*	2028	2028	2026	2028	2026
	On gas grid:	2035[2]	2035	2030	2033	2030
% of all homes assumed energy efficient by on gas grid regulation date[3]		90%	89%	76%	77%	76%

[1] 'Sufficient' defined as the level of energy efficiency uptake in the scenario i.e. 100% uptake is achieved by the backstop date. [2] Full region-by-region conversion from 2030. [3] Will remain a function both of deployment pace and level of energy efficiency in scenarios.

Key features of the Balanced Pathway scenario [1/2]

- The Balanced Pathway scenario is the basis for the CCC's 6th Carbon Budget recommendation.
- It presents a scenario which, up to the 6th Carbon Budget period, makes strong progress towards Net Zero while keeping open alternative pathways to that goal, and reflects a 'fuel poverty first' approach for buildings.
- The key features of the Balanced Pathway scenario are as follows:
  - Early deployment of energy efficiency, with the aims of:
    - gaining the fuel bill reduction benefits and wider benefits of low regrets measures, and
    - ensuring that sufficient energy efficiency is deployed to make the building stock suitable for low carbon heating over the timescales required.
  - Hy-ready boilers mandated from the mid-2020s (modelled as 2026), minimising potential scrappage costs in the case of widespread hydrogen rollout[1].
  - Strong growth in deployment of heat pumps during the 2020s:
    - to send a clear signal to the market and incentivise supply chains to mobilise and deliver at scale.
    - to keep options open and ensure that the scenario remains compatible with full electrification up to the mid-2030s. With the aim of full electrification and the assumed fossil fuel phase out dates (see previous slide), supply chains must progress in the 2030s such that they are able to supply between 1 and 2 million heat pumps a year by 2035.
    - to deliver additional benefits, including driving down near-term emissions, increasing consumer familiarity and driving down costs through learning by doing.
  - Hydrogen trials through the 2020s to enable decisions on the future of the gas grid in the mid 2020s.

[1] 2026 was chosen as a modelling assumption. Further work by the CCC has brought the policy recommendation in this area forward to 2025.

Key features of the Balanced Pathway scenario [2/2]

- The scenario is intended to remain flexible with regards to the level of deployment of certain technologies and the precise technology mix in 2050:
  - There is optionality to deploy low carbon heating, including HPs, faster than shown in the Balanced Pathway scenario without leading to unfeasible demands on the supply chain, so that if the deployment of certain key technologies such as solid wall insulation or other measures falls short, those technologies can make up the 'gap' to achieve the 6th Carbon Budget.
  - The extent and timing of hydrogen conversion is uncertain and further evidence is needed before a decision can be made on the role for hydrogen – the level of deployment in the Balanced Pathway scenario is only one possible approach to meeting the 6th Carbon Budget and the actual level of deployment could be higher or lower to achieve a similar outcome in carbon emissions terms.
  - The mix of heat pump types (ASHP vs. GSHP, full electric vs. hybrid, individual vs. communal), is intended to be illustrative, and the actual mix could vary materially without substantially impacting the level of the 6th Carbon Budget or the date of achieving Net Zero. It has only been possible to consider a subset of relevant factors in determining technology mixes (and on this basis the mix of heat pump types).

Findings – emissions abatement by scenario

	Direct emissions abatement[1]				Total emissions abatement[1]			
	2035	2035	2050	2050	2035	2035	2050	2050[2]
Scenario	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%
Balanced Pathway	25.8	43%	59.9	100%	24.3	41%	59.2	99%
Tailwinds	36.4	61%	59.9	100%	34.1	57%	59.4	99%
Widespread Engagement	32.1	54%	59.9	100%	30.5	51%	59.4	99%
Headwinds	24.4	41%	59.9	100%	23.5	39%	58.4	97%
Widespread Innovation	32.9	55%	59.9	100%	32.3	54%	59.8	100%

- The Balanced Pathway scenario represents 41% total yearly emissions abatement by 2035 at lowest cost, driven by:
  - deployment of 8 million heat pumps in existing homes (across stock segments), and
  - deployment of 11.9 million energy efficiency packages in existing homes across the private rented and local authority sectors in addition to all fuel poor homes (including owner-occupied fuel poor).
- Total emissions abatement in 2050 varies slightly between scenarios due to the addition of indirect emissions associated with hydrogen and biofuel use.
  - The effect is most pronounced in Headwinds, which has the highest use of both hydrogen and biofuels.
- Direct emissions abatement in 2035 varies by scenario from a low of 41% (Headwinds) to a high of 61% (Tailwinds).
- The pace of decarbonisation in the Balanced Pathway remains close to Headwinds. This reflects both the intent to advise on a budget level which remains compatible with widespread hydrogen conversion, and an ambitious pace of hydrogen conversion in Headwinds, led by industrial decarbonisation.

[1] Percentages represent yearly emissions abated as a % of baseline emissions in the specified year. [2] Total emissions abatement in 2050 varies slightly between scenarios due to the addition of indirect emissions associated with hydrogen and biofuel use.

Findings – summary of costs by scenario [1/2]

			Total abatement costs (£bn)		Total net investment costs (£bn)[1]		Total net opex costs (£bn)		Total net costs (£bn)
Scenario	Average cost effectiveness (£/tCO_2)	Average abatement cost (£bn/y)	To 2035	To 2050	To 2035	To 2050	To 2035	To 2050	To 2050
Balanced Pathway	229	6.3	34.2	190	117	256	-11.1	-37.4	218
Tailwinds	303	9.8	70.5	295	155	259	-15.3	-48.4	211
Widespread Engagement	230	7.2	44.8	217	158	302	-18.2	-69.9	232
Headwinds	267	7.0	30.3	211	94.3	182	-6.4	40.7	223
Widespread Innovation	341	9.5	82.7	286	167	252	-13.2	-54.3	198

- Total abatement costs to 2050 in the Balanced Pathway scenario are the lowest across scenarios, at £190 billion, whereas the highest costs are £295 billion in the Tailwinds scenario. Factors leading to the Balanced Pathway having the lowest cost include:
  - Other scenarios forcing in additional energy efficiency measures (further beyond those deemed cost-effective[2] by the model), such as in Widespread Engagement and Tailwinds.
  - Other scenarios deploying expensive low carbon heating technologies, such as high capex high temperature heat pumps in Widespread Innovation or high opex hydrogen boilers and hybrid H_2 heat pumps in Headwinds.
- Total net investment costs to 2050 in the Balanced Pathway are £256 billion (representing an average of £9,000 per home) and range from £182 billion in Headwinds (£6,400 per home) to £302 billion in Tailwinds (£10,700 per home).
- The Balanced Pathway scenario has the lowest average cost effectiveness, at £229/tCO_2, while the Widespread Innovation scenario has the highest, at £341/tCO_2.
  - Average cost effectiveness is influenced both by total abatement costs and the total cumulative emissions abated. A scenario which reaches Net Zero earlier (e.g. Tailwinds) abates more emissions cumulatively (i.e. has higher yearly abatement for a longer period), so has a lower average cost effectiveness than a scenario with similar total abatement costs e.g. Widespread Innovation.

[1] See footnote on next slide. [2] Cost-effectiveness is defined as the cost of a measure per unit of emissions abated, in £ per tonne of CO_2e. The costs do not account for wider social benefits such as improved health.

Findings – summary of costs by scenario [2/2]

			Total abatement costs (£bn)		Total net investment costs (£bn)[1]		Total net opex costs (£bn)		Total net costs (£bn)
Scenario	Average cost effectiveness (£/tCO_2)	Average abatement cost (£bn/y)	To 2035	To 2050	To 2035	To 2050	To 2035	To 2050	To 2050
Balanced Pathway	229	6.3	34.2	190	117	256	-11.1	-37.4	218
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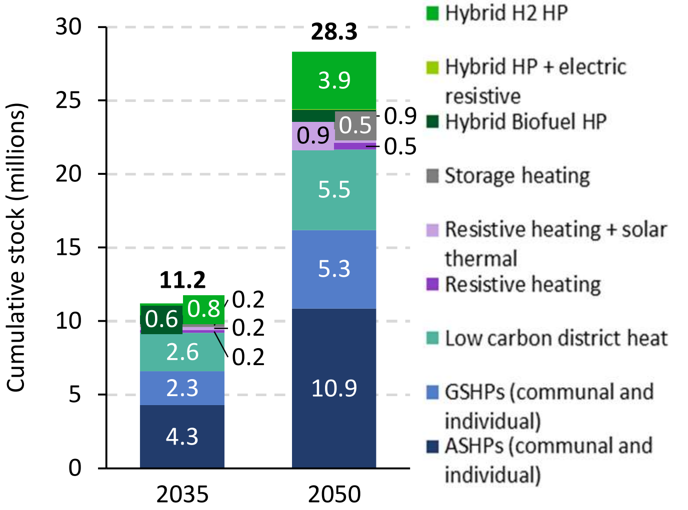
Widespread Innovation	341	9.5	82.7	286	167	252	-13.2	-54.3	198

- Investment costs only account for in-year, undiscounted capex, and therefore are unaffected by the cost of capital. Abatement costs, on the other hand, incorporate annualised capex discounted by the cost of capital in addition to opex and fuel costs discounted by the discount rate. The two figures are therefore not directly comparable.
  - The cost of capital used for Widespread Innovation and Tailwinds (7.5%) is higher than that used for the other scenarios (3.5%) overpowering more ambitious assumptions on cost reductions and leading to higher abatement costs in the former two scenarios (see slide). Additionally, in these scenarios the higher cost of capital is applied to energy efficiency measures. This is a pessimistic assumption, which partially explains the higher abatement costs.
  - Comparing total costs (investment + opex) with abatement costs shows a consistent pattern of net costs being higher than abatement costs for scenarios using the lower cost of capital.

[1] Investment costs in this modelling are expected to be overestimated to some degree, due to assuming renewal costs for all household conversion items including radiators. An adjustment has been made to remove these additional renewal costs in the CCC's final Balanced Pathway.

Findings – Balanced Pathway scenario overview

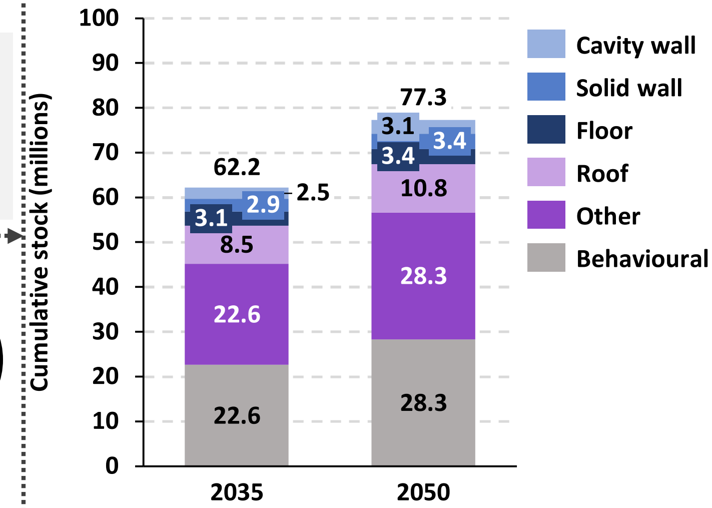
Low carbon heating breakdown

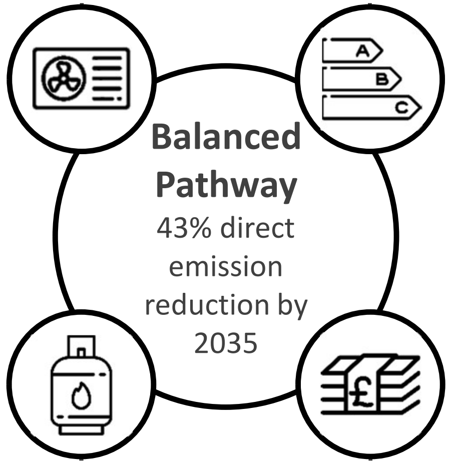


LCH & EE Key Numbers

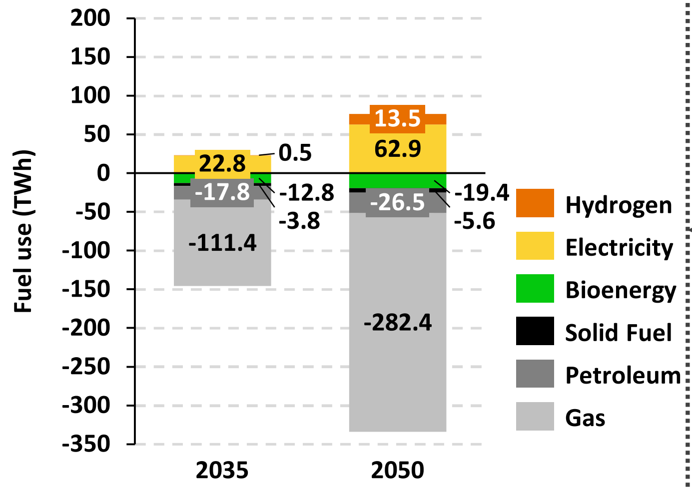
- Average £/tCO_2e: 229
- Heat pumps (all kinds): 21m
- Homes with HS: 1.4m
- All practicable cavities & lofts insulated. 3.4m solid walls.

Measure breakdown





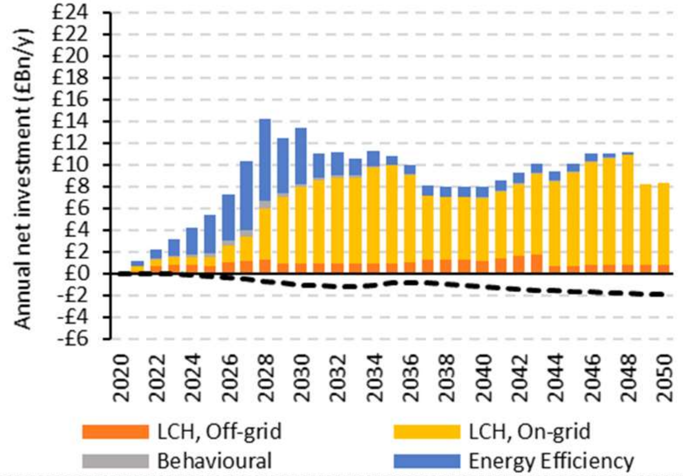
Fuel use (change vs. baseline)



Fuel Use & Investment Key Numbers

- Net investment: £256bn.
- Electricity demand: 86 TWh
- Average yearly abatement cost[1]: £6.3bn/yr.

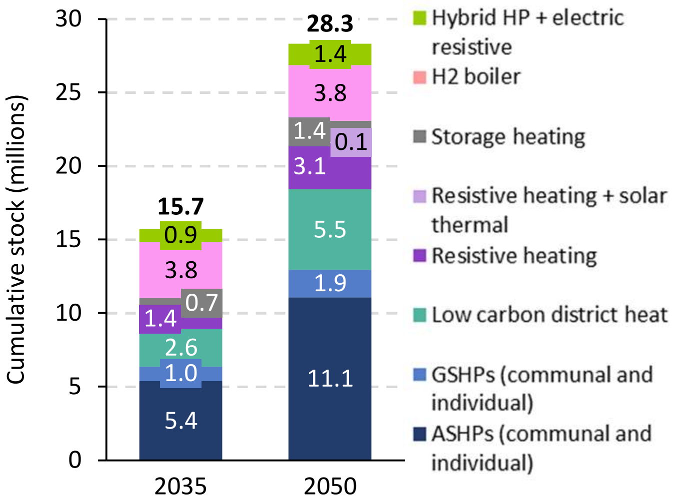
Annual investment, overlaid with opex (dotted line), associated with decarbonising heat in existing homes



LCH: Low Carbon Heating; EE: Energy Efficiency HS: Heat Storage. [1] Abatement costs incorporate annualised capex discounted by the cost of capital in addition to opex and fuel costs discounted by the discount rate.

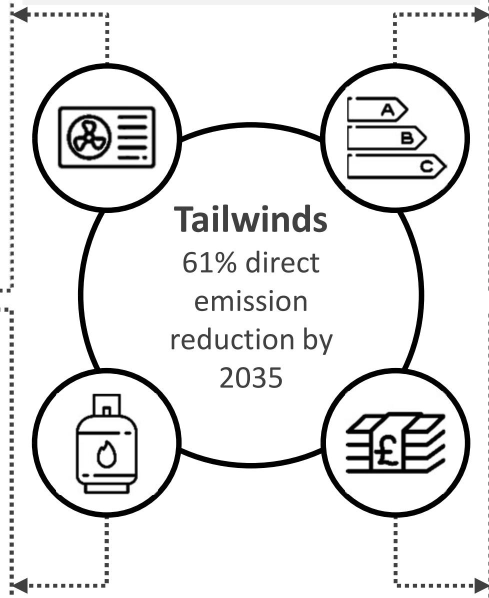
Findings – Tailwinds scenario overview

Low carbon heating breakdown

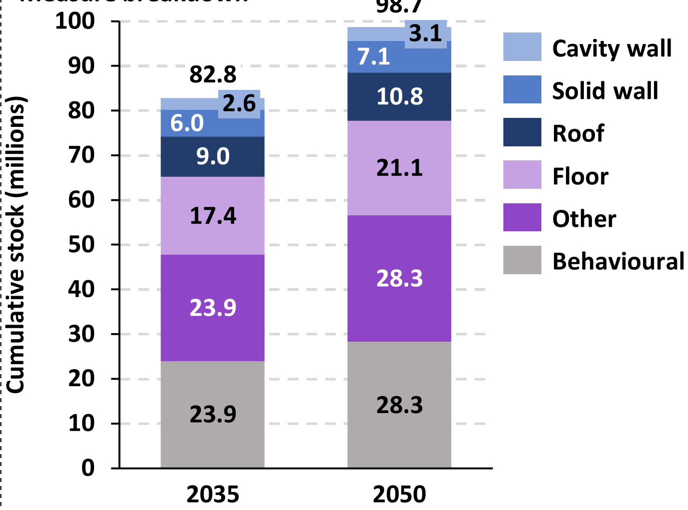


LCH & EE Key Numbers

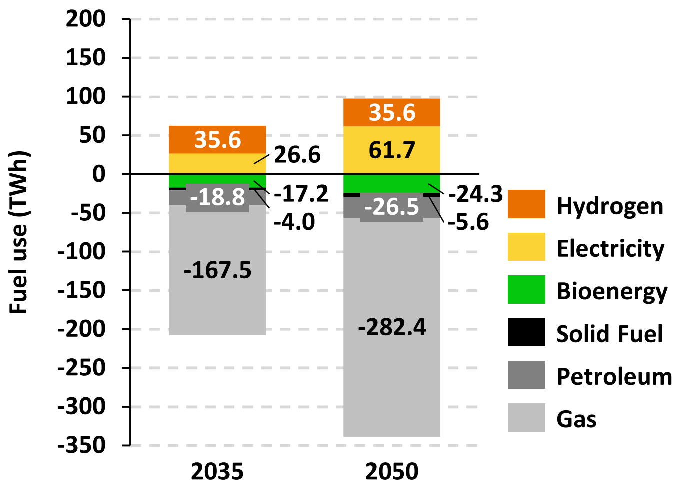
- Average £/tCO_2e: 303
- Heat pumps (all kinds): 14m
- Homes with HS: 5.9m
- Full economic potential deployed for fabric efficiency.



Measure breakdown



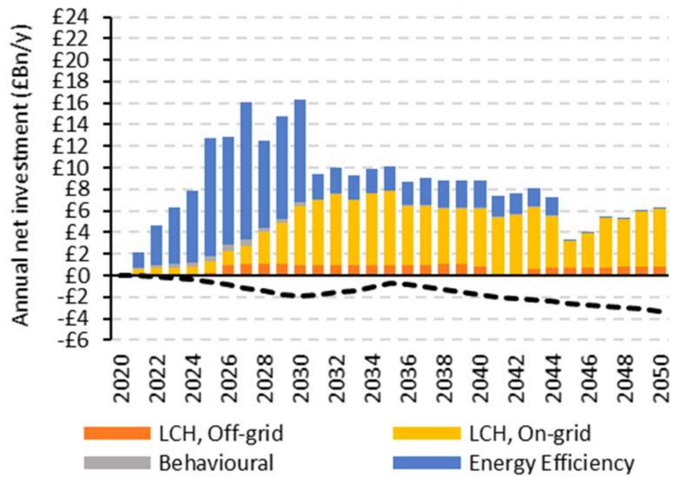
Fuel use (change vs. baseline)



Fuel Use & Investment Key Numbers

- Net investment: £259bn.
- Electricity demand: 84 TWh
- Average yearly abatement cost[1]: £9.8bn/yr.

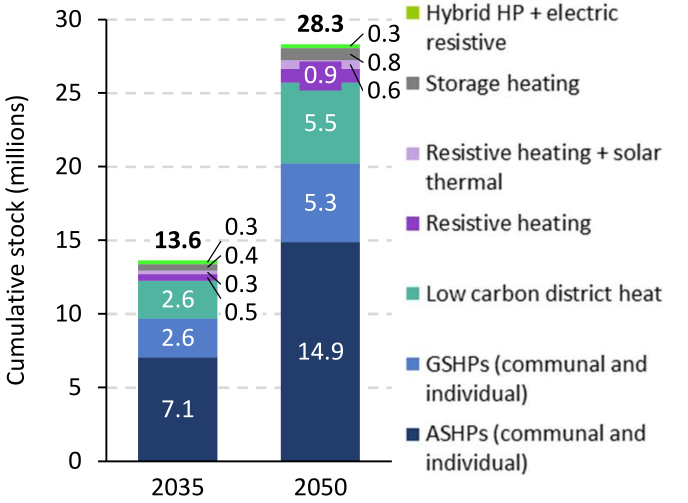
Annual investment, overlaid with opex (dotted line), associated with decarbonising heat in existing homes



LCH: Low Carbon Heating; EE: Energy Efficiency; HS: Heat Storage. [1] See footnote on “Findings – Balanced Pathway scenario overview” slide.

Findings – Widespread Engagement scenario overview

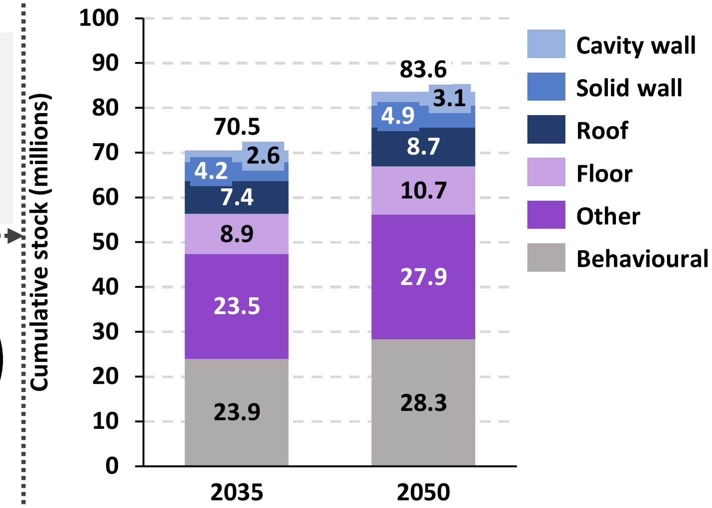
Low carbon heating breakdown



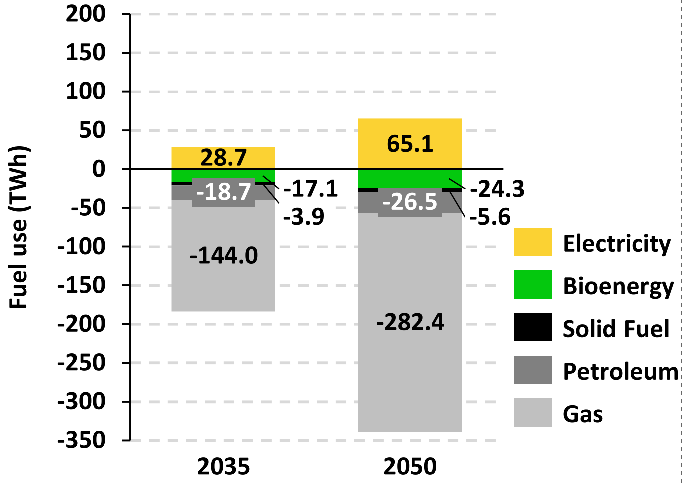
LCH & EE Key Numbers

- Average £/tCO_2e: 230
- Heat pumps (all kinds): 21m
- Homes with HS: 4m
- All practicable cavities insulated. 4.9m solid walls.

Measure breakdown



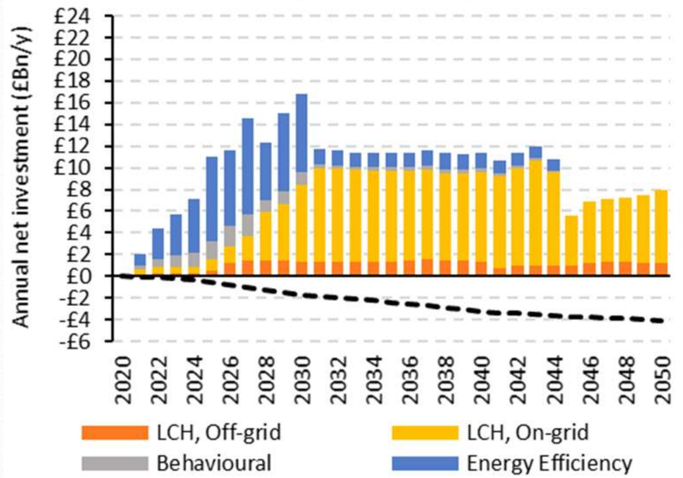
Fuel use (change vs. baseline)



Fuel Use & Investment Key Numbers

- Net investment: £302bn.
- Electricity demand: 88 TWh
- Average yearly abatement cost[1]: £7.2bn/yr.

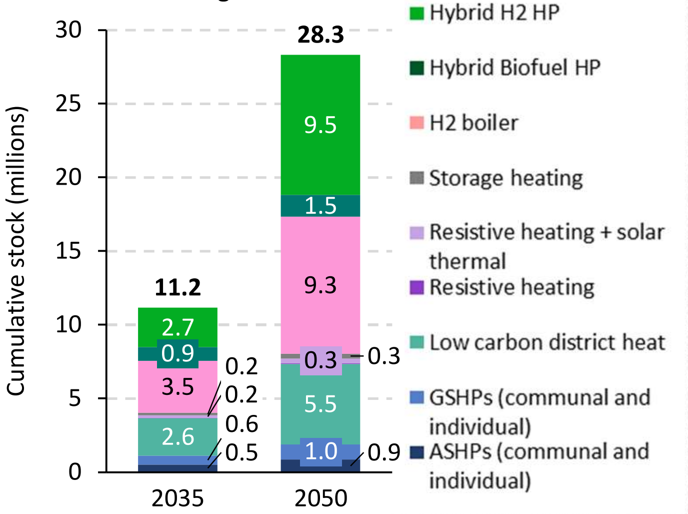
Annual investment, overlaid with opex (dotted line), associated with decarbonising heat in existing homes



LCH: Low Carbon Heating; EE: Energy Efficiency; HS: Heat Storage. [1] See footnote on “Findings – Balanced Pathway scenario overview” slide.

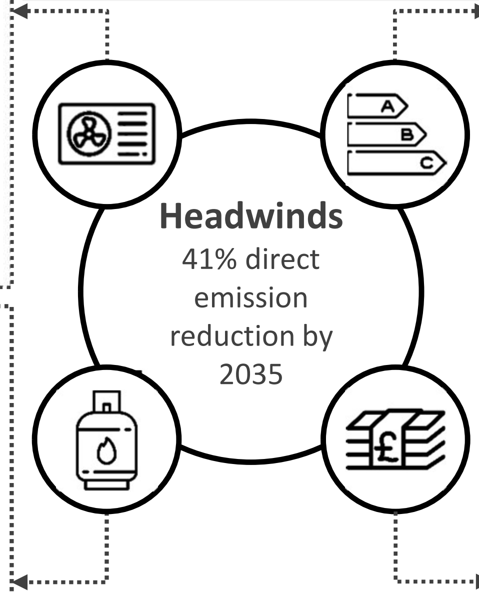
Findings – Headwinds scenario overview

Low carbon heating breakdown

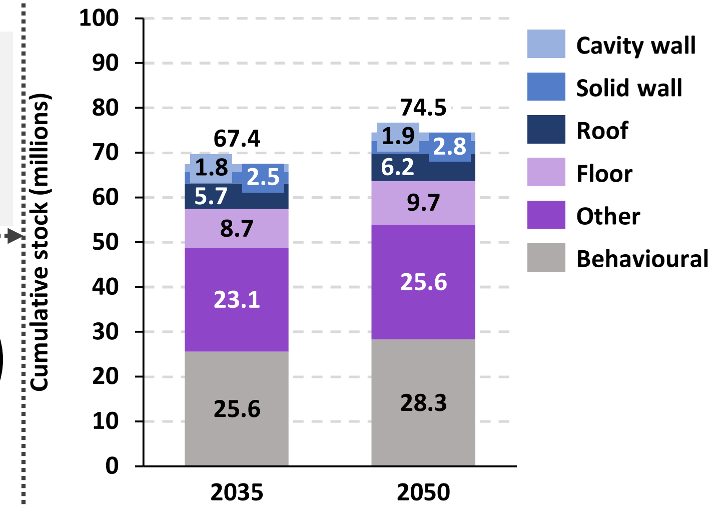


LCH & EE Key Numbers

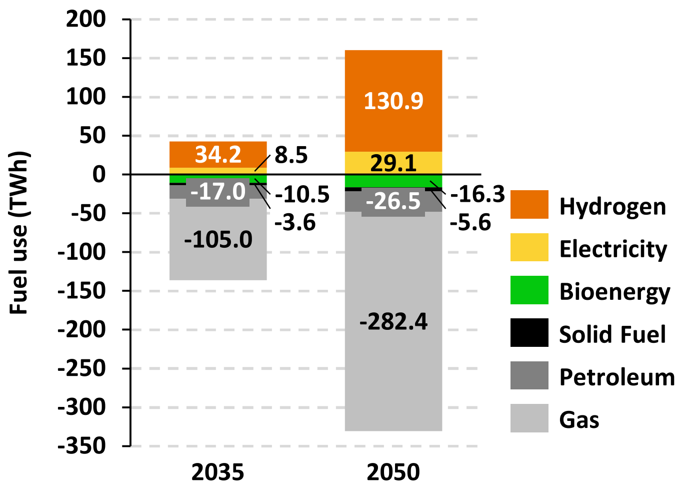
- Average £/tCO_2e: 267
- Heat pumps (all kinds): 13m
- Homes with HS: 0.4m
- Lower energy efficiency uptake[1].



Measure breakdown



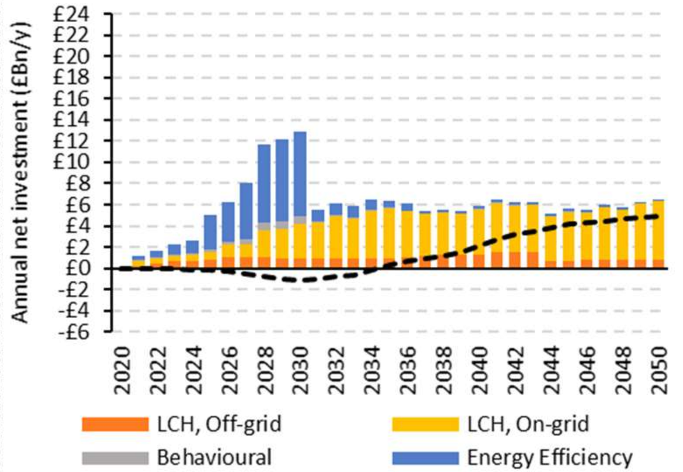
Fuel use (change vs. baseline)



Fuel Use & Investment Key Numbers

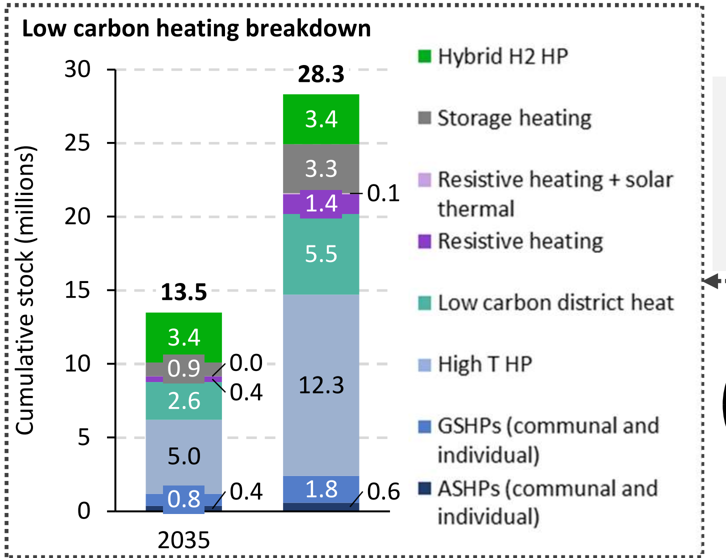
- Net investment: £182bn.
- Electricity demand: 52 TWh
- Average yearly abatement cost[2]: £7.0bn/yr.

Annual investment, overlaid with opex (dotted line), associated with decarbonising heat in existing homes



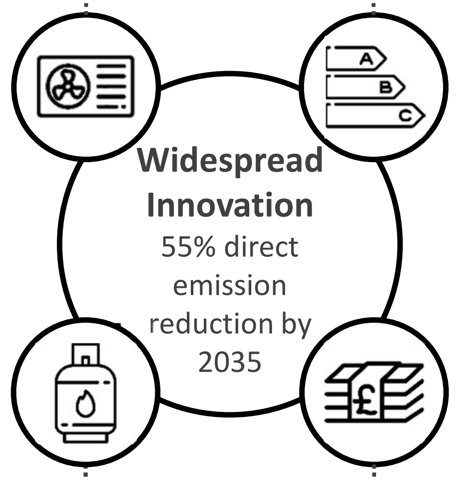
LCH: Low Carbon Heating; EE: Energy Efficiency; HS: Heat Storage. [1] Model allowed to determine 'cost effective' level (not reflecting wider benefits) for non-fuel poor homes but reflecting higher bound assumptions on hydrogen costs. [2] See footnote on "Findings – Balanced Pathway scenario overview" slide.

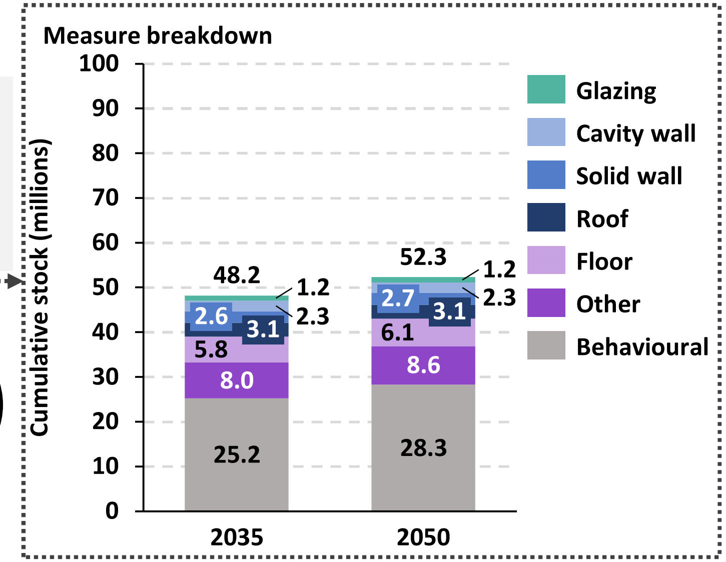
Findings – Widespread Innovation scenario overview

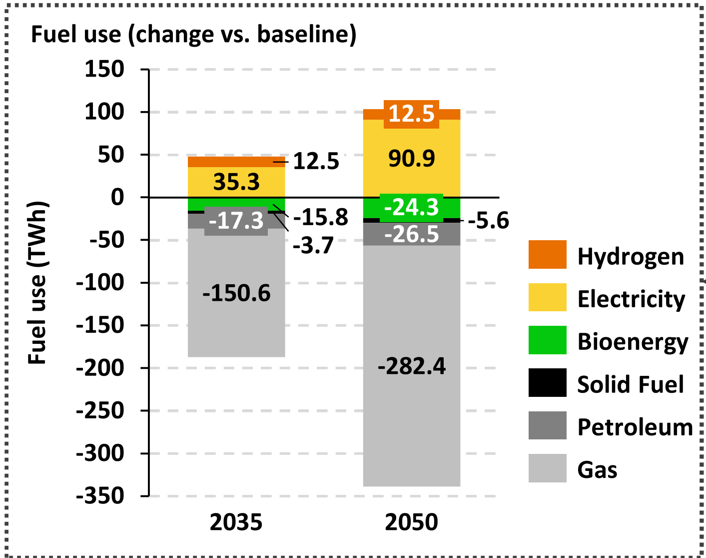


LCH & EE Key Numbers

- Average £/tCO$_2$e: 341
- Heat pumps (all kinds): 18m
- Homes with HS: 14.2m
- Lower efficiency uptake, with some deep retrofits[1].

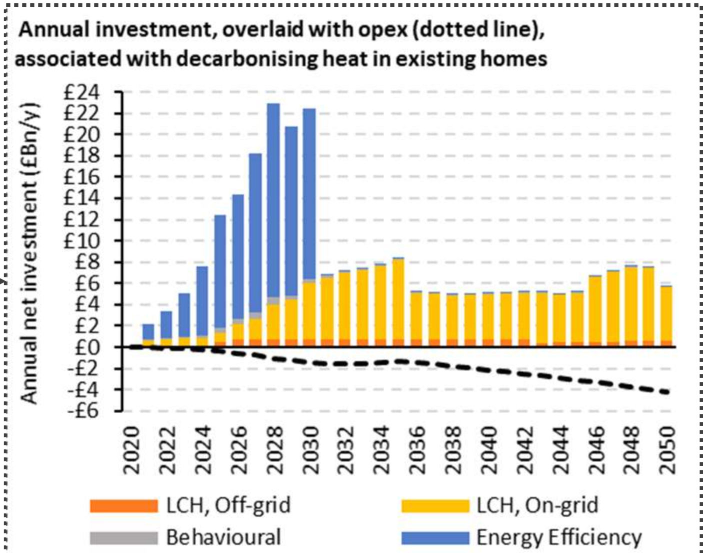






Fuel Use & Investment Key Numbers

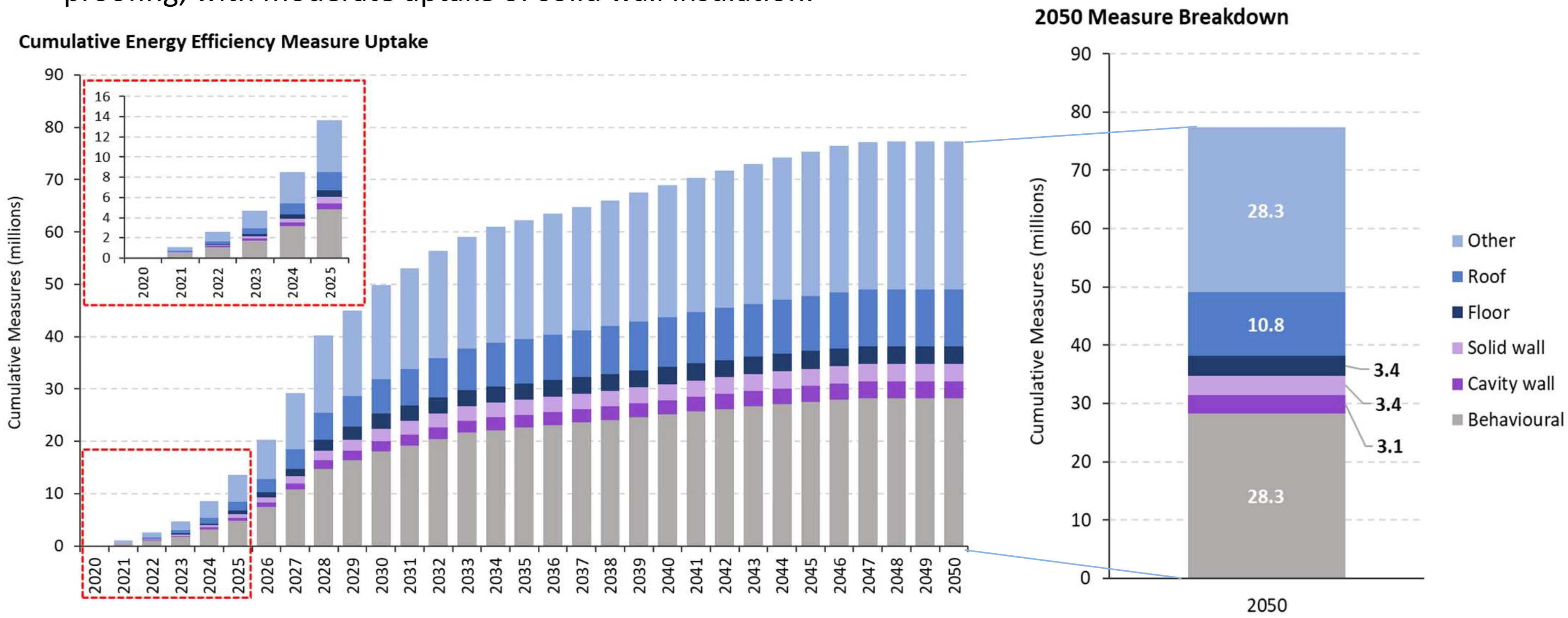
- Net investment: £252bn.
- Electricity demand: 114 TWh
- Average yearly abatement cost[2]: £9.5bn/yr.



LCH: Low Carbon Heating; EE: Energy Efficiency. [1] Model allowed to determine 'cost effective' level (not reflecting wider benefits) for non-fuel poor homes. All high packages (e.g. in fuel poor homes) modelled as deep retrofits. [2] See footnote on "Findings – Balanced Pathway scenario overview" slide.

Findings – Balanced Pathway energy efficiency uptake trajectory

- As the scenarios are based on an "energy efficiency first" approach; uptake of energy efficiency ramps up rapidly from current levels in the early years.
  - 64% of energy efficiency deployment in Balanced Pathway happens in the first 10 years (i.e. to 2030).
  - Urgent ramp-up is needed relative to deployment levels today to achieve the scenario's targets.
- The Balanced Pathway scenario represents a level of energy efficiency uptake which focuses on maximising uptake of low cost, low disruption measures such as loft insulation, cavity wall insulation and draught proofing, with moderate uptake of solid wall insulation.



Findings – Energy efficiency uptake ranges across scenarios [1/2]

	Number of measures deployed (millions)						Total heat demand (TWh/y)			
Scenario	Loft	Cavity wall	Solid wall	Floor	Other	Behavioural	2017	2050	Energy demand savings (TWh/y)	Reduction in heat demand as a result of EE
Balanced Pathway	10.8	3.1	3.4	3.4	28.3			276	37	12%
Tailwinds	10.8	3.1	7.1	21.1	28.3			245	68	22%
Headwinds	9.7	2.8	1.9	6.2	25.6	28.3	313	278	35	11%
Widespread Engagement	10.7	3.1	4.9	8.7	27.9			263	50	16%
Widespread Innovation	6.1	2.7	1.2	2.3	8.6			274	39	12%

- Energy efficiency levels are driven by different factors in each scenario:
  - **Balanced Pathway:** inclusion of all practicable loft and cavity insulation (i.e. all economic potential[1]), in addition to solid walls where the package they are taken up with had a cost effectiveness <£600/t.
  - **Tailwinds:** inclusion of full economic potential for all energy efficiency measures.
  - **Headwinds:** model permitted to optimise for the lowest lifetime cost energy efficiency + low carbon heating combination, given high H_2 prices, with no wider benefits costed for non-fuel poor homes. This is the only scenario with 'cost-effective' uptake at standard prices.
  - **Widespread Engagement:** deployment of a medium energy efficiency package in all households.
  - **Widespread Innovation:** model permitted to optimise for the lowest lifetime cost using lower-end costs, with no wider benefits costed for non-fuel poor homes; deep retrofits replace standard high packages.

- Solid walls in fuel poor homes are insulated across scenarios (implemented via the high energy efficiency package).
  - Given the high uncertainty over the achievable performance of solid wall insulation in particular, a broad range of uptake levels was modelled across the scenarios, with Tailwinds representing full economic potential.

[1] Generally, measures where costs came in above £700/tCO_2e for a typical home excluded from economical potential. A typical home was assumed to be a medium semi-detached home. Scaffolding and design costs were not included in calculations of economic potential.

Findings – Energy efficiency uptake ranges across scenarios [2/2]

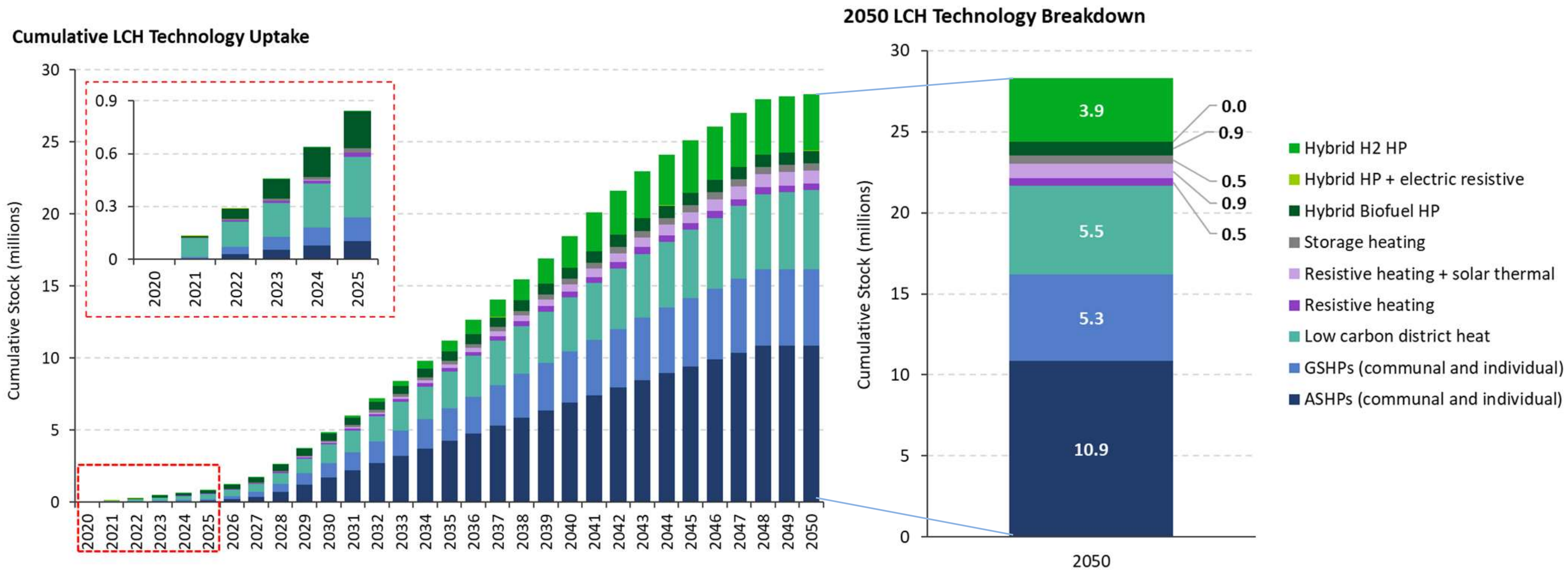
	Number of measures deployed (millions)						Total heat demand (TWh/y)			
Scenario	Loft	Cavity wall	Solid wall	Floor	Other	Behavioural	2017	2050	Energy demand savings (TWh/y)	Reduction in heat demand as a result of EE
Balanced Pathway	10.8	3.1	3.4	3.4	28.3	28.3	313	276	37	12%
Tailwinds	10.8	3.1	7.1	21.1	28.3			245	68	22%
Headwinds	9.7	2.8	1.9	6.2	25.6			278	35	11%
Widespread Engagement	10.7	3.1	4.9	8.7	27.9			263	50	16%
Widespread Innovation	6.1	2.7	1.2	2.3	8.6			274	39	12%

- The overall heat demand reduction has significant variation across homes:
  - A proportion of homes do not get any additional energy efficiency measures. This applies to homes where there is existing insulation or where additional measures would not be cost effective. The number of such homes varies from 0% in the Balanced Pathway and Tailwinds to 69% in Widespread Innovation.
  - In the Balanced Pathway scenario, a typical household which installs cavity wall insulation, loft insulation, and floor insulation sees heat demand savings of 30%.
  - A home getting a deep retrofit (applicable in Widespread Innovation) sees heat demand savings of 57%.

- Energy efficiency and behavioural packages in the Balanced scenario deliver a 12% reduction in heat demand to 2050, with a 22% reduction being delivered in our Tailwinds scenario.
  - The lower stock-level heat demand savings relative to the Net Zero analysis reflect a number of factors, including updated technical and economic potential (leading to lower deployment), and updated cost and savings assumptions (leading to lower cost effectiveness).

Findings – Balanced Pathway low carbon heat uptake trajectory

- Rapid ramp up of energy efficiency deployment prepares the stock for low carbon heating uptake, which also deploys rapidly in the early years.
- 3.3 million heat pumps are deployed in existing homes by 2030 and 8 million by 2035 in the Balanced Pathway scenario.
- Deployment of hybrid[1] H_2 heat pumps ensures consistency with scenarios in the industry sector, with hydrogen grid conversion potentially occurring all the way to 2050 (see slide). Hybrids are deployed steadily to 2050 to ensure they are only deployed in areas which will be converted to H_2.



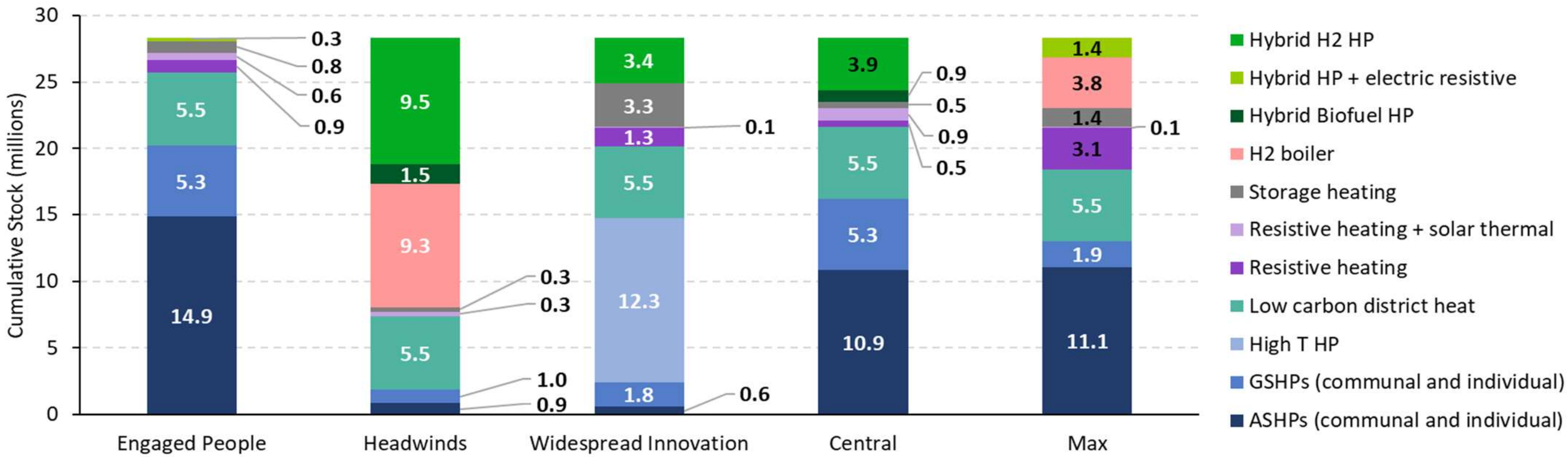
[1] While both ASHP and GSHP hybrids were tested in the modelling, ASHP hybrids were found to be more cost-effective and are therefore the variant deployed for all hybrid configurations.

Findings – 2050 low carbon heat uptake across scenarios

- The graph below shows the different end-state technology mixes in each scenario, illustrating how Net Zero can be achieved via various technology routes.
- Common themes across the scenarios include:
  - 5.5 million homes are connected to low carbon heat networks.
  - A high number (over 10 million) of heat pumps are taken up – of various types, including hybrids – even in a hydrogen-heavy scenario (Headwinds).
- Deployment of technologies with additional heat storage varies from 0.4 million in Headwinds to 14.2 million in Widespread Innovation.

Scenario	Number of technologies deployed with additional thermal storage[1] (millions)
Balanced Pathway	1.4
Tailwinds	5.9
Headwinds	0.4
Widespread Engagement	4.0
Widespread Innovation	14.2

2050 LCH Technology Breakdown

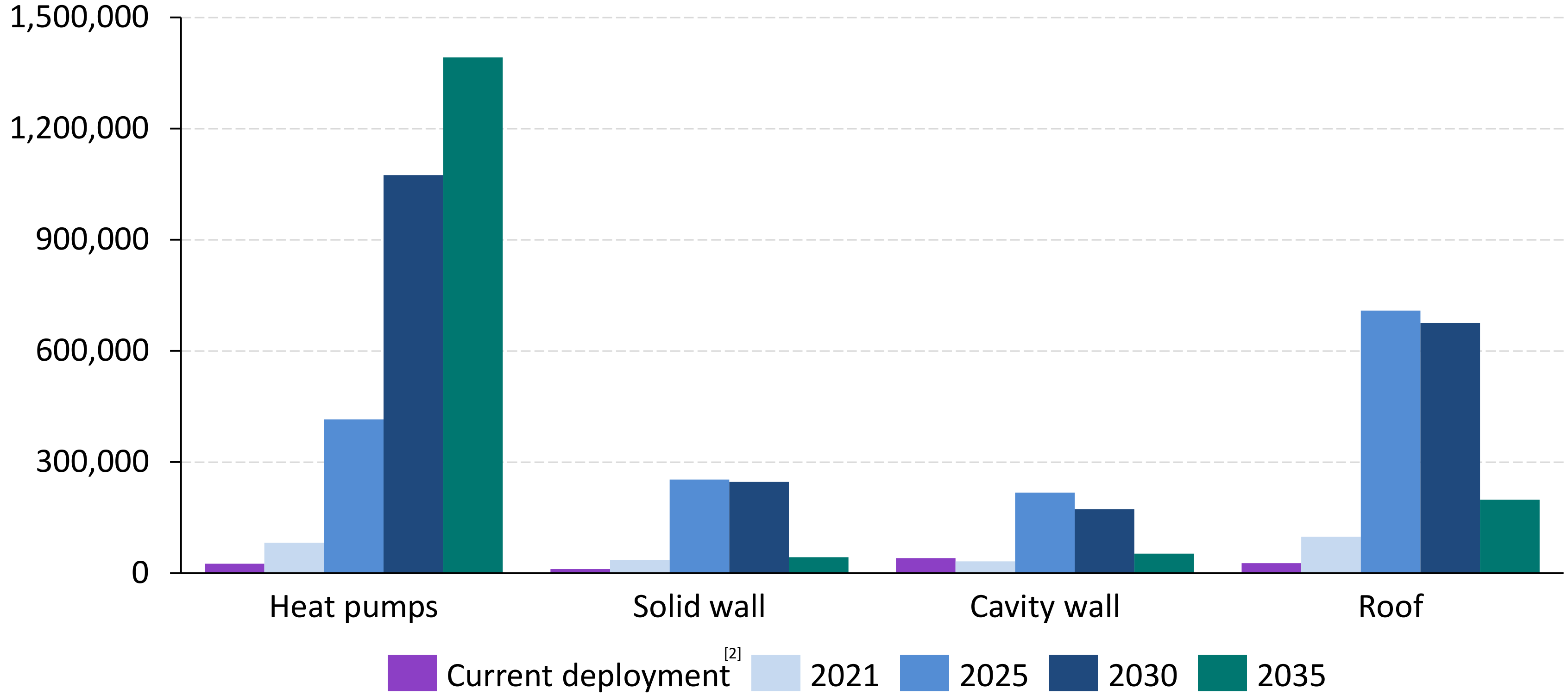


[1] Thermal storage is assumed to be delivered via a heat battery, but could equally be delivered via an electrical battery. The level of deployment of thermal storage affects the number of homes able to access cheaper electricity as a result of higher levels of flexibility.

Discussion – a fast expansion of critical supply chains is required to meet the modelled trajectories

- All scenarios require an aggressive increase in the deployment rate of heat pumps, particularly from 2030 onward.
  - A nearly ten-fold increase is required by 2025, with 1.4 million heat pumps deployed in 2035 in the Balanced Pathway scenario. [1]
- Rapid ramp up of deployment is also required for energy efficiency measures, with sustained growth in the 2020s.

Yearly deployment of heat pumps and selected energy efficiency measures in Balanced Pathway

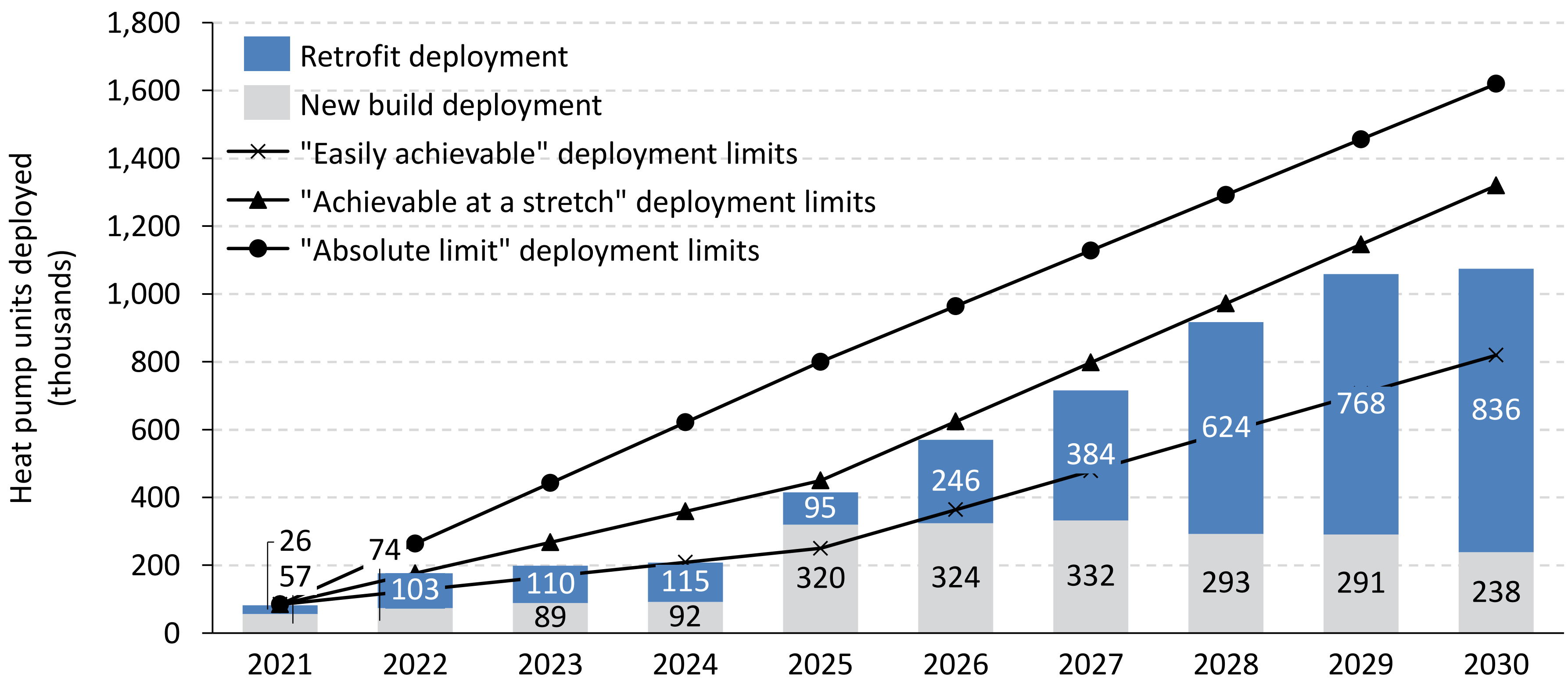


[1] Including new build deployment, which was not directly modelled in this work
[2] Heat pumps, 2018 figures; EE, 2019 figures

Discussion – heat pump deployment ramps-up rapidly in the early years but remains within "achievable at a stretch" deployment constraints

- To meet a net zero target in 2050, a major acceleration in heat pump deployment is required.
  - The envisaged deployment levels up to 2030 – particularly for heat pumps – are ambitious but achievable, being almost at the limit of constraints considered "achievable at a stretch" based on external expert stakeholder feedback in the industry.

Comparison of Balanced Pathway scenario heat pump deployment[1] against technology deployment limits

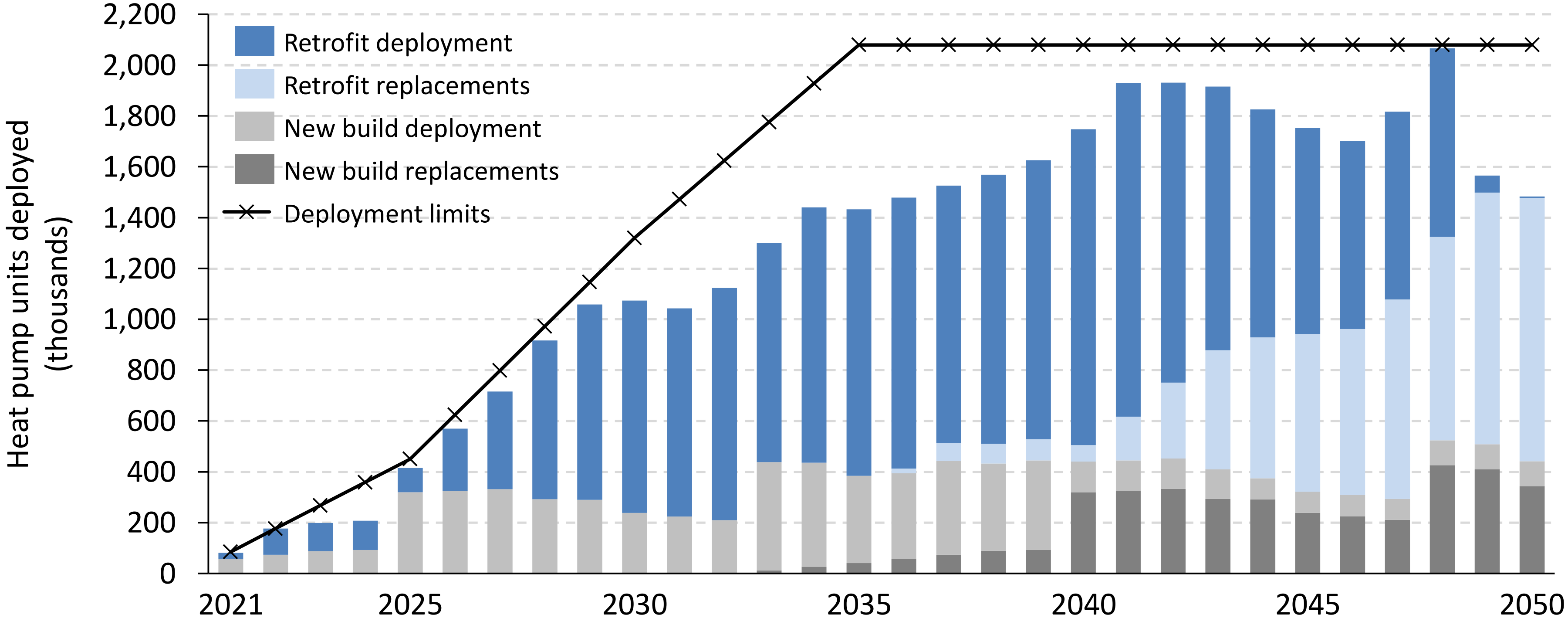


[1] Includes new build heat pumps, which were not directly modelled in this work

Discussion – total heat pump deployment represents a smooth ramp-up

- With new builds and replacements taken into account, the modelled heat pump uptake trajectory delivers a relatively smooth ramp-up of deployment. After 2030, deployment rates keep increasing, but at a slower rate than deployment limits.
- In the 2040s replacements become a significant part of total deployment, with new installations and replacements together approaching the deployment limits.
  - The limits are modelled as constant after 2035 but in reality would be expected to further increase, albeit at a slower rate compared with the period before 2035.

Comparison of Balanced Pathway heat pump deployment[1] against heat pump deployment limits



[1] Includes new build heat pumps and new build replacements, which were not directly modelled in this work. Replacements assume a 15-year heat pump lifetime for ASHPs and 20 years for GSHPs. New build replacements before 2036 are due to new build deployment before 2021, not shown in the graph.

Discussion – technology deployment at key dates

Cumulative deployment for selected technology groups
k: thousands; m: millions

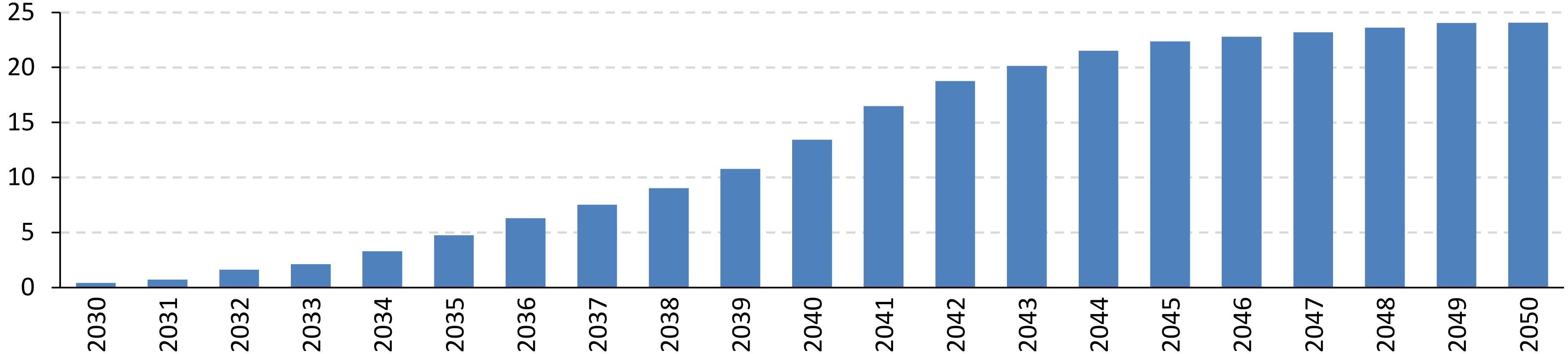
	Balanced Pathway deployment [range across scenarios]					
Low carbon heating technology group	**2022**	**2025**	**2028**	**2030**	**2040**	**2050**
Heat pumps	70k [24k – 70k]	240k [88k – 260k]	1.3m [450k – 1.5m]	2.7m [640k – 3.2m]	10.5m [1.6m – 16.1m]	16.2m [1.9m – 20.2m]
Hybrid heat pumps	59k [0 – 59k]	210k [10k – 240k]	450k [190k – 800k]	570k [250k – 1.4m]	3.0m [270k – 6.2m]	4.8m [280k – 11.0m]
Electric storage	7k [2k – 8k]	23k [8k – 28k]	56k [40k – 150k]	110k [80k – 340k]	390k [280k – 1.9m]	490k [330k – 3.3m]
Electric resistive	8k [2k – 8k]	26k [7k – 26k]	85k [45k – 120k]	180k [89k – 300k]	890k [310k – 2.5m]	1.4m [370k – 3.2m]
Hydrogen heating (boilers only)	0 [0 – 0]	0 [0 – 3k]	0 [0 – 12k]	0 [0 – 330k]	0 [0 – 6.6m]	0 [0 – 9.3m]
Hydrogen heating (boilers + hybrid H_2 heat pumps)	0 [0 – 0]	3k [0 – 75k]	12k [0 – 350k]	80k [0 – 1.1m]	2.2m [0 – 11.5m]	3.9m [0 – 18.8m]

- The table shows cumulative deployment of several low carbon heating technologies in selected years in the Balanced Pathway scenario, with the range across scenarios shown in square brackets.
- It is important to note that hybrid H_2 heat pumps may be deployed before grid conversion, and are assumed to operate on gas, in hybrid mode, until hydrogen becomes available.

Discussion – hydrogen trajectory assumptions and implications

- The trajectory for deployment of heating technologies using hydrogen is based on a set of assumptions describing a small set of illustrative approaches to a phased conversion of the gas distribution grid[1].
- The grid conversion trajectory, which is aligned with the parallel analysis on the industry sector for the 6th Carbon Budget, involves conversion of the gas grid between 2030 and 2050 over an increasing catchment area associated with seven identified industrial clusters.
  - Separate deployment of hydrogen trials – 12,300 units – in the 2020s is also assumed to occur.
  - Once homes fall within the radius of conversion, they are assumed to have potential access to hydrogen. This does not necessarily mean the entire grid within that radius is assumed to convert to hydrogen, as explained further below.
- In scenarios where the grid fully converts i.e. Headwinds, the conversion trajectory results in 4.7 million (20%) of current grid-connected homes having access to hydrogen by 2035, 13.4 million (56%) by 2040 and 24.1 million (100%) by 2050.
- For all other scenarios, the hydrogen conversion trajectory above does not assume that the grid is fully converted but assumes partial conversion of the grid in areas designated for conversion – this analysis does not attempt to specify which areas should be designated for conversion. Partial conversion is represented differently in different scenarios, with some assuming conversion of all homes in radius (with radial expansion limited) and others assuming partial conversion in radius (with radial expansion unlimited).
  - In the Tailwinds scenario, homes receiving hydrogen boilers are assumed to be in areas surrounding the industrial clusters.

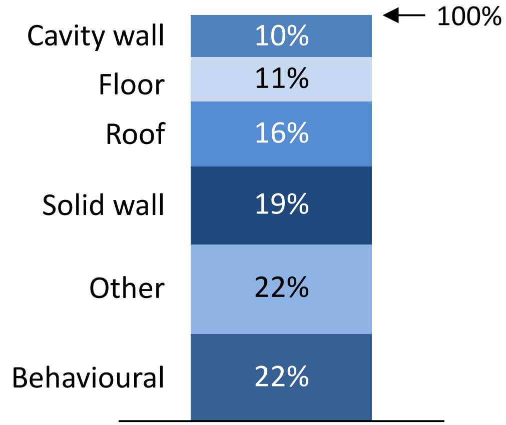
Homes with potential access to hydrogen



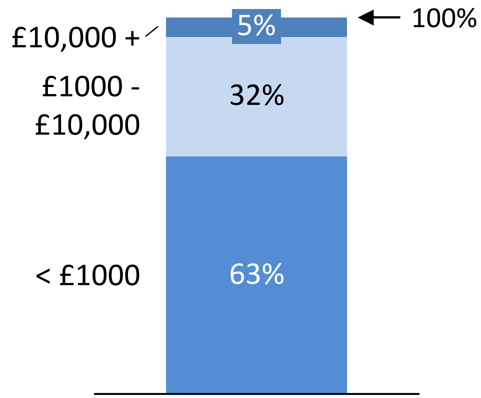
[1] The actual deployment of heating technologies using hydrogen varies between scenarios (see previous slides)

Discussion – substantial behavioural and energy efficiency savings in the scenarios can be delivered at low cost

- 63% of all homes need spend no more than £1000 on retrofitting energy efficiency measures, with these homes delivering 30% of the scenario-wide energy savings in the Balanced Pathway scenario.
  - 30% of all energy savings from energy efficiency in the Balanced Pathway scenario are associated with measure packages costing under £1000.
  - These are expected to typically be homes with behavioural and other measures (draught proofing, hot water tank insulation) only or with loft / cavity insulation alongside.
- The measures generating the highest savings in the Balanced Pathway scenario include behavioural measures, solid wall insulation, and 'other' measures, together making up around 3/5 of savings.
  - 'Other' measures include draught proofing and hot water tank insulation. Most of the savings here are expected to come from draught proofing as it delivers savings of ~3% per home, applied to the majority of the stock.
- 49% of savings in the Balanced Pathway scenario come from homes with retrofit packages costing between £1000 - 10,000.
  - These are largely concentrated in the able-to-pay owner occupied stock.
- The cheapest retrofit packages (under £1000) deliver on average 8.7% savings per home, whilst the mid-range packages (£1000 - £10,000) deliver 21% savings on average. The most expensive retrofits in the Balanced Pathway scenario cut heat demand by approximately a third.[1]



% of Scenario's Total TWh Savings from Energy Efficiency/Behavior Change



Household Energy Efficiency Cost Distribution

[1] The numbers provided for this point are derived from simple averages, rather than weighted by uptake, which would likely lead to lower values.

Discussion – energy efficiency measures contribute to bill savings, as well as delivering wider benefits

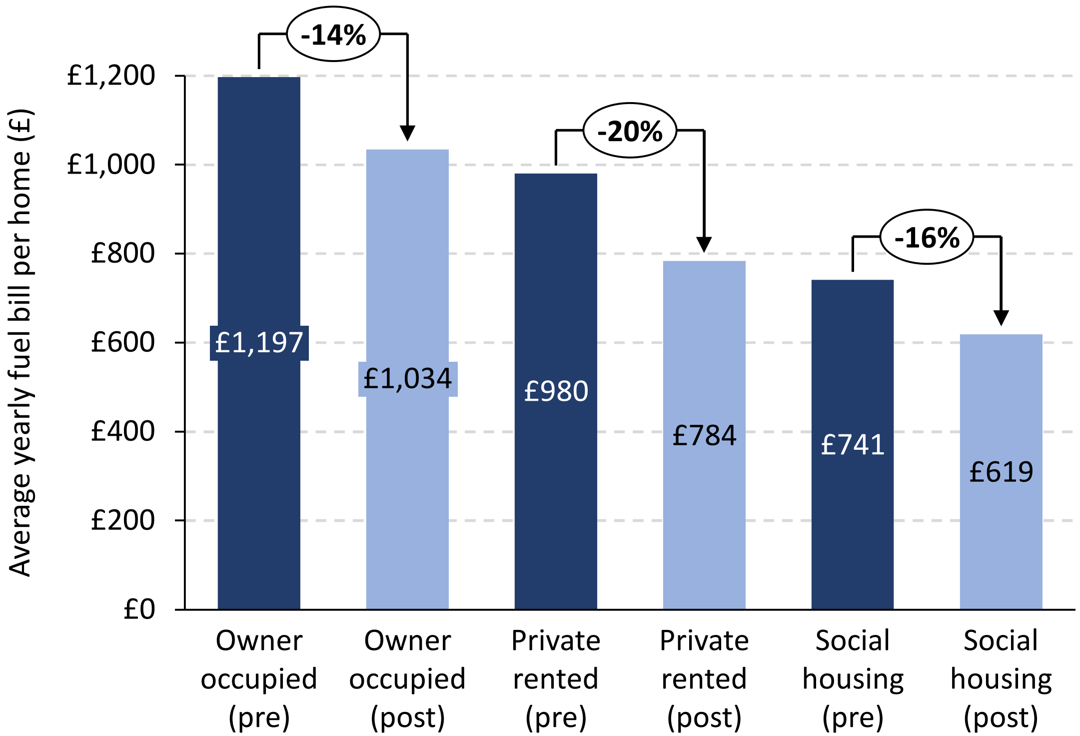
- Energy efficiency measures and behavioural changes should be deployed/implemented early and widely across the stock to drive down fuel bills in homes. This is valuable both to manage heat pump electricity demand and the high opex costs associated with any hydrogen use.
- Energy efficiency deployment in the early years is dominated by the local authority and private rented sectors, in addition to fuel poor homes.
- In terms of cost effectiveness towards abating CO_2 emissions, there is a wide range of benefit from different fabric measures for retrofit. For example, for a medium-sized terraced house:
  - Easy to treat cavity wall insulation is a low cost, high benefit measure, with an average cost effectiveness of -£94/tCO_2.
  - Based on the updated cost and savings assumptions, replacing old (pre-2002) double glazing with new double glazing is a higher cost, lower benefit measure, with £/tCO_2 cost effectiveness in the thousands. The scenarios do not model glazing upgrades (except as part of deep retrofits), but upgrades can still offer improved comfort in homes and current rates of upgrade would be assumed to continue.
- Though the direct heat demand savings are modelled in this work, there are a range of wider benefits[1] that the installation of energy efficiency would render including the following:
  - **Economic**: public and private sector investment and job growth.
  - **Health**: decreasing the number of cold homes and the near-term reduction of carbon-intensive supply.
  - **Flexibility**: (via pre-heating or other demand side response) for the grid.

[1] Energy Savings Trust: Capturing the "multiple benefits" of energy efficiency in practice: the UK example

Discussion – installing low carbon heating and energy efficiency leads to a 16% average reduction in fuel bills for households

- Installing energy efficiency and low carbon heating leads to a significant reduction in fuel bills for households.
  - The largest saving is seen in the private rented sector, where average yearly fuel bills decrease by 20%, or just over £200.
  - The smallest saving is in the owner occupied sector, where bills decrease by 14%, or about £160.
- This modelling does not include cooking decarbonisation or lighting and appliance efficiency which would be expected to drive additional savings.
  - The CCC's scenarios estimate additional savings in the order of £1.2 billion pounds per year across the existing stock by 2050 associated with lights and appliances.

Average yearly fuel bills[1] for homes before and after energy efficiency + low carbon heating installation, by tenure type



[1] Includes costs not associated with space or water heating, including cooking, lighting and appliances. Non-heating fuel use estimated from ECUK end-use data tables (2018 values)

Discussion – significant investment is required across stock segments both for energy efficiency measures and low carbon heating

Estimated investment costs to 2030 by scenario (billions)

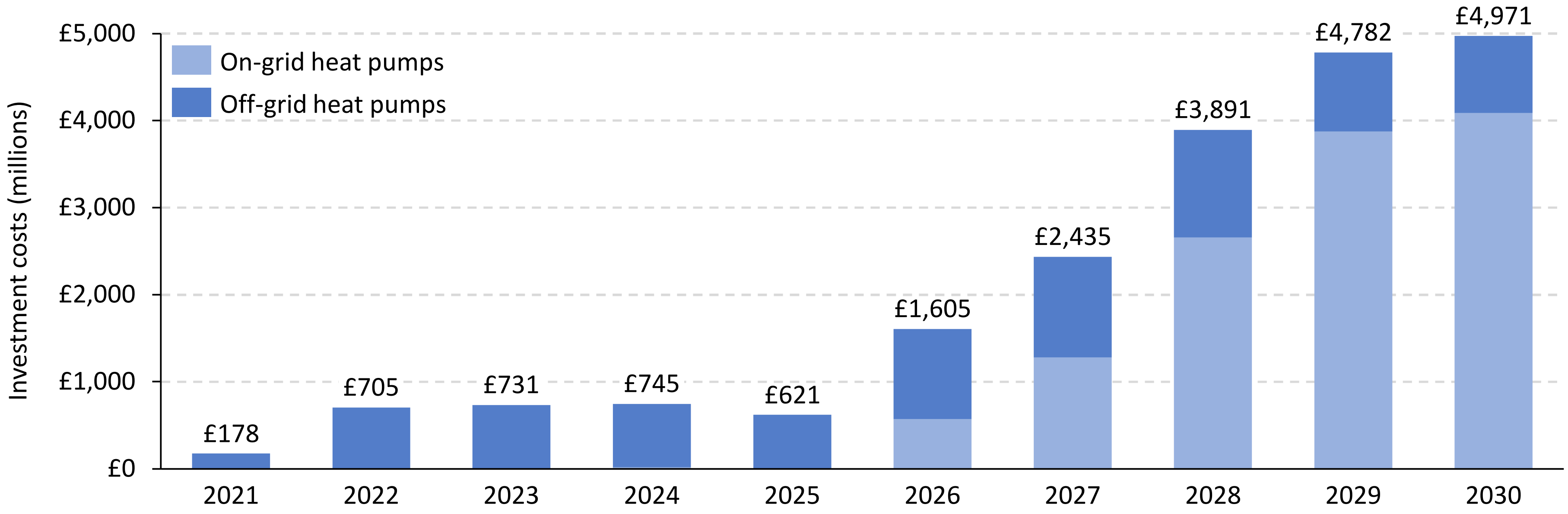
Stock segment	Balanced Pathway	Tailwinds	Headwinds	Widespread Engagement	Widespread Innovation
Fuel poor, owner occupied energy efficiency	£4.5 - £8.9	£3.8 - £6.6	£4.5 - £8.9	£4.5 - £8.9	£52.2 - £46.3
Social housing energy efficiency	£3.1 - £4.0	£8.3 - £8.8	£3.3 - £4.1	£5.0 - £5.9	£13.0 - £14.1
Private rented energy efficiency	£11.1 - £13.5	£19.3 - £20.9	£8.8 - £11.2	£14.0 - £16.4	£31.5 - £34.7
Non-fuel poor, owner occupied energy efficiency	£10.6	£41.4	£14.4	£24.6	£1.1
Heat pump scale-up	£20.6	£14.0	£10.9	£21.9	£13.1
Heat networks	£9.9	£9.9	£9.9	£9.9	£9.9

- The table shows total investments to 2030 for various stock segments, separating energy efficiency investment in various stock segments from investment in heat pumps and heat networks.[1]
  - Where ranges for energy efficiency investment are shown, the lower bound excludes costs associated with installing floor insulation in fuel poor homes, whereas the upper bound includes the costs of all appropriate energy efficiency measures. The floor insulation costs in fuel poor homes are excluded in the lower bound as they were a by-product of installing "High" energy efficiency packages in those homes to achieve the desired uptake – and accompanying wider benefits – of other energy efficiency measures in those homes, in particular wall insulation.
  - The high costs of energy efficiency in the Widespread Innovation scenario are due to the modelling of significantly more expensive deep retrofits (which are rarely taken up in the non-fuel poor owner occupied sector). This remains a first step in modelling deep retrofits in homes, and does not reflect the accompanying benefits that might be associated with retrofit models such as Energiesprong (which incorporate onsite generation and a business model which includes management of maintenance spend against the counterfactual).
- Total estimated investment costs for energy efficiency in the Balanced Pathway scenario amount to **£45** billion by 2035 and **£55** billion by 2050[1].

[1] Energy efficiency values exclude behavioural measures

Discussion – investment required for heat pumps increases rapidly from current levels with a 25-fold rise between 2021 and 2030

Investment costs for heat pumps in Balanced Pathway in the early years, by grid connection status[1]



- Significant investment is required for heat pumps in the next 10 years, with a total of £20.7 billion to 2030:
  - Investment costs are relatively constant between 2022 and 2025, to accommodate increased deployment of heat pumps in new builds in this period without breaching deployment constraints.
  - Heat pump investment is dominated by off-grid homes to 2025, and by on-grid homes to 2030.
  - Total investment in off-grid heat pumps to 2030 is £8.2 billion, compared to £12.5 billion for on-grid heat pumps.
- Cumulative investment in low carbon heat networks to 2030 is estimated at £9.9 billion to 2030. However this is subject to higher uncertainty given the different approach used for costing these systems.
- Cumulative investment in direct electric heating technologies[2] (electric resistive and electric storage) to 2030 is significantly lower, at £400 million.

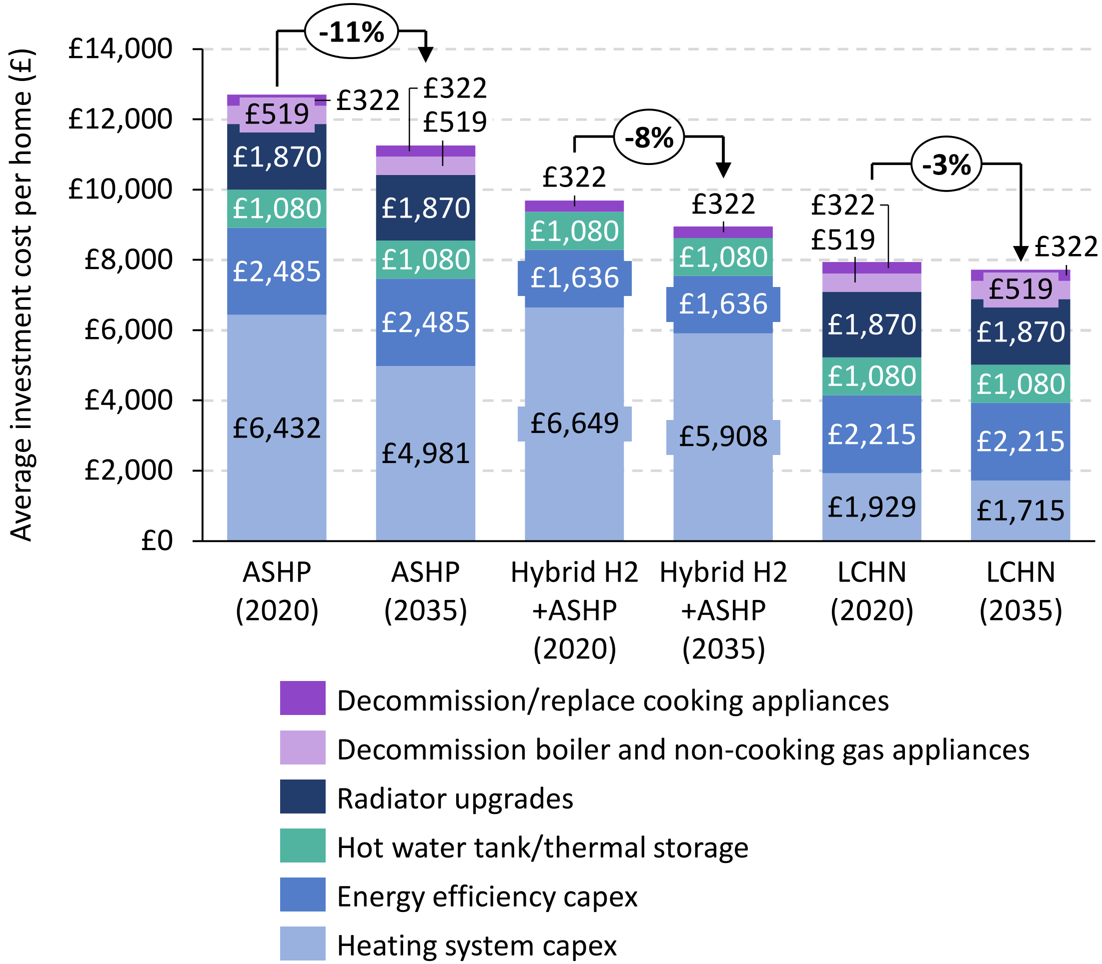
[1] Existing homes only

[2] Includes configurations with solar thermal

Discussion – average investment costs for households can vary substantially depending on the heating technology

- Across the stock, the average net investment per household in the Balanced Pathway scenario is £9,000.
- For an average household getting an air source heat pump and a suitable energy efficiency package, the total investment cost required in 2020 is just over £12,000.
  - This falls by £1,500 for a household upgrading in 2035, due to projected reductions in the capital costs of heat pumps.
  - The average size of an ASHP in the scenario is 5.4 kW.
  - In some instances, a buffer tank is also required when installing a heat pump. This would incur an additional cost of £300 for a medium-sized tank.
- For an average household connecting to a low carbon heat network and getting an energy efficiency package, the investment cost in 2020 is just under £8,000, reducing only marginally in 2035.
- Households may also require an additional investment for ventilation measures or shading:
  - £541 (extract fans, common)
  - £650 (high specification internal blinds, common in flats).

Average required capital expenditure[1] in Balanced Pathway for a home getting an air source heat pump (ASHP)[2], Hybrid ASHP and H_2 boiler, and a home connecting to a low carbon heat network (LCHN)[3], in 2020 and 2035

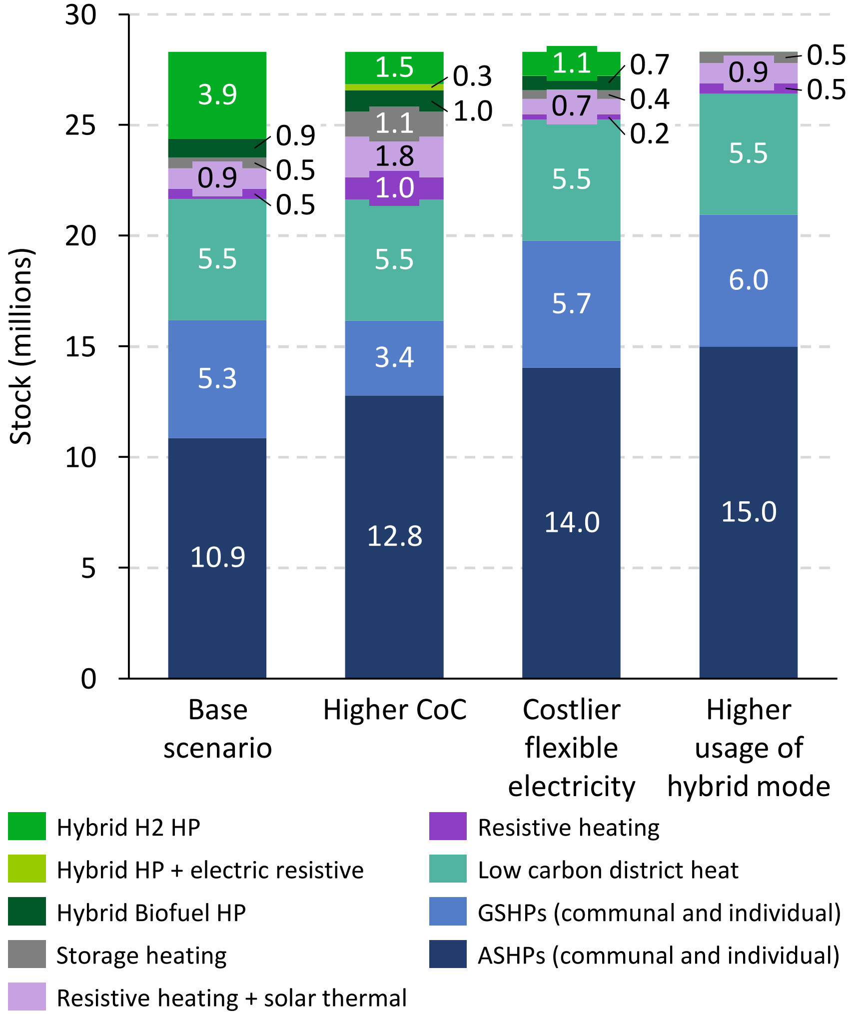


[1] Costs are absolute costs, not net costs i.e. the cost of a counterfactual system has not been subtracted. [2] HP costs correspond to the most common technology configuration rather than an average of all modelled configurations, which is only slightly different. [3] For low carbon heat networks, the heating system capex is the cost of a heat interface unit (HIU) and a heat meter

Discussion – slight changes to some of the assumptions can lead to significant differences in the technology mix, as a result precise technology mixes in the scenarios should be interpreted as illustrative

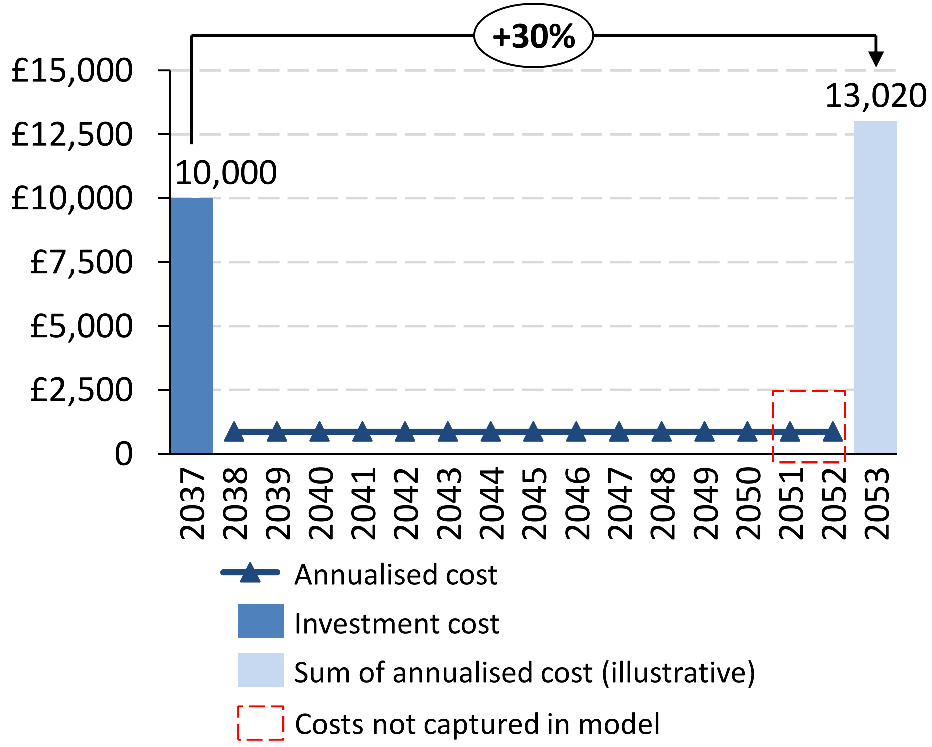
- To address some of the largest uncertainties in the analysis, several sensitivities were run to investigate the effect of different assumptions in areas where there is high uncertainty:
  - **Cost of capital (CoC):** A higher cost of capital increases annualised capex. With the discount rate fixed, the share of capex as a percentage of total costs increases. A higher cost of capital therefore favours lower capex technologies, leading to reduced deployment of hybrid H_2 heat pumps and increased deployment of electric resistive heating. ASHPs also become more favourable than GSHPs.
  - **Gains from flexible operation:** There is high uncertainty over the savings which could be gained from flexible operation of low carbon heating technologies. With lower savings (modelled as higher costs for flexible electricity), deployment of hybrid heat pumps – both biofuel and H_2 – reduces significantly in favour of higher deployment of pure ASHPs.
  - **Hybrid heat pump operation:** The operation of hybrid heat pumps – the percentage of time during which they will operate in heat pump mode versus hybrid mode – is also subject to high uncertainty. Modelling operation in hybrid mode 50% of the time (compared to 20% in the baseline case) leads to the cost-effective uptake of hybrid heat pumps falling from nearly 5 million in the baseline case to zero. The hybrids are replaced by conventional heat pumps, both air-source and ground-source. Accompanying measures such as smart controls are expected to be necessary to support effective use. Hybrid heat pumps are also identified by the CCC as offering a wider range of other benefits for the low-carbon transition.

End-state low carbon heating uptake in the Balanced Pathway scenario for selected sensitivities



Discussion – cost of capital and discount rate have a major effect on abatement costs but not on investment costs

- **Cost of capital:** a higher cost of capital (used in the Widespread Innovation and Tailwinds scenarios) leads to an increase in the annualised capex, disadvantaging technologies with high capital costs such as H_2 hybrid heat pumps.
- **Discount rate:** the discount rate is fixed across scenarios, at 3.5%, and is equal to the cost of capital except in the two above scenarios where it is lower. When the discount rate is lower than the cost of capital technologies with lower capital cost are favoured.
- Both the above factors influence the abatement costs, as those are calculated using the net present value of annual costs.
  - For technologies deployed after 2035, the annualised cost does not capture full lifetime costs but only costs up to 2050.
- Investment costs are unaffected by the cost of capital and discount rate since they are calculated in-year rather than annualised.
- The graph shows an illustrative comparison between investment cost and annualised cost:
  - For an illustrative £10,000 investment in a low carbon heating system assuming a cost of capital of 3.5% and a lifetime of 15 years, the annualised cost over the 15-year lifetime is £868. This rises to £1,133 with a cost of capital of 7.5%.
  - Summing the annualised cost over the lifetime gives a value of £13,020; this is higher than the investment cost by a factor of 30%, which is equivalent to the average discounting factor over the 15-year lifetime[1].
  - For a technology deployed after 2035, the portion of the annualised cost which occurs after 2050 is not captured in the model, as shown in the graph.
  - Total annualised costs also include fuel costs and opex (which are discounted using the discount rate), whereas investment costs only include undiscounted in-year capex.



[1] Discounting factor = $1 / (1 + r)^t$ where *t* is the year and *r* the cost of capital

Discussion – numerous factors drive investment and operational costs

Investment Cost

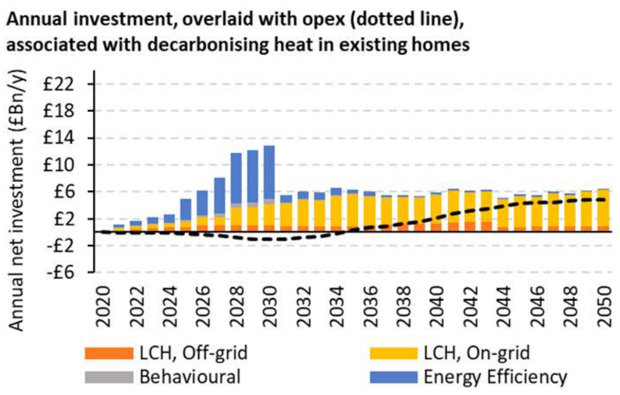
Investment costs are in-year values based on uptake of energy efficiency or low carbon heating measures/systems, affected by:

- choice of low carbon heating system and required system size (based on heating demand requirements),
- choice of energy efficiency package and applicable measures (based on existing insulation levels),
- year of uptake, particularly for low carbon heating systems which have cost reduction projections, and
- scenario, as this will affect the prices for measures and heating systems.

Operational Cost

Operational costs are in-year values required to maintain/achieve the heating requirements of the dwelling, affected by:

- heating system operational / maintenance costs (based on heating system choice),
- decrease in heating demand (based on level of fabric / behavioural measure uptake and climate warming),
- fuel type and level of use (based on the choice of carbon heating system and heating demand requirements),
- scenario, as this will affect fuel costs, and
- year in scenario, as this affects the fuel costs and level of climate warming.



Headwinds presents a unique case where there is a lower level of initial investment in energy efficiency and low carbon heating; however, this scenario is contrasted with higher energy demand and higher-cost fuel (H_2).

- With the lower level of energy efficiency, this scenario has minimal reduction in heating demand (i.e. that could offset high fuel prices).
- With similar heating demand and resulting required H_2 fuel use, this scenario sees a net increase in operational costs, with household fuel bills increasing (e.g. proportion of households paying <£1000/yr decreases from 52% to 41%).

Measures to address poor thermal efficiency, overheating, indoor air quality and moisture must be considered together when retrofitting homes [1/2]

- Whilst it has not been possible to undertake a detailed assessment of the overheating and ventilation measures which would need to accompany the scenarios, some indicative ranges of potential costs have been developed based on the housing stock.
- The below table sets out some of the shading measures which could help mitigate overheating risk. All costs are rounded to the nearest 10.
- These costs would be additional to the energy efficiency and low carbon heat costs discussed elsewhere in this slide pack.

Measures		Cost ranges for a large flat		Cost ranges for a typical semi-detached home		Total cost ranges where measures applied across stock to 2050	
		Min (£)	Max (£)	Min (£)	Max (£)	Min (£m)	Max (£m)
Low-regret (zero cost)	Existing curtain closure during the day to limit solar gains.	0	0	0	0	0	0
Medium intervention	Existing curtain closure during the day for all properties. In addition high specification internal blinds for all flats. Lower cost bound represents blinds with reflective backing, whilst higher bound represents blinds fitted to window which allow opening during use.	650	810	0	0	3,920	4,880
High intervention	Existing curtain closure during the day for all properties. High spec internal blinds fitted to all properties. In addition either external shading (external venetian blinds, roller screens or markisolettes) or external awnings fitted to all flats. Lower cost bound reflects the cheaper measures.	2,680	4,310	950	1,230	42,280	58,480

Source: CCC analysis based on evidence provided by the British Blind and Shutter Association

Measures to address poor thermal efficiency, overheating, indoor air quality and moisture must be considered together when retrofitting homes [2/2]

- It is critical to ensure that ventilation is considered as part of holistic home retrofits, to ensure that both indoor air quality and overheating risk can be addressed alongside carbon emissions reduction.
- The below table sets out a non-exhaustive list of ventilation measures which could help address indoor air quality and overheating risk. Other measures not costed (such as trickle vents) remain important components of in-home ventilation strategies.
- These costs are additional to the energy efficiency and low carbon heat costs discussed elsewhere in this report. All costs are rounded to the nearest 10.

Measures		Cost ranges for a large flat		Cost ranges for a typical semi-detached home		Total cost ranges where measures applied to relevant stock to 2050	
		Min (£)	Max (£)	Min (£)	Max (£)	Average (£m)	
Zero cost measures	Informed window opening including: - Opening of windows when room temperatures reach 22 °C and fully open when indoor temperature reaches 28 °C. - Windows remain closed if outdoor temperature is higher than indoor. - Night time ventilation through opening windows above ground floor during the night to purge heat. Ground floor windows shut for noise, security and air quality.	0		0		0	
Medium cost measures	Extract fans in kitchens and bathrooms installed where not already present.	540 [1]		540 [1]		~8,500[2]	
High cost measures	Lower bound reflects all homes which receive deep retrofits in the Widespread Innovation scenario having mechanical extract ventilation installed. Higher bound reflects these same homes having mechanical ventilation and heat recovery installed instead.*	1,670 [3]	3,340 [3]	2,060 [3]	4,120 [3]	14,030	20,620**

* This costing also accounts for non-deep retrofits (i.e. low and medium package uptake households) installing extract fans in kitchens / bathrooms where not already present

** A similar cost is realised in the Balanced Pathway scenario in the case where all homes which receive standard high packages install mechanical extract ventilation.

[1] Analysis Work to Refine Fabric Energy Efficiency Assumptions for use in Developing the Sixth Carbon Budget (2020). [2] Health effects of home energy efficiency interventions in England: a modelling study (Hamilton et al., 2017). [3] The costs and benefits of tighter standards for new buildings (Currie & Brown and AECOM) (2019). N.B. discussions with some technical experts suggest that these costings could be optimistic.

Policy recommendations [1/4]

The 'critical path' and a timeline for policy decisions

Low carbon heating

- The natural replacement cycle of heating systems is of the order 15-20 years. If scrappage is to be minimised, this implies the need for all new heating systems to be low carbon from the mid-2030s in order to achieve net zero by 2050.
- The scenarios have been developed to work within this natural replacement cycle as far as possible. The Balanced Pathway scenario is therefore based on a fossil fuel phase out date of 2033 for on-gas homes (with a range 2030 – 2035 across scenarios) and 2028 for off gas homes (with a range of 2026 – 2028 across scenarios). Whilst alternative regulatory approaches could be possible, they would need to deliver similar levels of ambition.
- The date chosen for on-gas homes in the Balanced Pathway scenario reflects a balance between minimising scrappage risks, remaining within supply chain constraints, and leaving time for energy efficiency deployment to be maximised in advance of fossil phase out. The earlier date for off-gas homes recognises Government ambition, and the fact that low carbon heating is more cost-effective and delivers higher carbon savings in these properties. The smaller number of such homes means the supply chain should also be able to deliver this at an earlier date.
- Whilst these phase out dates are assumed to apply to much of the stock in the Balanced Pathway scenario, there are some technologies (notably hydrogen and district heat) where uptake must necessarily be driven by geographically targeted switchovers rather than phase out dates. These technologies therefore follow geographically-led switchovers in the scenarios. On this basis, the scenarios imply that any homes in areas designated for hydrogen or district heat would need to be exempt from any regulated fossil fuel phase out before the switchover to hydrogen or district heat occurs. This in turn implies a need for areas to be designated as suitable for those solutions ahead of the fossil fuel phase out dates.

Policy recommendations [2/4]

The ‘critical path’ and a timeline for policy decisions (continued)

Energy efficiency

- An approach which works with replacement cycles for low carbon heating necessarily requires that homes have a sufficient and appropriate level of energy efficiency to ensure that low carbon heating is viable at reasonable cost by the time new fossil fuel systems are phased out.
- This defines the timeline for regulatory drivers relating to minimum standards of energy efficiency in the scenarios, as described on the next slide.
- The proposed fossil fuel phase out and regulations on minimum standards for energy efficiency would need to be set well in advance of the dates they will come into force, to provide a clear signal to the market and sufficient time to plan ahead.
- It will also be crucial for a comprehensive suite of support to be in place ahead of those dates to ensure affordability for every household.

Hydrogen and the gas grid

- Decisions on the future of gas grid across regions are expected to be required from the mid 2020s. Trialling, evidence gathering and analysis must progress in advance of this to facilitate these decisions.
- Fossil fuel phase out dates in the early 2030s mean that any areas to be converted to hydrogen (with conversion taking place from the 2030s) would need to be designated for hydrogen conversion well ahead of time. This is necessary for infrastructure planning and delivery. It also provides clarity over where any exemptions would be in place for fossil fuel phase out, in turn enabling effective planning for both energy efficiency and low carbon heat at a household level.
- Optionality exists over the role that Hy-ready boiler mandation could play in the transition. The scenarios assume mandation in the mid-2020s on a UK-wide basis, to minimise the potential cost of scrappage of gas boilers in areas of hydrogen conversion, but also in recognition of the economies of scale and cost reduction that would accompany widespread uptake.

Policy recommendations [3/4]

Regional and local approaches to decision-making

- Several components of the Balanced Pathway scenario will rely on a coordinated approach to decision making on the future of low carbon heat.
- Identification of areas suitable for deployment of heat network infrastructure, and the implementation of heat networks, will rely on coordination and decision-making at a local level.
- The decision on the future of the gas grid will likely need to be taken at a regional level. As described on the previous slide, the Balanced Pathway scenario assumes that some areas are designated for conversion to hydrogen before 2033, such that homes in those areas can be exempted from the mandation for low carbon heating systems from that date.
- It is also evident that the rollout of heat pumps would benefit from a detailed, coordinated plan for rollout at a highly local level, in order to plan and deliver required network upgrades without this becoming a constraint on deployment.

Policy recommendations [4/4]

Key regulatory levers and supporting policy measures

- Private and social rented homes are well suited to regulatory levers in the form of minimum standards for energy efficiency and/or carbon emissions, as is recognised by Government policy ambition – the Balanced Pathway scenario is based on a 'backstop' date of 2028 for all such homes to have a sufficient and appropriate level of energy efficiency to ensure that low carbon heating is viable and cost-effective.
- Owner occupiers are more challenging to reach using such levers.
- For owner occupied homes with mortgages, the Balanced Pathway scenario envisages strong incentives for lenders to drive a similar minimum level of energy efficiency by 2033.
- For outright owners of homes, the Balanced Pathway scenario is based on a regulation around minimum energy efficiency at the point of sale from 2028. This approach is already being considered in Scotland[1]
- As described on the previous slide, the scenario proposes a fossil fuel phase out date for all tenures, from which time all new heating systems must be low carbon – this is 2028 for off-gas homes and 2033 for on-gas homes.
- The intention of the scenarios is not to be prescriptive about how the regulations would look in practice (for example, whether minimum standards would be based on EPC rating, energy intensity per square metre, or the equivalent carbon based metrics) but rather to frame the level of ambition that is needed to meet legally binding targets.
- It should also be noted that, while not modelled explicitly, it is expected that a suite of policy measures to accompany these regulatory levers would be introduced. This includes financial incentives, price signals such as levies on fossil fuels and carbon pricing and a comprehensive package of support for supply chain and investment in skills and training.

[1] Energy Efficient Scotland: Improving energy efficiency in owner occupied homes

Summary of approach

1. **Develop a UK stock model,** archetypically capturing characteristics and insulation levels of dwellings regionally
2. **Define assumptions, guidance, and constraints** for energy efficiency, low carbon heating, and overarching scenarios
3. **Calculate cost effectiveness and carbon savings** of all possible archetype-package combinations
4. **Apply packages of energy efficiency measures and low carbon heating systems** to stock based on suitability and lifetime cost

2050 end-state uptake of low-carbon heating and energy efficiency uptake

5. **Apply uptake trajectories of energy efficiency and low carbon heating systems** based on guidance and trigger points

iterative process

6. **Check in-year deployment numbers against deployment constraints** and amend uptake trajectories as necessary
7. **Determine yearly cost and deployment characteristics** including investment req., abatement, operating costs, cost effectiveness, etc.

2020-2050 yearly uptake scenarios of low carbon heating and energy efficiency

Updates from previous work

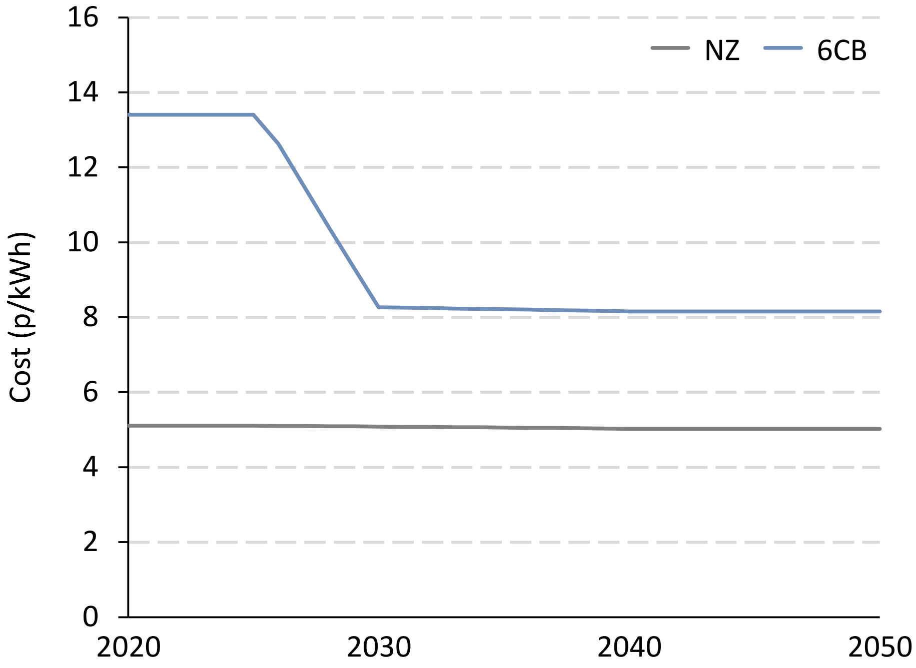
- Following on from work done for the 5th Carbon Budget and Net Zero, an extensive update to input assumptions was conducted, based on the latest available research and using input obtained via consultation with industry stakeholders (detailed further in later slides):
  - Fuel costs and emissions intensities for all fuels were updated, including an expansion from two to five distinct electricity categories to reflect different levels of flexibility (see next slide).
    - New assumptions led to an increase in hydrogen costs and a decrease in electricity costs relative to Net Zero.
  - The latest evidence on energy efficiency was incorporated: technical potential, cost data (including on hard to treat), and savings data from NEED.
    - The general trend was a reduction in cost effectiveness compared to previous work.
  - The costs of low carbon heating technologies were updated, with new configurations modelled.
    - Both air-source heat pump and ground-source heat pump lifetimes decreased relative to Net Zero, based on stakeholder feedback.
  - Additional technology costs were included, such as those for buffer tanks.
  - Updates were made to the sizing of heating technologies, including heat pumps and boilers.
    - Load factors for heat pumps – which determine the system size – were increased relative to Net Zero, in-line with BEIS NHM data[1].
  - Technical suitability of both energy efficiency measures and low carbon heating systems was updated.

[1] BEIS National Household Model, 2017

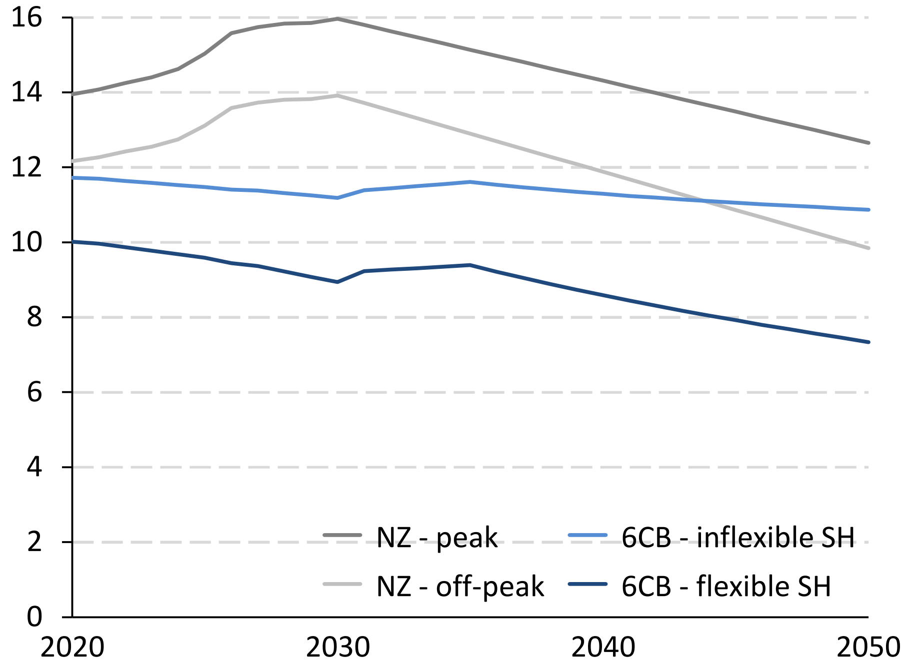
Updates from previous work – electricity and hydrogen costs

- Significant updates were made by the CCC to fuel cost assumptions, particularly electricity and hydrogen.
  - Hydrogen costs increased significantly compared to Net Zero (reflecting more conservative assumptions on the need for storage) – nearly three-fold in the early years and 60% in the later years – which strongly disadvantages hydrogen powered technologies.
  - Electricity costs decreased compared to Net Zero (reflecting the falling cost of renewables such as wind), by roughly 25% on average.
    - A refined approach to flexibility was also included in the 6th Carbon Budget modelling; see slide.

Hydrogen costs in the 6CB Balanced Pathway and NZ



Electricity costs in the 6CB Balanced Pathway and NZ[1]



[1] Only selected electricity types used in 6CB are shown

Contents

Updates from previous work – stock model

- The overall number of UK households was updated from Net Zero based on the latest Housing Survey data across all devolved administrations[1]
- Insulation categories used to distinguish between archetypes were updated from NZ to align with the technical potential split (see next slide).
- Total stock heating demand was calibrated to NEED data[3] by wall and loft type.

Measure	5CB categories	6CB categories
Walls	15 categories, subdivided by construction (cavity, solid, stone, timber, prefab) and insulation level (insulated, partial insulated, uninsulated)	7 categories, subdivided by construction (external stone, internal stone, cavity) insulation level (insulated, uninsulated) and ease of treatment (ETT, HTT, EHTT)[2]
Lofts	No loft and 6 loft categories, subdivided by type (pitched, flat) and thickness (0-100, 100-200, 200+ mm)	No loft and 7 loft categories, subdivided by thickness (0-100, 100-200, 200+ mm) and ease of treatment (ETT, HTT, EHTT)
Floors	None and 6 floor categories, subdivided by type (solid, suspended) and insulation level (insulated, partial insulated, uninsulated)	None and 4 floor categories, subdivided by type (solid, suspended) and insulation level (insulated, uninsulated)

EST: Energy Savings Trust; [1] Including the English Housing Survey 2016/2017, the Scottish House Condition Survey 2017, the Welsh Housing Conditions Survey 2017/2018, and the Northern Ireland House Condition Survey 2016; [2] Ease of treatment categories only applicable for cavity walls; [3] National Energy Efficiency Data-Framework, 2019

Updates from previous work – technical and economic potential

- Updates to total stock of insulation measures i.e. **technical potential**:
  - *Cavity walls*: starting with the number of standard and non-standard fillable cavity walls for Great Britain in June 2015 based on EST studies,[1] the number of standard or 'easy to treat' cavities was then adjusted to account for cavities insulated to 2019 based on Household Energy Efficiency Statistics. Of the non-standard or 'hard-to-treat' cavities, a proportion were assumed to be suitable for insulation at higher cost with the remaining not deemed economic to insulate (i.e. extra-hard-to-treat). These final numbers were scaled to a UK basis.
  - *Solid walls:* based on Housing Survey data (2016-2018), the number was adjusted to account for insulation to 2019.
  - *Lofts*: based on Housing Survey data (2016-2018), all lofts above 200mm were classified as insulated. For <200mm, it was assumed that some have been insulated since housing surveys were undertaken based on Household Energy Efficiency Statistics. For the remaining lofts, the EST proportions of standard (i.e. easy-to-treat) and non-standard (i.e. hard-to-treat) lofts were applied, with the latter category subdivided further into those suitable for insulation at higher cost and those deemed outside of economic potential.
- Generally, all measure sub-categories costing more than around £700/t for a typical home (assumed to be a medium semi-detached home) were excluded from **economic potential:**
  - *Cavity walls:* the hard-to-treat category economic potential includes and excludes homes as described in the top table[2].
  - *Lofts*: the hard-to-treat category economic potential includes and excludes homes as described in the bottom table[2].
  - The excluded categories were shown to cost more than around £700/t.

Included in hard-to-treat cavity wall economic potential	Excluded from hard-to-treat cavity wall economic potential (i.e. extra-hard-to-treat)
Homes with narrow masonry	Homes with metal or timber frames
Homes with conservatories	Homes with external cladding
Homes of concrete construction	Homes with mixed wall construction
Homes which incur additional costs due to height	Homes with uneven stone
	Homes in exposed locations
	Homes with DPC faults[3]

Included in hard-to-treat loft economic potential	Excluded from hard-to-treat loft economic potential (i.e. extra-hard-to-treat)
Lofts with access issues	Mansard roofs
	Homes with rooms in roof
	Chalet roofs
	Flat roofs

EST: Energy Savings Trust; DPC: Damp Proof Course [1] EST (2016) Quantification of non-standard cavity walls and lofts in Great Britain, EST (2019); Determining the costs of insulating non-standard cavity walls and lofts [2] Categories as defined in EE and EST report for CCC, 2013; [3] These homes can be insulated after addressing the DPC fault.

Approach to define archetypes

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, Wales, and Northern Ireland, providing an estimate of the breakdown of physical attributes and existing heating systems across the full United Kingdom (UK) stock, with an accurate mix of building attributes for each devolved administration.
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 relevant 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** • **Northern Ireland Housing 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			5 types with distinction between construction types and ease of treatment
	Floor type			5 types with various construction types and insulation levels
	Roof type			6 types with distinction between various insulations levels and ease of treatment
	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 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[1]** • **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, Listed
	Building age		Proxies were used where necessary	Not included in model

Strong data, low uncertainty — Strong data, some uncertainty — Weaker data, higher uncertainty — Poor/unavailable data

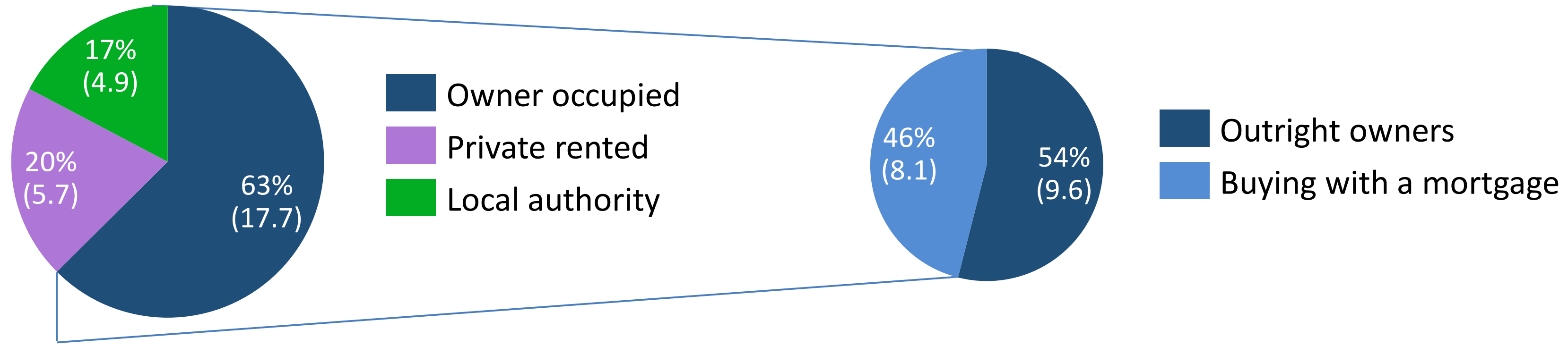
LSOA = Lower Layer Super Output Area [1] Data sources included sub-regional fuel poverty statistics and fuel poverty detailed tables (2018), based on Low Income High Cost definition of fuel poverty.

Contents

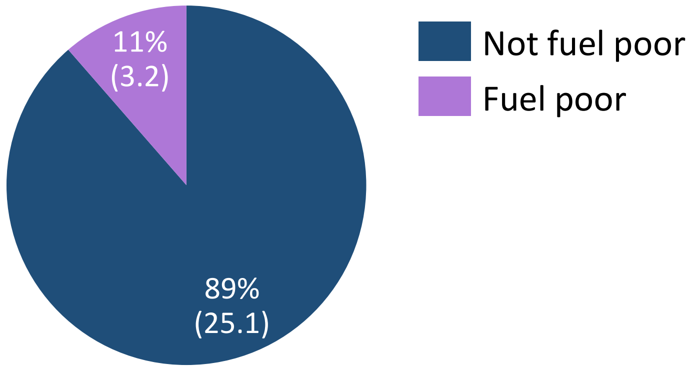
Stock demographics – full UK stock

- Owner occupied homes constitute nearly two-thirds of total stock.
  - Of the owner-occupied stock, a majority is owned outright[1].
- Most of the stock is connected to the gas grid (86%) and not fuel poor (89%).

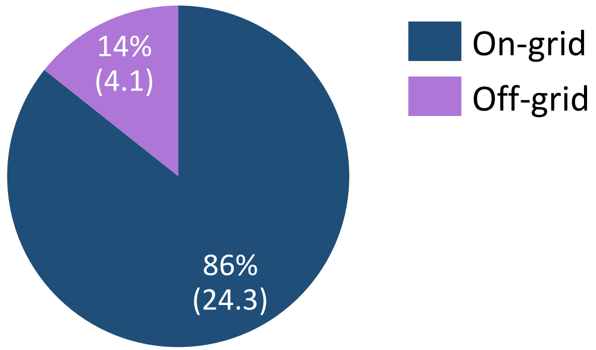
Total UK stock (millions) split by tenure



Total UK (millions) stock split by fuel poverty status



Total UK stock (millions) split by grid connection status

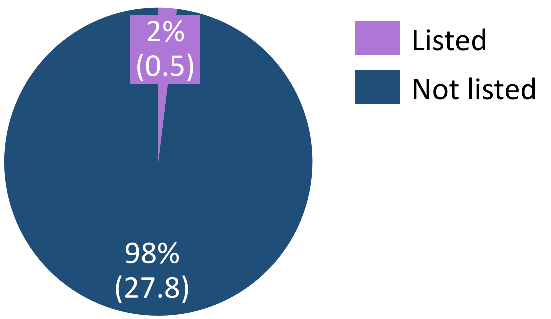


[1] The distinction between outright owners and mortgagors was modelled implicitly

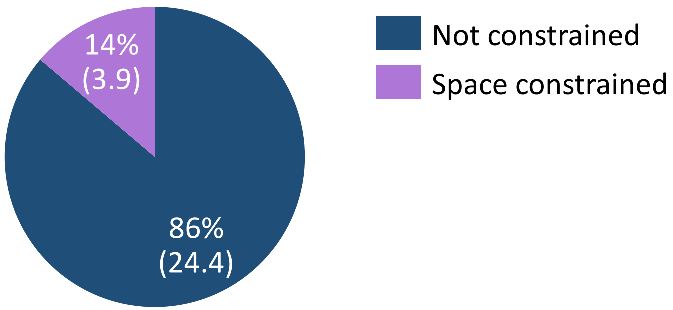
Stock demographics – space constrained and heritage homes

- Unlike the specified sourced attributes, based on available dwelling data (e.g. tenure status, grid connection status, and fuel poverty status), the definition of a space constrained home is based on a modelled methodology.
  - Internal space constraints were represented via a metric of ‘available dwelling floor area per habitable room’
  - In the absence of better data addressing the prevalence of internal space constraints, this metric was deemed to be a useful identifier of homes most likely to value the available space in the home and which may therefore be less willing to accept heating technologies requiring additional space in homes.
  - The metric was deemed a better single identifier than simply total floor area as it better represents the available space per occupant (it is assumed that the number of habitable rooms correlates with the number of occupants) and therefore better reflects the internal space constraints occupants are likely to experience.
  - Homes where the available dwelling floor area per habitable room is less than **16 m^2** were considered space constrained. The threshold was set to capture the ‘most space-constrained’ homes, representing 20% of the ‘most space constrained homes’ in the stock (excluding homes suitable for heat networks). Of the total stock, just under 14% are considered space constrained.
  - External space constraints were not modelled due to data limitations, but remain an important area for future work.
- Heritage homes, defined to include listed buildings and those in conservation areas, are treated differently in terms of cost and suitability of measures (see sections on EE modelling and LCH suitability).
  - However, it can be argued that all pre-1919 homes face similar issues to listed buildings and should therefore be treated similarly. It was not possible to account for this in this work, but it remains an important area for further analysis.

Total UK stock (millions) split by listed status



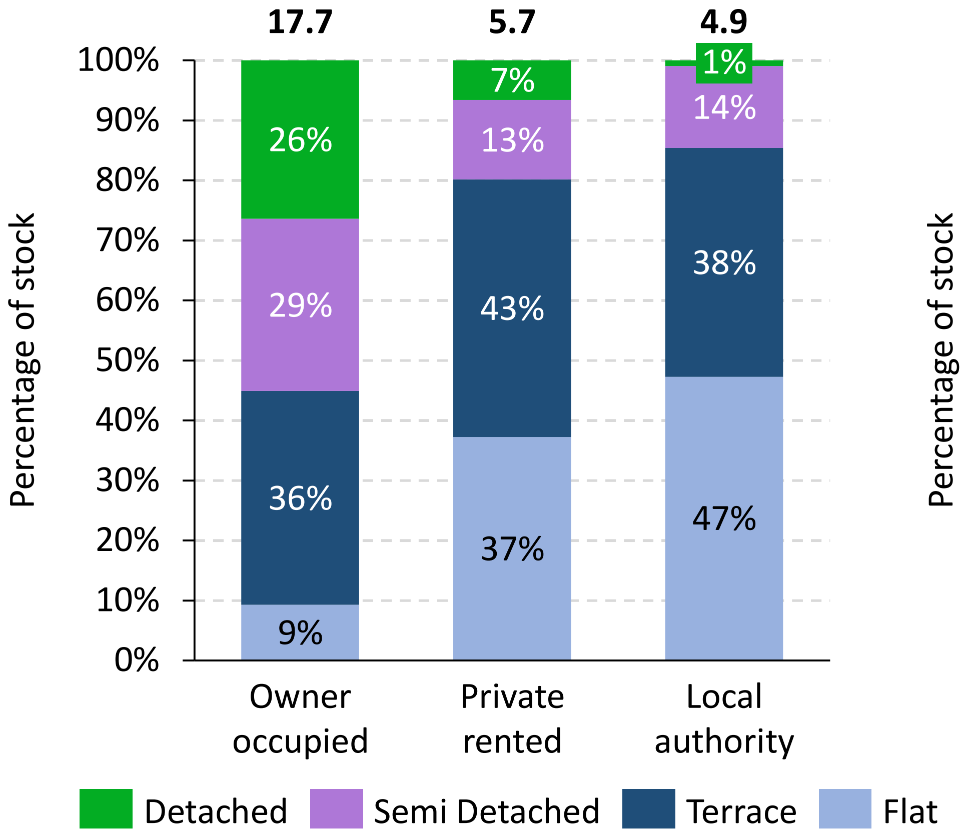
Total UK stock (millions) split by space constrained status



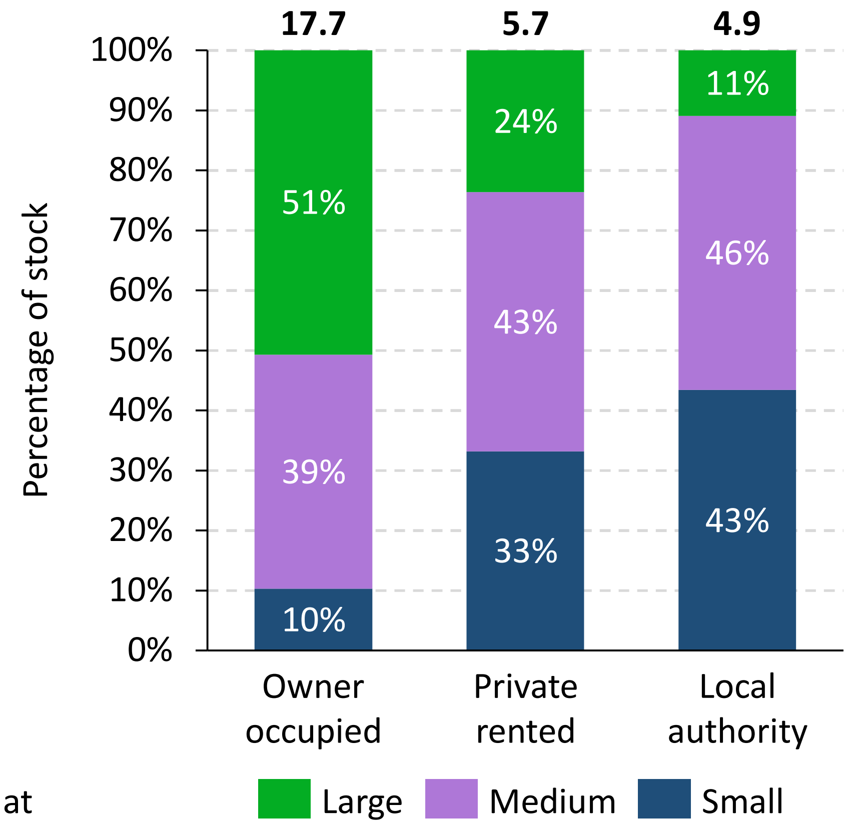
Stock demographics by tenure type

- Flats make up a minority of owner-occupied homes but nearly half of local authority homes.
- Most large homes are in the owner-occupied segment, whilst small and medium homes dominate the private rented and local authority segments.

Stock (millions) split by property type in each tenure



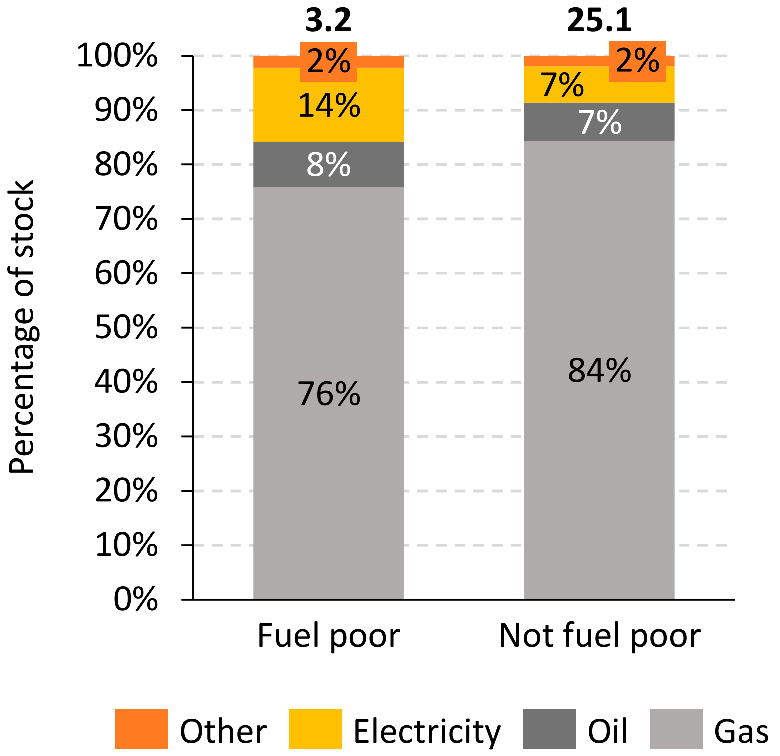
Stock (millions) split by property size in each tenure



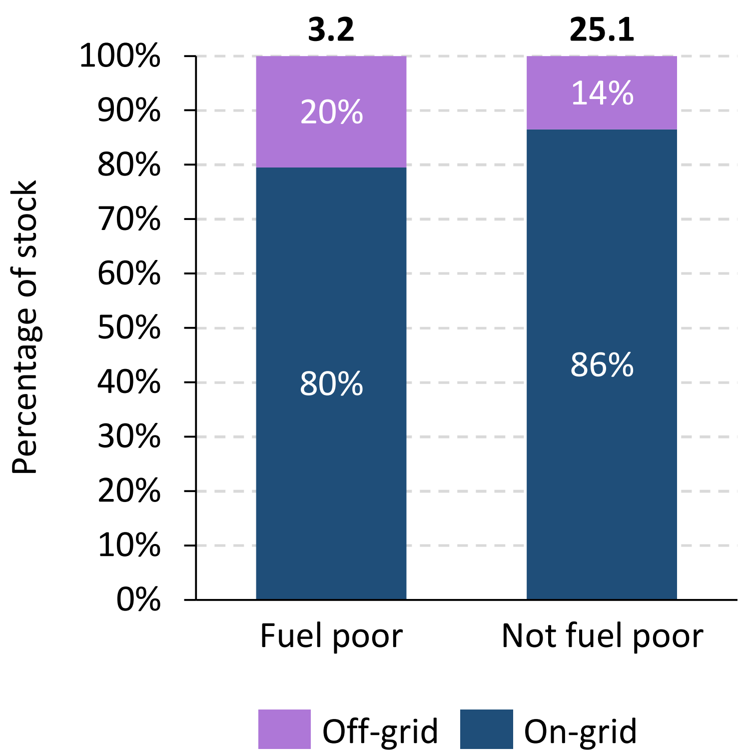
Stock demographics by fuel poverty status[1]

- A disproportionately high amount of fuel poor homes have direct electric heating systems.
- Off-gas grid homes are more prevalent in the fuel poor sector.

Stock split by counterfactual heating technology for each fuel poverty status. Totals in millions.



Stock split by grid connection status for each fuel poverty status. Totals in millions.

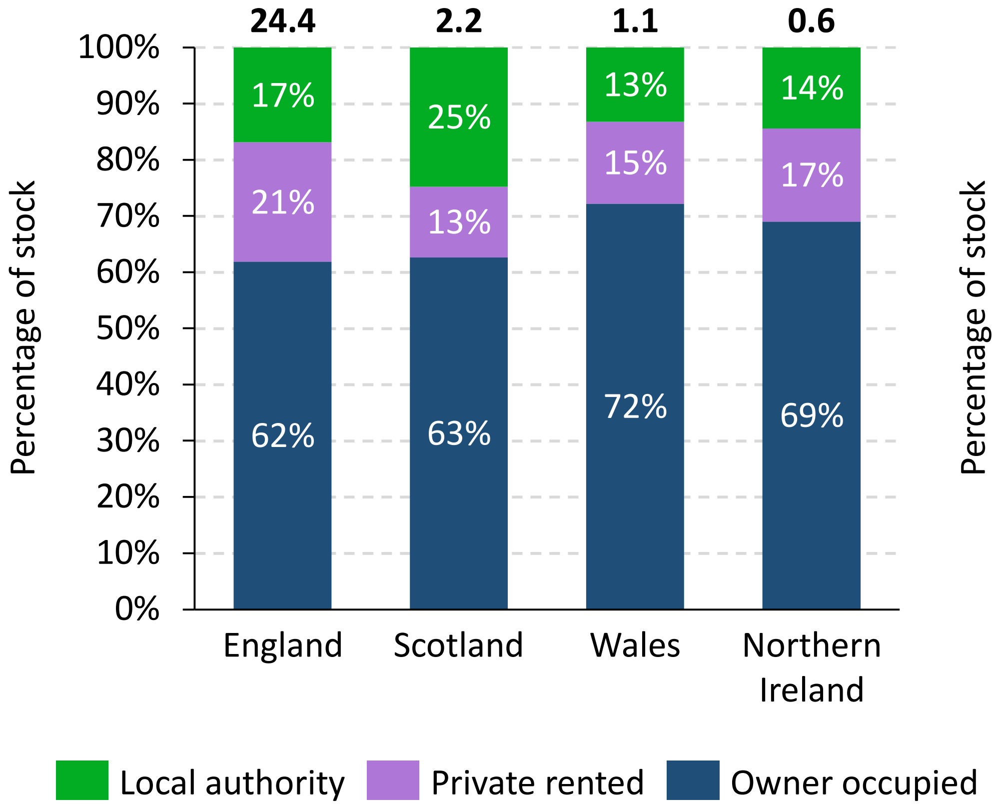


[1] The incidence of fuel poverty as an attribute was identified at LSOA level, and correlated with the archetype stock model both through the incidence at LSOA level and through the correlation with other attributes (building type, heating fuel and wall type). It should be noted that the modelling did not track household income and so was not able to directly model fuel poverty and how it evolved across scenarios.

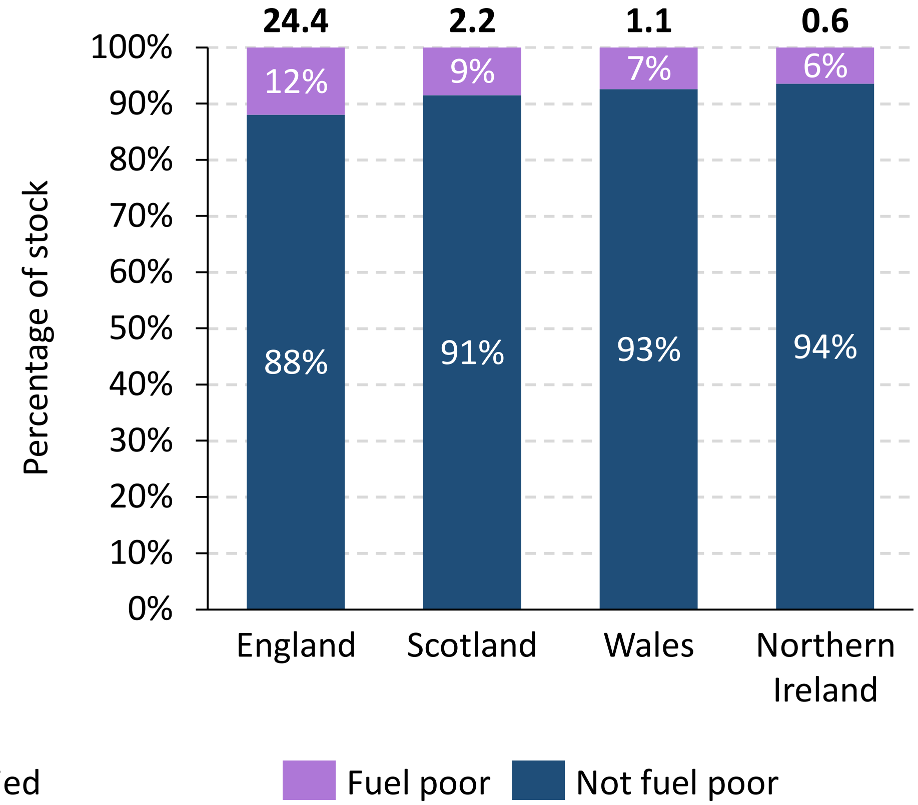
Stock demographics for each Devolved Administration (DA) [1/3]

- Local authority homes are more common in Scotland compared to the other DAs.
- The share of fuel poor homes is highest in England, double the share in Northern Ireland.

Stock split by tenure in each DA. Totals in millions.



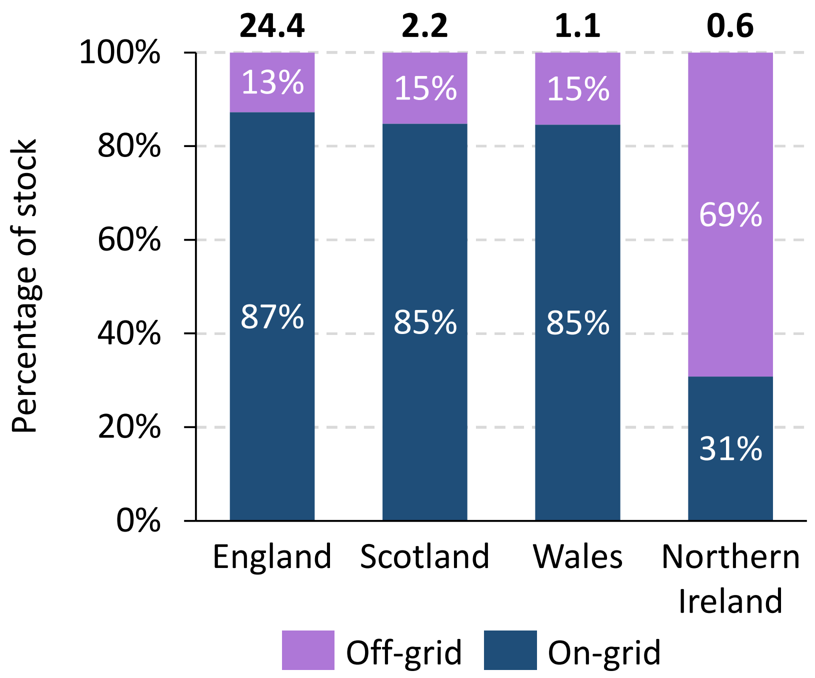
Stock split by fuel poverty status in each DA. Totals in millions.



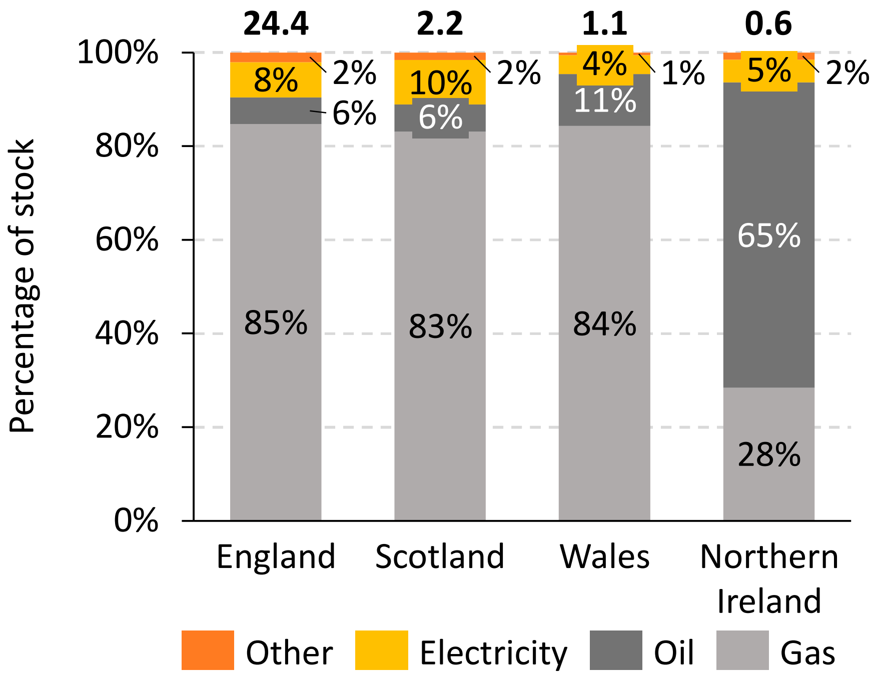
Stock demographics for each Devolved Administration (DA) [2/3]

- Northern Ireland uniquely has a majority of homes (69%) not connected to the gas grid.
  - The share of homes in Northern Ireland using oil as a counterfactual heating system is consequently high, at 65%.
- Scotland has the highest proportion of homes with direct electric heating technologies, at 10%.

Stock split by grid connection status in each DA. Totals in millions.



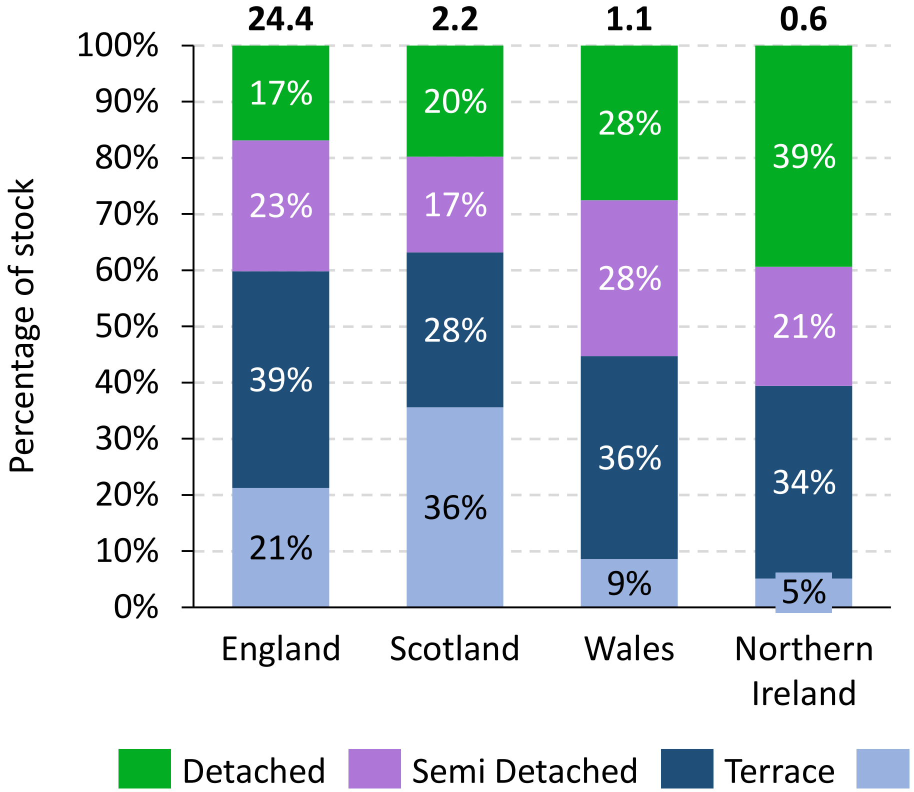
Stock split by counterfactual heating technology in each DA. Totals in millions.



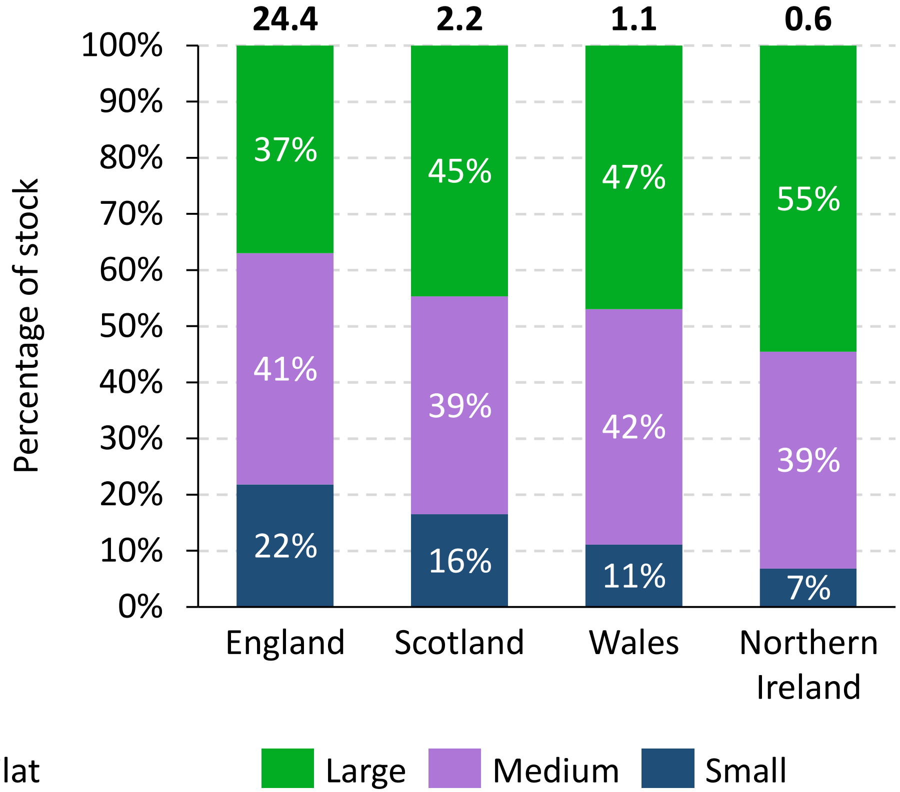
Stock demographics for each Devolved Administration [3/3]

- The most common property type varies by devolved administration, with terraced homes representing the highest proportion in England and Wales, flats in Scotland, and detached homes in Northern Ireland.
- In all devolved administrations except England, the most common home size is large.

Stock split by property type in each DA. Totals in millions.



Stock split by property size in each DA. Totals in millions.



Baseline heating demand approach

1. The EPC database was used to determine the initial archetype fuel use and heating demand.
2. This was then calibrated using NEED data to adjust for actual in-use fuel consumption.
3. The heating demand was consequently calibrated to match latest total ECUK fuel consumption (2018 values).

- The starting fuel consumption in the scenarios does not exactly match ECUK data due to:
  - A temperature adjustment factor incorporated in line with the CCC adjustment methodology used for annual progress reports.
  - Reallocation of heat sold to the “Other” fuel category – a combination of oil, solid fuel and biomass.
- The calibration of “Other” fuel also ensured total baseline emissions were consistent with CCC values.
- A climate adjustment was incorporated into the heating demand baselines to 2050, in the form of a % reduction in heating demand relative to the current baseline. This was based on an assessment of heating degree days, derived from UK Climate Projections (specifically Regional Climate Models), and provided by the Met Office.
  - The % reduction was set at 0.66% in 2021, rising to 6.6% by 2030 (and staying constant to 2050).

Heat fuel	Fuel demand for heating in 2020 (TWh)	Baseline Direct emissions in 2020 ($MtCO_2e$)	Baseline Direct emissions in 2050 ($MtCO_2e$)
Gas	327.5	59.7	51.5
Oil	29.7	4.1	3.7
Solid fuel	6.3	5.3	4.7
Electricity	23.9	0	0
Biomass	27.0	0	0
Hydrogen	0	0	0
TOTAL	**414.4**	**69.1**	**59.9**

Gas	Baseline emissions (MtCO2e)
CO_2	67.6
CH_4	1.3
N_2O	0.2

NEED: National Energy Efficiency Data-Framework. [1] Energy Consumption in the UK

Contents

Updates from previous work

- Compared to Net Zero, the main update to the modelling approach was the change of optimisation method:
  - In the Net Zero work, the model optimised based on the abatement cost (£/t) of a given package-technology combination.
  - In this work, the optimisation criteria was changed to lifetime NPV[1] of a given package-technology combination.
- Capability to target uptake into certain stock segments and deploy additional energy efficiency measures beyond those modelled as 'cost-optimal' was added e.g. installing high energy efficiency packages in fuel poor homes.
- Detailed trajectory modelling was added, allowing the definition of uptake trajectories (by year) tailored to specific technologies and/or stock segments e.g. off-grid hybrid heat pumps.

[1] Lifetime Net Present Value (NPV) is total cost annualised over lifetime – 20 years used in the model

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 lifetime NPV	*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

Overview of approach – behaviour change

- Behavioural measures are modelled first to reduce a household's energy demand (prior to energy efficiency or low carbon heating).
- Unless otherwise stated (e.g. pre-heating), behavioural measures applied in a scenario are applicable to the whole domestic stock (with aggregate savings assumptions designed to account for variations in behaviour).
- The process by which the behavioural measures, in the table below, were selected and applied is shown in the high-level process flow to the right.
- For the measures noted below, the only cost applied was in the Widespread Engagement scenario of £410[1], the average cost of zonal control technology (i.e. smart heating controls and thermostatic radiator valves). In the Tailwinds and Widespread Innovation scenario, these costs were excluded to account for more favourable consumer uptake.
- Water softening costs (i.e. single payment of £170[2]), which were applied across the stock (details on slide) were incorporated into the behavioural cost reporting as well.

1. **Conduct literature review of known behavioural measures** to develop a list of potential measures.
2. **Add additional novel behavioural measures** to the list, and check feasibility with relevant expert stakeholders.
3. **Select and model a few applicable measures** that are feasible for wide-scale uptake.
4. **Apply selected measures to scenarios** that align with the scenario narrative.

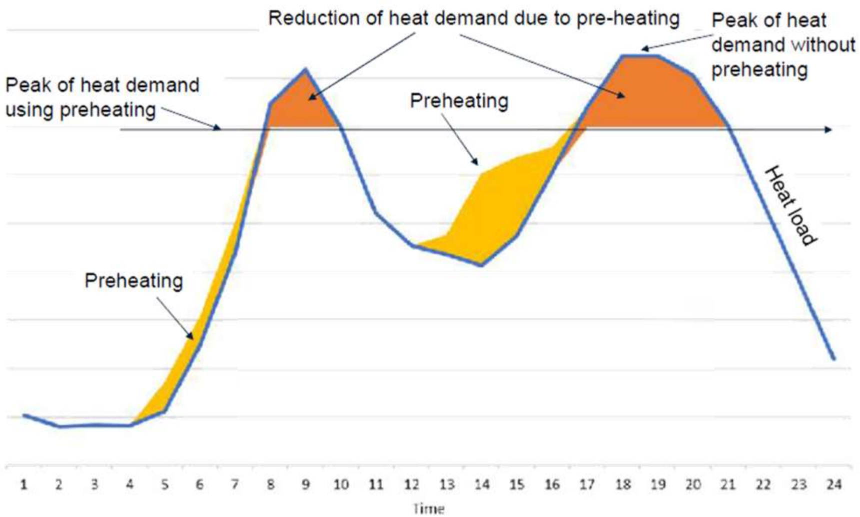
Innovation area	Balanced Pathway	Tailwinds	Widespread Engagement	Headwinds	Widespread Innovation
Pre-heating	Permitted in 25% of post-1952 homes.	Permitted in 50% of post-1952 homes	Permitted in 50% of post-1952 homes	Permitted in 25% of post-1952 homes.	Permitted in 50% of post-1952 homes
Heat as a service	No	Yes [a]	No	No	Yes [a]
Smart metering & control	Standard smart meter [b]	Smart meter with zonal control [c]	Smart meter with zonal control [c]	Standard smart meter [b]	Smart meter with zonal control [c]
Reduced water temperature	No	No	Yes, 50 °C [d]	No	No
Low flow shower head	Yes				

[a] Heat as a service modelled using: 7.5% cost of capital, 5% increase in heat demand, 3% financial savings, 15% increase in heat pump efficiency.
[b] Heat demand reduction based on actions including turning thermostat down and changing operating times.
[c] Heat demand reduction based on implementation of automated multizone control.
[d] 50 °C only applicable in dwellings which uptake a HP; allowance for daily legionella cycle of 1hr duration included.

[1] Based on multi-zone control systems available (e.g. Hive, Honeywell) [2] Scalewatcher brochure: Electronic Prevention of Hardwater Scale

Pre-heating

- Applied in all scenarios – with a varying proportion of homes deemed suitable for pre-heating depending on scenario assumptions.
  - The ability of a home to pre-heat will be a function of the thermal storage available in the fabric of the building (i.e. how well-insulated it is), the heating control systems available, and the appetite of the occupants to pre-heat.
  - Based on work by Imperial College London it is assumed that existing homes built after 1952 have the capability to pre-heat, with varying proportions of these homes choosing to do so across scenarios[1].
  - Where homes pre-heat, 4 hours of pre-heating is assumed (i.e. residents can offset their peak use via pre-heating their household up to 4 hours beforehand – see chart below).
- Where a home pre-heats, they are assumed to be able to access cheaper tariffs ('flexible space heat' costs in the modelling) which reflect the reduced costs associated with producing power off-peak and reducing requirements for network reinforcement to manage peak loads.
- Based on input from stakeholders, an overall 5% increase in heating demand for space heating is assumed to be associated with homes that pre-heat, as a result of the additional heat loss associated. In the case of hybrid heat pumps with boilers, the boiler is assumed to meet the peak demand, therefore the pre-heating demand increase is not applied.



Source: Assumptions developed by Imperial College (2018) Analysis of alternative heat decarbonisation pathways (see figure 4-5).

[1] Imperial College London (2018) *Analysis of alternative heat decarbonization pathways*

Heat as a Service

- Heat as a Service (HaaS) is a novel business model where a commercial organisation provides heating to a household, as a service, by leasing/controlling a heating asset to provide heat for a monthly fee. It may also involve the provision of insulation alongside the heating system (a model that has been demonstrated by Energiesprong). The organisation controls the technical and performance aspects while the resident receives the desired output of a heated home.
- Using the assets under the provider's portfolio, it is likely that the provider can be more flexible in the way they provide the heat, which may allow them to participate in Demand Side Management (DSM).
- HaaS is applied in the Widespread Innovation and Tailwinds scenarios as an alternate heating model, modelled as:
  - 7.5% cost of capital (against a default value of 3.5%)[1].
    - Based on the HaaS being operated commercially, and so using a commercial discount rate, rather than a domestic rate.
    - This is conservatively applied to both heating system and energy efficiency measure capex.
  - 5% increase in total heating demand[2].
    - This increase in total energy consumed is expected for this DSM approach, which involves significant time-shifting of heat demand, due to households losing heat to the environment for longer periods of time.
    - However, it should be noted that increases in demand are more likely when energy is more abundant and/or less carbon intensive; studies show reduced peaks for electricity demand, which could also result in the potential to reduce investment needed in network reinforcement.
  - 3% financial savings[3].
    - This value is a best-case figure, sensitive to modelling assumptions such as: future generation mix, wholesale market costs, future charging mechanisms for network costs and other schemes, and building archetype.
  - 15% increase in heat pump efficiency (applied through a 1.15 multiple in seasonal performance factor)[4].
    - This is based on the wide range of potential efficiencies available for heat pumps and the assumption that large-scale providers (in contrast with individual residents) will have better installation and operational processes that enable this increase in efficiency.

[1] Standard Green book declining discount rate. [2] Energy Systems Catapult: Smart Systems and Heat Phase 2 D10 - D14: Market Transformations Report (2019). [3] Energy Systems Catapult: EPO simulating Heat as a Service for Demand-Side Management (2019). [4] Based on expert feedback via external stakeholder discussion.

Smart Meters & Zonal Control

- Two levels of smart meter and feedback/control technology were modelled, with the applicability varying between scenarios.
- Both measures, in respective scenarios, are applied to the entire stock and so have the potential for significant space heat demand reduction.

Direct Feedback via Smart Meters and real-time displays

- Applied in the Balanced Pathway and Headwinds scenarios as a 3% reduction to baseline household heating demand via direct feedback from smart meters/real-time displays[1].
  - Assumptions on heat demand reduction are based on the average gas savings seen in smart meter trials across participants, and are expected to be associated with actions such as turning the thermostat down and changing operating times.

Direct Feedback and Zonal Control via Smart Meter and Smart Thermostatic Radiator Valves

- Applied in the Widespread Innovation, Widespread Engagement, and Tailwinds scenarios as a 6% reduction to baseline household heating demand via zonal control in both living and non-living spaces in a household[2].
  - Heat demand reduction based on using smart meters to implement automated multizone control.
- It should be noted that the reduction is taken as an average.
  - In some instances, increased usage is seen where residents opt to increase the temperature in one room more significantly for comfort purposes.

[1] Energy Demand Research Project (EDRP): Final Analysis (2011). [2] Taken as an average of recent studies based on: (i) Energy Systems Catapult: Pathways to Low Carbon Heating: Dynamic Modelling of Five UK Homes (2019), and (ii) Energy Systems Research Unit, University of Strathclyde: Potential energy savings achievable by zoned control of individual rooms in UK housing compared to standard central heating controls.

Reduced Water Temperature & Low Flow Shower Heads

- Two behavioural measures that affect the level of hot water demand were modelled, with applicability varying between scenarios.
- Both measures, in respective scenarios where applied, are only applicable to a sub-segment of the stock, either based on technology applicability or other dwelling-based suitability.

Reduced Hot Water Temperature for Households which Install Heat Pumps

- This behavioural change is applied only in the Widespread Engagement scenario. Feedback was received from expert external stakeholders to suggest this measure could be less known to residents. HSE is currently undertaking work with CIBSE looking at guidance for low-temperature systems to manage legionella risk.
- Hot water demand is based on residents who uptake heat pumps, setting their hot water temperature at 50^{o}C (as opposed to 60^{o}C).
  - The modelled savings account for a daily legionella cycle of 1hr duration to be completed, leading to a weighted average hot water temperature of 54^{o}C.
  - The resultant assumed savings in hot water demand are 18% for ASHPs and 13% for GSHPs.

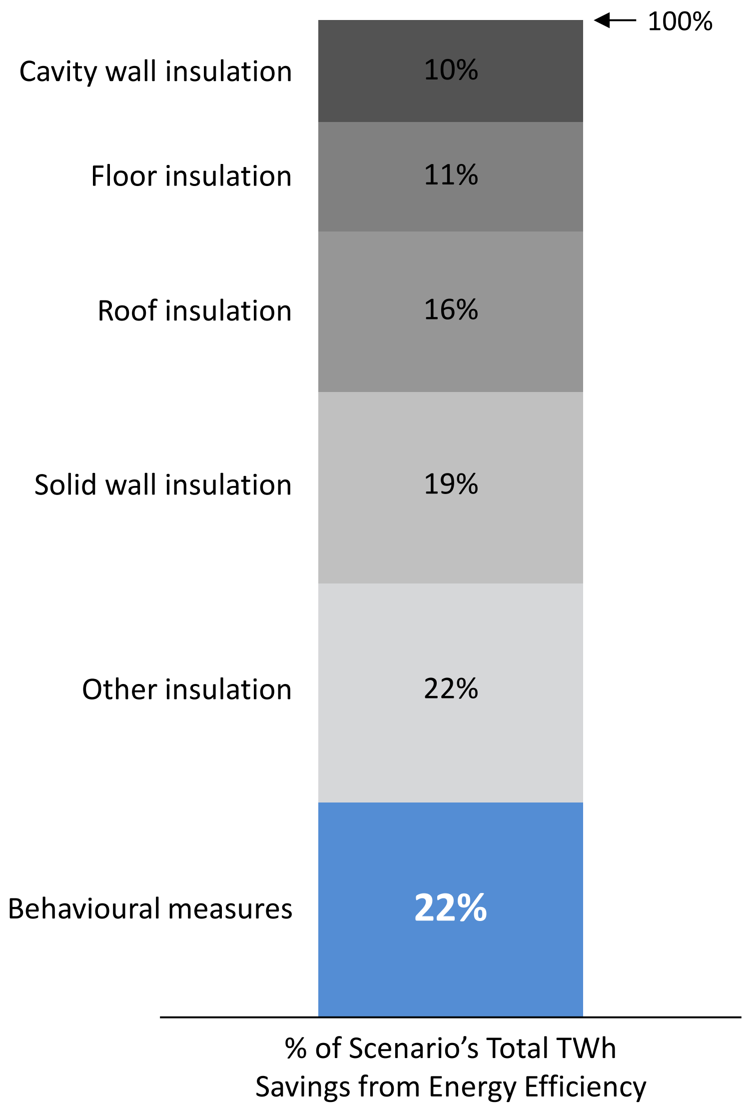
Reduced Hot Water Demand via Low Flow Shower Heads

- This measure is applied to all scenarios as a 5% reduction in hot water demand via the installation and use of a low flow shower head.
- Modelled accounting for:
  - a proportion of a household's hot water demand being attributed to showers (20%)[1],
  - only a proportion of UK homes being able to adopt the measure (40%)[2], and
  - a 67% decrease in volumetric flow rate compared to a standard shower head[3].

[1] WaterWise [2] Cambridge Architectural Research: How much energy could be saved by changing everyday household behaviours? (2012).
[3] Based on meeting the European Water Label green band, using (i) Hot Water Association and (ii) Department for Environment, Food and Rural Affairs: Government Buying Standards for showers, taps, toilets and urinals (2015).

Discussion – behavioural savings

- Of all measure categories the Balanced Pathway scenario, the highest savings are achieved by behavioural measures (over 1/5th of the total scenario savings).
  - This translates directly to a reduction in emissions which can be obtained prior to installing energy efficiency or switching to low carbon heating.
  - As these measures can be done relatively easily, early-on, on a wide-scale, and with minimal investment, they illustrate what the average householder can do immediately, and the level of impact it could make.
- Additionally, the cost benefits of many of the measures can be seen directly via lowered fuel bills.
  - This can be particularly important in higher operational cost scenarios, such as Headwinds, where lowered demand would effectively lower H_2 fuel use, which can be a significant cost reduction in the long-term.
  - For example, a household which simply uses the feedback from their smart meter (e.g. to turn down heating or otherwise) and installs a low flow shower head would save 3% off their heating bill and 5% off their hot water bill.



Contents

Updates from previous work [1/4] – Costs, savings, and packages

- Updated costs and savings for energy efficiency measures based on new evidence have decreased the overall cost effectiveness for a range of energy efficiency measures.
  - 5th Carbon Budget measure savings were based on modelled data using the Standard Assessment Procedure (SAP), and in-use factors. For this work, savings were based on real life observed data from Government's National Energy Efficiency Data (NEED) Framework (with sample sizes of thousands of homes) and adjusted to reflect some degree of performance gap closure.
  - Costs have also been updated to reflect the latest evidence based on the BEIS update of domestic cost assumptions, and to reflect new evidence on the number and cost associated with insulating non-standard cavity walls and lofts (decreasing the overall economic potential).
  - Cost effectiveness has also been impacted by an updated, lower, consumption baseline (via the calibration of baseline energy demand to NEED data) with measure savings (kWh) reduced as a result, and updated fuel costs (i.e. lower electricity costs decrease the value of additional energy efficiency in electrified scenarios).
  - For example, the Headwinds scenario, which sees the least optimistic energy efficiency assumptions (i.e. lower end performance gap closure, base cost and savings, and only cost-effective uptake rather than forced application), only sees a 11% reduction in heating demand due to energy efficiency measures.
- Package formulations have changed based on the updated cost and savings data, in addition to the modelling of a new ‘deep’ retrofit package in the Widespread Innovation scenario.
  - Glazing has not been modelled in the standard low, medium and high packages, due to the high costs implied by the latest evidence. Glazing installations would nonetheless be assumed to continue at current rates.
  - The deep retrofit package (which does include glazing) is modelled as a target-based approach with the aim of delivering a final dwelling heat demand of 40 $kWh/m^2/yr$.
  - Innovative technologies (such as thin internal wall insulation) have also been modelled.

SAP: Standard Assessment Procedure

Updates from previous work [2/4] – technical potential

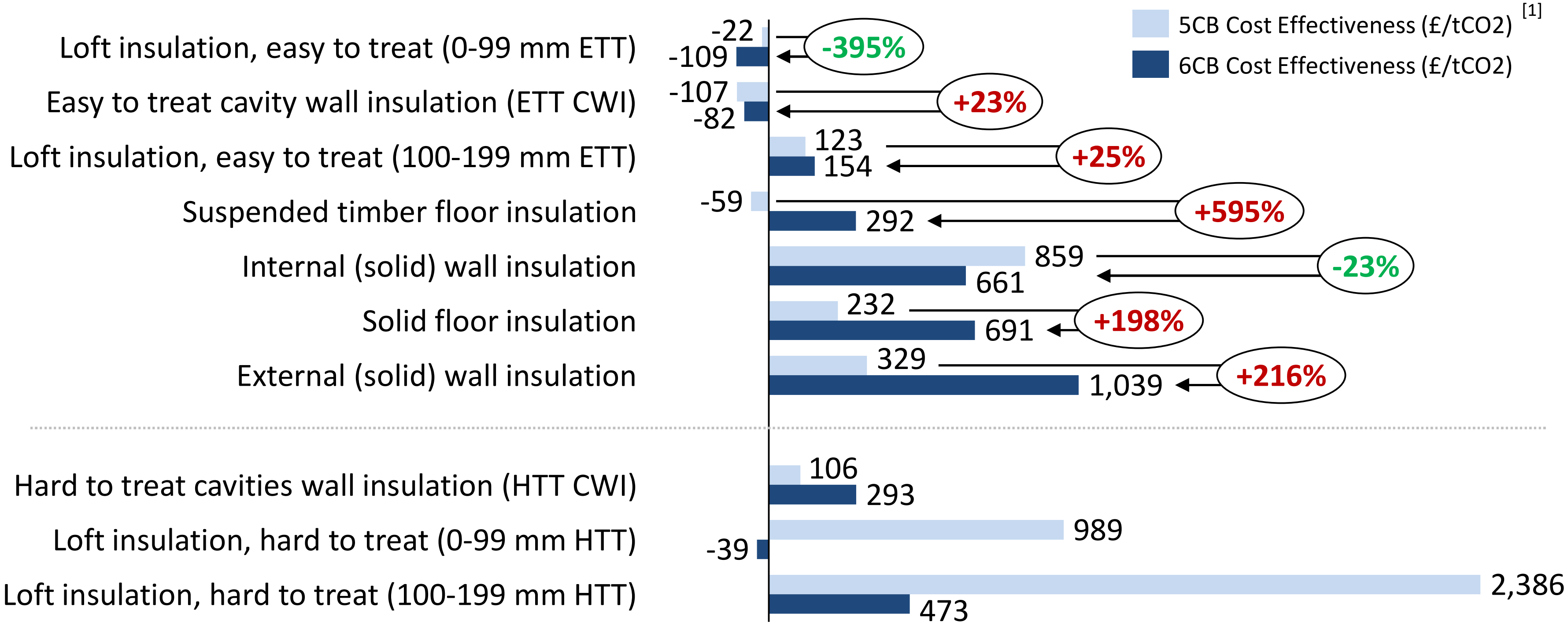
- The UK stock model was also updated to reflect the latest knowledge regarding the technical potential for energy efficiency measures. Additionally, some features were further broken down into level of ability to treat (i.e. EHTT – extra-hard-to-treat, HTT – hard-to-treat, and ETT – easy-to-treat). See Appendix for a breakdown of the UK stock by building feature type.
- The Net Zero work assumed that all homes with insulated lofts were candidates for further insulation, in the form of top ups to 300mm. This implied a significantly higher potential for loft upgrades than is likely to be realistic.
  - This assumption was amended in this work by only allowing the installation of loft insulation in already insulated homes in cases where the existing insulation is less than 200mm and not EHTT.
- Thought the total solid wall insulation technical potential is based on the updated housing survey data[1], the split between internal and external solid wall insulation is aligned with the 5th Carbon Budget technical potential split (i.e. 1/3 external, 2/3 internal).
  - Deployment is based on this potential and relative cost effectiveness, apart from the mixed deployment (of both) in fuel poor homes.
  - For example, in the Balanced Pathway the economic potential is deployed. Only a marginal fraction (<1%) of non-fuel poor external solid wall insulation technical potential is deployed compared to 54% deployment of the technical potential for non-fuel poor internal solid walls.
  - As such, due to this uncertainty in technical potential, if there is additional uptake of external vs. internal, costs would be driven up.
- Several sources were accounted for, including the latest housing survey data[1], EPC data[2], and government reports[3].

Building Feature Category	Building Feature	Measure category	Net Zero Technical Potential	6th Carbon Budget Technical Potential	% Change, relative to Net Zero
Wall Type	Cavity	Cavity insulated	12,909,932	14,219,975	+10%
		Cavity uninsulated EHTT	6,704,859	2,774,351	-12%
		Cavity uninsulated HTT		979,095	
		Cavity uninsulated ETT		2,115,298	
	Solid	Solid insulated	796,380	803,004	+1%
		Solid uninsulated (internal)	7,770,664	4,929,203	-5%
		Solid uninsulated (external)		2,483,132	
Roof Type	Insulated	200mm or more	10,653,333	11,081,376	+4%
	Partially Insulated	100 -199mm EHTT	9,592,984	1,746,204	-2%
		100 -199mm HTT		1,572,223	
		100 -199mm ETT		6,104,259	
		Less than 100mm EHTT	4,133,513	721,210	-6%
		Less than 100mm HTT		649,353	
		Less than 100mm ETT		2,521,154	
	No roof	No roof	3,802,004	3,908,280	+3%

[1] English, Scottish, Welsh, and Northern Ireland Housing Survey Data (2017-2018) [2] Energy Performance of Buildings Data: England and Wales [3] Energy Savings Trust (2019) Determining the costs of insulating non-standard cavity walls and lofts

Updates from previous work [3/4] – cost effectiveness

- The resulting changes, from the 5th Carbon Budget to the 6th Carbon Budget, to the cost effectiveness of the main building fabric measures modelled is shown in the graph below; largely a decrease in cost effectiveness (net positive change in £/tCO_2) is seen.
- However, based on the updated input data assumptions some measures (i.e. east-to-treat loft insulation in dwellings with minimal existing insulation and internal solid wall insulation) see the opposite trend.
- It is also important to note here that hard-to-treat categories (below) were treated differently in the 5th Carbon Budget vs. the 6th Carbon Budget(as presented in the previous slide, regarding the further breakdown between HTT and EHTT measures) and so relative cost effectiveness should not be compared directly without context.



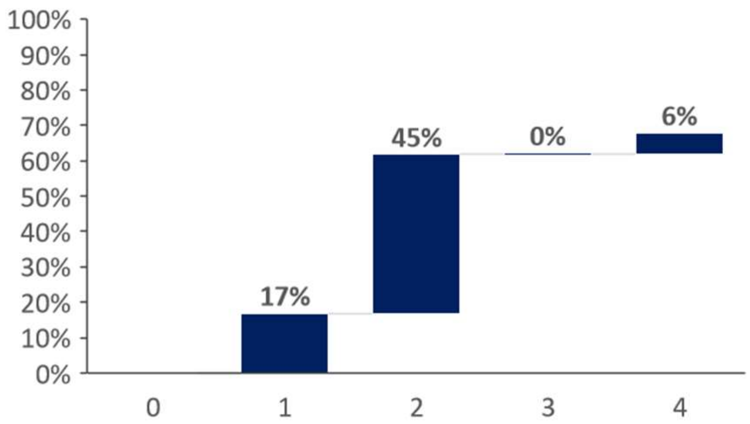
[1] Cost effectiveness from the 5th Carbon Budget report taken from: Element Energy & Energy Savings Trust: Review of potential for carbon savings from residential energy efficiency (2013)

Updates from previous work [4/4] – heat demand savings

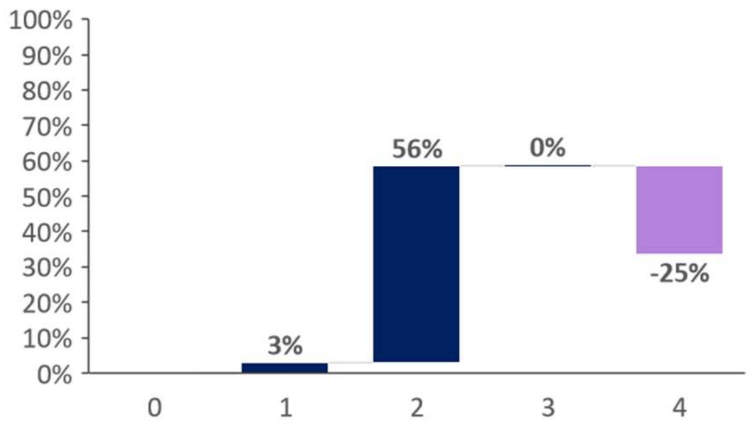
- This work sees relatively low heat demand savings compared to Net Zero due to several factors including those previously presented (i.e. less favourable cost-effectiveness resulting in lower cost-effective uptake as seen in Headwinds for example).
- Additional analysis was conducted to understand the relevant impact of key factors on the heat demand savings; factors include the updated consumption baseline, cost/savings assumptions, fuel costs, and lifetimes modelled.
- The below two graphs show two examples (for different fabric measures) for the impact of each of the key factors by illustrating the relative change in cost effectiveness (£/t) when the updated 6th Carbon Budget (6CB) factor is modelled in place of the Net Zero factor. From left to right (0-4), the graphs show (0) the baseline for Net Zero £/t, (1) the change in £/t by using the 6CB demand baseline, (2) the further change in £/t by modelling the updated cost/savings, (3) the further change in £/t by switching to 6CB fuel costs, and (4) the further change in £/t based on the updated measure lifetime.

Legend	
0	Net Zero £/t baseline
1	6CB baseline demand
2	6CB measure cost/savings
3	6CB fuel cost
4	6CB measure lifetimes

Easy-to-treat cavity wall insulation - net 68% increase in in £/t from Net Zero to 6CB*



Solid floor insulation - net 34% increase in £/t from Net Zero to 6CB (excluding supplementary cost)*



* Analysis, and graphs shown, do not account for performance gap uplifts or other factors not explicitly stated.

Findings – energy efficiency uptake ranges across scenarios [1/2]

- Energy efficiency levels are driven by different factors in each scenario:

  - **Balanced Pathway:** inclusion of all practicable loft and cavity insulation (economic potential <~£700/$tCO2_e$), in addition to all solid wall insulation in packages under £600/t. High packages for all fuel poor homes[1].
    - Due to the wider benefits of installing energy efficiency, this scenario deploys more than simply the cost-effective portion of measures; in addition to supporting dwellings in fuel poverty, this reflects additional benefits in both comfort and health.

  - **Tailwinds:** inclusion of full economic potential for all energy efficiency measures.
    - The cost assumptions for the package of fabric measures applied is also based on lower bound estimates.
    - This scenario aims to illustrate the highest take up assessed as economically feasible.

  - **Headwinds:** cost-effective basis (i.e. optimising for the lowest lifetime cost energy efficiency + low carbon heating combination), given high H_2 prices, with no wider benefits costed. This is the only scenario with cost-effective uptake for non fuel-poor homes at standard fabric prices and savings. High packages for all fuel poor homes.
    - This scenario, having the least consumer engagement and demand-side shift, as a result, sees the least take up of energy efficiency measures.
    - However, the modelling of energy efficiency uptake based on higher H_2 fuel prices is aimed at (i) accounting for the uncertainty in future H_2 prices and (ii) dwellings installing more energy efficiency than what is determined as strictly cost-effective (without accounting for wider benefits).

[1] The scenarios include wall and roof insulation (where uninsulated) for all fuel poor homes. This was implemented in the modelling by assigning high energy efficiency packages to these homes, and as such floor insulation was also included. In practice, it is likely that deployment of floor insulation may be more limited (particularly where this is more expensive solid floor insulation).

Findings – energy efficiency uptake ranges across scenarios [2/2]

- **Widespread Engagement:** deployment of at least a medium package in all households. High packages for all fuel poor homes.
  - The exception is a subset of heritage buildings where some fabric measures are unsuitable.
  - This scenario aims to represent consumers driving the take up of measures across the stock.

- **Widespread Innovation:** cost-effective basis using lower-end costs, with no wider benefits costed; deep retrofits replace standard high packages. All fuel poor homes receive these deep retrofits.
  - Additionally, thin internal wall insulation is modelled instead of standard internal wall insulation.
  - This scenario depicts the case where innovation reduces standard costs, and a portion of dwellings undergo a more holistic (or 'deep') retrofit.

- Solid walls in fuel poor homes are insulated across scenarios (implemented via the high energy efficiency package).
  - Given the high uncertainty over the achievable performance and costs of solid wall insulation, a broad range of uptake levels was modelled across the scenarios, with Tailwinds representing full economic potential (under ~£700/t), which in the case of solid wall insulation is equivalent to full technical potential.

- The overall figure for heat demand reduction has significant variation across homes:
  - A proportion of homes do not get any energy efficiency deployment, varying from 0%, in Balanced Pathway and Tailwinds, to 69%, in Widespread Innovation.
  - In the Balanced Pathway scenario, a typical household which installs cavity wall insulation, loft insulation, and floor insulation sees heat demand savings of 30%.
  - Undergoing a deep retrofit (applicable in Widespread Innovation) sees heat demand savings of 57%.

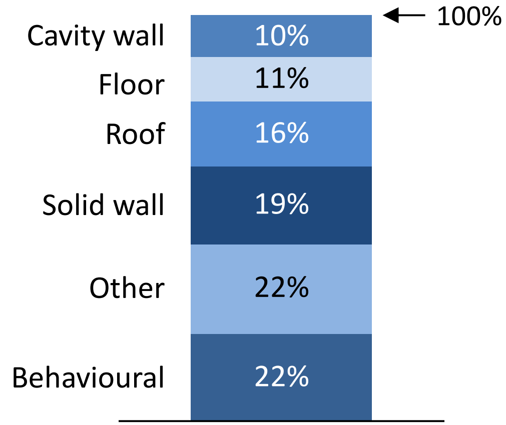
Discussion – energy efficiency [1/2]

- Energy efficiency measures and behavioural changes should be deployed/implemented early and widely across the stock to drive down fuel bills in homes. This is valuable both to manage heat pump electricity demand and the high opex costs associated with any hydrogen use.
- Energy efficiency deployment in the early years is dominated by the local authority and private rented sectors, in addition to fuel poor homes.
- In terms of cost effectiveness towards abating CO_2 emissions, there is a wide range of benefit from different fabric measures for retrofit. For example, for a medium-sized semi-detached house:
  - Easy to treat cavity wall insulation is a low cost, high benefit measure, with an average cost effectiveness of -£70/tCO_2.
  - Based on the updated cost and savings assumptions, replacing old (pre-2002) double glazing with new double glazing is a higher cost, lower benefit measure, with £/tCO_2 cost effectiveness in the thousands. The scenarios do not model glazing upgrades (except as part of deep retrofits), but upgrades can still offer improved comfort in homes and current rates of upgrade would be assumed to continue.
- Though the direct heat demand savings are modelled in this work, there are a range of wider benefits[1] that the installation of energy efficiency would render including the following:
  - **Economic**: public and private sector investment and job growth.
  - **Health**: decreasing the number of cold homes and the near-term reduction of carbon-intensive supply.
  - **Flexibility**: (via pre-heating or other demand side response) for the grid.

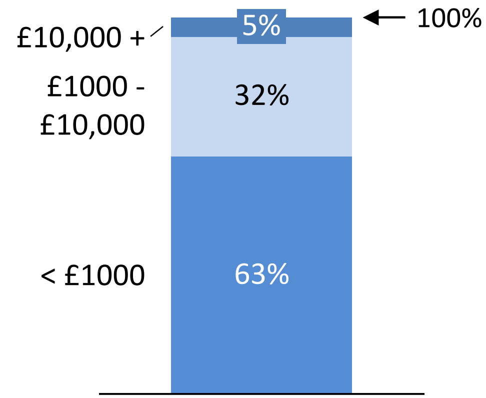
[1] Energy Savings Trust: Capturing the "multiple benefits" of energy efficiency in practice: the UK example

Discussion – energy efficiency [2/2]

- The measures generating the highest savings in the Balanced Pathway scenario include behavioural measures, solid wall insulation, and ‘other’ insulation measures, together making up around 3/5 of savings.
  - ‘Other’ measures include draught proofing and hot water tank insulation[1]. Most of the savings here are expected to come from draught proofing as it delivers savings of ~3% per home, applied to the majority of the stock.
- 63% of all homes need spend no more than £1000 on retrofitting energy efficiency measures, with these homes delivering 30% of the scenario-wide energy savings in the Balanced Pathway scenario.
  - 30% of all energy savings from energy efficiency in the Balanced Pathway scenario are associated with measure packages costing under £1000.
  - These are expected to typically be homes with behavioural and other measures (draught proofing, hot water tank insulation) only or with loft / cavity insulation alongside.
- 49% of savings in the Balanced Pathway scenario come from homes with retrofit packages costing between £1000 - 10,000.
  - These are largely concentrated in the able-to-pay owner occupied stock.
- The cheapest retrofit packages (under £1000) deliver on average 8.7% savings per home, whilst the mid-range packages (£1000 - £10,000) deliver 21% savings on average. The most expensive retrofits in the Balanced Pathway scenario cut heat demand by approximately a third[2].



% of Scenario’s Total TWh Savings from Energy Efficiency



Household Energy Efficiency Cost Distribution

[1] It should be noted that lagging of pipes in hot water systems also has potential to make a significant contribution to energy savings, although it has not been possible to model it in this work due to data limitations. [2] The numbers provided for this point are derived from simple averages (rather than weighted by uptake) which are likely lower.

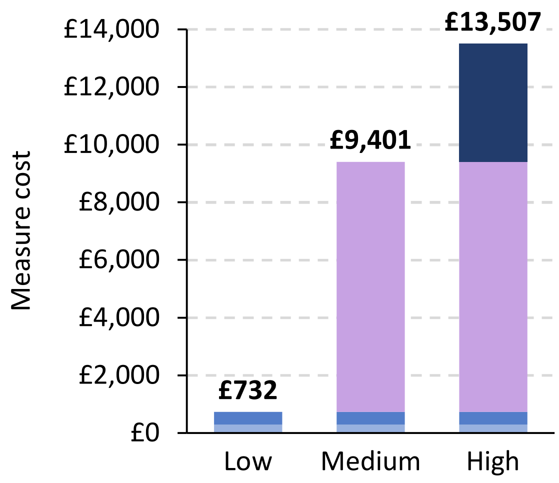
Scenario definitions and drivers – energy efficiency uptake ranges

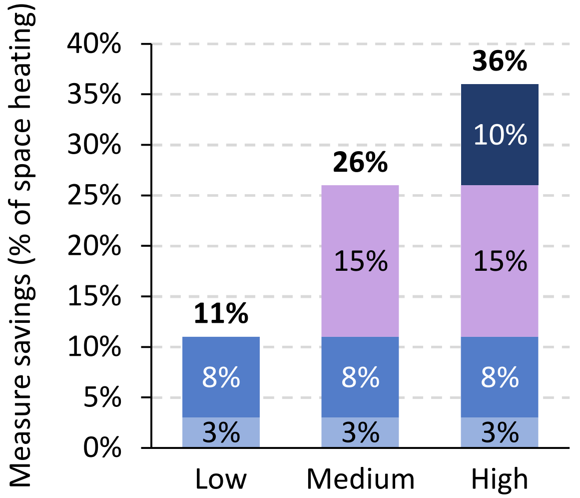
- The table below shows the total technical potential for each measure category in the UK stock; as shown previously, the wall and roof measures have been updated since the publishing of the 5th Carbon Budget.
- Cavity walls and insulated lofts are quite common, whereas most floors are uninsulated, particularly solid floors where ~16M uninsulated households exist.

Measure category	Measure subcategory	UK stock	% of UK stock
Wall	Cavity uninsulated EHTT	2,774,351	10%
	Cavity uninsulated HTT	979,095	3%
	Cavity uninsulated ETT	2,115,298	7%
	Cavity insulated	14,219,975	50%
	Solid uninsulated (internal)	4,929,203	17%
	Solid uninsulated (external)	2,483,132	9%
	Solid insulated	803,004	3%
Roof	No roof	3,908,280	14%
	Less than 100mm EHTT	721,210	3%
	Less than 100mm HTT	649,353	2%
	Less than 100mm ETT	2,521,154	9%
	100-199mm EHTT	1,746,204	6%
	100-199mm HTT	1,572,223	6%
	100-199mm ETT	6,104,259	22%
	200mm or more	11,081,376	39%
Floor	Solid uninsulated	16,009,093	57%
	Solid insulated	1,129,342	4%
	Suspended uninsulated	7,389,412	26%
	Suspended insulated	236,688	1%
	None	3,539,523	13%

Summary of measures included in the final packages

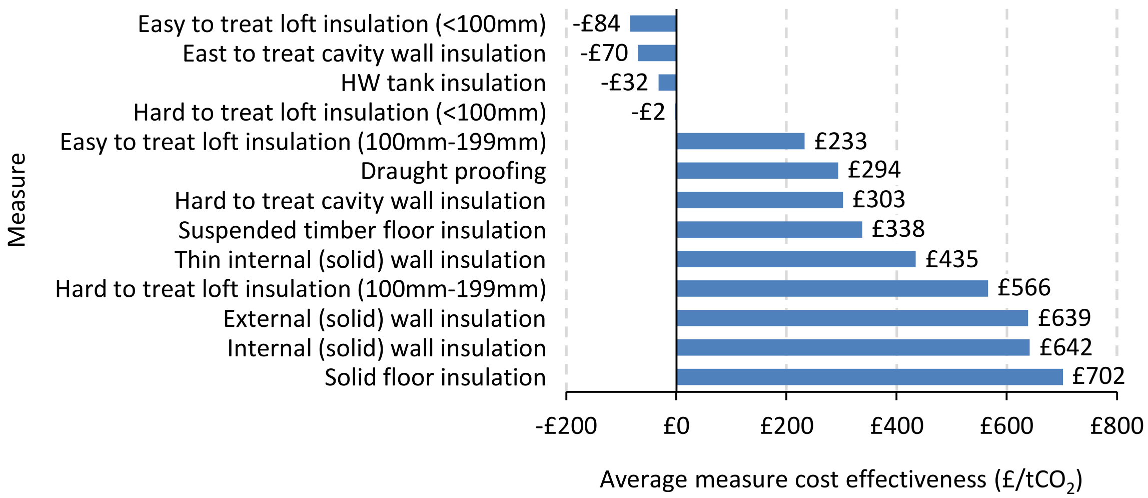
Example energy efficiency package costs and savings for a medium, semi-detached house with measure breakdown





- This example shows the relative benefit (at minimum cost) a household may obtain by installing a 'low' package of measures (e.g. draught proofing and loft insulation).
- Not all dwellings will need solid wall or solid floor insulation; however, though less cost effective than some other measures, there are significant additional savings that can be achieved via uptake of these measures.

Example cost effectiveness associated with fabric measures for a medium, semi-detached house



- This graph illustrates the range of cost-effectiveness breakdown by measure for a typical medium-sized semi-detached house.
  - All measures are under ~700£/tCO_2.
  - Installing loft insulation (<100mm), easy-to-treat cavity wall insulation, and hot water tank insulation are all cost-negative measures.
- However, it should be noted that these values do not account for supplementary costs or other costs not modelled in this work; further details are presented later in this section.

Overview of approach – energy efficiency [1/2]

1. **Determine the cost (£) and demand savings (%/kWh)** per measure for different property types and sizes based on relevant studies →
2. **Apply a savings uplift factor for partial closure of a measure's performance gap** based on a measure type's in-use factor →
3. **Create three energy efficiency packages,** putting measures into low, medium, and high packages based on their cost effectiveness and levels of disruption →
4. **Determine the annualised cost (£) and savings (£)** of each package for each archetype including capex and fuel savings. →

2050 end-state energy efficiency packages based on suitability and lifetime cost

- Three main energy efficiency packages were modelled, each made up of different sets of building fabric and behavioural measures.
  - **Low**: Only the least cost, least disruptive measures.
  - **Medium**: More measures than the low package, providing higher savings.
  - **High**: All measures under economic potential, to achieve the higher energy demand savings at a higher cost.
- An additional, more extensive, 'deep retrofit' package was modelled particularly for the Widespread Innovation scenario. It is modelled as a whole-house, integrated retrofit approach which delivers an increased level of heat demand savings at higher cost.
- It is important to note that the values shown in this table do not include the modelled supplementary costs for solid wall insulation.
  - Internal: survey and design / planning.
  - External: survey, design / planning and construction overheads.

Measure	Cost Effectiveness (£/tCO2)	Low	Medium	High
Loft insulation, easy to treat (0-99 mm ETT) [1]	-84	✓	✓	✓
Easy to treat cavity wall insulation (ETT CWI)	-70	✓	✓	✓
Hot water tank insulation	-32	✓	✓	✓
Loft insulation, hard to treat (0-99 mm HTT) [1]	-2	✓	✓	✓
Loft insulation, easy to treat (100-199 mm ETT) [1]	233	✓	✓	✓
Draught proofing (draught stripping)	294	✓	✓	✓
Hard to treat cavities wall insulation (HTT CWI)	303		✓	✓
Suspended timber floor insulation	338		✓	✓
Thin internal (solid) wall insulation	435		[2]	[2]
Loft insulation, hard to treat (100-199 mm HTT) [1]	566		✓	✓
Internal (solid) wall insulation	642		✓	✓
External (solid) wall insulation	639			✓
Solid floor insulation	702			✓
Double glazing (from single glazed)	3150			
Triple glazing (from double glazed pre 2002)	6091			[3]
Double glazing (from double glazed pre 2002)	8013			

[1] Potential savings for varying existing levels of loft insulation is based on a calibration to NEED data; a level of uncertainty is present based on this.
[2] Thin internal (solid) wall insulation replaces standard internal (solid) wall insulation in the Widespread Innovation scenario.
[3] Glazing is present as part of the deep retrofit, which replaces the standard high package, in the Widespread Innovation scenario.

Overview of approach – energy efficiency [2/2]

	Balanced Pathway	Tailwinds	Widespread Engagement	Headwinds	Widespread Innovation
Energy efficiency packages and deployment - non-fuel poor*	Inclusion of full economic potential for low regret measures including loft and cavity wall insulation. Solid walls deployed where part of a package with a cost effectiveness of <£600/t.	Full economic potential deployed.	All homes receive at least a medium package (except a subset of heritage homes where a Medium package is unsuitable).	Model permitted to deploy energy efficiency on basis of lowest lifetime cost of package of energy efficiency and low carbon heat, with higher bound hydrogen prices assumed. No wider benefits costed.	Model permitted to deploy energy efficiency on basis of lowest lifetime cost of package of energy efficiency and low carbon heat. No wider benefits costed.
Adjustments to measure assumptions	Base costs & savings.	Lower bound costs for low, medium, and high packages.	Base costs & savings.	Base costs & savings.	Lower bound costs for all low and medium packages. TIWI (thin IWI) replaces IWI in packages. All high packages assumed to deliver heat demand of 40kWh/m^2/yr, with associated costs of high packages uplifted to reflect evidence on potential for cost reduction in deep retrofits[1].

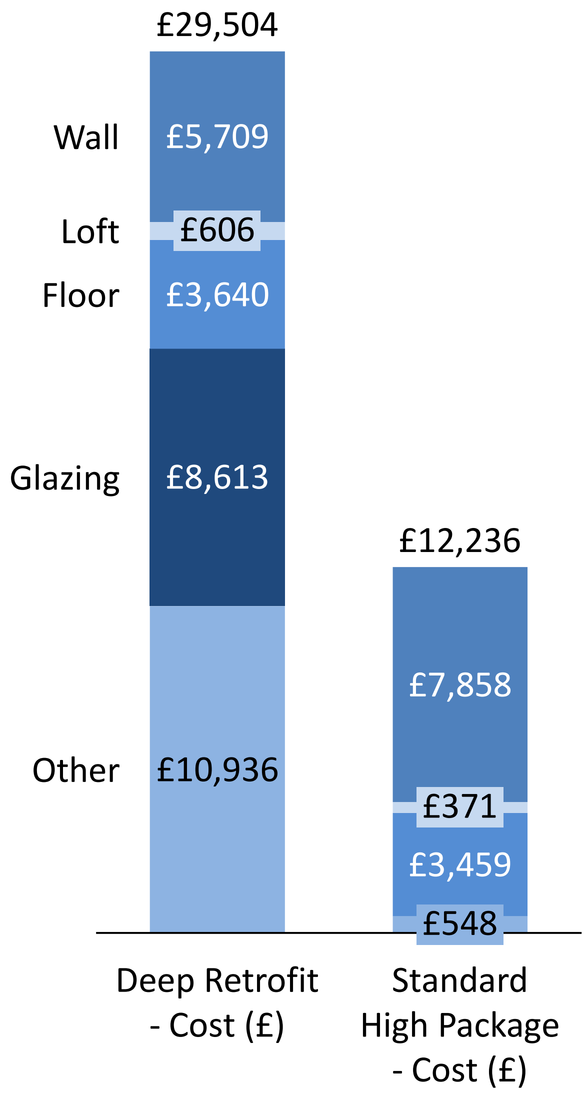
Water softening

- Water softening technology, in the form of an electronic water conditioner for the domestic hot water supply, was included in all homes to ensure optimum performance of heating technologies, given that:
  - Hard water leads to deterioration of performance of water heating technologies, such as reduced efficiency for heat pumps, over time[2].
  - The majority of homes in the UK are in hard water areas[2].
- With water softening technology installed in all homes, it can be assumed that low carbon domestic hot water systems perform according to their modelled efficiency over their entire lifetime. This includes wet heating systems used for space heating.
- Electronic water conditioning was chosen as the default technology due to its lower capital and operating costs compared to conventional technologies[3],[4].

* Solid wall insulation is modelled for all fuel poor homes, via the application of high packages as a simplification; however, in reality, it may be that the uptake of other measures (e.g. solid floor insulation) is lower than assumed in the scenarios.
[1] Green Alliance, Reinventing retrofit; discussions with Energiesprong, discussions with retrofit experts. [2] Aqua cure; [3] Aqua cure softeners; [4] ScaleWatcher

Deep retrofit package

- The costs and savings assumptions for deep retrofit packages have been derived from source evidence provided by Energiesprong, with adjustments made to align with the energy efficiency modelling approach in this work.
  - The costs modelled are intended to represent the costs that might be achievable where deployment of deep retrofits at scale is achieved, based on progress in The Netherlands.
  - It should be noted that the costs do not reflect an Energiesprong retrofit; this modelling of deep retrofits differs from the Energiesprong model in a number of important ways – notably not modelling onsite generation or lifetime net maintenance costs which are core to the Energiesprong business case.
  - For further discussion of the benefits of the Energiesprong retrofit model see CCC (2018) UK housing: Fit for the future.
- Deep retrofits are applied only in the Widespread Innovation scenario as a replacement to the standard high package; they have been modelled as unsuitable to high-rise flats and listed buildings.
  - Uptake is via all fuel-poor homes and additional cost-effective dwellings. The savings of a deep retrofit package are modelled to achieve a 40 kWh/m2/yr space heating demand goal, rather than a specified savings percentage.
  - This could be anywhere from 0% (where a dwelling is already achieving this goal, and so is not suited to further retrofitting) to 80% (for a disproportionally under-insulated dwelling which has the highest potential for savings). The average across homes receiving this package is 57%.
- The graph to the right shows an illustrative example (i.e. for a single archetype) of the breakdown of costs for a deep retrofit (with a 57% savings) compared to a standard high package (with a 35% savings).
  - Other measures in the deep retrofit may include: draught proofing, insulated doors, hot water tank insulation, and integration to achieve the savings target.



Savings uplift and closure of performance gap [1/2]

- There is often a substantial difference between the theoretical performance of insulation measures when modelled, and the actual performance of those measures once installed. This gap is called the ‘performance gap’.
- A number of factors impact the performance gap, including consumer behaviour (comfort taking is a known effect whereby internal temperatures increase following an improvement in insulation, reducing associated savings), the practicalities of real homes (which may mean a proportion of the building cannot be treated or is ‘inaccessible’) and the systematic difference between physics-based models and real-life (which can be associated with factors such as modelling inaccuracies or poor design or workmanship on site).
- The CCC’s analysis for the 5th Carbon Budget took modelled savings as the basis for the assumptions, and made an adjustment to reflect the above factors and better approximate predicted ‘real-life’ performance. A different approach has been taken for the 6th Carbon Budget analysis whereby real-life performance data from NEED is used as the starting point for assumptions. Whilst this presents a reasonable basis for modelling current performance, the scenarios are predicated on best-practice delivery and therefore assume some uplifts to savings are achievable, specifically those which can be achieved through better design and construction[1].

SAP modelled savings

5th Carbon Budget adjustment

Inaccessibility factor: Adjusting for proportion of building stock’s surface area which cannot be treated

Comfort factor: Adjusting for comfort taking

IUF: Adjusting for modelling inaccuracies

IUF: Adjusting for physical underperformance (poor design, substitution of materials on site, poor workmanship)

Achievable savings

6th Carbon Budget adjustment – 12% moderate uplift, 18% high uplift (example of a terraced dwelling with all measures available).

Actual savings

IUF: In-Use Factor.

[1] See CCC (2019) *UK housing: Fit for the future?* For recommendations on closing the performance gap

Savings uplift and closure of performance gap [2/2]

- Whilst a large body of evidence points to a substantial gap between the theoretical performance of buildings as measured at design stage, and the actual performance when built, there is a lack of robust data, based on large sample sizes, to quantify the precise scale of the gap.
- For the purposes of the 5th Carbon Budget, an exercise was undertaken to identify the best available estimates to quantify the performance gap for each measure, and the contribution of different factors to this gap[1].
- These assumptions have been repurposed for the 6th Carbon Budget. A performance gap uplift factor has been modelled for all fabric measures as a proportional closure relative to a fabric measure's in-use factor. That is to say, some scenarios assume an uplift in performance can be achieved which is commensurate with a one third closure of the in-use factor, whilst other scenarios assume an uplift commensurate with 50% closure of the in-use factor.
- This work assumes no further uplift based on the other portions of the total IUF (i.e. the comfort factor, the inaccessibility factor), on the basis that these are real-life dynamics that are expected to persist.
- It should be noted that this process has an intrinsic level of uncertainty. In particular the scale of the performance gap, and contribution of different factors in driving it, remain highly uncertain. There would be benefit in further research to better quantify the potential for improvements here.
- The diagram on the preceding slide illustrates the approach taken to the adjustment. Additionally, as an example:
  - Cavity wall insulation has an in-use factor of 35% and total IUF of 50%.
  - This work models a one-third (33%) closure of the 35% in-use factor as the measure uplift factor: ((1 - 35%) + (35% * 33%)) / (1 - 35%) = 118%.
  - This 118% would then be multiplied by the cavity wall insulation savings (pre-uplift) to determine the final savings (e.g. 118% * 10% = 11.8%).
- The next slide outlines the IUFs and corresponding performance gap uplifts by measure and scenario.

IUF: In-Use Factor. [1] Element Energy and Energy Saving Trust for the CCC (2013) Review of potential for carbon savings from residential energy efficiency .

Refinement and validation of package cost and savings

Performance gap uplift by measure and scenario

	Closure	33%	50%	33%	33%	50%
Measure	**In-Use Factor [1]**	**Balanced Pathway**	**Tailwinds**	**Widespread Engagement**	**Headwinds**	**Widespread Innovation**
Behavioural	*0%*	100%	100%	100%	100%	100%
Cavity wall	*35%*	118%	127%	118%	118%	127%
Solid wall	*33%*	116%	125%	116%	116%	125%
Roof	*35%*	118%	127%	118%	118%	127%
Floor	*15%*	106%	109%	106%	106%	109%
Glazing	*15%*	106%	109%	106%	106%	109%
Other	*15%*	106%	109%	106%	106%	109%

Supplementary costs included in the package formulation

	Scaffolding	Survey and Design
Measure / Cost Type	**Construction Overheads**	**Design & Planning**
External (solid) wall insulation	✔	✔
Internal (solid) wall insulation		✔

- Regarding energy efficiency costs, scaffolding and survey and design costs have been added for some measures where expected to be necessary.
- Nevertheless, not all associated costs have been included in this modelling. Costs not included would be additional to the costs quoted:
  - Building control costs will be incurred for any work meeting the criteria, but the extent to which they are associated with energy efficiency measures specifically will vary according to whether these retrofits are undertaken at the same time as wider works.
  - Similarly, regarding the costs of refitting kitchens and/or removing radiators with internal wall insulation, the extent to which they are incurred will depend on whether the retrofits are undertaken at the same time as wider works.
  - Planning permission costs can also be expected for some measures such as external wall insulation; however, this is a function of policy and could change in the future based on a more or less permissive planning regime.
- It should also be noted that the costs associated with retrofit coordinator roles are not costed; this work focuses on including design and planning costs for the most complex measures.
  - Nevertheless, effective design and planning is required for all retrofits and so plays a role both at the point of assessing the decarbonisation pathway for a home (via a green building passport) and at the point work is undertaken (via retrofit coordinators).

IUF: In-Use Factor. [1] Element Energy and Energy Saving Trust for the CCC (2013) Review of potential for carbon savings from residential energy efficiency .

Contents

Updates from previous work

- Costs of all technology configurations and ancillary components, including scope for reductions over time, were updated and refined relative to previous work, based on the latest data and on consultation with stakeholders:
  - Technology sizing assumptions were updated, based on BEIS National Household Model data (and influenced also by updated assumptions on heat demand and the impact of warming), leading to a smaller average system size for heat pumps compared to the Net Zero analysis (5 kW in the Balanced Pathway scenario, compared to 8 kW in Net Zero for pure heat pumps).
  - Heat pump efficiencies remained broadly in-line with 5CB assumptions in the absence of new evidence.
  - Heat pump cost reduction assumptions were updated, reflecting more ambitious reductions relative to assumptions used for the 5th Carbon Budget
  - Lifetimes of technologies (in particular heat pumps) were updated in line with feedback from stakeholders:
    - Air-source heat pump lifetimes were reduced from 18 years in Net Zero to 15 years in the Balanced Pathway scenario.
    - Ground-source heat pump lifetimes remained unchanged from Net Zero, at 20 years, but the lifetime of the unit was separated from the lifetime of the ground loop, which is significantly longer.
- Representation of heating technologies was improved compared to Net Zero, by adding new configurations and refining existing configurations:
  - Modelled ground-source heat pump configurations were broadened to include individual systems, communal systems and hybrid systems.
  - The number of solar thermal configurations modelled was increased to two[1]; one where solar thermal covers a share of hot water demand only and one where it covers shares of both space heating and hot water demand.
  - High temperature heat pumps (defined as heat pumps operating at a flow temperature above 60°C) were added as a technology. Compared to conventional heat pumps, high temperature variants operate at lower efficiencies (leading to higher operating costs) and have a higher capital cost, but in most cases remove the need for radiator upgrades.
  - A more nuanced representation of flexibility in homes was included. This covers the inclusion of a range of electricity prices (varying from 7 to 13 p/kWh in 2050 in the Balanced Pathway scenario) and the inclusion of configurations with thermal storage.

[1] The total number of modelled technology configurations incorporating solar thermal is greater than two, as solar thermal was modelled both with heat pumps and direct electric heating.

Summary of low carbon heating technologies modelled

- 3 groups of low carbon heating technologies were modelled, with numerous configurations:

- **Heat Pumps**
  - Air-source / Ground-source
  - **Type**: Conventional / Communal / High temperature
  - **Equipped with**: Hot water storage / Hot water & thermal storage
- **Hybrid heat Pumps**
  - Air-source / Ground-source
  - **Hybrid mode**: Hydrogen / Biofuel / Electric resistive / Solar thermal[1]
  - **Equipped with**: Hot water storage / Hot water & thermal storage
- **Direct electric heating**
  - **Type**: Electric resistive / Electric storage
  - **Equipped with**: Hot water storage / Hot water & thermal storage / Solar thermal[2]

- **Hydrogen boilers** and **low carbon heat networks** were also modelled.
- Solar thermal was modelled in two different configurations, providing either (i) a portion of hot water demand, or (ii) a portion of hot water and space heating demand.
- Certain configurations were also split further, depending on the type of electricity used (e.g. flexibility of electricity demand of the technology configuration).

In total, **53** technology configurations were modelled. The list of suitable technologies and assumptions (e.g. costs, lifetimes), were varied between scenarios.

[1] Only air source heat pumps were modelled in the solar thermal hybrid configuration
[2] Includes configurations with added hot water storage and thermal storage

Scenario-based definitions and drivers of low carbon heating technologies

	Innovation area	Balanced Pathway	Tailwinds	Widespread Engagement	Headwinds	Widespread Innovation
Technology	Low-carbon heating restrictions	Hydrogen only permitted via hybrid boilers Biofuel only permitted in off-gas grid hybrids	Hydrogen limited to clusters No biofuel permitted	Electric-only scenario (no hydrogen or biofuel)	Biofuel only permitted in off-gas grid hybrids	High temperature HPs included No biofuel permitted
		All resistive heating accompanied by thermal storage or solar thermal.				
	Heat pump lifetimes[1]	15yrs for ASHPs 20yrs for GSHPs (100 yrs for ground loop)	17yrs for ASHPs 22yrs for GSHPs (100yrs for ground loop)	15yrs for ASHPs 20yrs for GSHPs (100yrs for ground loop)	15yrs for ASHPs 20yrs for GSHPs (100yrs for ground loop)	17yrs for ASHPs 22yrs for GSHPs (100yrs for ground loop)
	Heat pump cost reduction[1]	20% to 2030 30% of 2050	30% to 2030 40% to 2050	20% to 2030 30% of 2050	20% to 2030 30% of 2050	30% to 2030 40% to 2050
	Heat pump load factors[1]	Average	High-end	High-end	Low-end	High-end
	Heat batteries	Used in space constrained homes	As standard rather than hot water cylinders	Used in space constrained homes	Used in space constrained homes	As standard rather than hot water cylinders
	Thermal storage	Cost effective deployment				Deployed widely such that all homes can consume more flexibly
	Hy-ready boilers	All boiler replacements from 2026 are Hy-ready				
	Low carbon heat Networks mix	Electrified	Electrified	Electrified	Incl. hydrogen peaking	Electrified

[1] Assumptions were tested extensively with heat pump stakeholders.

Approach to costing low carbon heating – counterfactuals approach summary

- The cost of the counterfactual heating system was determined based on the annual space heating demand of the building archetype.
- BEIS National Household Model data – indicating that 50% of gas boilers and 15% of oil boilers are combi boilers – was used to determine the number of existing homes with hot water cylinders.
  - All homes with non-combi boilers were assumed to have an existing hot water cylinder.
- The proportion of homes connected to the gas grid requiring replacement of gas cooking appliances was assumed to be 62%, based on work by Imperial College[1].

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

Costing low carbon heating – summary of additional costs [1/2]

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	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
AHSP/GSHP *inc. option with solar thermal*	Gas						*[8]*	*[2]*	*[3]*		*[1]*	
	Oil						*[8]*	*[2]*	*[3]*			
	Electric resistive								*[3]*			
	Electric storage								*[3]*			
	Community							*[2]*	*[3]*			
Communal ASHP/GSHP	Gas						*[8]*	*[2]*	*[3]*		*[1]*	
	Oil						*[8]*	*[2]*	*[3]*			
	Electric resistive								*[3]*			
	Electric storage								*[3]*			
	Community							*[2]*	*[3]*			
Electric resistive *inc. option with solar thermal*	Gas						*[8]*	*[4]*			*[1]*	
	Oil						*[8]*	*[4]*				
	Electric resistive											
	Electric storage											
	Community							*[4]*				
Storage heating *inc. option with solar thermal*	Gas						*[8]*	*[4]*			*[1]*	
	Oil						*[8]*	*[4]*				
	Electric resistive											
	Electric storage											
	Community							*[4]*				
Hybrid heat pump *All options*	Gas						*[5]*	*[4]*				*[6]*
	Oil						*[5]*	*[4]*				*[6]*
	Electric resistive											*[6]*
	Electric storage											*[6]*
	Community						*[5]*	*[4]*				*[6]*

[1] 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); [2] Where heat battery required (space constrained homes), applied instead of a conventional hot water tank; [3] Applied when standard radiators are deemed to be insufficient (see later slides); [4] Small heat battery for domestic hot water is an option to provide on-demand hot water where a combi boiler is not available (or not used) to provide hot water in space constrained homes. This is therefore applied in space-constrained homes assumed not to have a hot water cylinder; [5] 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); [6] Applicable in on-gas hybrids only; [8] Based on BEIS NHM data (2014), 50% of gas boilers are combi boilers and 15% of oil boilers are combi boilers; each proportion of non-combi boilers is assumed to have an existing hot water tank present.

Costing low carbon heating – summary of additional costs [2/2]

- 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	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Hydrogen	Gas										*[1]*	
	Oil											
	Electric resistive											
	Electric storage											
	Community											
Low carbon heat networks	Gas			*[9]*					*[3]*		*[1]*	
	Oil			*[9]*					*[3]*			
	Electric resistive			*[9]*					*[3]*			
	Electric storage			*[9]*					*[3]*			
	Community			*[9]*					*[3]*			
Biofuel	Gas									*[7]*	*[1]*	
	Oil											
	Electric resistive											
	Electric storage											
	Community											

[1] 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] Applied when standard radiators are deemed to be insufficient (see later slides); [7] Cost is applied in the model but suitability assumptions do not allow biomass boilers in on-gas homes therefore this cost is not applied in practice; [9] Communal heating pipework and metering is costed implicitly as part of the deployment of low carbon heat networks.

Buffer tanks

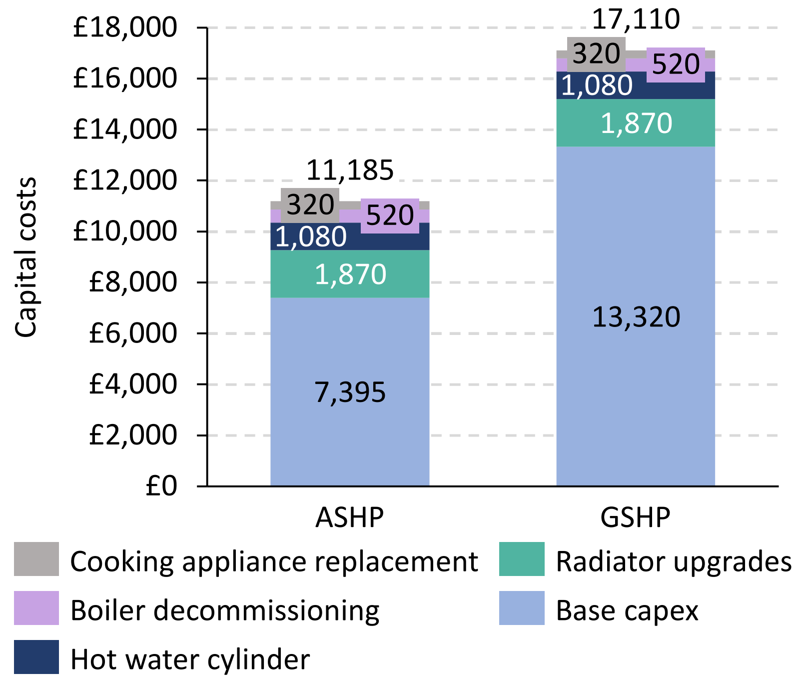
- In addition to the costs in the above table, buffer tanks are assumed to be required for heat pumps in 50% of cases, at a cost of £300 for mid-sized tank.
  - 50% assumption is based on mixed views from external stakeholders on when, and if, buffer tanks are required.
  - Costs are based on stakeholder feedback[1],[2].

[1] Panasonic Ampair
[2] Kensa

Heat pumps – summary of costs

- Heat pump sizes were costed and modelled based on each scenario's unique input assumptions; as such, the average heat pump size uptaken varies between scenarios (see Results).
- Additional costs applied for heat pumps vary substantially based on the type of dwelling:
  - Hot water cylinders are only required in homes where there is no existing cylinder i.e. primarily homes with a combi gas or oil boiler.
  - Heat batteries are only required in space constrained homes where the heat pump is meeting the hot water demand.
  - Buffer tanks are assumed to be required in 50% of homes (see previous slide).
  - Radiator upgrades may be needed to optimise flow temperature and heat pump efficiency (see slide).
- For ground-source heat pump groundworks, boreholes are assumed for urban homes, and trenches for rural homes, based on the rural/urban split in the UK[1].
  - Boreholes are roughly twice as costly as trenches[2].
- It is assumed that cost reductions of 20-30% can be achieved by 2030 and 30-40% can be achieved by 2050 depending on the scenario. 30-40% cost reductions are assumed to be achievable in ground-source heat pump ground works by 2030[3].

Illustrative capital costs in 2020 of ASHP and GSHP for a dwelling with an existing gas boiler and an annual 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	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
***AHSP/GSHP** inc. option with solar thermal*	**Gas**						*[8]*	*[2]*	*[3]*		*[1]*	
	Oil						*[8]*	*[2]*	*[3]*			
	Electric resistive								*[3]*			
	Electric storage								*[3]*			
	Community							*[2]*	*[3]*			

[1] Rural population 2014/15 (2020); [2] The Cost of Installing Heating Measures in Domestic Properties, Delta-EE for BEIS (2018). [3] Evidence sources included Potential cost reductions for air source heat pumps, DECC (2016); Energy Innovation Needs Assessment, Sub-theme report: Heating and cooling, consortium led by Vivid Economics (2019); and a survey conducted by the CCC with heat pump experts.

Heat pumps – efficiency and performance

Unsuitable

Suitable

		Specific heat demand (W/m²)						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		

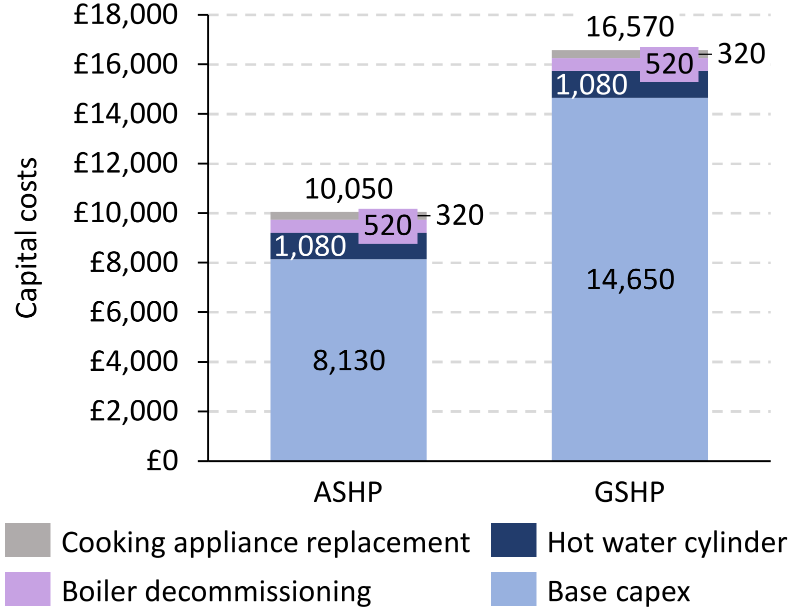
- The assumptions for heat pump efficiencies were designed to remain broadly in-line with those used for the 5th Carbon Budget.
  - Stakeholder engagement did not reveal any material new publicly available evidence which could be used to update efficiency assumptions.
  - It is acknowledged that the quality of existing evidence, including the MCS heat emitter guide and RHPP performance data, is limited.
  - Further improved evidence is required to refine efficiency assumptions in future.
- In-line with the 5th Carbon Budget, an air-source heat pump operating at a flow temperature of 50 °C is assumed to have a combined efficiency of 2.54. The equivalent value for a ground-source heat pump is 2.84. A 0.5 improvement in efficiency is assumed by 2030, in line with 5th Carbon Budget.
  - Separate efficiency values for space heating and hot water were derived from the combined efficiency assuming a space heating to hot water demand ratio of 3.5:1.
  - The MCS emitter guide was used to infer how the 5th Carbon Budget assumptions vary with flow temperature.
  - 5th Carbon Budget assumptions were based on two sets of field trials conducted by EST and DECC, in addition to results from monitoring of heat pumps under the RHPP scheme. These were retested with stakeholders for the 6th Carbon Budget.
- Radiator upgrades are required where standard radiators are deemed to be insufficient to meet peak heating demand (see slide).

RHPP: Renewable Heat Premium Payment; EST: Energy Savings Trust; DECC: Department of Energy & Climate Change

High temperature heat pumps – costs and assumptions

- High temperature heat pumps were defined as heat pumps operating at flow temperatures above 60°C.
- Individual configurations, both air-source and ground-source, were modelled.
- Compared to conventional heat pumps, it is assumed that high temperature heat pumps:
  - operate at lower efficiencies (leading to higher operating costs),
  - have higher capital costs,
  - do not require radiator upgrades in most cases, and
  - are suitable in homes with a higher heat loss rate.
- With the exception of radiators, additional costs applied for high temperature heat pumps are similar to those applied for conventional heat pumps.
- Evidence received from stakeholders on the performance of high temperature heat pumps indicates that even at very cold external temperatures, COPs remain above 1.5 (see Appendix). This means the technology offers benefits relative to conventional electric heating.

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



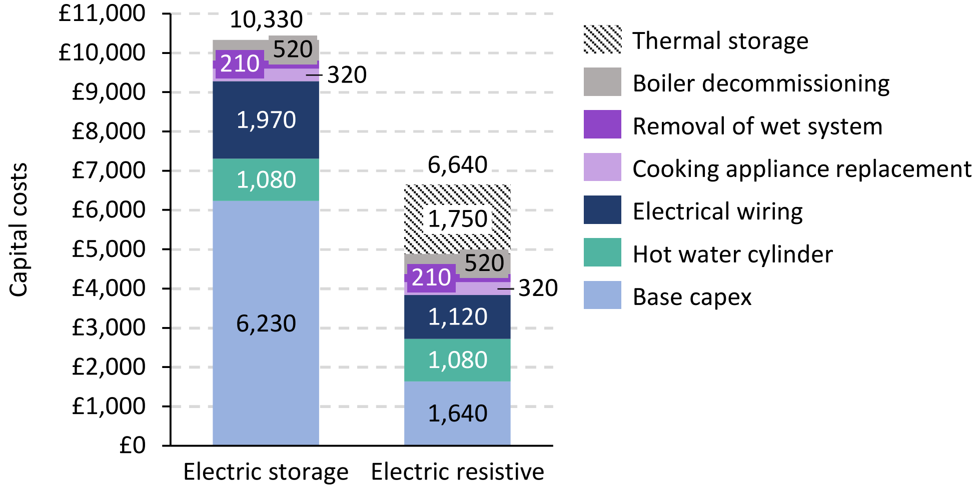
Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
AHSP/GSHP ***inc. option with solar thermal***	**Gas**						*[8]*	*[2]*	*[3]*		*[1]*	
	Oil						*[8]*	*[2]*	*[3]*			
	Electric resistive								*[3]*			
	Electric storage								*[3]*			
	Community							*[2]*	*[3]*			

Electric heating – costs and assumptions

- Two types of direct electric heating were modelled: electric resistive based on modern panel heaters and electric storage based on storage heaters.
- Electric resistive technologies were only included if combined with thermal storage or solar thermal to allow some shifting of demand, and hence limit network impacts.
- Additional costs applied vary depending on the home:
  - Installation of wiring is required where the existing system is not conventional electric heating e.g. boiler.
  - Homes with existing electric heating are assumed to have hot water storage, so would not incur the cost of a hot water cylinder (or a heat battery for a space constrained home).

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



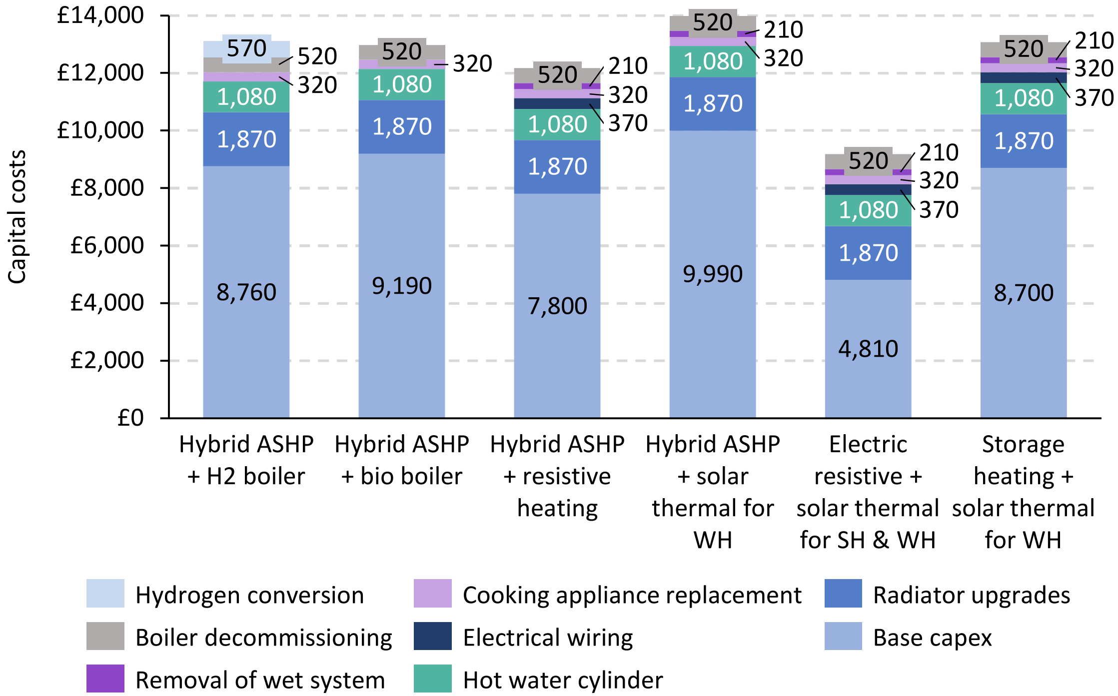
Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Electric resistive ***inc. option with solar thermal***	**Gas**						*[8]*	*[4]*			*[1]*	
	Oil						*[8]*	*[4]*				
	Electric resistive											
	Electric storage											
	Community							*[4]*				
Storage heating ***inc. option with solar thermal***	**Gas**						*[8]*	*[4]*			*[1]*	
	Oil						*[8]*	*[4]*				
	Electric resistive											
	Electric storage											
	Community							*[4]*				

Hybrid systems – costs

- Several hybrid configurations were modelled, including:
  - ASHP with gas, hydrogen or biofuel boiler.
  - ASHP with electric resistive heating.
  - GSHP with gas, hydrogen or biofuel boiler.
  - GSHP with electric resistive heating.
  - ASHP with solar thermal.
- Additional costs applied vary based on the home and the hybrid system e.g.:
  - Hybrids with an H_2 boiler incur a hydrogen pipework and boiler conversion cost.
  - Hybrids with electric resistive heating incur an electrical wiring cost (where the existing system is not electric resistive.

Illustrative example of capital costs of several hybrid systems for a dwelling with an existing gas boiler and an annual 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	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Hybrid heat pump ***All options***	**Gas**						*[5]*	*[4]*				*[6]*
	Oil						*[5]*	*[4]*				*[6]*
	Electric resistive											*[6]*
	Electric storage											*[6]*
	Community						*[5]*	*[4]*				*[6]*

Hybrid heat pumps – operation and efficiencies

Operation and efficiency

- Based on work by Imperial College London,[1] the heat pump component is assumed to meet 80% of the space heating demand, with the additional heating system meeting 20% i.e. only peak heating periods. This assumption remained unchanged from the Net Zero work but is subject to significant uncertainty; therefore a sensitivity where the additional system meets 50% of the space heating demand was also modelled.
- Two options for hot water heating were modelled (assumptions in-line with the Net Zero work):
  - 100% of the hot water demand met by the boiler. This is applicable in homes which do not have a water storage solution, such as a cylinder or a heat battery.
  - 80% of the hot water demand met by the heat pump and 20% met by the additional heating system. This is applicable in homes where a hot water cylinder or heat battery is installed.
- Efficiencies were set to those of the individual components:
  - Hy-ready boilers are assumed to be 80% efficient in both gas and hydrogen mode, based on BEIS feedback.
  - Biofuel boilers for off gas homes are assumed to be 84% efficient. This is in-line with the oil boiler efficiency assumed in the 5th Carbon Budget.
  - Conventional electric heating (electric resistive heating and storage heating) is assumed to be 100% efficient, in-line with 5th Carbon Budget assumptions.

[1] CCC calculations based on Imperial College (2018) Analysis of alternative heat decarbonisation pathways (Hybrid heat pump 10 Mt scenario).

Hybrid heat pumps – biofuels

- The modelling aimed to minimise the use of biofuels for the decarbonisation of residential buildings, on the basis of the *best use of biomass* analysis undertaken by the CCC[1].
- Where biofuel boilers are used, they are only included as part of a hybrid system with a heat pump to meet demand on the coldest days in the hardest to heat homes not connected to the gas grid.
- The modelling of biofuels is necessarily simplified and is intended to incorporate broadly representative cost and efficiency assumptions across biofuel types.
  - Biofuel costs were modelled based on BioLPG, but a range of bio-derived liquid fuels would be expected to be used in reality.
  - Whilst this work does not imply a preference for any individual biofuel, it is important that the biofuels used can meet the relevant sustainability criteria, and that air quality impacts are considered. Certain fuels will be better than suited than others to providing peaking demand in a hybrid heat pump configuration.

Costs

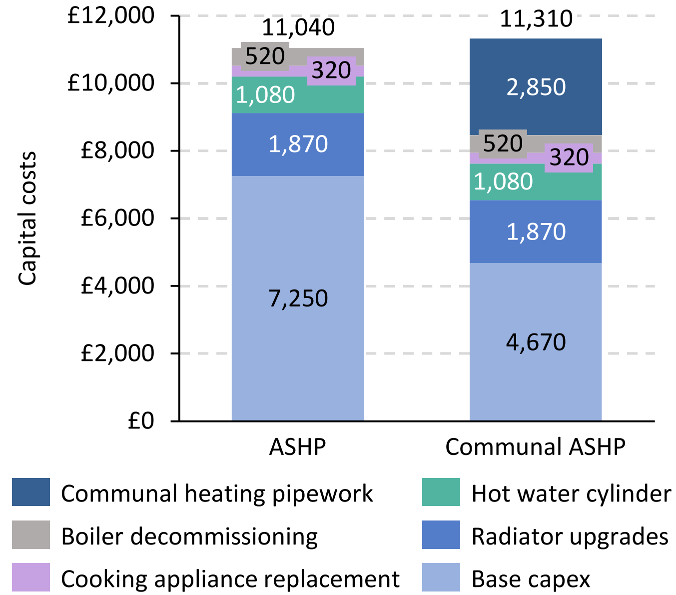
- The capital cost of a biofuel boiler is assumed to be equal to that of an oil boiler, with the latter sourced from work by Delta-EE[2].
- An additional £65 is added to operating costs for biofuel systems, to account for delivery and storage of gas[3].
- BioLPG fuel costs, based on CCC work, are used as fuel costs for biofuel systems.
- The simplified costing approach may underestimate the costs associated with some forms of bio systems, such as those where additional costs are incurred for removal of existing tanks.
  - Further details on configurations are set out in separate research[4].

[1] Biomass in a low-carbon economy, CCC (2018), building on Bioenergy Review, CCC (2011); [2] The Cost of Installing Heating Measures in Domestic Properties, Delta-EE for BEIS (2018); [3] Household Quotes (2020); [4] Evidence Gathering for Off-Gas Grid Bioliquid Heating Options, NNFCC for BEIS (2019).

Communal heat pumps

- A communal heat pump was modelled[1] as one where a large centralised heat pump supplies an ambient loop at 25 °C, and smaller individual heat pumps in dwellings boost the temperature to for space heating (as necessary) and for hot water (60°C).
  - A typical configuration is assumed to supply ten dwellings (flats or terraced houses[2][3]).
- The costs of a communal heat pump were derived from the costs of conventional heat pumps, with stakeholder feedback indicating the assumptions are at the lower bound of the suggested range.
- Further to the additional costs which may be incurred when installing conventional heat pumps, communal systems also incur pipework costs, which vary significantly depending on the house type:
  - Flats incur a cost of £2,850 – as illustrated in the graph – compared to £6,280 for terraced homes[4].
  - A system deployed in flats requires a building pump, a lateral pipe, heat riser pipes for each floor and service pipes for each flat.
  - A system deployed in terraced houses requires a shared external pipeline and service pipes for each home.
- Assumptions for communal configurations, particularly for GSHPs, are subject to high uncertainty due to limited publicly available or stakeholder evidence on the topic.

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



Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Communal ASHP/GSHP	Gas						[8]	[2]	[3]		[1]	
	Oil						[8]	[2]	[3]			
	Electric resistive								[3]			
	Electric storage								[3]			
	Community							[2]	[3]			

[1] Both ASHP and GSHP configurations were modelled; [2] MHCLG Internal analysis, English Housing Survey, 2018 dwelling sample; [3] Ambient loop design for communal ASHP from Daikin, (2020); [4] EE modelling for private sector client (2018).

Low carbon heat networks (LCHNs)

- The cost of low carbon heat networks was taken from Element Energy's analysis for the 5th Carbon Budget[1], which was updated with new assumptions:
  - Supply mixes were updated to make them net zero compatible. In the Headwinds scenario (high hydrogen), the source of heat for the heat networks is a mix of heat pumps (including waste heat-source and water-source) and gas transitioning to hydrogen for peaking.
  - In all other scenarios, additional thermal storage capacity is included (to cover peaking demand, otherwise provided by gas) and a switch from biomass and energy from waste, to waste heat-source and water-source heat pumps is accounted for; therefore, all heat demand is met by heat pumps. See Appendix for more information on heating sources.
  - The fuel demands associated with LCHNs evolve over time with the most cost-effective sources being used in the nearer term (largely the high and low temperature industrial waste heat sources which require no or little electricity in heat pumps to boost the heat source to the required temperature), with an increased role for water-source heat pumps over time as waste heat sources are depleted and district heat is taken up in other areas. Whilst only LCHNs are modelled, in reality it is expected that gas CHP systems would be used initially, before being replaced by LCHNs. This is discussed further in CCC (2020) the Sixth Carbon Budget Methodology report, box 3.4.
  - Costs and carbon intensities for LCHN fuel were derived from the electricity, gas and hydrogen fuel costs used in the modelling. For LCHN electricity, a blended cost was derived from the 'highly flexible space heating' and the 'water heating with storage' costs (see slide)[2], assuming an 82/18 split between space heating and hot water demand, based on baseline archetype heating demand.
  - The network costs were adjusted to be annualised over a 40-year period in line with a lower bound lifetime assessment for networks, with a 7.5% cost of capital assumed for all capex.
- Using adjusted outputs from Element Energy's analysis for the 5th Carbon Budget, the cost of heat to the consumer was derived. This includes the cost of the heat network energy centre, the heat network infrastructure, connection to individual homes via in-building heat interface units (HIU) and heat meter, and fuel costs.
- As with other technologies, LCHN are subject to additional costs such as boiler decommissioning.

Additional costs applied:

New system	Existing system	Removal of wet system	Installation of wet system	Communal heating pipework	Storage heating electrical wiring	Resistive heating electrical wiring	Hot water tank	Heat battery	Radiator upgrades	Decommission boiler	Replace cooking appliances	Hydrogen pipework and conversion
Low carbon heat networks	Gas			*[9]*					*[3]*		*[1]*	
	Oil			*[9]*					*[3]*			
	Electric resistive			*[9]*					*[3]*			
	Electric storage			*[9]*					*[3]*			
	Community			*[9]*					*[3]*			

[1] *District heating and local approaches to heat decarbonisation,* Element Energy for the CCC (2015);
[2] Commercial hydrogen costs and carbon intensities were also used in the Headwinds scenario.

Hydrogen boilers

Cost and efficiency

- Hydrogen boilers and hy-ready gas boilers were treated similarly in the modelling.
- The cost of such boilers was assumed to be £100 more than that for a conventional gas boiler, based on research for BEIS[1] and input from external stakeholders.
- The efficiency of a boiler running on hydrogen was assumed to be 80%, based on feedback from BEIS.
  - This is lower than the 87% efficiency assumed for gas boilers.
  - The lower efficiency is due to the different thermodynamic properties of hydrogen compared to natural gas, which lead to lower efficiency when considering the Higher Heating Value (HHV).

Home conversions

- The pipework costs associated with converting a home to a hy-ready or hydrogen boiler are assumed to be £500.
  - This is in-line with 5th Carbon Budget assumptions, and is based on research for BEIS[1].
- There is emerging evidence from Hy4heat which suggests there is no need for any pipework changes in the home when switching to a hy-ready or hydrogen boiler.

Availability date

- It is assumed that hy-ready boilers are mandated from 2026. This is based on consultation with industry and is considered a relatively conservative date, chosen to ensure that a range of manufacturers are able to develop the technology.
- There is optionality around the date for mandating hy-ready boilers, with a potential for earlier delivery.

[1] Hydrogen supply chain evidence base, Element Energy for BEIS (2018)

Additional modelled options

Solar thermal

- Two configurations of solar thermal were modelled:
  1. Based on research for BEIS (formerly DECC)[1], solar thermal provides 60% of the hot water demand only. Illustrative costs for systems with this configuration are shown in the graph.
  2. Based on stakeholder evidence[2], solar thermal provides 60% of the hot water demand and 50% of the space heating demand.
- Solar thermal was modelled with air source heat pumps and direct electric heating technologies.
- A 20% cost reduction in solar thermal capex by 2030 was assumed[2].

Thermal storage options

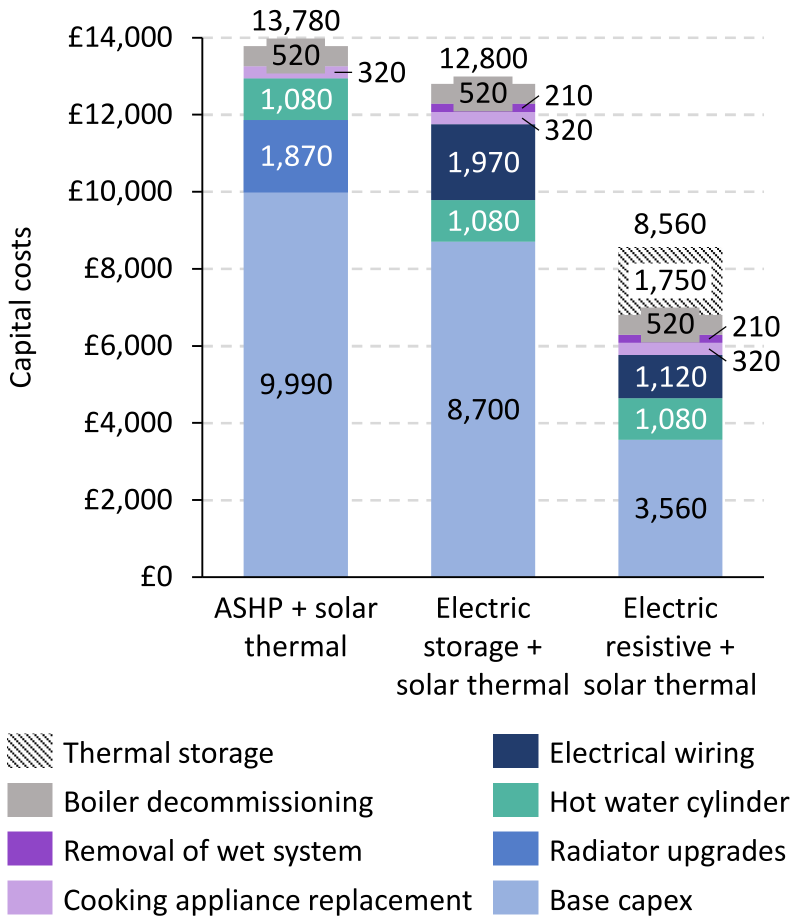
Small heat batteries

- Small heat batteries (6 kWh) were modelled as alternative hot water storage solutions in space constrained homes, and were applied in place of hot water cylinders in applicable homes/technologies.
- The batteries were assumed to achieve cost parity with a hot water cylinder by 2030 (cost of £1,750 in 2020, £1,080 in 2030).

Thermal storage for space heating

- For heat pumps and direct electric heating, the option of shifting some of the space heating demand to off-peak times was modelled by applying the cost of a heat battery (£1,750). This would be in addition to a hot water cylinder (or a heat battery in space constrained homes) in cases where hot water storage is required.

Illustrative example of capital costs of heating systems with additional solar thermal (configuration 1) for a dwelling with an existing gas boiler and an annual heating demand of 11,000 kWh



Fuel costs and emissions

- For the purposes of this modelling, the CCC provided Long Run Variable Costs (LRVCs) and carbon emissions for natural gas, oil, solid fuel, bioLPG, biomass, electricity and hydrogen.
- The LRVCs of electricity were differentiated into 5 categories by end use and level of flexibility, 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 times.

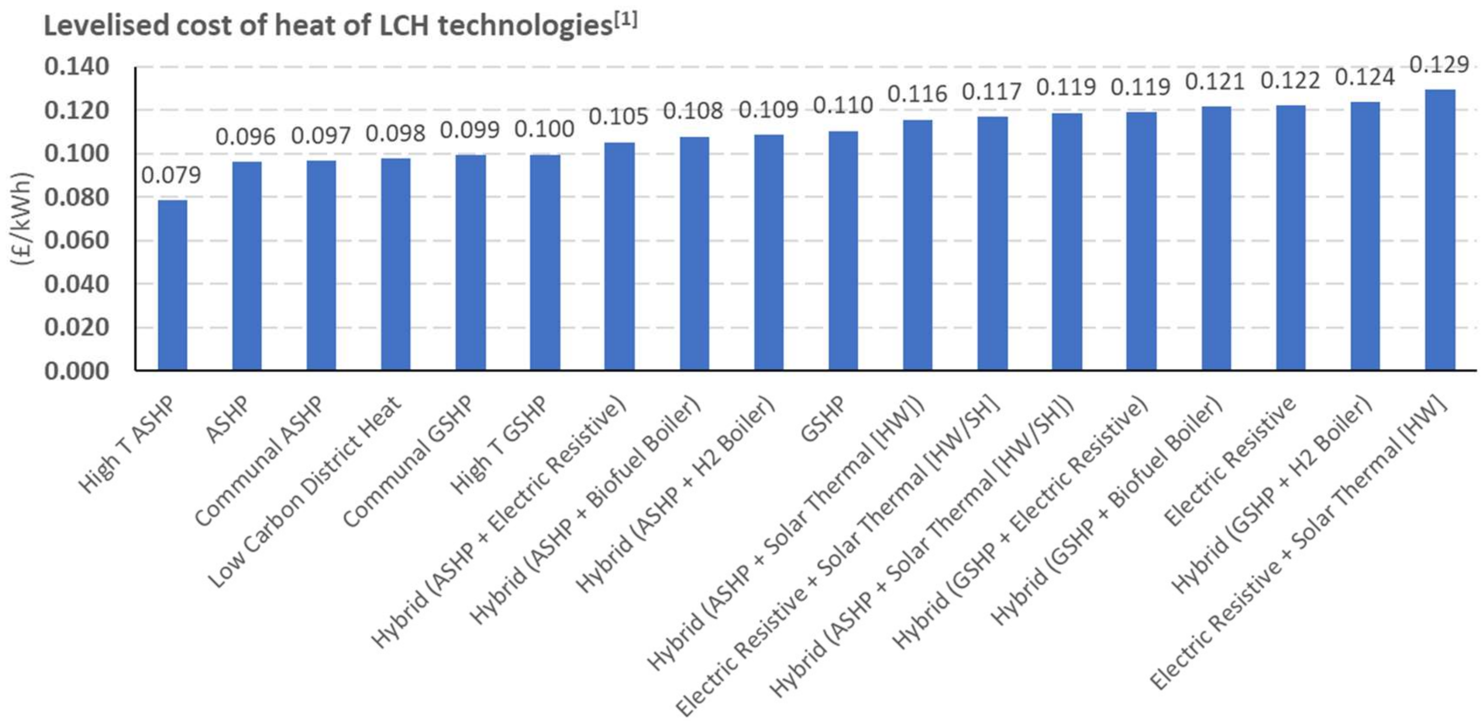
Space heating

- **Space heating electricity – inflexible**: assumes that homes that cannot pre-heat (i.e. bring electricity demand for heating earlier), and have neither thermal storage nor a hydrogen/biofuel hybrid, cannot move energy demand away from peak time periods, and thus pay higher electricity prices on average. Quantitatively, inflexible costs are a blended cost that reflects the costs of paying peak prices 40% of the time and average costs 60% of the time.
- **Space heating electricity – flexible**: assumes a proportion of post-1952 existing homes pre-heat up to four hours outside of peak hours. The same cost is used for homes with hydrogen/biofuel hybrid heat regardless of whether they can pre-heat. None of the homes subject to flexible costs have thermal storage. These flexible electricity costs include a discount of 10% on the average costs, due to being able to shift demand outside of peak periods.
- **Space heating electricity – highly flexible**: Homes with storage heaters or thermal storage (regardless of whether they can pre-heat) are assumed to be fully flexible, meaning that demand can be moved to match the moment when renewables are generating (and prices are lower). These flexible electricity costs include a discount of 15% on the Balanced costs, due to being able to shift demand outside of peak periods.

Hot water

- **Hot water electricity – without storage**: assumes that end-users cannot move away from peak time and thus pay higher electricity prices on average. Assumes that end-users thus pay peak costs 80% of the time and baseline prices 20% of the time. The electricity costs reflect a blend of these two prices.
- **Hot water electricity – with storage**: assumes that the consumption of hot water occurs up to 4 hours outside of peak hours.

Levelised cost of heating (LCOH) of low carbon heating technologies



- The graph shows the average LCOH of the modelled low carbon heating technologies across scenarios.
  - With the exception of one configuration of high temperature air-source heat pumps, the differences between many of the technology groups are only marginal. This means minor changes in assumptions can lead to significantly different technology mixes (see Sensitivities section).
  - Generally, air-source heat pumps (ASHPs) offer a lower LCOH than ground-source heat pumps (GSHPs), particularly for hybrid systems, leading to modelling uptake of ASHPs tending to be higher than that of GSHPs. Nevertheless GSHPs can offer advantages in terms of reduced noise levels, and may be more widely applicable in some types of home including where less obtrusive solutions are required, where there are internal space constraints, or where there is a greater risk of corrosion from the air such as in coastal areas.

[1] Only the most cost-effective configuration of each technology group is shown in the graph

Summary of additional measures and numbers e.g. radiators

Legend: red = Unsuitable; green = Suitable

		Specific heat demand (W/m²)						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	Suitable	Suitable	Suitable	Unsuitable	Unsuitable	Unsuitable	3.6	4.1	2.1	2.6	3.8	4.2	2.5	3.0
40	4.3	Suitable	Suitable	Suitable	Suitable	Unsuitable	Unsuitable	3.4	3.9			3.6	4.1		
45	3.1	Suitable	Suitable	Suitable	Suitable	Suitable	Unsuitable	3.0	3.5			3.2	3.7		
50	2.4	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	2.7	3.2			3.0	3.5		
55	1.9	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	2.4	2.9			2.7	3.2		
60	1.6	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	2.1	2.6			2.5	3.0		

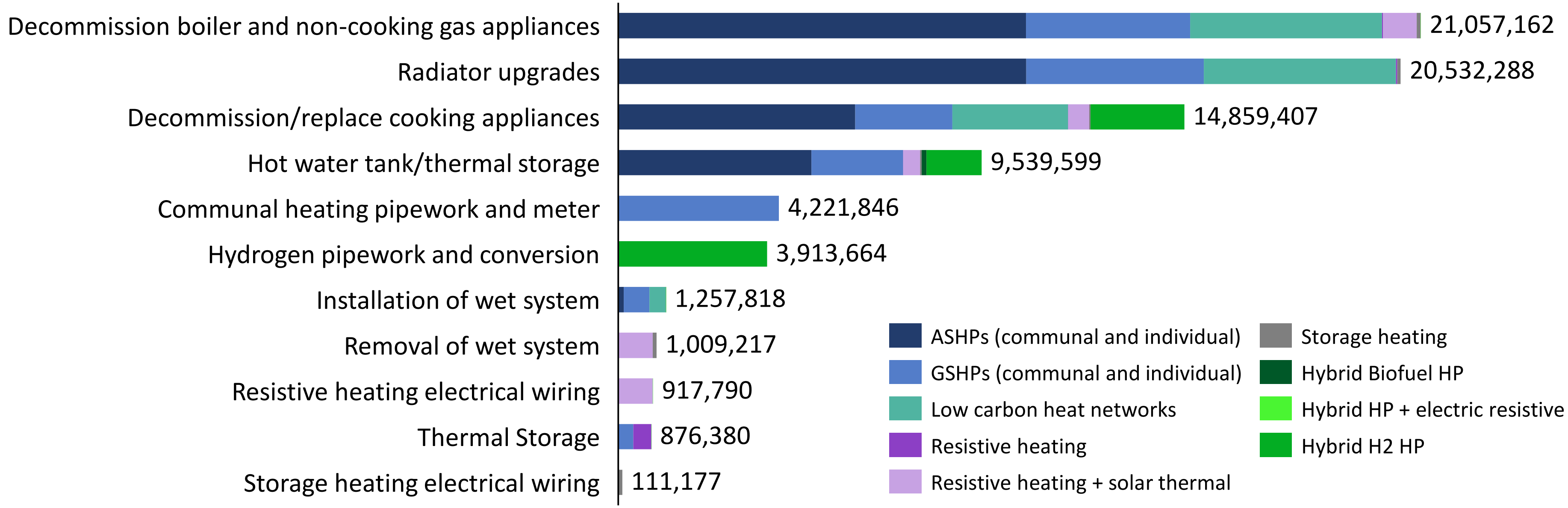
Radiator sizing

- The model determines if standard radiators are sufficient or if radiator upgrades are required, based on the flow temperature of the system.
- For pure heat pumps and hybrids with solar thermal, the flow temperature of the system was assigned by the model by choosing the lowest flow temperature suitable to meet the specific heat demand, according to the above table.
  - The suitability decision is based on average floor area and number of rooms for each archetype.
- An oversize factor was specified for each flow temperature (see table above). This is defined as 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 assumed to be required (and the relevant additional cost applied) in cases when the baseline heat demand multiplied by 1.3[2] was less than the new heating demand – after installing energy efficiency – multiplied by the respective oversize factor (see table above).
- The resulting weighted average space heat flow temperature for non-hybrid ASHPs in the Balanced Pathway was approximately 41° C (with a 60° C temperature assumed for hot water demand). The space heat flow temperature for hybrid heat pumps would be expected to be higher (given they do not receive radiator upgrades), increasing the overall weighted average slightly for the Balanced Pathway.

[1] 60° C for hot water demand not applicable in the Widespread Engagement scenario, see slide. [2] A typical oversize factor of 1.3 is assumed for standard radiators, in line with 5th Carbon Budget assumptions. This is also broadly in line with recent evidence, see BEIS (2021) Domestic Heat Distribution Systems Evidence Gathering.

Summary of additional measures [1/2]

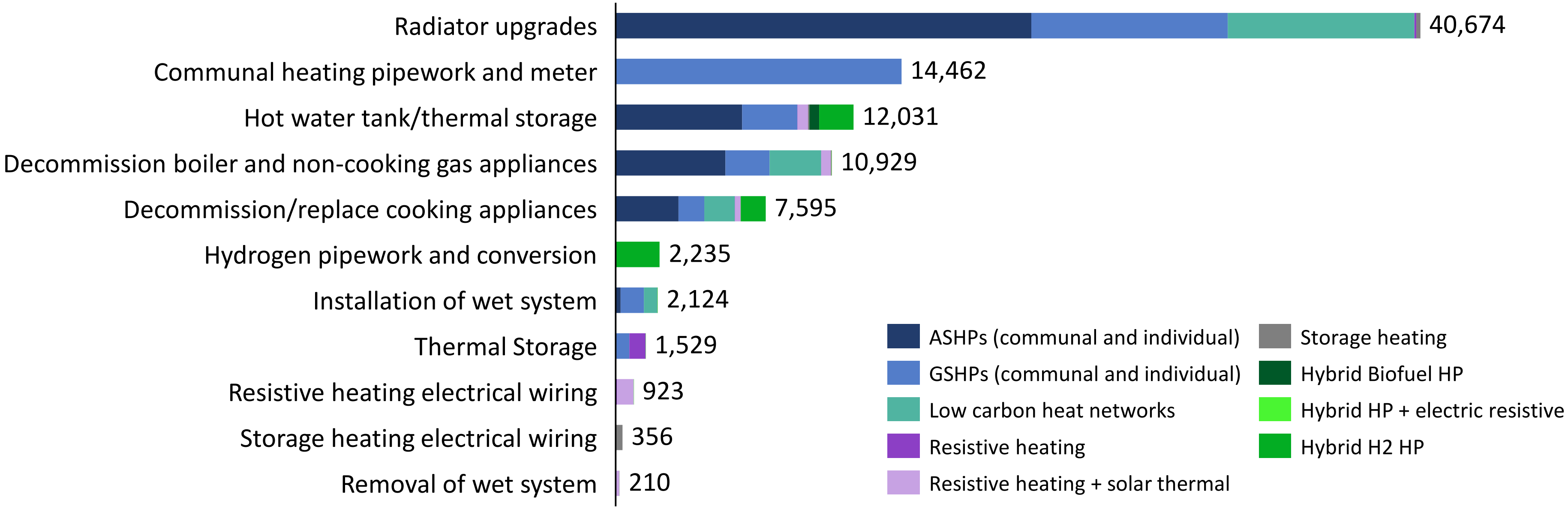
Unit count of additional measures in the Balanced Pathway, breakdown by measure and low carbon heating system



- In the Balanced Pathway, many homes will require the decommissioning of boilers, non-cooking gas appliances, and cooking appliances.
- Additionally, based on conservative assumptions, the vast majority of those moving to low temperature heating systems are assumed to receive radiator upgrades. This assumption is conservative on the basis that it aims to facilitate the operation of heat pumps at the lowest possible flow temperatures and highest efficiencies. It is also dependent of the level of insulation and comfort levels acceptable per household. Finally, it assumes radiator replacements remain the most cost-effective route to increasing heat transfer. It is acknowledged other innovative solutions, such as fan-assisted radiators, could contribute.
- Apart from hot water tanks for most technologies, specific technologies will require communal heating pipework and metering or hydrogen pipework and conversions, among other minor measures.

Summary of additional measures [2/2]

Additional measure capex (£m) in the Balanced Pathway, breakdown by measure and low carbon heating system



- In contrast to the unit numbers presented on the previous slide, the above graph shows a clear depiction that radiator upgrades, though not the most taken up additional measure, incur the most capital cost across the Balanced Pathway scenario as presented in these slides.
- The second most significant cost is for heating pipework and metering for communal heat pump systems.
- Apart from these, the remaining costs are largely associated with hot water tanks and the decommissioning of boilers, cooking appliances, and non-cooking gas appliances; this is applicable, where relevant by building archetype, across several different technologies.
- This modelling is expected to represent an overestimate of additional measure capex, as it assumes these measures will be due for replacement at the same point as the wider heating system. In reality, items such as radiators are expected to have much longer lifetimes and are only expected to be installed once in the trajectory to 2050. For the purposes of the CCC's published data book and reporting, an adjustment to the above investment costs was made for the Balanced Pathway to remove the impact of these replacements.

Contents

Summary of factors affecting viability of decarbonisation options

Factor	Effect on viability	Technologies affected
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 boilers
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 terraced houses and flats.	• Communal ASHP • Communal GSHP
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
Internal space constraints	• Heating systems that require large cylinders for hot water will be unsuitable in houses where space is limited. Such houses may be able to install systems which use less bulky heat batteries for thermal storage.	• Heat pumps and hybrid heat pumps (except communal heat pumps with heat batteries for hot water storage) • Systems with thermal storage for hot water and/or space heating
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 • Technologies with solar thermal

- There are other factors which influence suitability but which were not modelled in this work due to lack of evidence and to manage complexity. These include external space constraints, geological constraints and location (particularly constraints associated with exposed locations).

Technical feasibility of renewable heating technologies in space constrained homes

- In the model, ‘space constrained’ is defined by the internal space availability in the building.
- ‘Space constrained’ homes are assumed to be suitable for some technologies, namely resistive and storage heating, low carbon heat networks and communal heat pumps. However, this is only valid when a heat battery, rather than a hot water cylinder, is used for thermal storage[1].
- Heat pumps and hybrid heat pumps are generally deemed more challenging for space constrained homes, and are therefore assumed to be suitable in only a fraction of space constrained homes.
- Ground-source heat pumps are modelled as having higher suitability in space constrained homes relative to air-source heat pumps. This reflects feedback from assumptions testing, and is intended to reflect greater potential for configurations where key components are positioned outside, although it should be acknowledged that monobloc air-source heat pumps are also a viable solution for homes with internal space constraints.
- External space availability is also a constraining factor. This was accounted for by:
  - Assuming that in listed homes, heat pumps are not suitable in flats and have some limited suitability for other listed archetypes.
  - Assuming a split of boreholes and horizontal ground loops to reflect the space constraints applying to ground source heat pump ground loops.
- It has not been possible in this modelling to further refine the assessment of limitations to deployment due to external space constraints, access constraints and geological constraints, but these could be valuable areas for further work.

[1] In reality, Point of Use hot water is an alternative solution to a heat battery for hot water storage in space constrained homes.

Assumptions for heritage homes [1/2]

- There are a wide range of buildings that can face additional challenges in decarbonising, including those formally recognised as having some form of heritage value and traditional buildings more widely – generally considered to be those built prior to 1919.
- Listed homes and homes in conservation areas (estimated to be around 540,000 homes in the UK[1]) can be subject to more onerous planning restrictions, and traditional buildings more broadly (estimated to be around 25% of the UK housing stock) can require more costly and bespoke solutions which enable the character of the property to be retained and the fabric of the building to be protected.
- There are a range of valuable resources which can help inform retrofit approaches for these homes including the STBA's responsible retrofit guidance wheel, as well as the PAS 2035 framework and wider body of work on unintended consequences on retrofit.
- For the purposes of modelling, there remains limited evidence in the public domain on the cost uplifts which can be associated with retrofitting these homes. The accompanying research undertaken by UCL sought to consolidate the evidence base here by gathering further views from retrofit professionals and incorporating cost data on retrofits from Bath and North East Somerset Council's 'Retrofitting Estimate Spreadsheet'[2]
- As with the previous modelling for Net Zero, it has not been possible at this time to incorporate age of home into the building stock model used. As such, the modelling of cost uplifts remains focused on homes with heritage classifications, rather than the broader pre-1919 stock. This is expected to lead to an underestimate of the number of homes which face additional costs from decarbonising. This is an area that would benefit from further development in future work.

STBA: Sustainable Traditional Buildings Alliance; [1] Historic England, scaled up to the UK and adjusted to include conservation area homes;
[2] Analysis work to refine fabric energy efficiency assumptions for use in developing the 6th Carbon Budget, UCL for the CCC (2020).

Assumptions for heritage homes [2/2]

- Several updates to assumptions have been made relative to the Net Zero analysis:
  - Identical suitability criteria have been applied to all homes which are listed or are in a conservation area. This is a simplification and is expected to lead to a cautious assessment of suitability for some homes, whilst also underestimating the number of pre-1919 homes in the wider stock that may face additional costs.
  - The additional cost evidence for energy efficiency measures has led to a 183% average cost uplift being assumed, compared with 57% for Net Zero[1]. It is acknowledged the evidence remains extremely limited and the cost uplifts remain highly uncertain.
  - It has been assumed that 50% of detached, semi-detached and terraced homes with a heritage classification are suitable for air-source heat pumps. For ground-source heat pumps, the suitability is set at 75% based on external stakeholder feedback suggesting that ground-source heat pumps have higher suitability compared to air-source heat pumps.
  - A 50% uplift in the cost of heat emitters was assumed for these homes, based on external stakeholder feedback. This assumption was unchanged from Net Zero due to lack of new evidence. Evidence from the National Trust suggests that there may be broader cost uplifts associated with installing low carbon heating in these homes (separate to those related to higher heat demands and driven by the need for adaptations to distribution systems, electrical supplies, wiring or building/fabric layout), but further research would be needed to quantify this.
- The assumptions applied to heritage homes in this work remain a first and early step in understanding the additional costs which could be applicable and are not intended as recommendations or detailed assessments of actual decarbonisation pathways needed for this segment of the housing stock. The modelling instead seeks to provide indicative illustrations of the higher costs and challenges which could be faced by some homes when decarbonising.

[1] Percentages reflect the uplift additive to the baseline cost (such that for Net Zero the heritage costs were the baseline costs plus a further 57%), taken as a simple average across the three energy efficiency packages. N.B. A true like-for-like comparison cannot be made as the uplift factors are influenced by the measures included in the packages which differ between Net Zero and the Sixth Carbon Budget. [2] Base Cost Model, BATHNES (2013).

Suitability of heat pumps

- The factors influencing the suitability of heat pumps (and the assumptions used for each) remained unchanged from Net Zero due to limited new evidence. As summarised in previous slides, the main factors incorporated into the modelling are:
  - Fuse limit:
    - In the modelling, the fuse limit – set at 100 Amperes – rarely prevents a home from installing a heat pump. There is a peak time buffer accounted for in the modelling (between 24-29 Amperes dependent on dwelling type) such that the heat pump demand must not exceed the remaining fuse capacity (i.e. 71-76 Amperes).
    - BEIS evidence[1] suggests that for high temperature heat pumps, the biggest barrier to adoption is achieving a sufficiently high COP such that demand does not exceed the fuse limit. Notwithstanding, the fuse limit constraint does not prevent a significant number of homes from installing a high temperature heat pump in the modelling.
    - It should be noted that fuse limit constraints will be impacted by home electric-vehicle charging, which is out of scope for this modelling.
  - Peak heat demand (W/m^2):
    - Homes with a peak heat demand exceeding 150 W/m^2 are assumed unsuitable for heat pumps. By comparison, BEIS research[1] suggests that conventional heat pumps are suitable in all homes with a heat loss up to 100 W/m^2, and high temperature heat pumps are suitable up to heat loss rates of 150 W/m^2.
    - In the modelling, this constraint does not prevent any home from installing a heat pump. This is in-line with stakeholder feedback indicating that heat demand is not usually a constraint to installing a heat pump. Further, the 150 W/m^2 threshold used is rarely seen in properties (with the heat demands of homes in the modelling having been calibrated using real-life data from NEED).
  - Space constraints (discussed in previous slides).
  - Heritage status (discussed in previous slides).
- Due to the fact that neither fuse limit nor heat demand limit pose a significant constraint to heat pump uptake in the modelling, even less insulated homes – such as those with uninsulated solid walls – typically receive heat pumps, although those would typically cost more to run. It should also be noted that many of the homes with the highest heating demand connect to low carbon heat networks, and this includes a substantial portion of less insulated homes (28% of homes with uninsulated solid walls connect to low carbon heat networks in the Balanced Pathway scenario).

COP: Coefficient of Performance

[1] Technical Feasibility of Electric Heating in Rural Off-Gas Grid Dwellings, Delta-EE for BEIS (2018)

Overview of suitability criteria used in the model [1/2]

Legend
Suitable for all dwellings
Suitable for some dwellings
Unsuitable for all dwellings

Heating system	W/m2 constraint	Fuse limit	Dwelling type				Space constraint (Total floor area divided by number of habitable rooms)			Gas grid		Heat density	Heritage status			
			Detached	Semi-detached	Terrace	Flat	<16m² (BP / HW / WI)	<16m² (EP / TW)	>16m²	Connected	Not connected	<30kWh/m²	Conservation area	Grade I	Grade II*	Grade II
ASHP/High T ASHP - hot water cylinder serving DHW only or thermal store to allow off-peak space heating	Up to 150 W/m² peak demand	Fuse limit											50% of Detached, Semi-detached and Terraces suitable, no Flats suitable			
ASHP/High T ASHP - small heat battery serving DHW only							50% of dwellings suitable	75% of dwellings suitable								
GSHP/High T GSHP - hot water cylinder serving DHW only or thermal store to allow off-peak space heating													75% of Detached, Semi-detached and Terraces suitable			
GSHP/High T GSHP - small heat battery serving DHW only							75% of dwellings suitable; all systems to use boreholes (not trenches)	All systems to use boreholes (not trenches)								
Hybrid ASHP (on-gas, with gas/hydrogen boiler) - no hot water cylinder							50% of dwellings suitable	75% of dwellings suitable					50% of Detached, Semi-detached and Terraces suitable, no Flats suitable			
Hybrid ASHP (on-gas, with gas/hydrogen boiler) - hot water cylinder																
Hybrid ASHP (off-gas, with biofuel boiler) - no hot water cylinder							50% of dwellings suitable	75% of dwellings suitable								
Hybrid ASHP (off-gas, with biofuel boiler) - hot water cylinder																
Hybrid ASHP with resistive heating							Small heat battery (for DHW)	Small heat battery (for DHW)								
Hybrid GSHP (on-gas, with gas/hydrogen boiler) - no hot water cylinder							75% of dwellings suitable						75% of Detached, Semi-detached and Terraces suitable			
Hybrid GSHP (on-gas, with gas/hydrogen boiler) - hot water cylinder																
Hybrid GSHP (off-gas, with biofuel boiler) - no hot water cylinder							75% of dwellings suitable									
Hybrid GSHP (off-gas, with biofuel boiler) - hot water cylinder																
Hybrid GSHP with resistive heating							Small heat battery (for DHW)	Small heat battery (for DHW)								

BP: Balanced Pathway; HW: Headwinds; WI: Widespread Innovation; EP: Widespread Engagement; TW: Tailwinds

[1] Heat supply temperature constraint applicable to low temperature emitters; [2] applicable to all electric heating technologies.

Overview of suitability criteria used in the model [1/2]

- Suitable for all dwellings
- Suitable for some dwellings
- Unsuitable for all dwellings

Heating system	W/m2 constraint	Fuse limit	Dwelling type				Space constraint (Total floor area divided by number of habitable rooms)			Gas grid		Heat density	Heritage status			
			Detached	Semi-detached	Terrace	Flat	<16m^2 (BP / HW / WI)	<16m^2 (EP / TW)	>16m^2	Connected	Not connected	<30kWh/m^2	Conservation area	Grade I	Grade II*	Grade II
Communal ASHP - hot water cylinder serving DHW only or thermal store to allow off-peak space heating	Up to 150 W/m^2 peak demand	Fuse limit														
Communal ASHP - small heat battery serving DHW only	Up to 150 W/m^2 peak demand	Fuse limit														
Communal GSHP - hot water cylinder serving DHW only or thermal store to allow off-peak space heating	Up to 150 W/m^2 peak demand	Fuse limit														
Communal GSHP - small heat battery serving DHW only	Up to 150 W/m^2 peak demand	Fuse limit														
Electric resistive heating (including with solar thermal) - thermal store to allow off-peak space heating		Fuse limit														
Electric resistive heating (including with solar thermal)		Fuse limit					Small heat battery (for DHW)	Small heat battery (for DHW)								
Storage heating		Fuse limit														
Heat network																
Hydrogen boiler																
Solar thermal													50% of dwellings suitable		50% of dwellings suitable	50% of dwellings suitable

BP: Balanced Pathway; HW: Headwinds; WI: Widespread Innovation; EP: Widespread Engagement; TW: Tailwinds

[1] Heat supply temperature constraint applicable to low temperature emitters; [2] applicable to all electric heating technologies.

Contents

Comparison of all suitable low carbon heating + energy efficiency package options

Calculation steps

- For each archetype in the model, all combinations of the available low carbon heating technologies and energy efficiency packages are considered.
- For each applicable combined package per archetype, given suitability constraints, the following key metrics are calculated:
  - *Annualised capital cost (£/yr) of the low carbon option and the counterfactual*. The total annualised capital cost of the low carbon option includes all equipment and installation costs at the building-level, as well as costs incurred relating to supporting infrastructure. The total annualised capital 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.
  - *Operating cost (£/yr)* is the sum of the in-year, undiscounted, operating / maintenance costs and fuel costs of the low carbon heating system over its lifetime. Fuel costs are based on heating demand, which is in turn influenced by the energy efficiency measures installed.
  - *Investment cost (£/yr)* represents the cost of investment for a household, and is therefore the sum of in-year, undiscounted capital costs associated with installation of low carbon heating and energy efficiency measures.
  - *Carbon emissions abatement (tCO_2e) of the option versus the counterfactual (direct and indirect emissions)*.
  - *Abatement cost (£/tCO_2e) of the option versus the counterfactual (where abatement includes direct and indirect savings)*. The abatement cost is equal to the net lifetime present cost, as defined in the below, divided by the carbon emissions abatement. The net lifetime present cost incorporates the discounted annualised capital cost and the discounted operating cost.

Annualised cost

$$\text{Lifetime present cost (£)} = \text{Present value of annualised capital cost (£)} + \text{Present value of annual operating cost (£)}$$

$$\text{Net lifetime present cost (£)} = \text{Lifetime present cost of low carbon heating} + \text{energy efficiency (£)} - \text{Lifetime present cost of counterfactual heating (£)}$$

$$\text{Annauliased capital cost (£)} = \frac{c}{1 - \frac{1}{(1+c)^n}} \times \frac{1}{(1+c)} \times \text{Capital cost (£)}$$

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

Abatement cost

$$\text{Abatement cost (£}/tCO_2e) = \frac{\text{Net lifetime present cost (£)}}{\left(\text{Present value of annual emissions from counterfactual } (tCO_2e) - \text{Present value of annual emissions from EE and LCH } (tCO_2e)\right)}$$ [1]

[1] EE: energy efficiency, LCH: low carbon heating

Low Carbon Heat Network (LCHN) costing

- District heating costs for existing homes are calculated on a simplified basis relative to other segments of the modelling and should be interpreted as indicative only.
- Total investment costs were taken from the 5th Carbon Budget, adjusted to reflect the changing heat supply mix, then scaled to correspond to total heat demand supplied by LCHN in the 6th Carbon Budget[1]. For the purposes of deriving the profile of investment costs over time, some network capex was reapportioned to reflect better the fact that a proportion of heat networks are expected to be built with gas CHP in the near term.
  - The deployment, energy and emissions scenarios take a simplified approach of modelling district heat deployment only at the point at which it becomes low-carbon. Heat network deployment in our scenarios is therefore more limited in early years than is expected in reality, with additional deployment being seen in later years to represent the point at which legacy CHP schemes convert to low carbon sources.
  - Nevertheless, some of the early heat network deployment is accounted for in the investment costs. To achieve this, investment costs were profiled to reflect the additional network spend that might be expected in early years as fossil fuel heat networks are built, with the energy centre costs being incurred in later years at the point at which legacy CHP schemes convert to low carbon sources.
- Network costs were annualised over 40 years, whereas all other components of capital cost were annualised over 20 years.
- Costs and carbon intensities per kWh of heat supplied were derived from the electricity, gas and hydrogen fuel costs used in the modelling. For LCHN electricity, a blended cost was derived from the 'highly flexible space heating' and the 'water heating with storage' costs (see slide)[2], assuming an 82:18 split between space heating and hot water demand, based on baseline archetype heating demand.
- The fuel consumption per kWh of heat supplied is based on the 5th Carbon Budget Central scenario and incorporates the fuel mix used and the efficiencies of the various technologies.
- The Cost of Capital (CoC) used for all capital costs (covering networks, energy centres, in-building heat interface units and in-building heat meters) was assumed to be 7.5% – higher than the default value of 3.5% for other low carbon heating technologies in the Balanced Pathway scenario – on the basis that the bulk of these costs will be incurred by commercial entities in the first instance.
  - It is recognized that this assumption represents an overestimate of CoC for in-building components (heat interface units and heat meters). However, it was deemed a reasonable simplification as these costs are understood to constitute a minor, albeit non-negligible, component of total capital costs.
- The levelised cost of heating (i.e. the cost in p/kWh of heat supplied, excluding fuel costs) for a Low Carbon Heat Network (LCHN) was calculated by first summing annualised network and non-network capital costs, and operating costs, then dividing the total by the total heat supplied by LCHN in each year.

[1] The total heat demand figure in the 5th Carbon Budget included both domestic and non-domestic demand.

Default approach for selection of energy efficiency + low carbon heating system package

- **In each 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 package with the lowest lifetime cost is selected (taking suitability into account).
    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 lowest lifetime cost, when combined with the energy efficiency package chosen as above, is selected.
    4. Any further constraints on minimum heating system stock (e.g. forcing hydrogen technologies) are applied.
- 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 results in reduced emissions savings relative to earlier in the period. 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 and with the energy efficiency first approach followed by the scenarios.
- **The selection of low carbon heating system deployment is undertaken for 2050, to reflect the long-term 'cost-optimal' solution**. The definition of cost-optimal in the 6th Carbon Budget is different from the definitions used for Net Zero and the 5th Carbon Budget:
    - The 5th Carbon Budget was based on a trajectory of target-consistent carbon values, which examined the point at which the deployment of a given technology would become 'cost-effective' relative to the trajectory.
    - Net Zero defined the most 'cost-effective' mix of low carbon heating and energy efficiency measures as the one with the lowest abatement cost (£/t).
    - The 6th Carbon Budget defines the most 'cost-effective' mix of low carbon heating and energy efficiency measures as the one with the lowest lifetime cost, over a 20-year time horizon.

NPV: Net Present Value

Specification of additional EE deployment beyond cost-optimal level

- Given the wider benefits of installing energy efficiency (including improved comfort, health and well-being, reduction in fuel poverty, regeneration, job creation, and improved energy security) are a key part of the CCC's assessments, additional energy efficiency is deployed in the model, in every scenario, 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).
  - This is in-line with work done for the 5th Carbon Budget.
- The extra deployment is achieved by:
  - Defining the total required uptake for individual measures, either across the stock or for specific archetypes.
  - Using the defined uptake to deploy additional energy efficiency measures in certain archetypes or in archetypes where the incremental cost would be lowest.
- Extra energy efficiency deployment is primarily directed in fuel poor homes (which receive high energy efficiency packages in all scenarios).
- Most of the scenarios additionally include extra energy efficiency deployment for non-fuel poor homes, to recognise the wider benefits associated with deployment for the UK stock as a whole.
  - An example of this is the Balanced Pathway scenario which includes all practicable loft and cavity insulation (i.e. all economic potential[1]), in addition to solid wall insulation where part of an overall measure package with a cost effectiveness <£600/t.
  - Carbon values of £600-700/tCO_2e are well above the expected net zero consistent carbon value of £350/tCO_2e in 2050[2], with this additional deployment intended to reflect the wider benefits associated with energy efficiency. There would be value in further bottom-up analysis to explicitly quantify the value of wider benefits, with a view to refining the appropriate boundary for economic potential.

[1] Generally, measures where costs came in above £700/tCO_2e for a typical home excluded from economical potential. A typical home was assumed to be a medium semi-detached home. Scaffolding and design costs were not included in calculations of economic potential; [2] For further discussion of carbon values see The Sixth Carbon Budget Methodology Report, CCC (2020), p21 onwards.

Energy efficiency uptake ranges across scenarios

Scenario	Number of measures deployed (millions): Loft	Cavity wall	Solid wall	Floor	Other	Behavioural	Total heat demand (TWh/y): 2017	2050	Energy demand savings (TWh/y)	Reduction in heat demand as a result of EE
Balanced Pathway	10.8	3.1	3.4	3.4	28.3	28.3	313	276	37	12%
Tailwinds	10.8	3.1	7.1	21.1	28.3			245	68	22%
Headwinds	9.7	2.8	1.9	6.2	25.6			278	35	11%
Widespread Engagement	10.7	3.1	4.9	8.7	27.9			263	50	16%
Widespread Innovation	6.1	2.7	1.2	2.3	8.6			274	39	12%

- Energy efficiency levels are driven by different factors in each scenario:
  - **Balanced Pathway:** inclusion of all practicable loft and cavity insulation (i.e. all economic potential[1]), in addition to solid walls where the package they are taken up with had a cost effectiveness <£600/t.
  - **Tailwinds:** inclusion of full economic potential for all energy efficiency measures.
  - **Headwinds:** model permitted to optimise for the lowest lifetime cost EE + LCH combination, given high H_2 prices, with no wider benefits costed for non-fuel poor homes. This is the only scenario with 'cost-effective' uptake at standard prices.
  - **Widespread Engagement:** deployment of at least a medium energy efficiency package in all households.
  - **Widespread Innovation:** model permitted to optimise for the lowest lifetime cost using lower-end costs, with no wider benefits costed for non-fuel poor homes; deep retrofits replace standard high packages.

- Solid walls in fuel poor homes are insulated across scenarios (implemented via the high energy efficiency package).
  - Given the high uncertainty over the achievable performance of solid wall insulation in particular, a broad range of uptake levels was modelled across the scenarios, with Tailwinds representing full economic potential.

[1] Generally, measures where costs came in above £700/tCO_2e for a typical home excluded from economical potential. A typical home was assumed to be a medium semi-detached home. Scaffolding and design costs were not included in calculations of economic potential.

Method limitations

- As with all models, there are a few drawbacks and limitations to the approach used (see slide):
  - Heating system uptake trajectories are based on final 2050 end-states and do not allow the explicit modelling of multiple technology transitions over time, which might nonetheless be expected to happen in reality (e.g. a home transitioning from a fossil fuel heating system to a hybrid heat pump, then transitioning to a conventional heat pump at a later date).
  - The insulation measures included in each package are identical across all archetypes, as opposed to being optimised for individual archetypes (nevertheless the costs for each measure remain specific to each archetype).
  - System impacts and benefits of electric heating options (e.g. to make use of potential renewable curtailment) are not explored.
  - Only thermal storage options are included in the model, with electrical storage options not considered.
  - Thermal storage sizing is not calculated based on archetype-specific demand and heating system sizing.

Contents

Summary of scenario assumptions

Each of the five scenarios uses differing sets of assumptions to reflect distinct futures

- **Widespread Innovation:** This scenario sees high innovation in several carbon mitigation technologies and measures. Costs fall faster than central projections. This allows more widespread electrification, a more resource and energy efficient economy, and more cost-effective technologies to remove CO_2 from the atmosphere. Main assumptions include:
  - Deployment of high temperature heat pumps.
  - Prevalence of Heat as a Service model.
  - High energy efficiency packages modelled to represent deep retrofits (i.e. higher costs and savings).
  - Some uptake of hydrogen but no biofuel-powered technologies.
  - More ambitious closure of performance gap.
- **Widespread Engagement:** People and businesses are willing to make more changes to their behaviour. This reduces the demand for the most high-carbon activities and increases the uptake of some climate mitigation measures. Main assumptions include:
  - More behaviour change.
  - Stronger uptake of energy efficiency measures relative to the Balanced Pathway.
  - Full electrification (i.e. no hydrogen or biofuel technologies).
- **Headwinds:** People change their behaviour and new technologies develop, but neither widespread behavioural shifts nor innovations that significantly reduce the cost of green technologies ahead of current projections are seen. This scenario is more reliant on the use of large hydrogen and CCS infrastructure to achieve net zero. Main features include:
  - Widespread deployment of hydrogen technologies, via both hydrogen boilers and hybrid heat pumps with hydrogen.
- **Balanced Pathway:** Deployment trajectory that makes strong progress towards Net Zero and keeps open alternative states of the world. Reflects a ‘fuel poverty first’ approach for buildings.
- **Tailwinds:** Pursues behaviour change, innovation and heavy infrastructure, and succeeds on all fronts. Helps inform whether an earlier date for delivery of net zero is feasible. Generally combines the most optimistic assumptions of the 3 alternative scenarios (Headwinds, Widespread Engagement and Widespread Innovation).

Scenario descriptions – forcing

- In addition to the deployment of energy efficiency measures beyond the 'cost-optimal' level (see slide), each exploratory scenario has different constraints on the range of low carbon technologies permitted, reflecting the different 'worlds' each scenario represents:

  - **Widespread Innovation**: This scenario portrays a world with high levels of innovation (including the use of Heat as a Service). High temperature heat pumps are modelled as a technology option in this scenario (and in no others). Biofuel systems are assumed not to be required, with hydrogen technologies seeing limited deployment. Thermal storage technology is also deployed widely, allowing many homes to operate flexibly.

  - **Widespread Engagement:** This scenario portrays a world with high levels of behaviour change from consumers. Full electrification is assumed, with no biofuel or hydrogen technologies. Energy efficiency is widely deployed, and engaged consumers widely utilise pre-heating, turn down thermostats, and implement automated multizone control. For homes with heat pumps, hot water temperature is reduced to 50 °C, notwithstanding a 1-hour legionella cycle per day.

  - **Headwinds:** This scenario portrays a world without widespread behavioural shifts from consumers or innovations leading to steep cost reductions of green technologies. Hydrogen is therefore the dominant fuel used for heating systems (roughly evenly split between hydrogen boilers and hybrid heat pumps with hydrogen). The use of biofuels (in the form of hybrid heat pumps with biofuel boiler) is relatively widespread in off-grid homes. The deployment of energy efficiency measures and the pre-heating are more limited compared to other scenarios.

Scenario definitions and drivers – behavioural

	Innovation area	Balanced Pathway	Tailwinds	Widespread Engagement	Headwinds	Widespread Innovation
Behavioural	Pre-heating	Permitted in 25% of post-1952 homes	Permitted in 50% of post-1952 homes	Permitted in 50% of post-1952 homes	Permitted in 25% of post-1952 homes	Permitted in 50% of post-1952 homes
	Smart metering & control	3% heat demand reduction[1]	6% heat demand reduction[2]	6% heat demand reduction[2]	3% heat demand reduction[1]	6% heat demand reduction[2]
	Water temperature	60 °C	60 °C	50 °C[3]	60 °C	60 °C
	Low flow shower head	Yes				
	Heat as a service	No	Yes[4]	No	No	Yes[4]

[1] *Heat demand reduction based on the average gas savings seen in smart meter trials across participants, and are expected to be associated with actions such as turning the thermostat down* and changing operating times.
[2] *Heat demand reduction based on implementation of automated multizone control.*
[3] *50 degrees only applicable in dwellings which uptake a heat pump; allowance for daily legionella cycle of 1hr duration included.*
[4] *Heat as a service modelled using: 7.5% cost of capital, 5% increase in heat demand, 3% financial savings, 15% increase efficiency*

Scenario definitions and drivers – buildings

<table>
<tr><th></th><th colspan="2">Innovation area</th><th>Balanced Pathway</th><th>Tailwinds</th><th>Widespread Engagement</th><th>Headwinds</th><th>Widespread Innovation</th></tr>
<tr><td rowspan="4">Buildings</td><td rowspan="2">Energy efficiency packages and deployment</td><td>Non-fuel poor homes</td><td>Full economic potential for low regret measures including loft and cavity walls

All ISWI in packages under £600/t</td><td>Full economic potential</td><td>Medium packages for all other homes</td><td>Uptake based on lowest lifetime cost of package (energy efficiency and low carbon heating) using high hydrogen prices</td><td>Uptake based on lowest lifetime cost of package (energy efficiency and low carbon heating)</td></tr>
<tr><td colspan="6">High packages for fuel poor homes.</td></tr>
<tr><td colspan="2">Measure costs & savings</td><td>Base costs & savings</td><td>Lower bound costs for low, medium, and high packages</td><td>Base costs & savings</td><td>Base costs & savings</td><td>Lower bound costs for all low and medium packages

High packages modelled as deep retrofits[1]</td></tr>
<tr><td colspan="2">Performance gap closure of IUF</td><td>1/3</td><td>1/2</td><td>1/3</td><td>1/3</td><td>1/2</td></tr>
</table>

[1] *The savings of a deep retrofit package are modelled to achieve a 40 kWh/m²/yr space heating demand goal, rather than a specified savings percentage. Costs based on evidence provided by Energiesprong, representing a view of the cost reductions that might be achievable in deep retrofits, with adjustments made to align with CCC modelling approach. It should be noted that the costs do not reflect an Energiesprong retrofit.*

Scenario definitions and drivers – technologies

	Innovation area	Balanced Pathway	Tailwinds	Widespread Engagement	Headwinds	Widespread Innovation
Technology	Low-carbon heating restrictions	Hydrogen only permitted via hybrid boilers Biofuel only permitted in off-gas grid hybrids	Hydrogen limited to clusters No biofuel permitted	Electric-only scenario (no hydrogen or biofuel)	Biofuel only permitted in off-gas grid hybrids	High temperature HPs included No biofuel permitted
		All resistive heating accompanied by thermal storage or solar thermal.				
	Heat pump lifetimes	15yrs for ASHPs 20yrs for GSHPs (100 yrs for ground loop)	17yrs for ASHPs 22yrs for GSHPs (100yrs for ground loop)	15yrs for ASHPs 20yrs for GSHPs (100yrs for ground loop)	15yrs for ASHPs 20yrs for GSHPs (100yrs for ground loop)	17yrs for ASHPs 22yrs for GSHPs (100yrs for ground loop)
	Heat pump cost reduction	20% to 2030 30% of 2050	30% to 2030 40% to 2050	20% to 2030 30% of 2050	20% to 2030 30% of 2050	30% to 2030 40% to 2050
	Heat pump load factors	Average	High-end	High-end	Low-end	High-end
	Heat batteries	Used in space constrained homes	As standard rather than hot water cylinders	Used in space constrained homes	Used in space constrained homes	As standard rather than hot water cylinders
	Thermal storage	Cost effective deployment				Deployed widely such that all homes can consume more flexibly
	Hy-ready boilers	All boiler replacements from 2026 are Hy-ready				
	Low carbon heat network mix	Electrified	Electrified	Electrified	Incl. hydrogen peaking	Electrified

Contents

Trajectory development – overview [1/2]

- Deployment trajectories were developed based on an energy efficiency first approach, with the aim of readying the stock for uptake of low carbon heating technologies ahead of fossil fuel phase out.
- The building stock was broken down by gas grid connection status (on or off grid), fuel poverty (fuel poor or not fuel poor) and tenure (local authority, private rented and owner occupied)[1].
- Each stock segment was then assigned a deployment trajectory representing a regulatory approach, based on levers for delivery which were deemed realistic:
  - A backstop approach (100% deployment by the backstop date) was used for energy efficiency deployment in the fuel poor, local authority, and private rented segments as those were considered easier to regulate (and in some cases already have government targets for energy efficiency).
  - For energy efficiency deployment in owner occupied homes, which were considered more difficult to regulate, an approach based on incentives for lenders and regulations at Point of Sale (PoS) was used.
  - For most low carbon heating technology deployment, a mandation date approach based on setting phase out dates for fossil heating technologies was used, with the phase out date for off-grid homes set earlier than that for on-grid homes. This approach aims to work with replacement cycles and minimize scrappage costs.
  - For the deployment of hydrogen technologies and low carbon heat networks, the trajectories were based on geographical conversion profiles (e.g. hydrogen technologies being deployed in homes as they gain access to a converted gas grid).

Early years (2020 – 2025): Trajectories primarily based on specific measure deployment constraints, developed via input from external stakeholders

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Later years:
Trajectories modelled to reflect various policies, and to reflect four approaches

- **Backstop dates**
- **Mandation dates**
- **Geographical conversion**
- **Incentives and PoS regulations**

[1] Building stock was broken down further but only the 3 categories mentioned were used to define trajectories; [2] The Headwinds scenario does not use the 'whole-house' approach for any homes; [3] The exact number of curves per scenario varies based on the scenario definition.

Trajectory development – overview [2/2]

- In terms of installing energy efficiency measures, local authority homes are modelled as deploying a 'whole-house' approach, whereby all energy efficiency measures in a given package are deployed simultaneously, while other homes use an 'incremental' approach, deploying energy efficiency measures over several years[1]. This is intended to reflect the fact that a 'whole-house' approach can deliver improved outcomes relative to an incremental approach[2], but it requires a concentrated outlay of capital funding which may be better suited to some segments of the stock (including social housing) than others.
- Regardless of the regulatory approach driving each deployment trajectory, deployment constraints play a~~n~~ dominant role in determining deployment levels in the early years.
  - The constraints were developed for both energy efficiency measures and low carbon heating systems (particularly heat pumps) with input from external stakeholders, to reflect supply chain and other considerations which could limit the number of measures deployed in any given year.
  - The deployment constraints for heat pumps prevent the 'whole-house' approach from being modelled as one where both low carbon heating and energy efficiency are installed simultaneously.
- The regulatory approach used to develop deployment trajectories for this study is intended to be representative of a range of ambition that could be delivered in different ways, for example via different approaches to regulation than the ones used.
- The model does not represent technology transitions, for instance a home using a fossil fuel heating system first converting to a hybrid heat pump system, then converting to a conventional heat pump at a later date. Transitions are therefore not a feature of the trajectories but may be a feature of a real-world transition.
- In total, around **28** [3] distinct trajectories were developed per scenario.

Early years (2020 – 2025): Trajectories primarily based on specific measure deployment constraints, developed via input from external stakeholders

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Later years:
Trajectories modelled to reflect various policies, and to reflect four approaches

- **Backstop dates**
- **Incentives and PoS regulations**
- **Mandation dates**
- **Geographical conversion**

[1] The Headwinds scenario does not use the 'whole-house' approach for any homes; [2] Analysis work to refine fabric energy efficiency assumptions for use in developing the 6th Carbon Budget, UCL for the CCC (2020); [3] The exact number of curves per scenario varies based on the scenario definition.

Trajectory development – Balanced Pathway

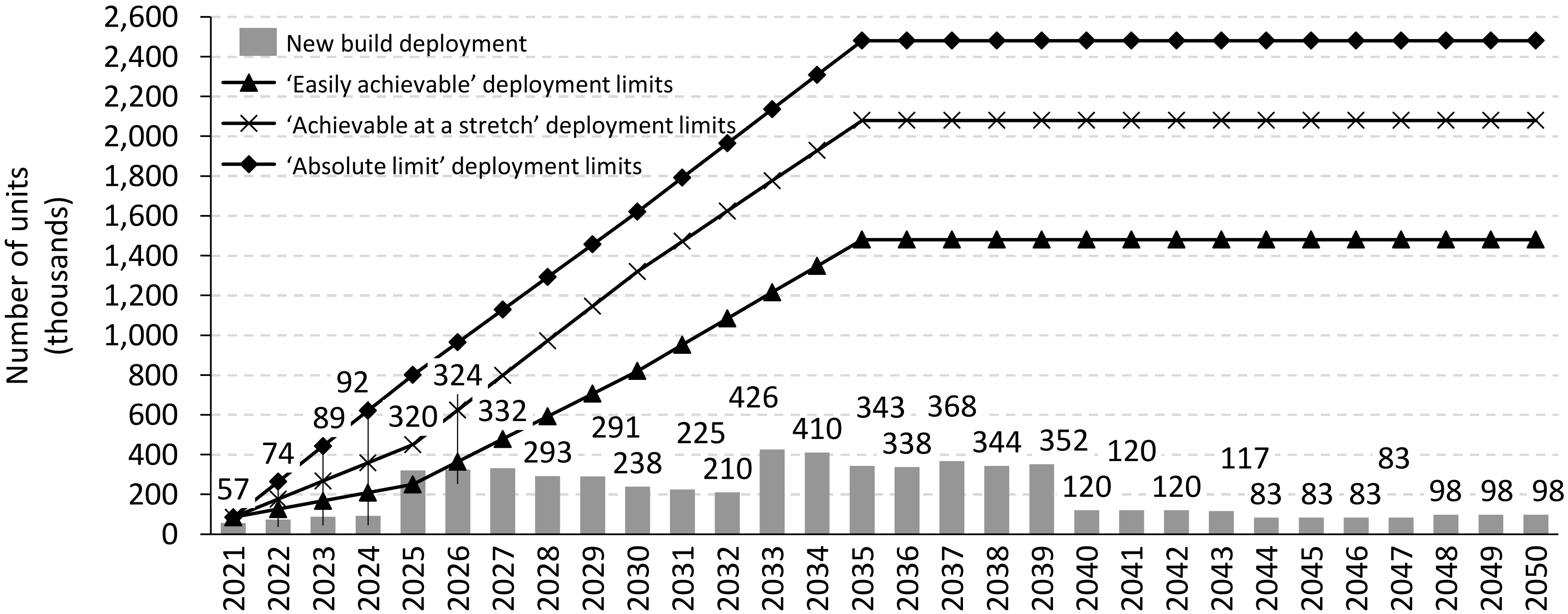
- The trajectory for the Balanced Pathway was developed based on the view that even in a high hydrogen world, strong electrification both on and off the gas grid remains valuable. Electrification is seen as likely to remain the primary route to decarbonise, with hydrogen providing flexibility/playing a role in regional grids[1]. This conclusion leads on from the findings of previous work that:
  - **Different pathways for heat decarbonisation are similar cost.** Imperial's analysis for a previous CCC report on hydrogen[2] found that a range of pathways to 2050 for heat decarbonisation, based on hydrogen and/or electrification, have similar costs (a conclusion backed up by separate analysis by the National Infrastructure Commission).
  - **There are likely to be challenges with pursuing a full hydrogen pathway.** It would require very large volumes of hydrogen which, depending on how the demand is met, would lock in significant residual emissions and/or mean extremely challenging build rates for low carbon infrastructure. Greater public acceptability challenges could also be associated with a solution that focuses solely on hydrogen (or electrification). The CCC advised in 2018 that it would not be prudent to plan on achieving the necessary emissions reductions by 2050 on the gas grid only from hydrogen[2].
- Based on the above, the Balanced Pathway trajectory is heavily electrified, with heat pumps dominating the final mix (see Results). Ambitious levels of early deployment are included on the basis that[1]:
  - **Early deployment drives benefits.** This includes increasing consumer familiarity ahead of any widespread adoption and driving down near term emissions (reducing the scale of the challenge to move to full decarbonisation by 2050). It also locks in a minimum level of electrification, even where hydrogen increases in dominance post-2030.
  - **Clear signals to the market.** It sends a clear signal to the market on strong near-term uptake, providing the policy certainty which is critical to support the levels of electrification seen as necessary across scenarios (see Results).
  - **It prepares supply chains to keep options open for full electrification.** For full electrification, boiler lifetimes imply a need to scale up markets and supply chains to cover all new installations by the mid-2030s at the latest, representing up to 1.8 million heat pumps a year in existing homes. Supply chains must grow steadily to accommodate not only first-time heat pump installations in existing homes, but also new build installations (including retrofits for those homes being built now with gas) and replacements. The Balanced Pathway represents relatively stable year by year heat pump growth over the trajectory when both new builds and replacements are included.
  - **The deployment levels are readily achievable.** The envisaged deployment levels remain with 'achievable at a stretch' deployment constraints (see slide). Further, the modelling suggests nearly 7m homes do not require significant energy efficiency upgrades, implying that an ambitious level of deployment to 2030 would not necessarily be contingent on significant energy efficiency retrofits. Finally, the deployment could come in the form of hybrid heat pumps which are more readily deployable across different types of homes.

[1] Policies for the Sixth Carbon Budget and Net Zero, CCC (2020);

[2] Analysis of Alternative UK Heat Decarbonisation Pathways, Imperial College London for the CCC (2018).

Trajectory development – deployment constraints

- Deployment constraints for all technologies and energy efficiency measures were developed in consultation with stakeholders, and informed by past deployment rates and published evidence[1].
- Whilst all constraints were taken into account within the modelling, the most influential were heat pump deployment constraints.
- For heat pumps, both replacements and deployment in new builds[2] alongside retrofits were considered when setting uptake trajectories for heat pumps.
- Whilst the deployment constraints were assumed to remain constant after 2035, in reality further increases can be expected.
- The modelling aimed to remain within 'achievable at stretch' constraints for all technologies and measures in most scenarios including the Balanced Pathway.



[1] For further detail on deployment constraints and the evidence informing them, please see accompanying assumptions log;
[2] New build deployment was not modelled in this work, with modelling being undertaken by the CCC.

Trajectory development – influence of Government policy

Several government ambitions or policies were considered when modelling uptake trajectories, as summarised in the below table[1]

Issued by	Policy target
Central Government[2]	As many homes as possible to reach EPC Band C by 2035 where practical, cost-effective and affordable.
	Private rented sector to reach EPC Band C by 2030 where practical, cost-effective and affordable.
	Social housing to reach EPC Band C by 2030 where practical, cost-effective and affordable.
	All fuel poor homes to be upgraded to EPC band C by 2030.
	Phase out high carbon fossil fuel heating off the gas grid in the 2020s.
Scottish Government[3]	All homes at least EPC band C where technically feasible and cost effective by 2040.
	Number of socially rented homes to be achieving EPC band B to be maximised by 2032, and all socially rented housing to be at least EPC band D for new lets from 2025.
Decarbonisation of Homes in Wales Advisory Group[4]	By 2050, housing stock to be retrofitted to achieve an EPC Band A rating, recognising that not all homes will be able to achieve this.
	Ten-year programme to bring every socially-owned home and every privately-owned home in fuel poverty up to EPC band A by 2030.

- To manage complexity, all trajectories were developed based on Central government policies. Distinct trajectories for each devolved administration were not directly modelled, however policies in devolved administrations were used to inform the ranges of ambition considered across scenarios.

[1] Policies were included as they stood at the time of trajectory development. In some cases, updated policy has been issued since that time; [2] Primarily drawn from Clean Growth Strategy, 2017; [3] Energy Efficient Scotland programme; [4] Ambitions set out in Better Homes, Better Wales, Better World (2019), with the recommendations accepted in principle by the Welsh Minister for Housing and Local Government.

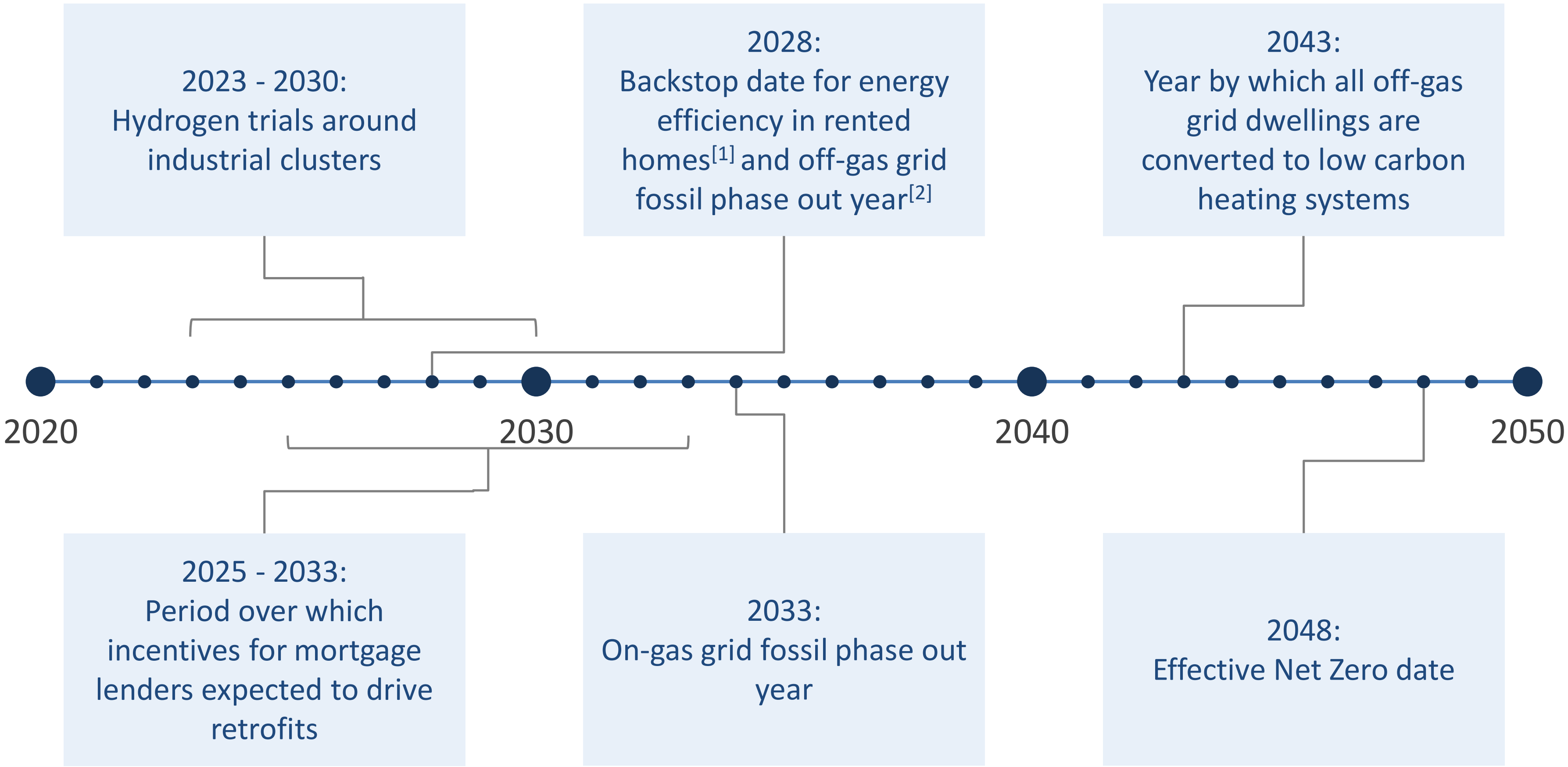
Trajectory development – key dates

	Stock segment	Headwinds	Widespread Innovation	Widespread Engagement	Balanced Pathway	Tailwinds
Backstop date by which sufficient energy efficiency required across all eligible homes	**Private rented sector:**	2030	2028	2027	2028	2027
	Social homes:	2030	2028	2027	2028	2027
	Owner occupied fuel poor homes:	2030	2030	2030	2030	2030
Period over which incentives for lenders expected to drive retrofits	**Owner occupiers (mortgagors):**	2025-2035	2025-2035	2025-2030	2025-2033	2025-2030
Date by which regulations at trigger points (Point of Sale) are implemented	**Owner occupiers (outright owners):**	2030	2030	2025	2028	2025
Date by which all new heating systems must be low carbon[1]	**Off gas grid:**	2028	2028	2026	2028	2026
	On gas grid:	2035/Full region by region conversion from 2030	2035	2030	2033	2030

- In the Balanced Pathway and Headwinds scenarios, all heating systems become low carbon 15 years after the date by which all new heating systems must be low carbon, reflecting the average lifetime of gas boilers.
- In the Tailwinds, Engaged People and Widespread Innovation scenarios, the rate of replacement is slightly quicker (effectively assuming a boiler lifetime of 13.8 years). This reflects BEIS research[1] which suggests 13% of people would be willing to replace their heating system before it reaches end of life.
- Trajectories for non-fuel poor owner occupiers were derived based on an assumed rate of turnover of 10 years for mortgagors and 23.8 years for outright owners, as per English Housing Survey statistics[3].

[1] Excluding zones designated for low carbon heat network or hydrogen conversion; [2] BEIS Public Attitudes Tracker, December 2019; [3] English Housing Survey: Home ownership, 2016-17.

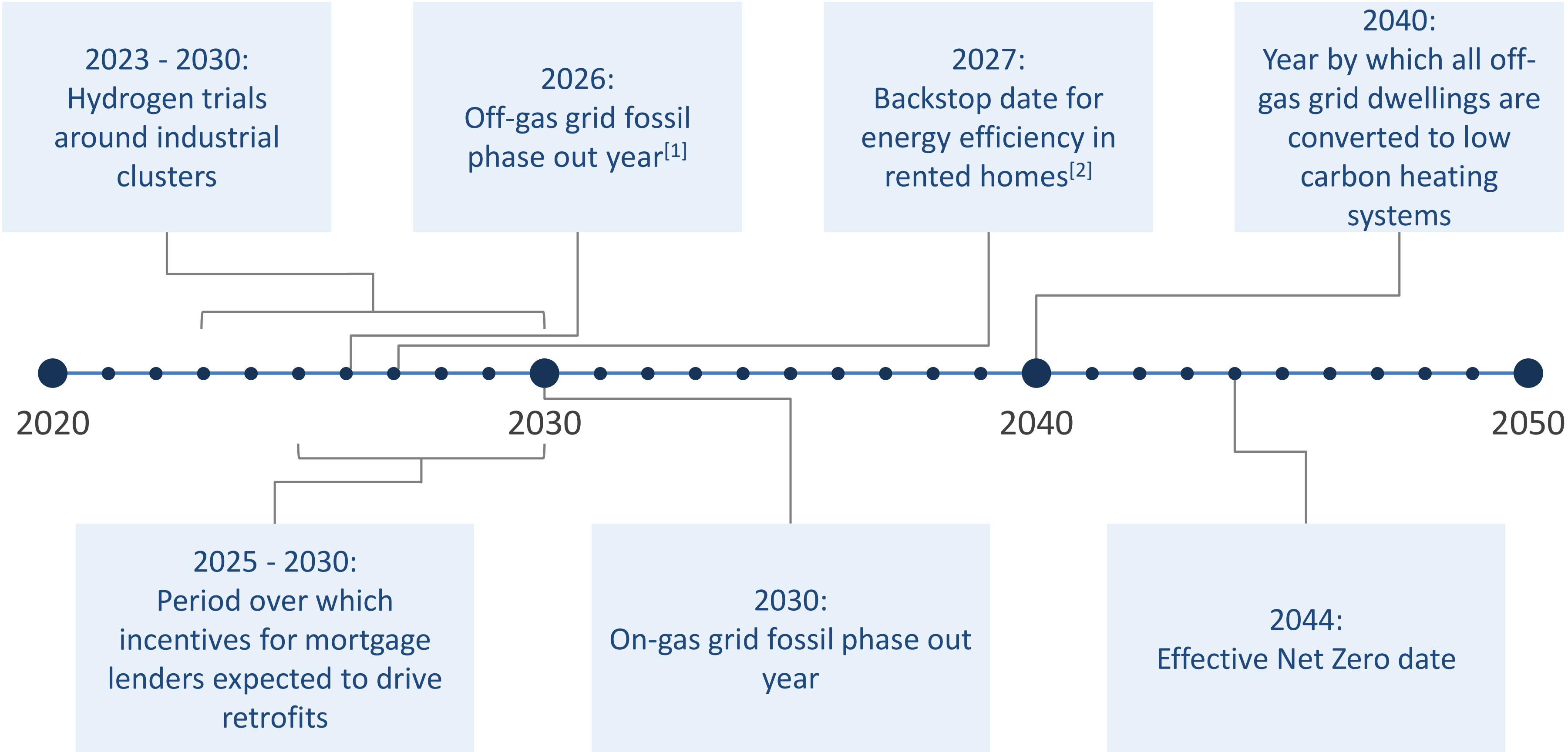
Trajectory development – trigger point timeline for the Balanced Pathway scenario



- The effective Net Zero date is the date by which almost all dwellings (off-gas and on-gas) are converted to low carbon heating system.
  - The exception is dwellings getting technologies where the deployment trajectory is based on geographical conversion i.e. low carbon heat networks or hydrogen technologies.

[1] Year by which all dwellings must install their required energy efficiency measures.
[2] Year after which new fossil-fuel-based heating systems are no longer permitted to be installed in dwellings.

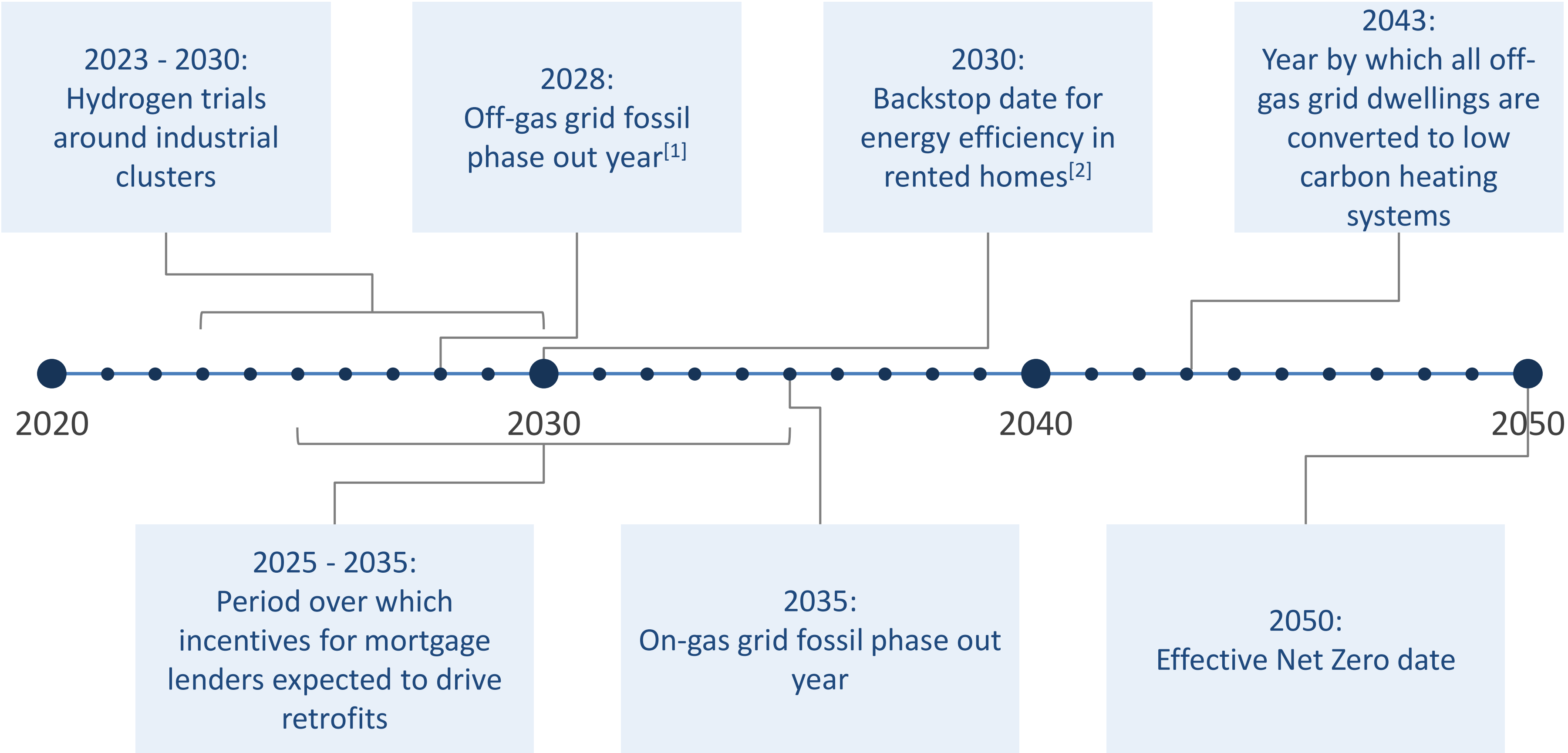
Trajectory development – trigger point timeline for the Tailwinds scenario



- The effective Net Zero date is the date by which almost all dwellings (off-gas and on-gas) are converted to low carbon heating system.
  - The exception is dwellings getting technologies where the deployment trajectory is based on geographical conversion i.e. low carbon heat networks or hydrogen technologies.
- The 2026 off-gas grid fossil phase out date was deemed the earliest feasible date which would not breach deployment constraints and would maintain a smooth ramp up in the deployment rate of heat pumps.

[1] Year after which new fossil-fuel-based heating systems are no longer permitted to be installed in dwellings.
[2] Year by which all dwellings must install their required energy efficiency measures. Social housing and private rented homes only

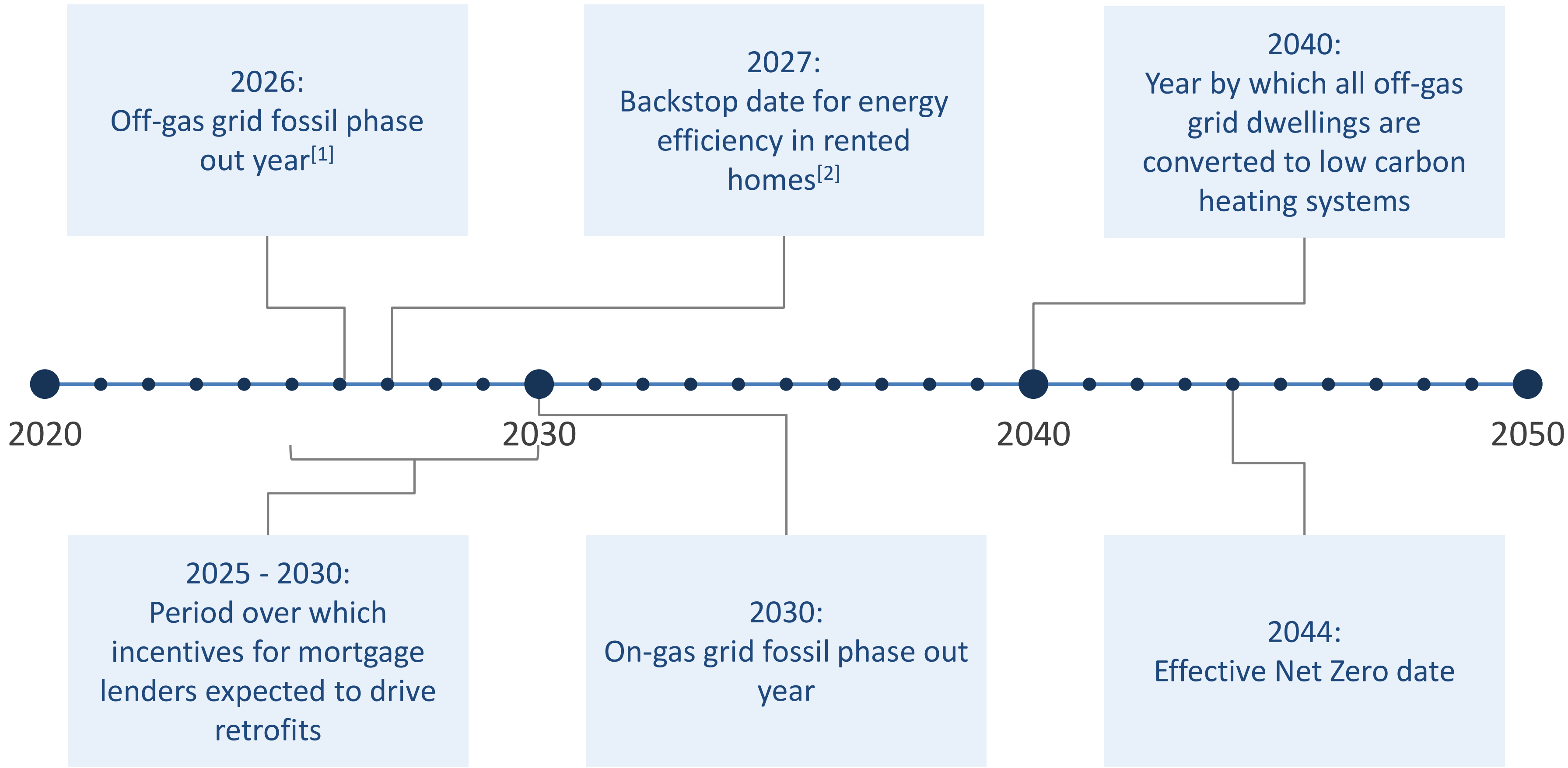
Trajectory development – trigger point timeline for the Headwinds scenario



- The effective Net Zero date is the date by which almost all dwellings (off-gas and on-gas) are converted to low carbon heating system.
    - The exception is dwellings getting technologies where the deployment trajectory is based on geographical conversion i.e. low carbon heat networks or hydrogen technologies.
- The Headwinds scenario is dominated by hydrogen technologies, for which deployment is based on geographical conversion (see slide). As such, fossil phase out dates are not as impactful as for other scenarios.

[1] Year after which new fossil-fuel-based heating systems are no longer permitted to be installed in dwellings.
[2] Year by which all dwellings must install their required energy efficiency measures. Social housing and private rented homes only

Trajectory development – trigger point timeline for the Widespread Engagement scenario

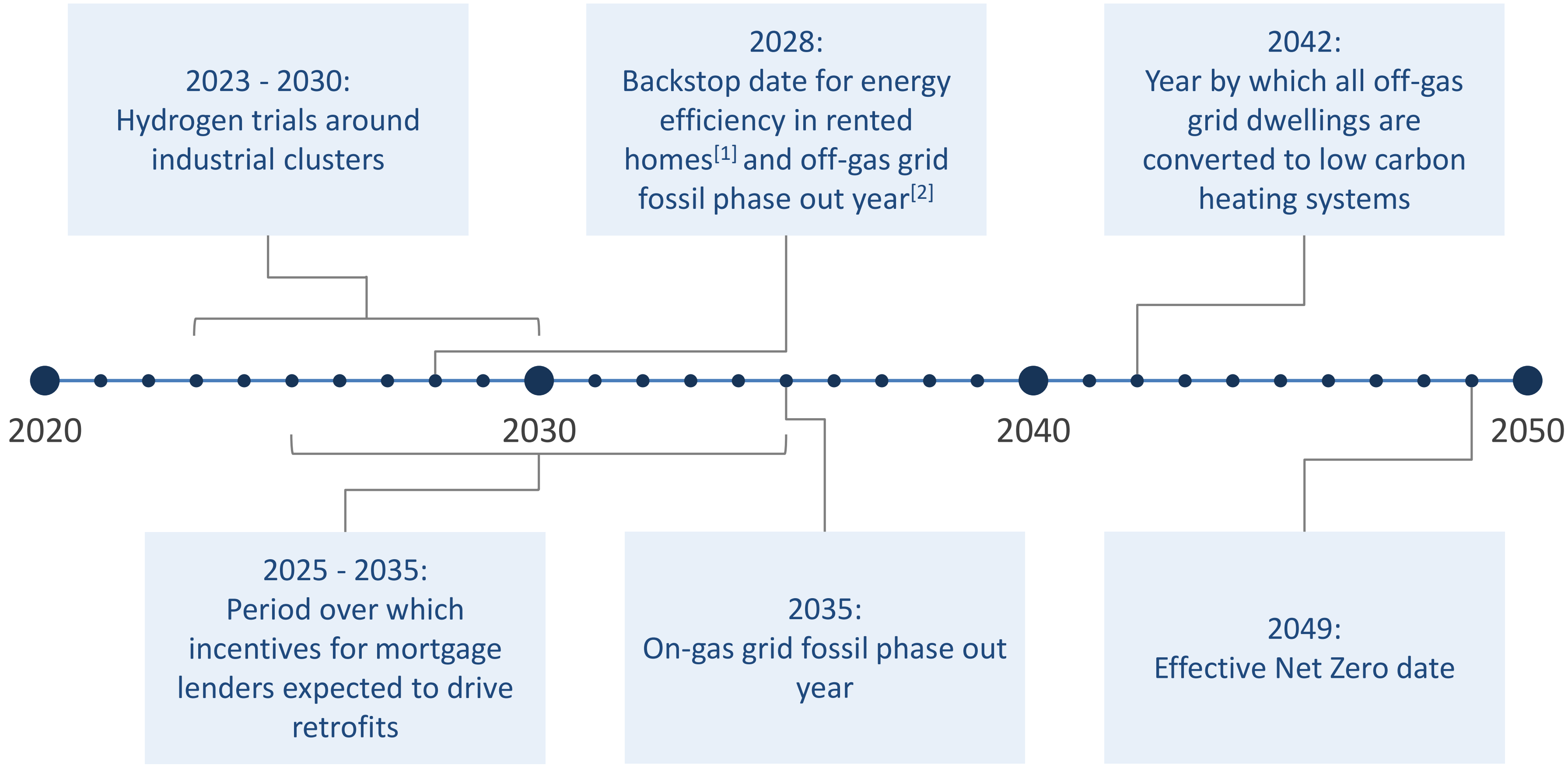


- The effective Net Zero date is the date by which almost all dwellings (off-gas and on-gas) are converted to low carbon heating system.
  - The exception is dwellings getting technologies where the deployment trajectory is based on geographical conversion i.e. low carbon heat networks or hydrogen technologies.

[1] Year after which new fossil-fuel-based heating systems are no longer permitted to be installed in dwellings.

[2] Year by which all dwellings must install their required energy efficiency measures. Social housing and private rented homes only

Trajectory development – trigger point timeline for the Widespread Innovation scenario



- The effective Net Zero date is the date by which almost all dwellings (off-gas and on-gas) are converted to low carbon heating system.
  - The exception is dwellings getting technologies where the deployment trajectory is based on geographical conversion i.e. low carbon heat networks or hydrogen technologies.

[1] Year by which all dwellings must install their required energy efficiency measures.
[2] Year after which new fossil-fuel-based heating systems are no longer permitted to be installed in dwellings.

Low Carbon Heat Network (LCHN) trajectories

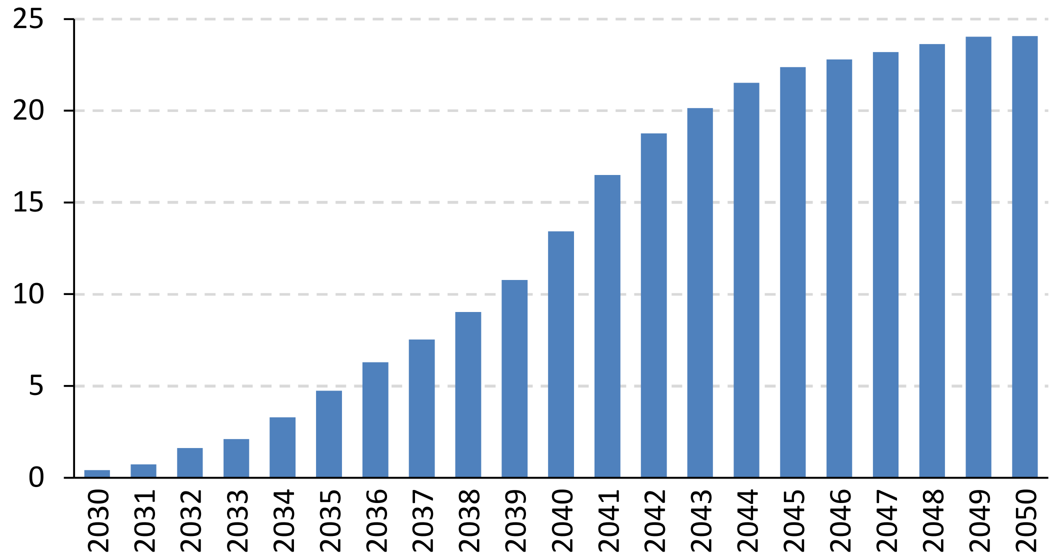
- The deployment trajectories for Low Carbon Heat Networks (LCHN) are based on those developed for the 5th Carbon Budget.
- The 5th Carbon Budget trajectories were based on detailed geographical modelling for LCHN[1].
- By 2050, approximately 18% of the total domestic building stock is assigned to LCHN.
  - This is based on the total share of heat demand across the domestic and non-domestic sectors met by LCHN in the 5th Carbon Budget.
  - The 18% figure is derived from an assumption that the 20% of homes with the highest heating demand (according to the baseline), uptake LCHN, assuming a 90% connection fraction.
- Several amendments were made to the 5th Carbon Budget trajectories to arrive at the trajectories employed for 6CB:
  - It was assumed that the level of deployment achieved by 2025 in the 5th Carbon Budget trajectory would be reached by 2027 in the 6th Carbon Budget (i.e. the pace of deployment over the next five years is slower than in the 5th Carbon Budget).
  - To ensure overall deployment levels to 2050 are maintained, additional deployment was apportioned between 2040 and 2044.
  - It was assumed that all new heat network connections from 2025 are low carbon[2]. This builds on the ambition in the Future Homes Standard[3], which will ensure that from 2025 new heat networks in England are low carbon and ready for 2050. Sector regulation may be used to encourage decarbonisation of heat networks attached to existing buildings from 2025.
  - The trajectory was amended so that it only represents the point at which homes move onto LCHN (given the modelling covers low carbon heat networks only). This was done by assuming that all heat network connections in the early years (which are assumed to connect to gas CHP) are retrofitted with low carbon heat sources from 2033. In these cases, the trajectory accounts for the retrofits only.
  - The above approach ensures all homes are running on decarbonised heat networks by 2040. The exception to this is the Headwinds scenario, where hydrogen is included in the fuel mix to cover peaking demand. In this scenario, full decarbonisation is achieved in accordance with the assumed hydrogen conversion trajectory (see next slide).

CHP: Combined Heat and Power; [1] Research on district heating and local approaches to heat decarbonisation, Element Energy for the CCC (2015); [2] Where hydrogen is used to cover peaking demand (Headwinds scenario), gas is included in the LCHN fuel mix in the years before conversion to hydrogen; [3] Future Homes Standard (2019).

Hydrogen deployment trajectory – consistency with industry [1/3]

- The trajectory for deployment of heating technologies using hydrogen is based on a set of simple assumptions describing one possible approach to a phased conversion of the gas distribution grid.
- The grid conversion trajectory, which is aligned with the parallel analysis on the industry sector for the 6th Carbon Budget, involves conversion of the gas grid between 2030 and 2050 over an increasing catchment associated with seven identified industrial clusters.
- Beginning 5 years after the date of first availability of hydrogen at the industrial cluster, which varies between 2025 and 2030 depending on the cluster, the grid is assumed to convert at a radius of 10 km/yr.
- This means that rollout of hydrogen-using technologies, aside from the early trials which are deployed in the 2020s, starts in 2030 around the earliest clusters, and in 2035 around the latest clusters.
- Once homes fall within the radius of conversion, they are assumed to have access to hydrogen if this option is selected.
- The resulting number of homes with access to hydrogen over time was estimated by finding the number of homes falling within a given radius of the nearest industrial cluster[1].
- This grid conversion trajectory results in 4.7 million (20%) current grid-connected homes having access to hydrogen by 2035, 13.4 million (56%) by 2040 and 24.1 million (100%) by 2050.
- All grid-connected homes have access to hydrogen by 2050 at the latest.
- This underlying grid conversion trajectory is assumed across all scenarios except for the Widespread Engagement scenario, in which there is no grid conversion in any regions.
- However, the actual deployment of heating technologies using hydrogen varies between the scenarios (see also next slide).
- The hydrogen conversion trajectory above does not assume that the grid is fully converted, but assumes partial conversion of the grid in areas designated for conversion – this analysis does not attempt to specify which areas should be designated for conversion.

Homes with access to hydrogen[2]



[1] This analysis used a single point location for each local authority to represent all homes within that local authority

[2] Includes homes suitable for low carbon heat networks, which never uptake hydrogen-powered technologies

Hydrogen deployment trajectory – consistency with industry [2/3]

Scenario	Hydrogen technologies included[1]	Deployment trajectory pre-2030 (trials)	Deployment trajectory post-2030 (see slide for further detail)
Balanced Pathway	Hybrid HPs only	Hydrogen trials of 300 homes in 2023, 3000 in 2024, and a further 3 pilots of 3000 homes each around industrial clusters in the late 2020s (all Hybrid HPs).	Rollout of Hybrid HPs between 2030 and 2050, in line with the national grid conversion trajectory, distributed across the country (not only around industrial clusters). 3.9m Hybrid heat pumps are assumed to be deployed at the point of grid conversion, such that they go straight onto hydrogen. This assumes that areas are designated for conversion to hydrogen ahead of the fossil phase-out date of 2033, so these homes are exempted and able to remain on gas boiler heating (and install new Hy-ready gas boilers) until the grid has converted to hydrogen, by 2050 at the latest.
Tailwinds	Hydrogen boilers only	Hydrogen trials of 300 homes in 2023, 3000 in 2024, and a further 3 pilots of 3000 homes each around industrial clusters in the late 2020s (all Hydrogen boilers).	Rollout of Hydrogen boilers limited to early deployment around industrial clusters, ensuring no new gas boilers are installed beyond 2035. 3.8m Hydrogen boilers are deployed by 2035. This assumes that areas are designated for conversion to hydrogen ahead of the fossil phase-out date of 2030, so these homes are exempted and able to remain on gas boiler heating (and install new Hy-ready gas boilers) until the grid has converted to hydrogen, by 2035 at the latest.
Widespread Engagement	None	None	None
Widespread innovation	Hybrid HPs only	Hydrogen trials of 300 homes in 2023, 3000 in 2024, and a further 3 pilots of 3000 homes each around industrial clusters in the late 2020s (all Hybrid HPs).	Rollout of Hybrid HPs limited to early deployment around industrial clusters. 3.4m Hybrid HPs are by 2035. The fossil phase-out date of 2035 means no exemptions are needed for the homes taking up hydrogen heating in this scenario.

[1] The technologies chosen are illustrative, and aim to represent a range of possible approaches across scenarios.

Hydrogen deployment trajectory – consistency with industry [3/3]

Scenario	Hydrogen technologies included[1]	Deployment trajectory pre-2030 (trials)	Deployment trajectory post-2030 (see next slide for further detail)
Headwinds	Hydrogen boiler and Hybrid HPs	Hydrogen trials of 300 homes in 2023, 3000 in 2024, and a further 3 pilots of 3000 homes each around industrial clusters in the late 2020s (all Hydrogen boilers).	Widespread rollout of Hydrogen boilers and Hybrid HPs across all regions between 2030 and 2050, in line with the national grid conversion trajectory. Assumes homes associated with clusters in the 'north' of the UK take up Hydrogen boilers (9.3m) whereas homes associated with clusters in the 'south' of the UK take up Hybrid HPs (9.5m)[2]. This assumes that areas are designated for conversion to hydrogen ahead of the fossil phase-out date of 2035, so these homes are exempted and able to remain on gas boiler heating (and install new Hy-ready gas boilers) until the grid has converted to hydrogen, by 2050 at the latest.

Hy-ready boiler mandation and scrappage costs

- All scenarios assume 2026 as the date when hy-ready boilers will be mandated. There remains optionality over this date, with possibilities ranging from mandating Hy-ready boilers early/for all households in order to minimise scrappage to mandating later/for a smaller number of homes in order to minimize the number of household exposed to inflated boiler costs.
- With the 2026 assumption, scrappage costs are low, at £20 million for the Balanced Pathway (compared to a total net investment cost of £256 billion), and £1.2 billion for the Headwinds scenario.
- There is effectively a trade-off between widespread early deployment of hy-ready boilers, such that all households are subject to a small premium in terms of boiler costs and scrappage costs are minimised, or later/more targeted mandation, whereby fewer household would be subject to a premium but scrappage costs would be higher.
- A sensitivity on the costs associated with scrappage costs assuming different hy-ready mandation dates was carried out (see slide).

[1] The technologies chosen are illustrative, and aim to represent a range of possible approaches across scenarios; [2] Cluster in the 'north' of the UK include Humberside, Teesside, Merseyside and Grangemouth; clusters in the 'south' of the UK include South Wales, Southampton and Isle of Grain / Medway. Based on Hybrid – H2 North scenario in Analysis of Alternative UK Heat Decarbonisation Pathways, Imperial College London for the CCC (2018).

Partial H2 grid conversion interpretations

- The interpretation of the hydrogen grid conversion differs between scenarios:
  - In the Headwinds scenario, all homes falling within the conversion area (which radiates out from the seven identified industrial clusters shown in the figure) get access to hydrogen. The uptake of hydrogen technologies grows in proportion to the number of homes that get access to hydrogen over time. The vast majority of homes within the conversion radius are converted to hydrogen.
  - In the Balanced Pathway scenario, it is assumed that the uptake of hydrogen technologies grows in proportion to the number of homes assumed to get access to hydrogen over time, as conversion radiates out from the industrial clusters. It is not assumed that the full stock of homes within each radius is converted to hydrogen, but rather a proportion. This reflects partial grid conversion within each radius and/or individual consumer preference on heating type.
  - In the Widespread Innovation and Tailwinds scenarios, it is assumed that the vast majority of homes within a radius get converted to hydrogen, but that hydrogen conversion stops after a certain point (set at 2035 in the modelling, when the maximum distance of a converted homes from an industrial cluster is 60 km). The date was chosen as it roughly corresponds to the point at which the number of homes on hydrogen in the end-states is reached.

Hydrogen deployment trajectory – timeline

2020 - 2023:
Feasibility studies completed for building trials, followed by infrastructure and household retrofits

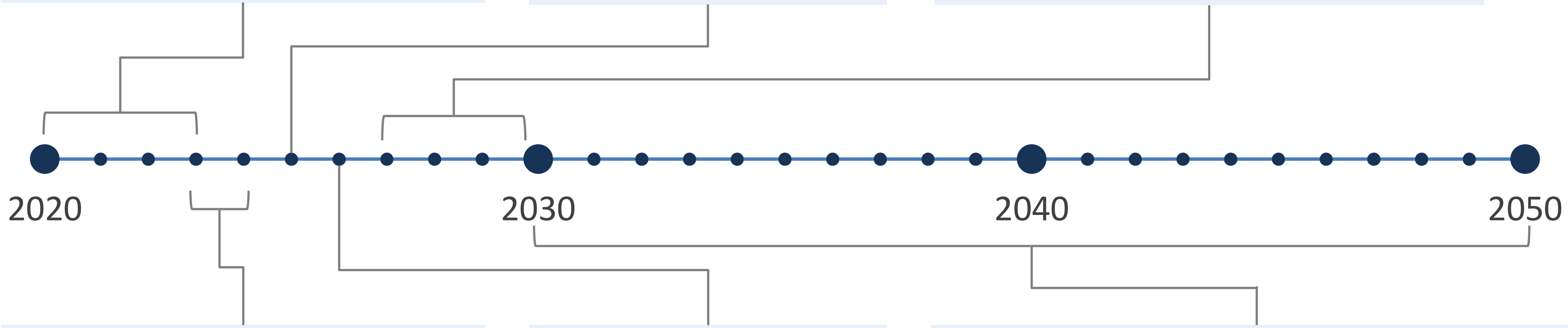
2023 - 2024:
Trial of 300 homes in 2023 (new distribution network), followed by 3000 homes in 2024 (repurposing of distribution network). Hydrogen supply likely via electrolysis

2025:
Decisions from 2025 on the future of gas grids and plan for delivery

2026:
All new boilers Hy-ready from 2025/2026 (assumption for scenario, options exist here)

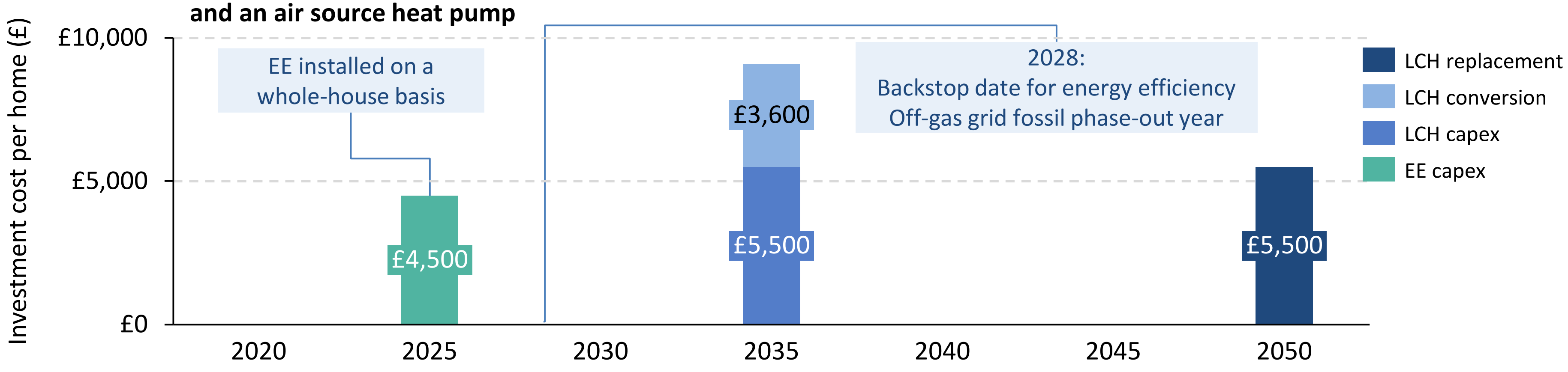
Late 2020s:
Preparations underway for widescale hydrogen rollout, pilots continue to roll out around industrial clusters (3 further pilots with 3000 homes each)

2030-2050:
Conversions commence from 2030 on a regional basis focused around key industrial clusters with full conversion targeted by 2050. Percentage of homes on gas grid with hydrogen is 20% by 2035, 56% by 2040, 93% by 2045 and 100% by 2050)

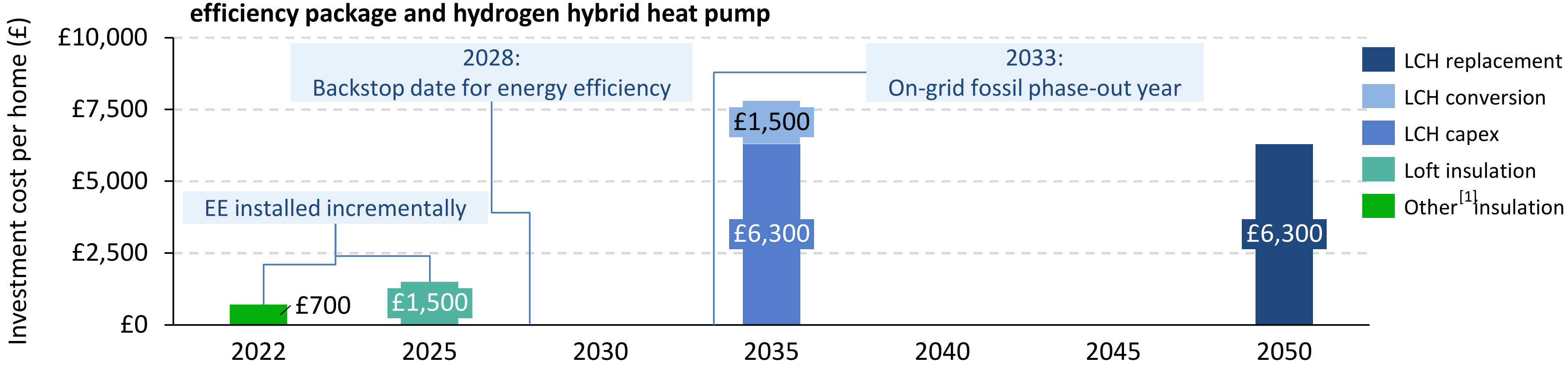


Illustrative pathways for selected archetypes in the Balanced Pathway scenario

In-year investment costs for an off-grid, fuel poor social home getting a high energy efficiency package and an air source heat pump



In-year investment costs for an on-grid, non-fuel poor, private rented home getting a medium energy efficiency package and hydrogen hybrid heat pump



- The illustrative timelines in the graphs above are not meant to indicate exactly when measures are installed.
  - Energy efficiency installation, which works on a “backstop” basis, can occur anytime up to the backstop date.
  - Low carbon heating installation can occur at any time, provided the necessary energy efficiency measures are in place, but is more likely to occur after the fossil phase-out date.

[1] Includes draught proofing and hot water tank insulation.

Contents

Balanced Pathway and Tailwinds scenarios headline outputs – emissions

	Direct emissions abatement[1]				Total emissions abatement[1]			
	2035	2035	2050	2050	2035	2035	2050	2050[2]
Scenario	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%
Balanced Pathway	25.8	43%	59.9	100%	24.3	41%	59.2	99%
Tailwinds	36.4	61%	59.9	100%	34.1	57%	59.4	99%

- The Balanced Pathway scenario represents 41% total yearly emissions abatement by 2035 at lowest cost, driven by:
  - deployment of 8 million heat pumps in existing homes (across stock segments), and
  - deployment of 11.9 million energy efficiency packages in existing homes across the private rented and local authority sectors in addition to all fuel poor homes (including owner-occupied fuel poor).
- The Tailwinds scenario represents 57% total yearly emissions abatement by 2035, nearly 50% higher than what is achieved by the Balanced Pathway, but at significantly higher cost (see next slide).

[1] Percentages represent yearly emissions abated as a % of baseline emissions in the specified year. [2] Total emissions abatement in 2050 varies slightly between scenarios due to the addition of indirect emissions associated with hydrogen and biofuel use.

Balanced Pathway and Tailwinds scenarios headline outputs – costs

			Total abatement costs (£bn)		Total net investment costs (£bn)[1]		Total net opex costs (£bn)		Total net costs (£bn)
Scenario	Average cost effectiveness (£/tCO_2)	Average abatement cost (£bn/y)	To 2035	To 2050	To 2035	To 2050	To 2035	To 2050	To 2050
Balanced Pathway	229	6.3	34.2	190	117	256	-11.1	-37.4	218
Tailwinds	303	9.8	70.5	295	155	259	-15.3	-48.4	211

- Total abatement costs to 2050 in the Balanced Pathway scenario are the lowest across scenarios, at £190 billion, whereas the highest costs are £295 billion in the Tailwinds scenario. Factors leading to the Balanced Pathway having the lowest cost include:
  - Other scenarios forcing in additional energy efficiency measures (further beyond those deemed cost-effective[2] by the model), such as in Tailwinds.
  - Other scenarios deploying relatively more expensive low carbon heating technologies.
  - Other scenarios (specifically Tailwinds and Widespread Innovation) being subject to a higher cost of capital associated with heat as a service.
- Total net investment costs to 2050 in the Balanced Pathway are £256 billion (representing an average of £9,000 per home), compared with £302 billion in Tailwinds (£10,700 per home). These costs represent the net investment costs over the period to 2050, including replacements[3] and net of the counterfactual boiler costs that would otherwise be incurred in the absence of any action being taken. Total investment costs to 2050 are £429 billion in the Balanced Pathway and £432 billion in Tailwinds.
- The Balanced Pathway scenario has the lowest (i.e. most favourable) average cost effectiveness, at £229/tCO_2
  - Average cost effectiveness is influenced both by total abatement costs and the total cumulative emissions abated. A scenario which reaches Net Zero earlier (e.g. Tailwinds) abates more emissions cumulatively (i.e. has higher yearly abatement for a longer period), so has a lower average cost effectiveness than a scenario with similar total abatement costs (e.g. Widespread Innovation; see slide for details regarding the cost effectiveness and average abatement cost of the exploratory scenarios).
- Investment costs only account for in-year, undiscounted capex, and therefore are unaffected by the cost of capital. Abatement costs, on the other hand, incorporate annualised capex discounted by the cost of capital in addition to opex and fuel costs discounted by the discount rate. The two figures are therefore not directly comparable.
  - The cost of capital used for Tailwinds (7.5%) is higher than that used for the Balanced Pathway scenario (3.5%) overpowering more ambitious assumptions on cost reductions and leading to higher abatement costs in Tailwinds (see slide). The higher cost of capital is applied to both low carbon heating systems and energy efficiency measures. This is a pessimistic assumption, which partially explains the higher abatement costs.

[1] See footnote on slide; [2] Cost-effectiveness is defined as the cost of a measure per unit of emissions abated, in £ per tonne of CO_2e. The costs do not account for wider social benefits such as improved health; [3] I.e. the costs associated with installing a second heat pump after the first has reached end of life.

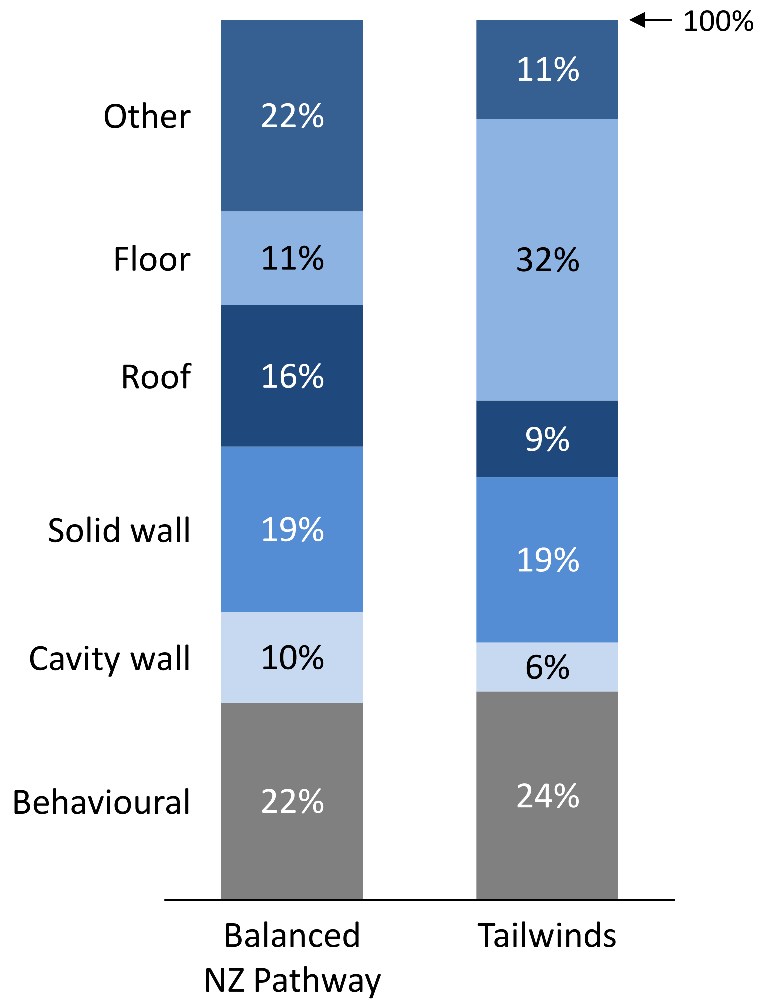
Balanced Pathway and Tailwinds scenarios headline outputs – behavioural

- In both central scenario cases, behavioural measures constitute the largest or second-largest share of demand-side savings. Relative to the overall scenario savings,
  - the Balanced Pathway sees a 22.4% contribution; and
  - the Tailwinds scenario sees a 23.6% contribution, with the highest TWh savings (aligned to Widespread Engagement) of all scenarios.
- These savings are achieved differently, as each scenario accounts for a different level of behavioural engagement from consumers:

Behavioural measure	Balanced Pathway	Tailwinds
Pre-heating	Permitted in 25% of post-1952 homes.	Permitted in 50% of post-1952 homes
Heat as a service	No	Yes [a]
Smart metering & control	Standard smart meter [b]	Smart meter with zonal control [c]
Reduced water temperature	No	No
Low flow shower head	Yes	

[a] Heat as a service modelled using: 7.5% cost of capital, 5% increase in heat demand, 3% financial savings, 15% increase in heat pump efficiency.
[b] Heat demand reduction based on actions including turning thermostat down and changing operating times.
[c] Heat demand reduction based on implementation of automated multizone control.

% of scenario's total TWh savings from energy efficiency and behaviour change



Balanced Pathway and Tailwinds scenarios headline outputs – energy efficiency uptake

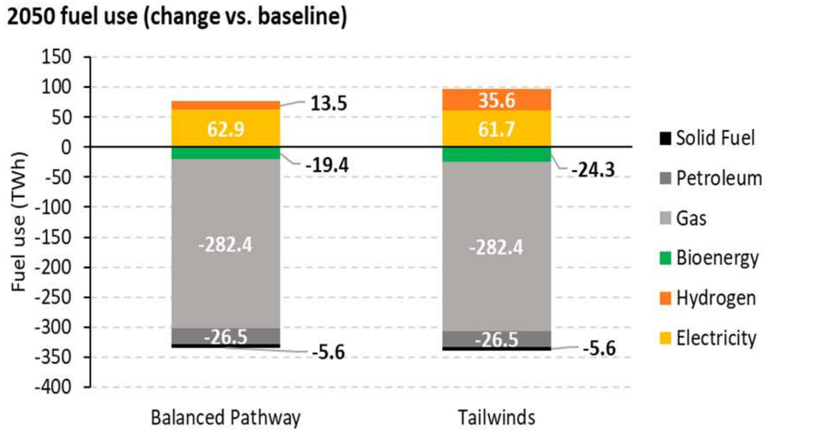
- Energy efficiency levels are driven by different factors in each scenario:
  - **Balanced Pathway:** All practicable lofts and cavities insulated, in addition to all solid walls in packages under £600/tCO_2e. In non-fuel poor homes, most such solid walls are deployed in owner-occupied homes, primarily those installing an air-source heat pumps or low carbon heat networks. More generally, larger homes tend to make most cost-effective candidates for solid wall insulation.
  - **Tailwinds:** Full economic potential for all energy efficiency measures.
- Solid walls in fuel poor homes are insulated across scenarios (implemented via a High package).
  - Given the high uncertainty over the achievable performance and costs of solid wall insulation, a broad range of uptake levels was modelled across the scenarios, with Max representing full economic potential.
- The overall figure for heat demand reduction masks significant variation across homes:
  - In the Balanced Pathway scenario, a typical home which installs cavity wall insulation, loft insulation, and floor insulation sees heat demand savings of 30%.
  - The overall figure is lower – at 12% – due to many homes having existing energy efficiency measures (and therefore lower capacity for further savings), or having very hard to treat lofts and cavities which mean they are not deemed economic to insulate[1].

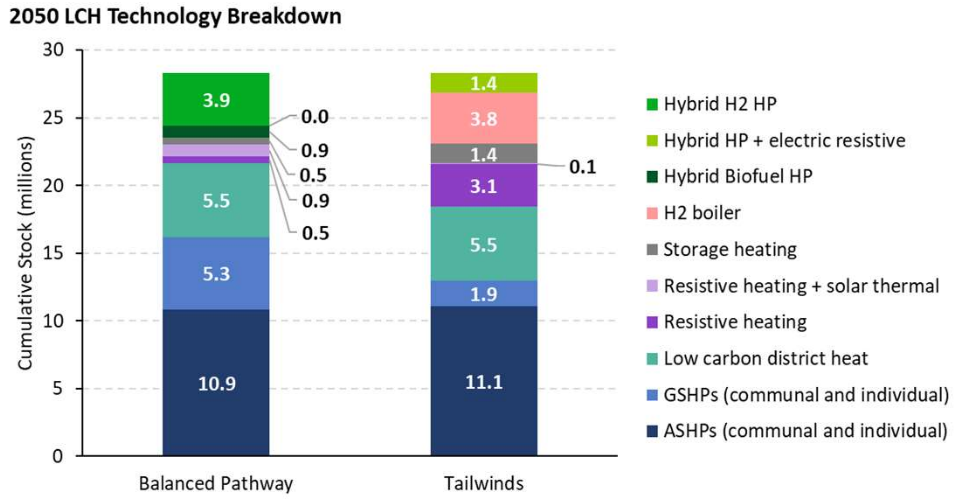
Number deployed (millions)	Balanced Pathway	Tailwinds
Measure		
Loft	10.8	10.8
Cavity wall	3.1	3.1
Solid wall	3.4	7.1
Floor	3.4	21.1
Other	28.3	28.3
Behavioural	28.3	28.3
Package		
None	0	0
Low	6.8	0.3
Medium	13.5	0.3
High	8.0	27.8
Energy demand savings (TWh/yr)	37	68
Total heat demand in 2017 (TWh/yr)	313	
Total heat demand in 2050 (TWh/yr)	276	245
Reduction in heat demand as a result of energy efficiency	12%	22%

[1] The lower stock-level heat demand savings relative to the Net Zero analysis reflect a number of factors, including updated savings assumptions based on data from the National Energy Efficiency Database, and the latest evidence on costs and technical and economic potential. These factors lead to lower deployment relative to Net Zero, but similar deployment to that modelled for the Fifth Carbon Budget.

Balanced Pathway and Tailwinds scenarios headline outputs – fuel use change and low carbon heating uptake [1/2]

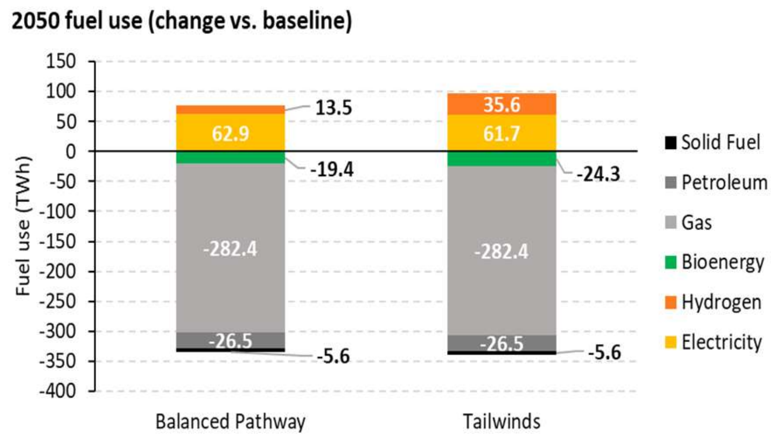
- The technology mixes shown in all scenarios are intended to represent different approaches and a range of possible realities across scenarios. The split between different technologies, particularly types of heat pumps, remains illustrative with multiple variations possible.
- Heating demand from low carbon heat networks is 45.2 TWh in the Balanced Pathway, compared to 40.7 TWh in Tailwinds. The lower value in tailwinds is due to the higher levels of energy efficiency in the scenario.
- Hydrogen fuel use in Tailwinds is relatively high, at 35.6 TWh, compared to only 13.5 TWh in the Balanced Pathway, due to:
  - Tailwinds deploying 3.8 million H_2 boilers.
  - The Balanced Pathway deploying 3.9 million hybrid H_2 heat pumps, which use significantly less hydrogen than boilers.
  - Both scenarios represent partial grid conversion (see slide).
- The increase in electricity use in the Balanced Pathway and Tailwinds scenarios is of similar value, due to:
  - The Balanced Pathway deploying significantly more heat pumps.
  - Tailwinds deploying a large amount of direct electric heating technologies, which are less efficient than heat pumps.

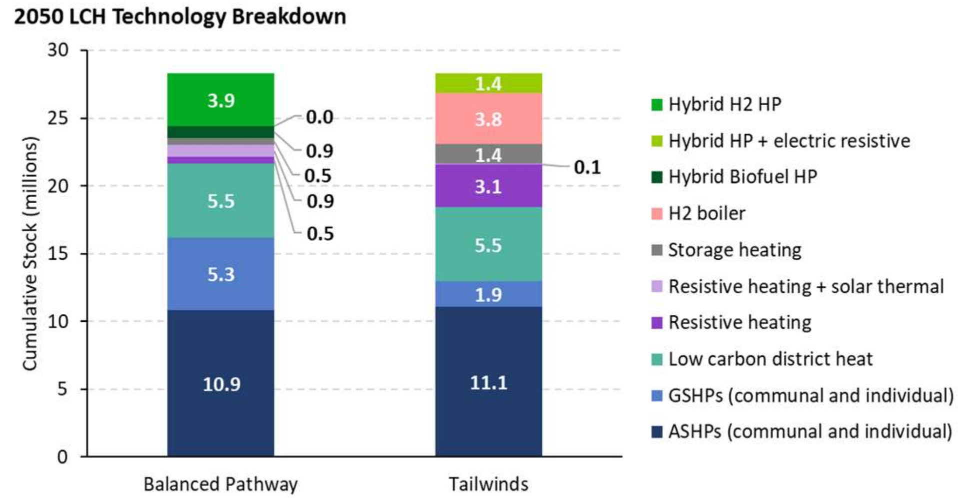




Balanced Pathway and Tailwinds scenarios headline outputs – fuel use change and low carbon heating uptake [2/2]

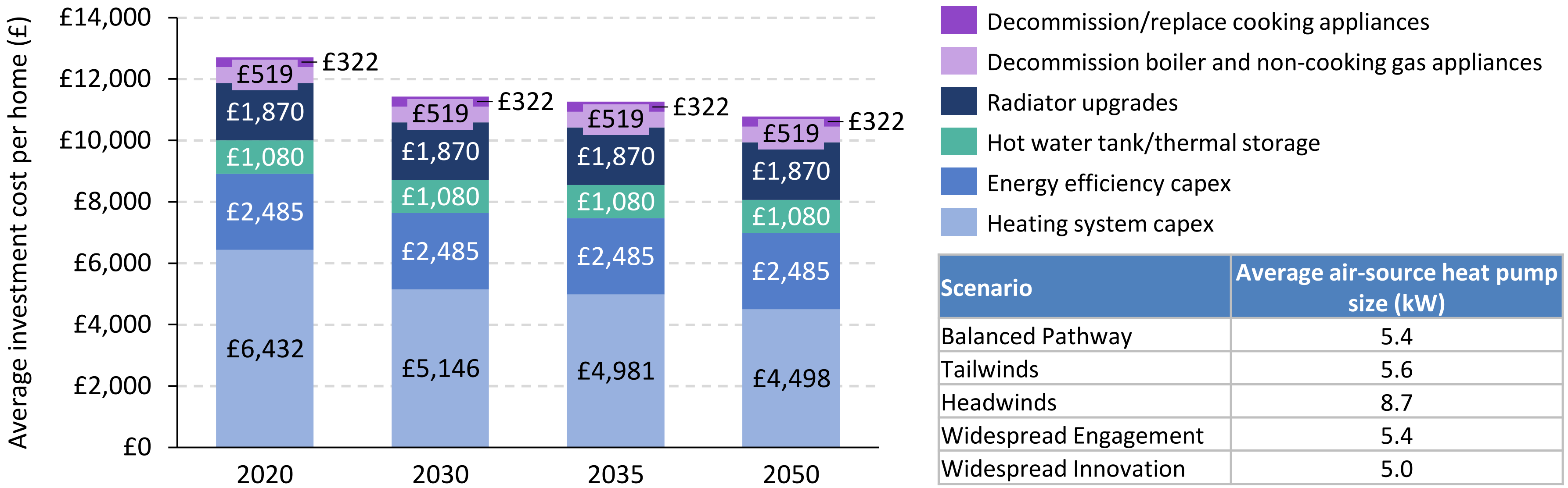
- The main features of the technology mix in the Balanced Pathway include:
  - ASHPs as the dominant heat pump technology, accounting for 75% of all heat pump installations.
  - Significant uptake of GSHPs, which make up 33% of all sole heat pump installations and 25% of all heat pump installations including hybrids.
  - Just under 50% of homes installing direct electric heating technologies utilise solar thermal to help meet both space heating and hot water demands.
  - The remainder of homes installing direct electric heating install some form of storage (either directly as storage heaters or as additional heat batteries).
  - In total, 1.4 million homes (5% of the stock) install some form of heat storage.
  - 17% of homes install hybrid heat pumps. Hybrids potentially have larger transitional role which can be an area for future work.
- The main features of the technology mix in the Tailwinds scenario include:
  - Deployment of 3.8 million H_2 boilers (assuming partial grid conversion, see slide).
  - A relatively high deployment of direct electric heating (4.7 million units), which mostly displace heat pumps. This is driven by the lower electricity costs assumed in Tailwinds.





Average investment cost for the uptake of an air-source heat pump in the Balanced Pathway scenario

Average required capital expenditure[1] in Balanced Pathway for a home getting an ASHP[2] in various years



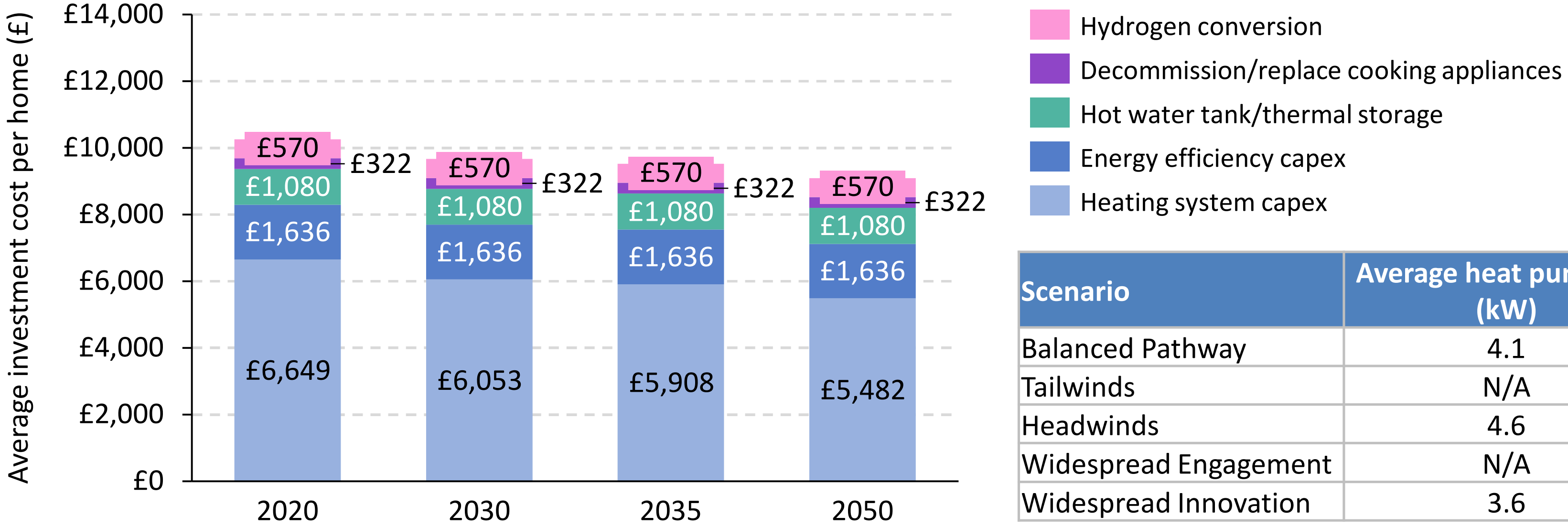
Scenario	Average air-source heat pump size (kW)
Balanced Pathway	5.4
Tailwinds	5.6
Headwinds	8.7
Widespread Engagement	5.4
Widespread Innovation	5.0

- For a home upgrading in 2020, the cost of a heat pump makes up the majority of the total investment cost, which comes out at just over £13,000. Radiator upgrades add to the costs substantially, but could be reduced
- As technology/labour costs fall, both total investment cost and heat pump cost as a % of total investment fall. The latter is due to conversion costs and energy efficiency measure costs modelled as stagnant with time.
  - The reduction in the capital cost of a heat pump is attributed to the increased maturity of the market and the supply chain over time. The % reduction between 2020 and 2050 was tested with external heat pump stakeholders and ranges from 30% to 40% depending on scenario.
- The relatively low cost of energy efficiency due to a significant share of the heat pump uptake occurring in already insulated homes.
- The average heat pump size across scenarios is between 5 and 6 kW. The exception is Headwinds where the average size is nearly 9 kW. This is likely due to the lower levels of energy efficiency seen in that scenario, alongside the lower load factors assumed which will be driving larger heat pumps.

[1] Costs are absolute costs, not net costs i.e. the cost of a counterfactual system has not been subtracted. [2] HP costs correspond to the most common technology configuration rather than an average of all modelled configurations, which is only slightly different.

Average investment cost for the uptake of a hybrid air-source heat pump with H_2 boiler in the Balanced Pathway scenario

Average required capital expenditure[1] in Balanced Pathway for a home getting a hybrid ASHP with H_2 boiler[2] in various years



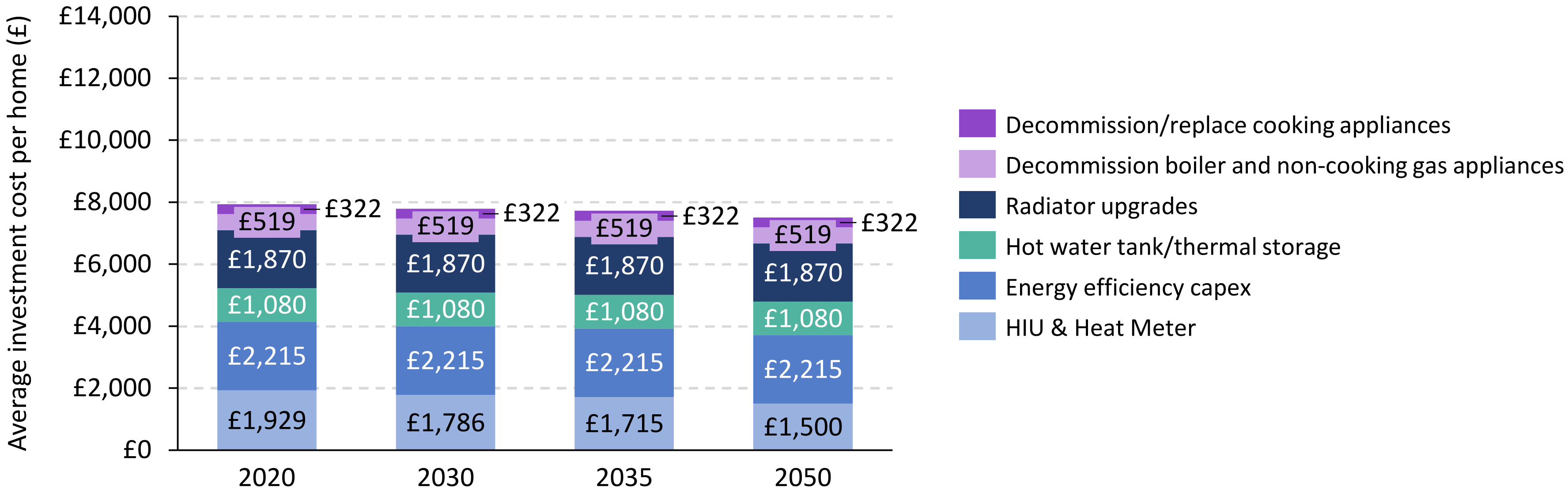
Scenario	Average heat pump size (kW)
Balanced Pathway	4.1
Tailwinds	N/A
Headwinds	4.6
Widespread Engagement	N/A
Widespread Innovation	3.6

- For a home upgrading in 2020, the cost of the hybrid heat pump makes up the majority of the total investment cost, which comes out at just over £10,000.
  - The lower total cost when compared to a sole heat pump (i.e. not a hybrid) is due to lower conversion costs, as radiator upgrades are not required for hybrid systems with boilers.
- Due to the lower conversion costs and average energy efficiency costs, the cost of the heating system remains the biggest component of the total investment cost, despite cost reductions over time.
- The relatively low cost of energy efficiency measures is due to a significant share of the heat pump uptake occurring in already insulated homes in addition to the potentially low value of fuel cost savings compared to the cost of energy efficiency.
- The average system size across scenarios is ~4 kW. This is lower than the average size for pure heat pumps, which explains the near-equivalence in the costs of the two systems in 2020.
  - Costs diverge in later years due to the boiler component of hybrid systems not being affected by cost reductions.

[1] Costs are absolute costs, not net costs i.e. the cost of a counterfactual system has not been subtracted. [2] HP costs correspond to the most common technology configuration rather than an average of all modelled configurations, which is only slightly different.

Average investment cost to connect to a low carbon heat network in the Balanced Pathway scenario

Average required capital expenditure[1] in Balanced Pathway for a home connecting to a low carbon heat network[2] in various years



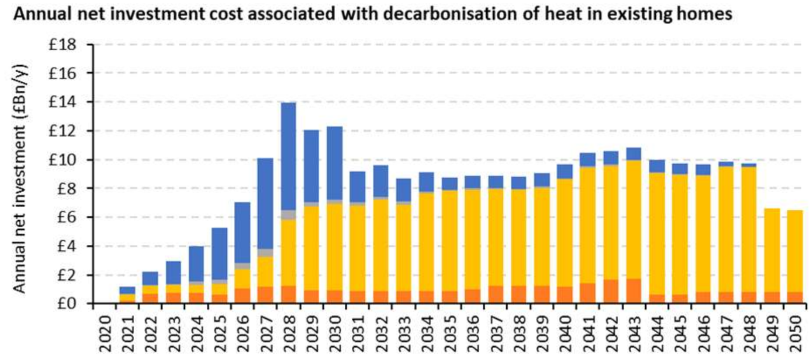
- Low carbon heat networks are one of the cheapest options when it comes to replacing one's counterfactual heating system, with an average total cost of £8,000 in 2020.
  - The lower total cost when compared to heat pumps is primarily due to the lower capital costs; connecting to a low carbon heat network only requires the installation of a heat interface unit (HIU) and a heat meter.
  - Due to the relatively small contribution of capex to total investment cost, cost reductions over time do not lead to significant reduction in the total investment cost.
  - Radiator upgrades are required for vast the majority of homes connecting to low caron heat networks, given that deployment is focused in homes with the highest baseline heating demand (see slide and slide).
- It should be noted that the approach used for costing low carbon heat networks is slightly different to that used for other heating systems (see slide).
- Since connecting to a low carbon heat network does not involve installing an actual system in the home, there is no average system size.

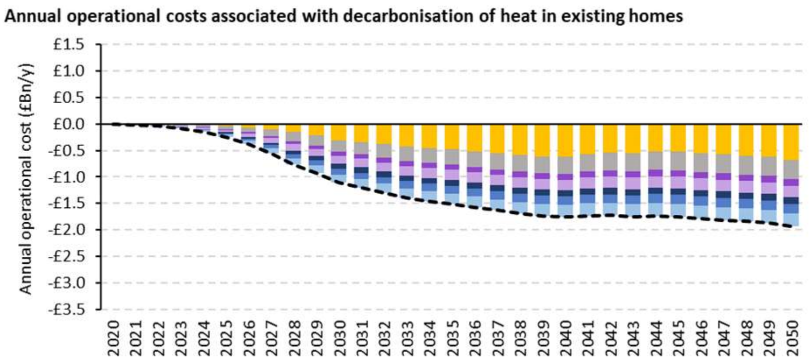
[1] Costs are absolute costs, not net costs i.e. the cost of a counterfactual system has not been subtracted. [2] For low carbon heat networks, the heating system capex is the cost of a heat interface unit (HIU) and a heat meter. Costs obtained from Research on district heating and local approaches to heat decarbonisation, Element Energy et al. for the CCC (2015).

Balanced Pathway and Tailwinds scenarios headline outputs – cost trajectories

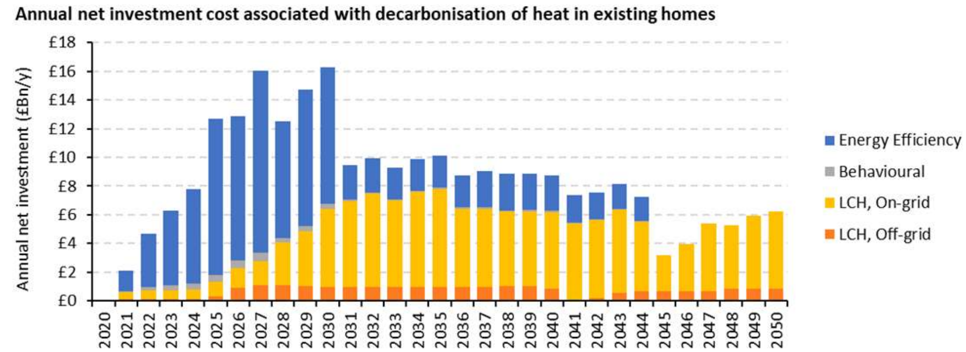
- The Tailwinds scenario shows that there is potential for more ambitious early deployment of energy efficiency which can successfully drive opex costs down; this could result in higher fuel bill savings for households.
  - Total energy efficiency investment to 2030 in the Balanced Pathway is £36 billion, compared to £78 billion in Tailwinds (which assumes lower bound costs for energy efficiency measures)[1].
  - The higher investment delivers higher savings (22% versus 12% on average across the stock).
  - The deployment of 4 million H_2 boilers partially counteracts the savings from higher investment in energy efficiency, due to high H_2 fuel costs. The use of more optimistic assumptions on LCH cost reduction also contributes to the lower LCH costs.
  - These factors result in similar total investment costs being seen across the two scenarios. Substantially higher opex savings are achieved which are expected to be a function both of lower energy use, and more ambitious assumptions on low-carbon fuel costs.
- Whilst ambitious, the Balanced Pathway scenario represents a moderate level of energy efficiency deployment – there is scope to go further to achieve higher savings and deliver wider benefits.

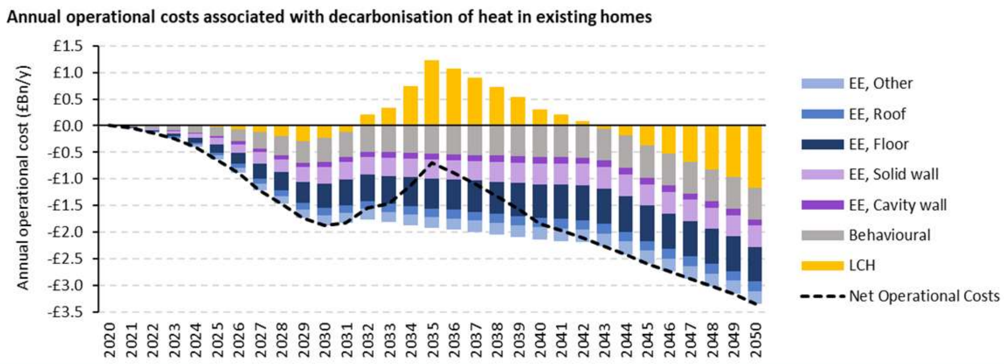
Balanced Pathway – total investment cost £256 Bn





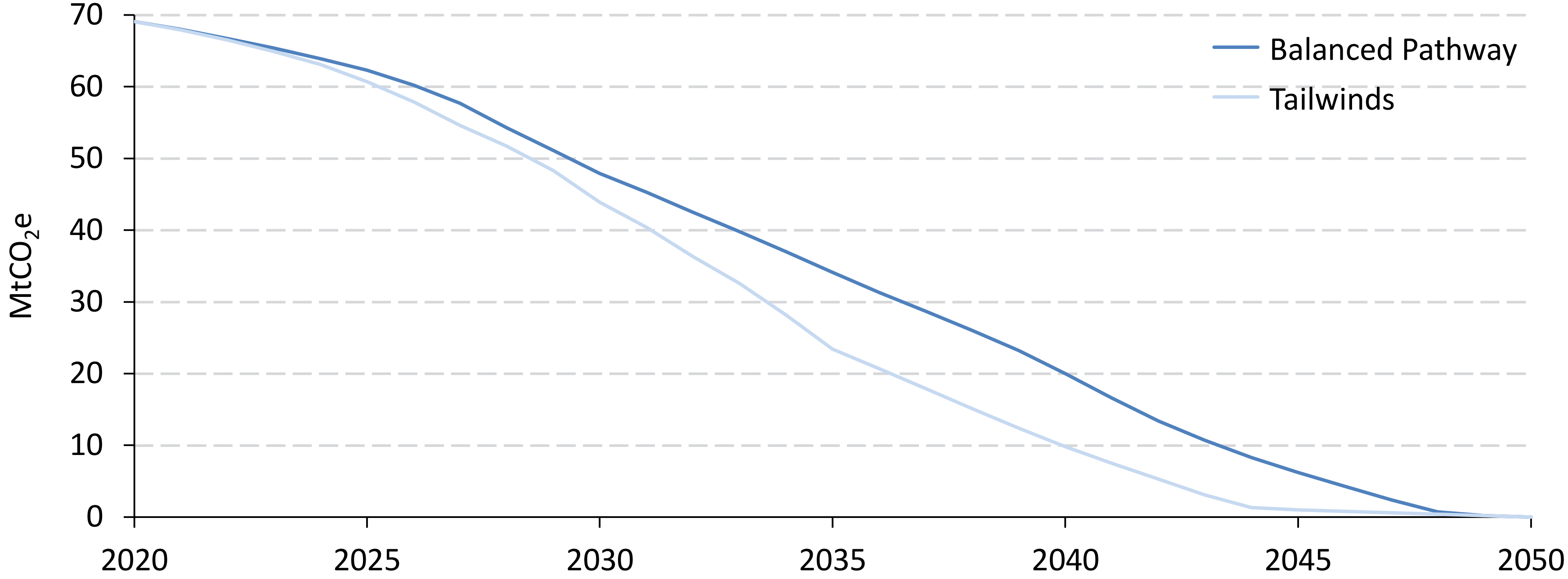
Tailwinds – total investment cost £259 Bn





[1] Including behavioural measures.

Balanced Pathway and Tailwinds scenarios headline outputs – emissions trajectories



- The faster decarbonisation in the Tailwinds scenario – which effectively reaches Net Zero in 2044, compared to 2048 for the Balanced Pathway scenario – is due to:
  - More ambitious deployment of energy efficiency.
  - Deployment of 3.9 million hydrogen boilers by 2035 (see slide) – the noticeable reduction in the rate of decarbonisation in Tailwinds after 2035 is due to completing this deployment by then.
  - Earlier fossil phase-out dates – set at 2026 for off-grid homes and 2030 for on-grid homes – and a slightly faster technology replacement rate (see slide) allowing homes to have installed a low carbon heating system by 2044.
    - The few systems installed after 2044 are low carbon heat networks, which follow a deployment trajectory based on geographical conversion and hence are not modelled as subject to the fossil phase-out date.

Balanced Pathway and Tailwinds scenarios headline outputs – emissions by Devolved Administration

Emissions	Direct emissions abatement				Total emissions abatement			
	2035	2035	2050	2050	2035	2035	2050	2050
DA	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%
Balanced Pathway								
UK	25.8	43%	59.9	100%	24.3	40%	59.2	99%
Scotland	1.8	42%	4.4	100%	1.7	39%	4.3	99%
Wales	1.2	43%	2.8	100%	1.1	39%	2.8	99%
Northern Ireland	1.2	61%	1.9	100%	1.1	55%	1.9	99%
Tailwinds								
UK	36.4	61%	59.9	100%	34.1	56%	59.4	99%
Scotland	2.4	55%	4.4	100%	2.3	52%	4.3	99%
Wales	1.6	56%	2.8	100%	1.5	53%	2.8	99%
Northern Ireland	1.3	67%	1.9	100%	1.2	63%	1.9	99%

- The vast majority of emissions abatement in the UK is attributable to England, which in the Balanced Pathway scenario accounts for 20.4 $MtCO_2e$ of total emissions abatement by 2035, out of a total of 24.3 $MtCO_2e$ (84%).
  - The share of abatement by devolved administration reflects the share of the total UK population in each devolved administration[1].
- Northern Ireland decarbonises significantly faster than the UK as whole and other devolved administrations due to having a much larger share of off-grid homes (according to the stock data – see slide), which are prioritised to receive low carbon heating systems before on-grid homes.
- The scenarios do not differentiate between England and the devolved administrations in terms of the of regulatory levers applied, although it remains the case that there is scope for some parts of the UK to pursue higher levels of ambition than others.

[1] Office of National Statistics, 2019

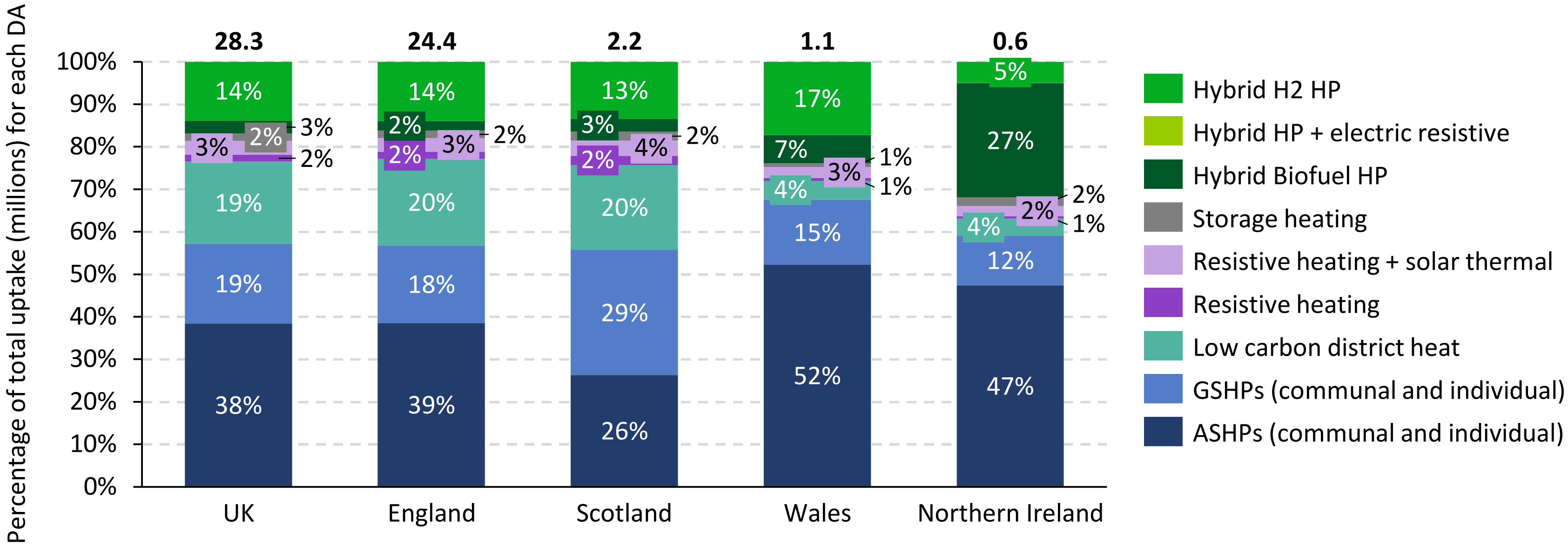
Balanced Pathway and Tailwinds scenarios headline outputs – costs by Devolved Administration

Costs			Total abatement costs (£bn)		Total net investment costs (£bn)		Total net opex costs (£bn)		Total net costs (£bn)[1]
DA	**Average cost effectiveness (£/tCO_2)**	**Average abatement cost (£m/y)**	**To 2035**	**To 2050**	**To 2035**	**To 2050**	**To 2035**	**To 2050**	**To 2050**
				Balanced Pathway					
UK	229	6,329	34	190	117	256	-11	-37	218
Scotland	214	427	2.2	12	7.8	18	-0.7	-2.6	15
Wales	217	275	1.5	8.3	4.4	10.4	-0.3	-0.9	9.5
Northern Ireland	180	189	1.6	5.7	3.0	6.4	-0.1	-1.0	5.4
				Tailwinds					
UK	303	9,832	71	295	155	259	-15	-48	211
Scotland	266	610	4.3	18	10	18	-1.2	-4.8	13
Wales	267	392	2.8	12	6.5	11	-0.8	-3.1	8.2
Northern Ireland	182	198	1.8	5.9	4.1	7.1	-0.8	-3.9	3.1

- Cost trends for the devolved administrations are similar to emissions abatement trends.
  - By 2035, total net investment costs for England in the Balanced Pathway scenario (£102 million) constitute 87% of the UK total.
  - In the Tailwinds scenario, net opex savings by 2050 in Northern Ireland are equivalent to 55% of net investment costs (compared to 19% for the UK as a whole), primarily due to:
    - Increased incidence of off-grid homes in Northern Ireland, which cannot uptake any of the 3.9 million (high fuel cost) hydrogen boilers deployed in the scenario.
- Total investment costs, by devolved administration in the Balanced Pathway are as follows: £429 billion (UK), £31.5 billion (Scotland), £17.7 billion (Wales), and £10.5 billion (Northern Ireland). A similar trend is seen in the Tailwinds and alternative scenarios.

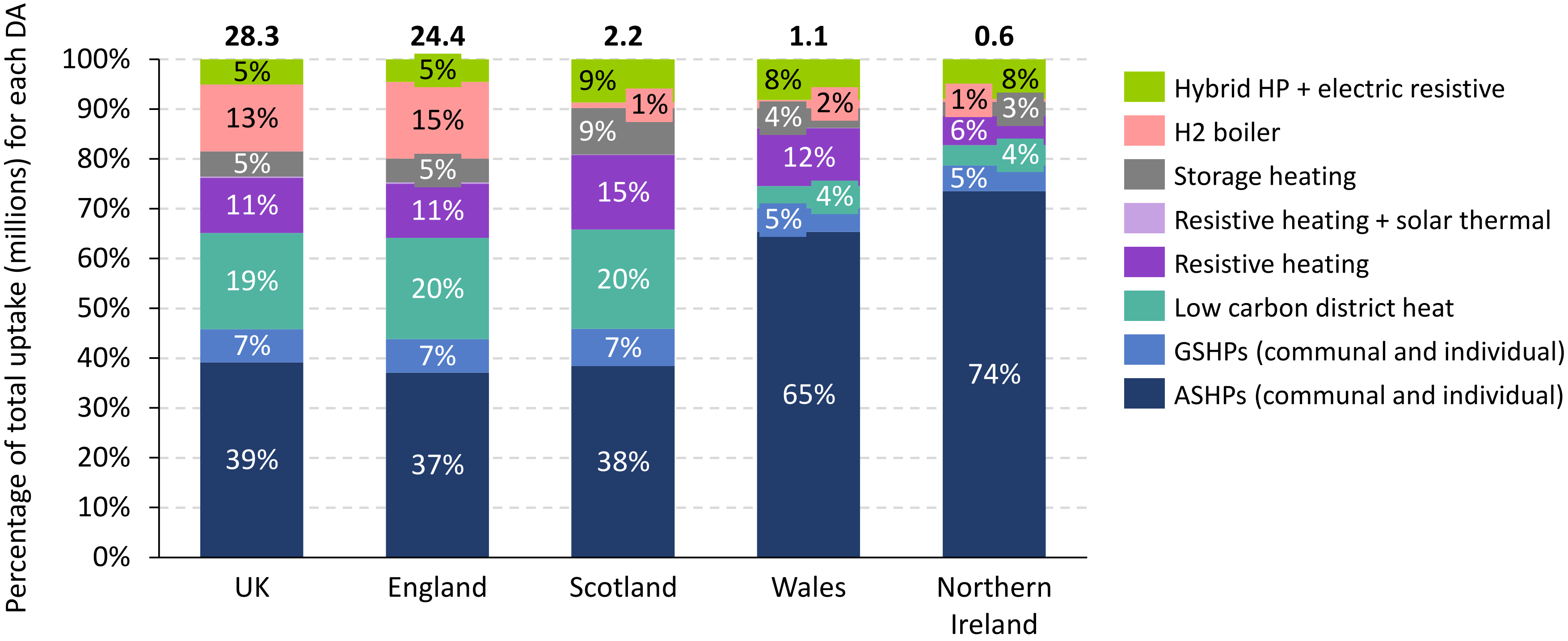
[1] Values may not match sum of net investment and opex due to rounding

Balanced Pathway – summary of heating system deployment across Devolved Administrations



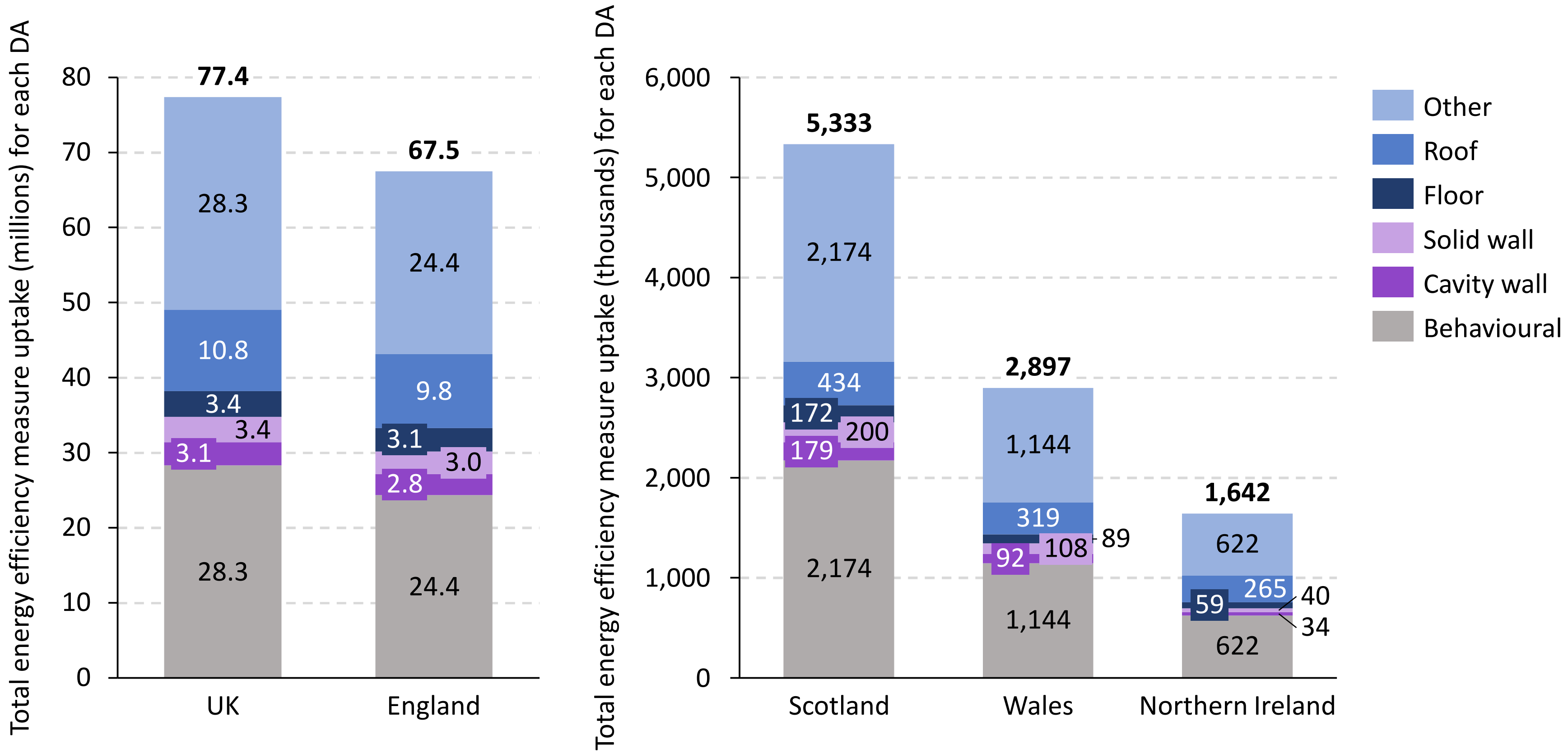
- Relative to low carbon heating deployment across the UK, Scotland has a higher proportion of ground source heat pumps, whilst Wales has a higher proportion of air source heat pumps.
  - Given that Devolved Administration (DA) was not itself a factor determining heating system uptake in the modelling, the differences in the mixes between DA's are attributable only to the different stock characteristics in each DA (e.g. more off-grid homes in Northern Ireland).
  - In Scotland, the relatively higher proportion of ground-source heat pumps is due to higher uptake of communal systems. Unlike pure heat pumps (where air-source is typically more favourable than ground-source based on the modelling assumptions), communal ground-source heat pumps are slightly more cost-effective over their lifetime compared to the air-source equivalent in the modelling, due to higher lifetimes and better efficiencies.
- Heat pumps are more common in Wales and Northern Ireland, partly due to the low proportion of homes which are suitable for (and hence uptake) low carbon heat networks.
- Hybrid biofuel heat pumps make up a significant share of final uptake in Northern Ireland, due to the prevalence of off-gas grid homes (which also explains the lower uptake of hybrid H_2 heat pumps).

Tailwinds – summary of heating system deployment across Devolved Administrations



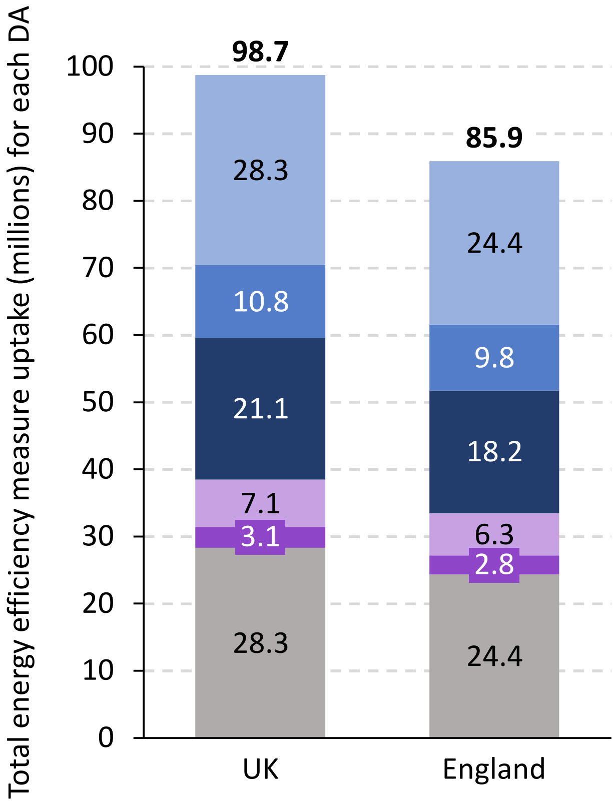
- The vast majority of the 3.9 million hydrogen boilers deployed in Tailwinds are found in England, with few deployed in the other devolved administrations.
  - This is again primarily due to the stock characteristics, with most on-grid homes being situated in England.
- Heat pumps are more common in Wales and Northern Ireland, partly due to the low proportion of homes which are suitable for (and hence uptake) low carbon heat networks.
- Hybrid biofuel heat pumps make up a significant share of final uptake in Northern Ireland, due to the prevalence of off-gas grid homes (which also explains the lower uptake of hybrid H_2 heat pumps).

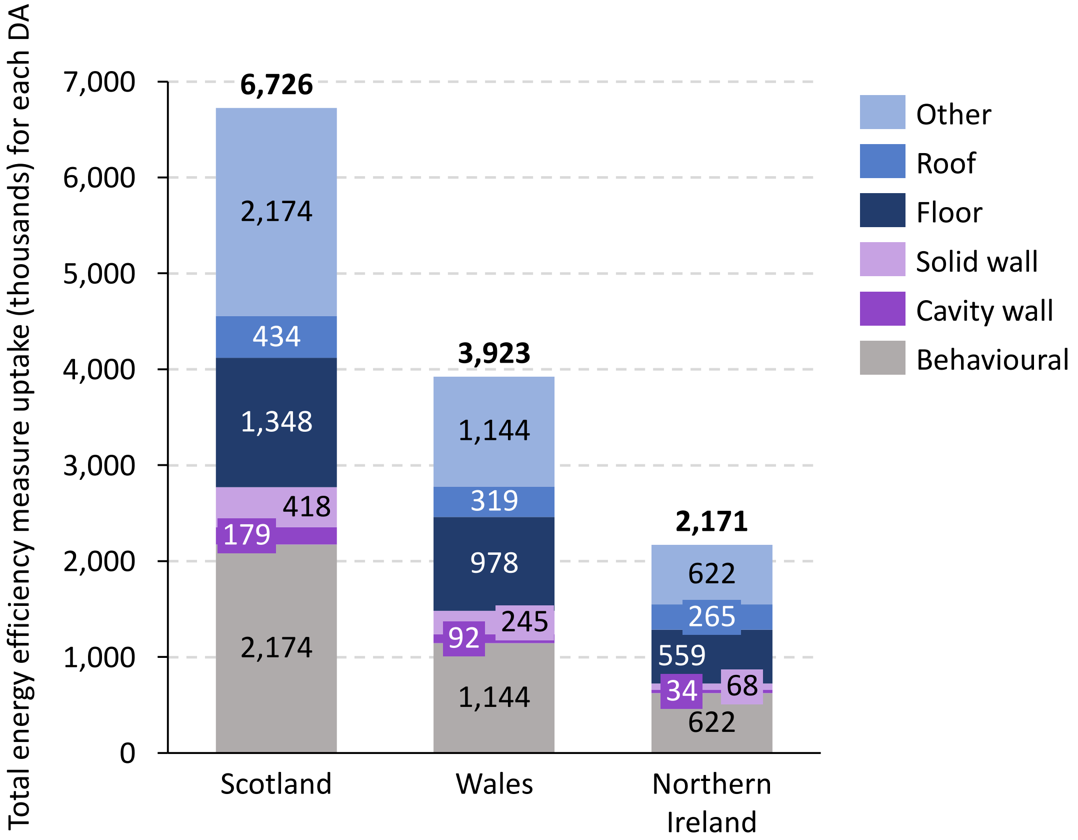
Balanced Pathway – summary of energy efficiency deployment across Devolved Administrations



- Deployment is dominated by Behavioural and Other measures across devolved administrations, as those are modelled to deploy across the stock, whereas the other fabric measures are deployed by package and only where applicable.
- 200,000 solid walls are deployed in Scotland, 108,000 in Wales and 40,000 in Northern Ireland.
- 179,000 cavity walls are deployed in Scotland, 92,000 in Wales and 34,000 in Northern Ireland.

Tailwinds – summary of energy efficiency deployment across Devolved Administrations





- The Max scenario deploys the full economic potential of energy efficiency across the stock, therefore any variations between devolved administrations are due primarily to the features of the existing stock.
  - For instance, a relatively large number of floor insulation measures deployed in Wales and Northern Ireland suggests homes in those devolved administrations are more likely to have uninsulated floors.
- A significantly larger number of energy efficiency measures is deployed in Tailwinds compared to the Balanced Pathway.
  - 418,000 solid walls are deployed in Scotland, with 245,000 in Wales and 68,000 in Northern Ireland.

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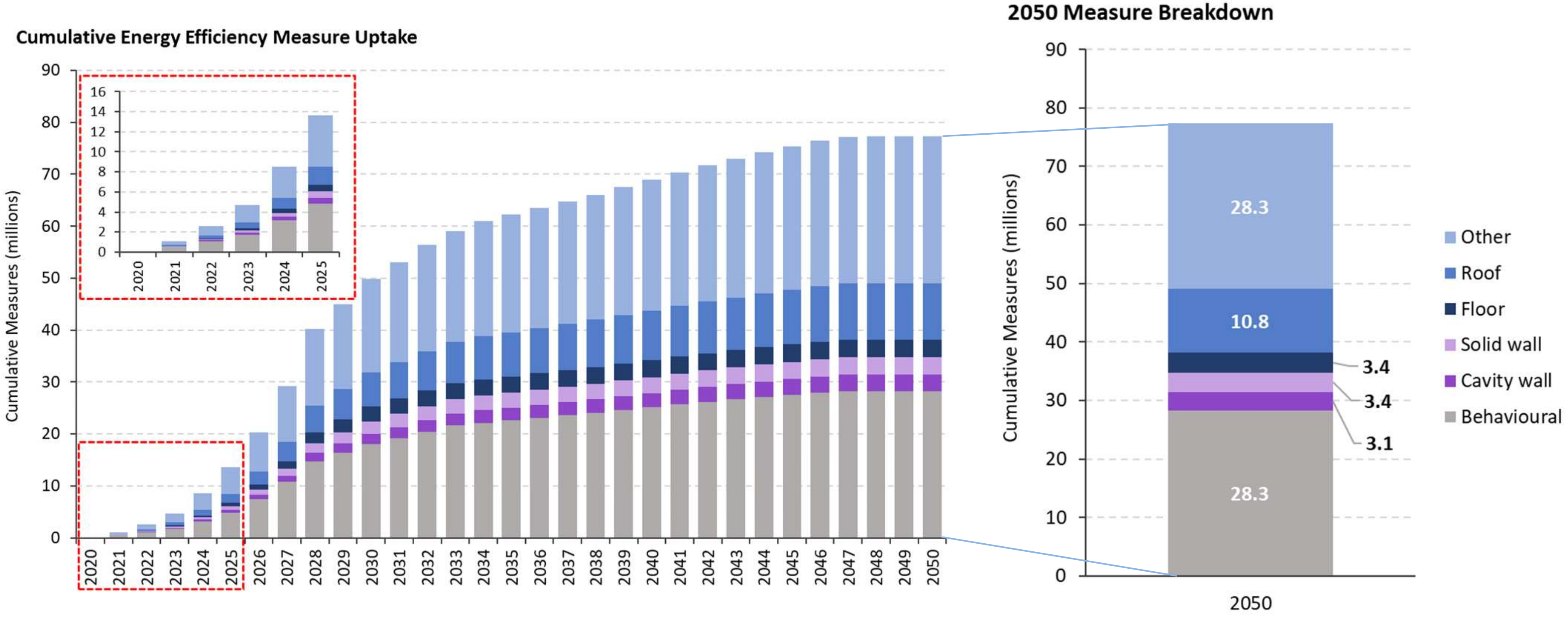
Balanced Pathway – cumulative energy efficiency uptake trajectory

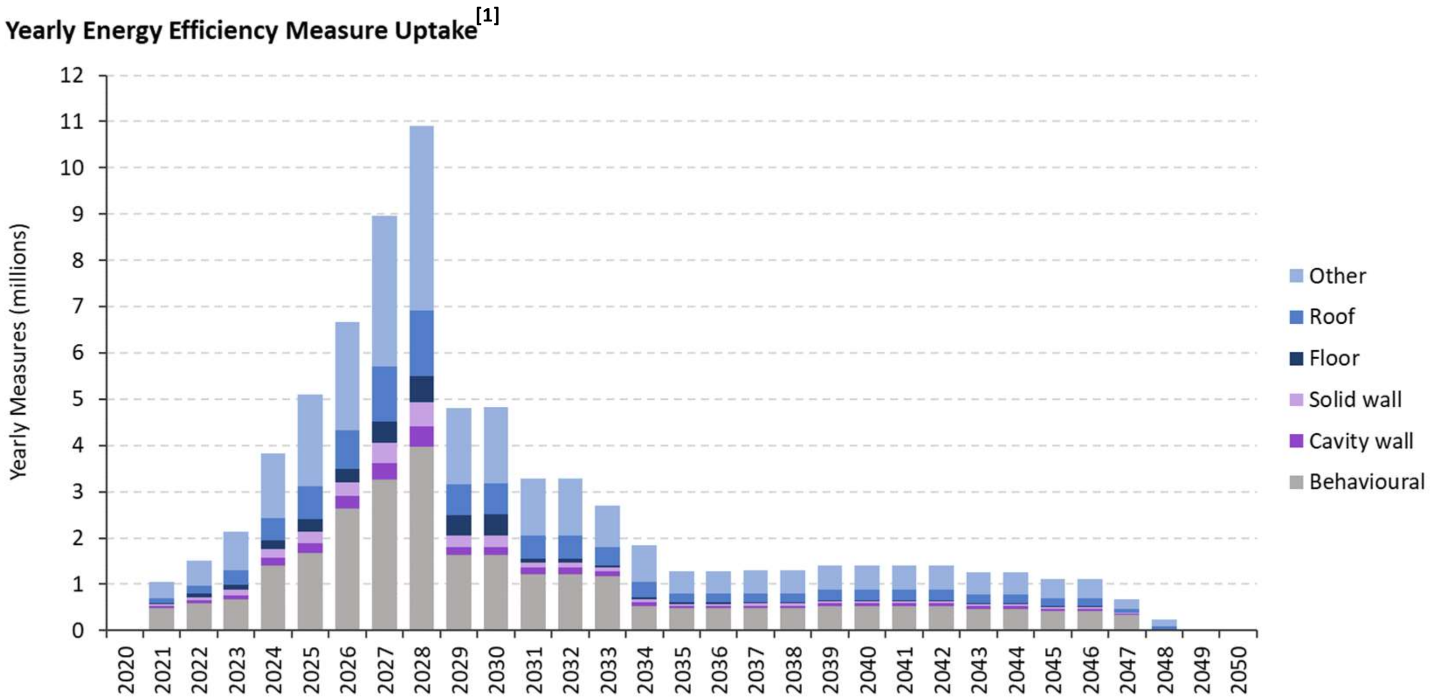
- A once-in-a-lifetime infrastructure programme is required to upgrade the efficiency of UK homes. All scenarios are based on an "energy efficiency first" approach, with a view to preparing the stock for low carbon heating technology uptake and reducing emissions and fuel bills in the near term, and hence require rapid ramp-up of energy efficiency uptake.
  - The trajectory in the Balanced Pathway implies that by 2025, cumulative new measure deployment should reach 1.8 million loft insulation measures (including top-ups), 550,000 cavity walls insulated, and 670,000 solid walls insulated[1].
  - 64% of all energy efficiency measures are installed in the first 10 years of the trajectory (i.e. to 2030), with 76% deployed by the fossil phase-out date of 2033.
- The Balanced Pathway scenario represents a level of energy efficiency uptake which maximises uptake of low cost, low disruption measures such as draught proofing, loft insulation and cavity wall insulation, with moderate uptake of solid wall insulation.



[1] Technical potential for modelling accounted for existing installations to December 2019. Installations from 2020 onwards would be counted as 'new' installations on this basis.

Balanced Pathway – in-year energy efficiency uptake trajectory

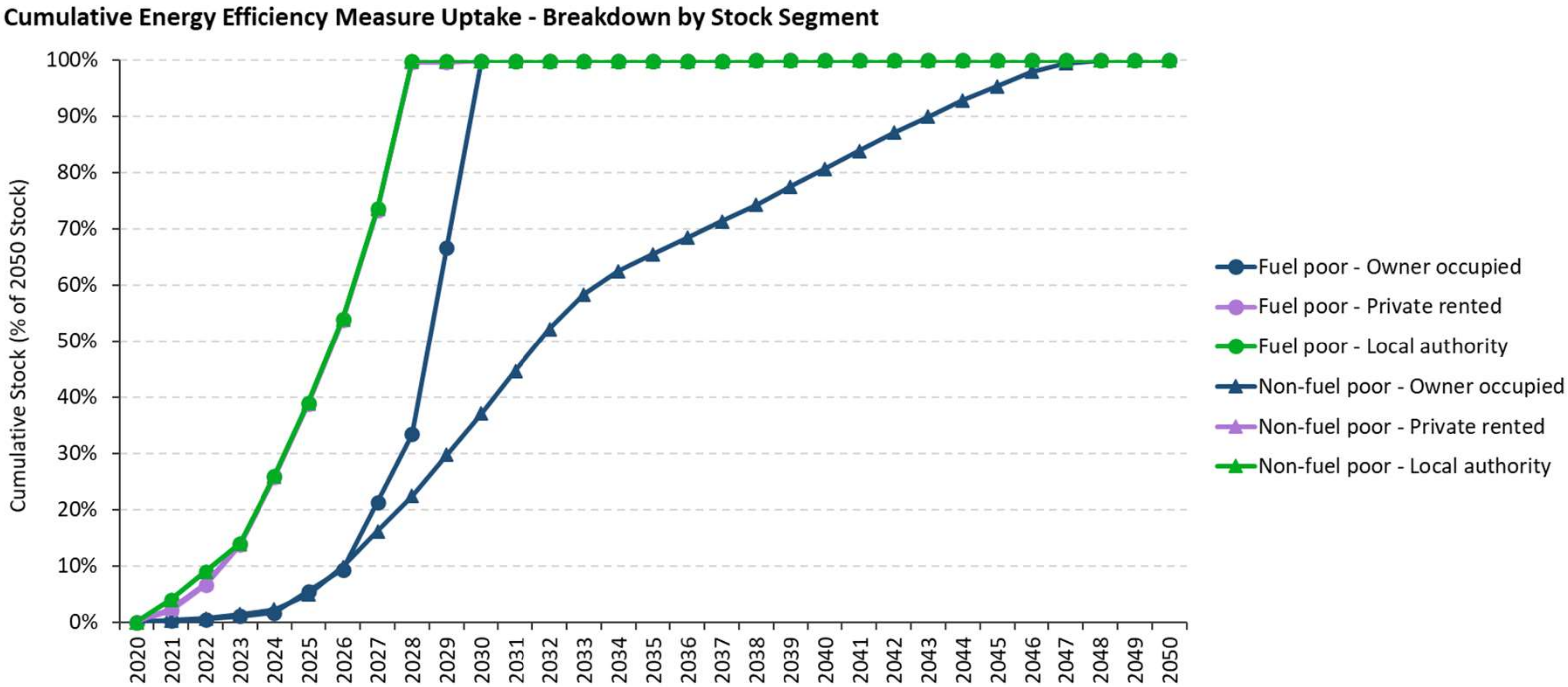
- Yearly deployment of energy efficiency measures starts at 1 million in 2021, and peaks in 2028, at 11 million.
  - By 2025, yearly deployment of solid walls, cavity walls and loft insulation is on average more than 20 times higher than current rates of deployment, with 253,000 solid walls, 217,000 cavity walls and 709,000 lofts deployed in 2025.
  - Deployment peaks in 2028, which is the backstop dates for both social housing and private rented homes (i.e. the year by which deployment is modelled to be completed) .
- As a once-in-a-lifetime infrastructure programme, energy efficiency deployment has the potential to create large numbers of jobs over the coming decade. However, the “energy efficiency first” approach coupled with the long lifetimes of energy efficiency measures also implies the need for careful skills planning to ensure jobs can be effectively transitioned as the infrastructure upgrade programme nears completion.



[1] Draught proofing replacements, required every 10 years, are not shown in the graph. Draught proofing is shown under ‘Other’ measures. All other energy efficiency measures have lifetimes exceeding 30 years and hence do not require replacement.

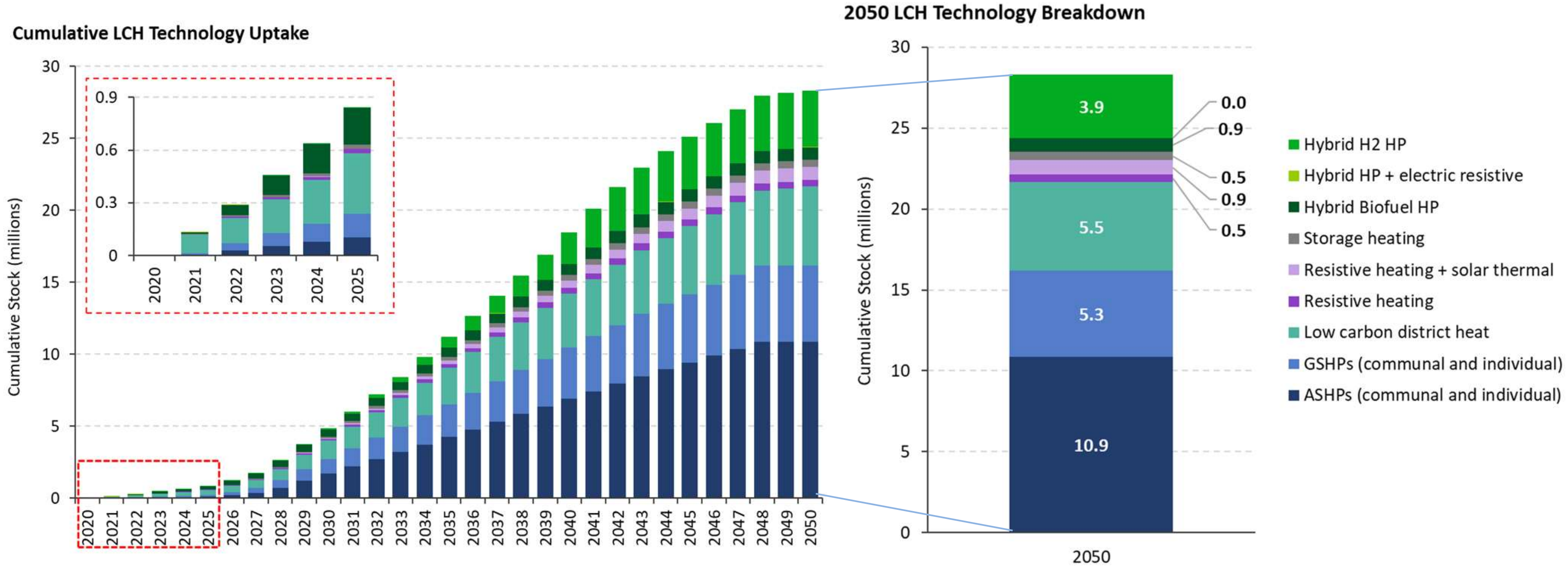
Balanced Pathway – energy efficiency uptake trajectory by stock segment

- The first segments to achieve 100% deployment, in 2028, are social homes and private rented homes (fuel poor and non-fuel poor).
- This is followed by owner-occupied fuel poor homes, which achieve 100% deployment by 2030.
- By 2030, 55% of non-fuel poor, owner-occupied homes remain without upgrades. Those are upgraded steadily from 2030 onward.
- Full energy efficiency deployment across the stock is achieved in 2048.
- Whilst the ramp-ups in deployment are steep over the next decade, particularly for fuel poor owner-occupied homes, overall deployment rates remain within deployment constraints. The focus of this analysis was on ensuring overall ramp-up across the stock remains within deployment constraints and represents a reasonable profile of growth. As such, profiles for individual stock segments should be taken to be illustrative only, with reprofiling between segments viable.



Balanced Pathway – cumulative low carbon heating uptake trajectory

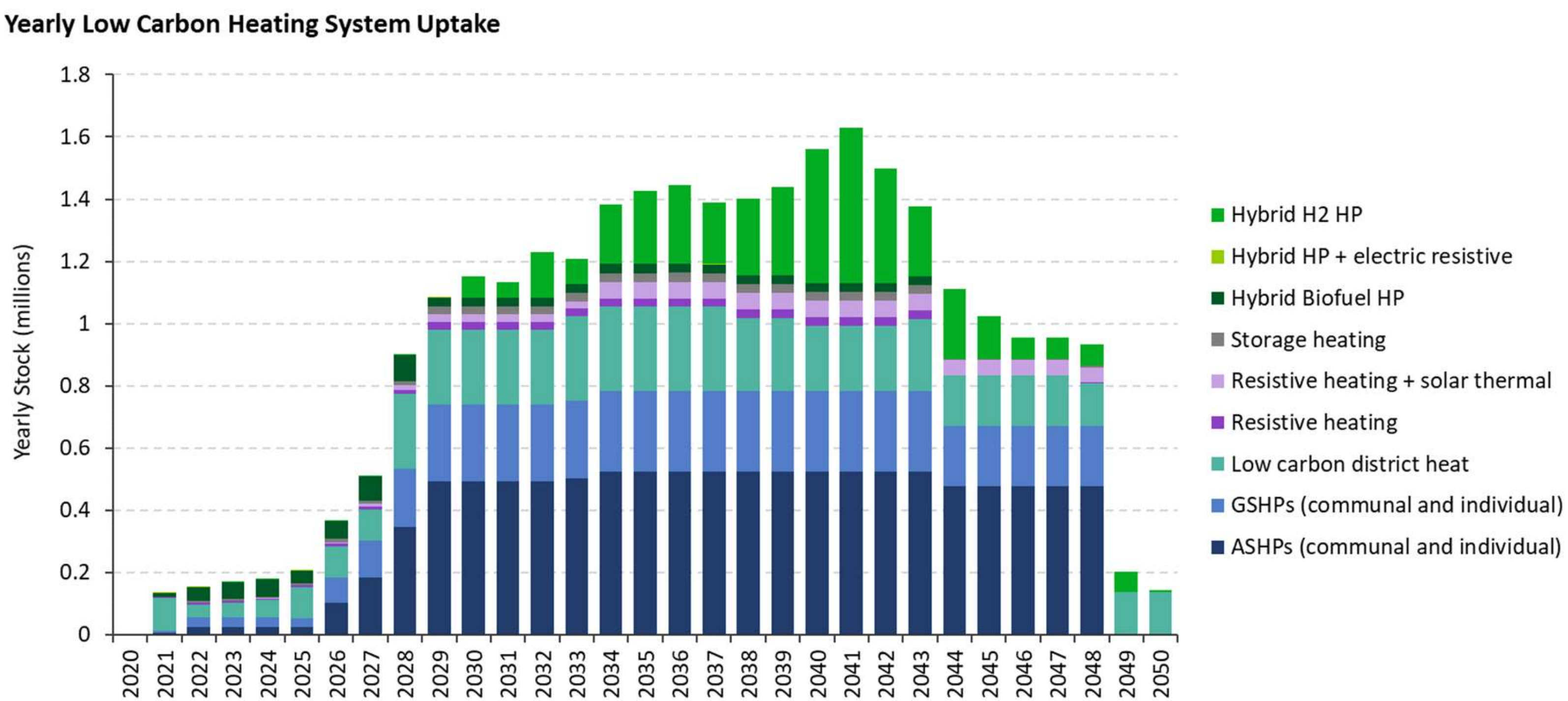
- Rapid ramp up of energy efficiency deployment prepares the stock for low carbon heating uptake.
- 3.3 million heat pumps are deployed by 2030, and 8 million by 2035 in the Balanced Pathway scenario[1]. A rapid ramp up in deployment is required to deliver this - the Balanced Pathway deploys 450,000 heat pumps in existing homes by 2025.
- Deployment of hybrid H_2 heat pumps ensures consistency with scenarios in the industry sector, with hydrogen grid conversion assumed to occur on a partial basis all the way to 2050 in the Balanced Pathway (see slide). In the Balanced Pathway, hybrids are deployed steadily to 2050 at the point at which areas are converted to H_2 (in reality there is scope for them to play a wider transitionary role).



[1] Figures exclude deployment in new builds and replacements.

Balanced Pathway – in-year low carbon heating uptake trajectory

- In the early years, off-grid deployment dominates, with on-grid deployment ramping up from 2026.
  - Low carbon heat networks and hybrid biofuel heat pumps dominate the low carbon heating uptake up to 2025.
- Yearly deployment increases six-fold between 2025 and 2030, from 200,000 units per year to nearly 1.2 million units[1].
- Deployment of hybrid H_2 heat pumps begins in 2030 and continues steadily to 2050 (with peak deployment of around 500,000 units in 2041[1].
- Total yearly deployment of first-time installations peaks in 2041, at just over 1.6 million units[1]. Replacements will be additional to this.

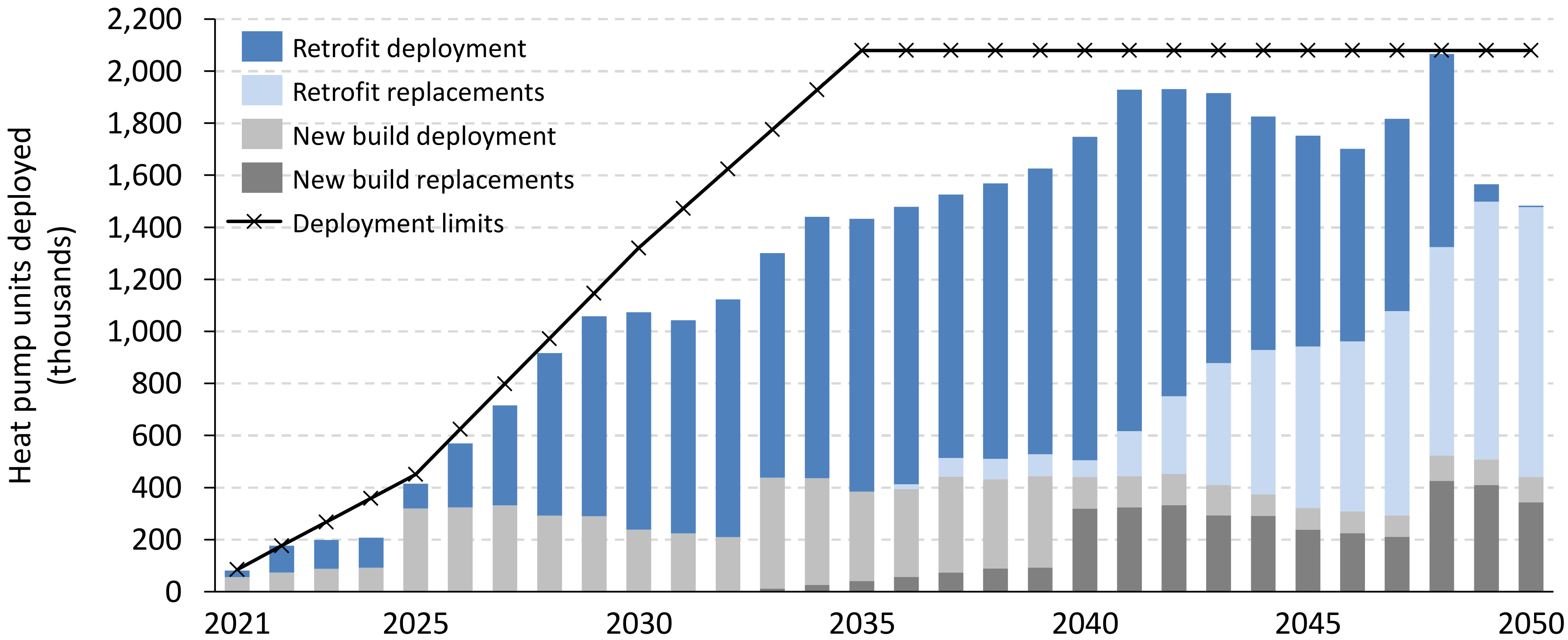


[1] Figures exclude deployment in new builds and replacements.

Balanced Pathway – total heat pump deployment

- With new builds and replacements taken into account, the modelled heat pump uptake trajectory delivers a relatively smooth ramp-up of deployment. After 2030, deployment rates keep increasing, but at a slower rate than deployment limits.
- In the 2040s, replacements become a significant part of total deployment, with new installations and replacements together approaching the deployment limits.
  - The limits are modelled as constant after 2035 but in reality would be expected to further increase, albeit at a slower rate compared with the period before 2035.

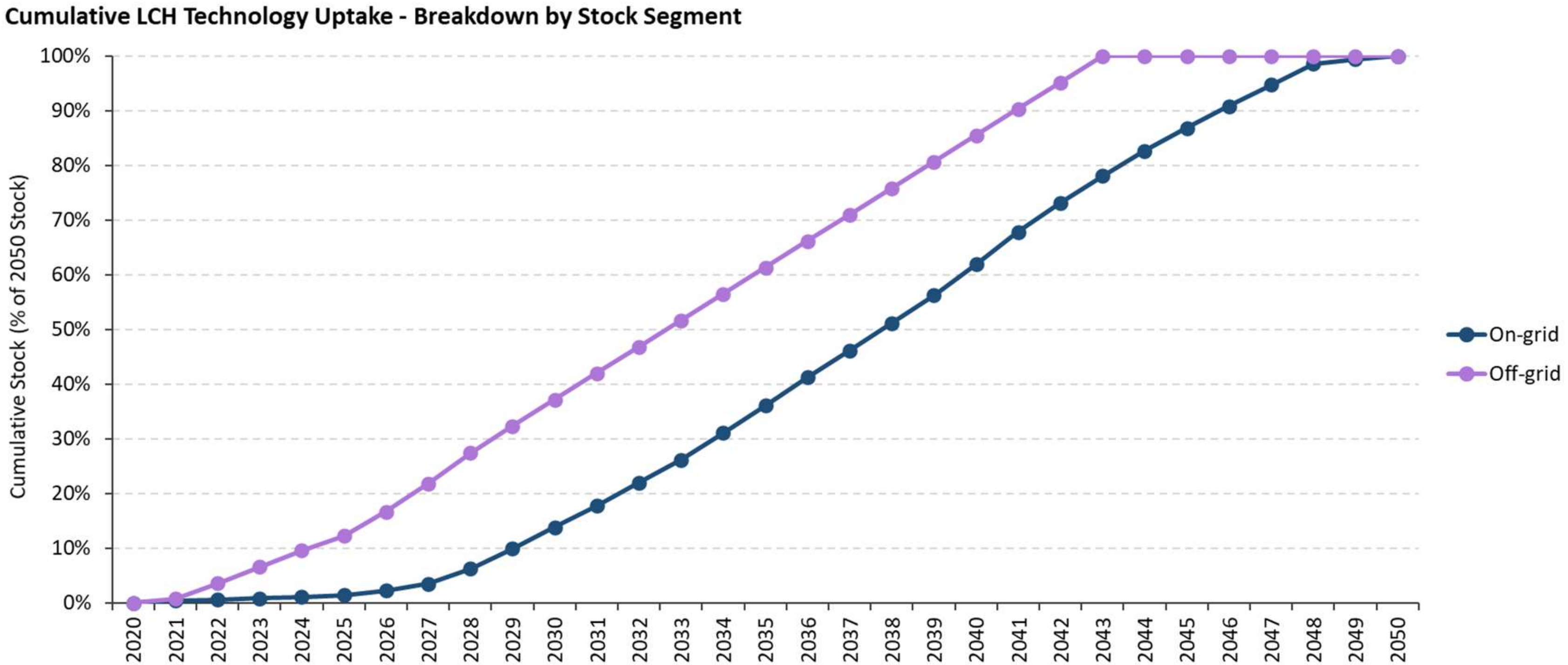
Comparison of Balanced Pathway heat pump deployment[1] against heat pump deployment limits



[1] Includes new build heat pumps and new build replacements, which were not directly modelled in this work. Replacements assume a 15-year heat pump lifetime for ASHPs and 20 years for GSHPs. New build replacements before 2036 are due to new build deployment before 2021, not shown in the graph.

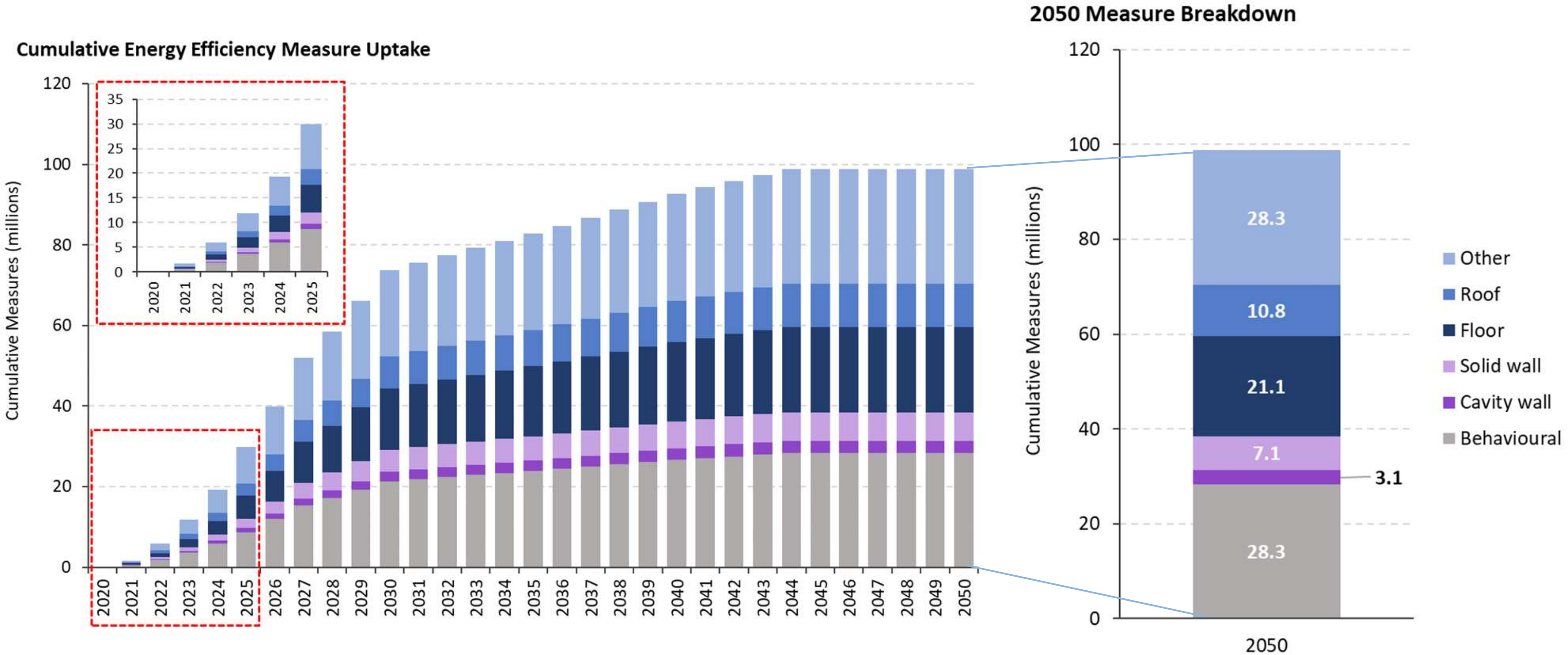
Low carbon heating uptake by stock segment – Balanced Pathway

- Deployment of low carbon heating in off-grid homes begins and ends before that in on-grid homes.
- After the fossil phase-out dates – 2028 for off-grid homes and 2033 for on-grid homes – the rate of deployment increases steadily until full deployment is reached.
  - The exceptions are technologies which deploy according to geographical conversion, namely low carbon heat networks and hybrid H_2 heat pumps.
- Full deployment is achieved in 2043 for off-grid homes and 2048 for on-grid homes (with the exception of about 300,000 homes which uptake either low carbon heat networks or a hybrid H_2 heat pump in 2049 and 2050).



Tailwinds – cumulative energy efficiency uptake trajectory

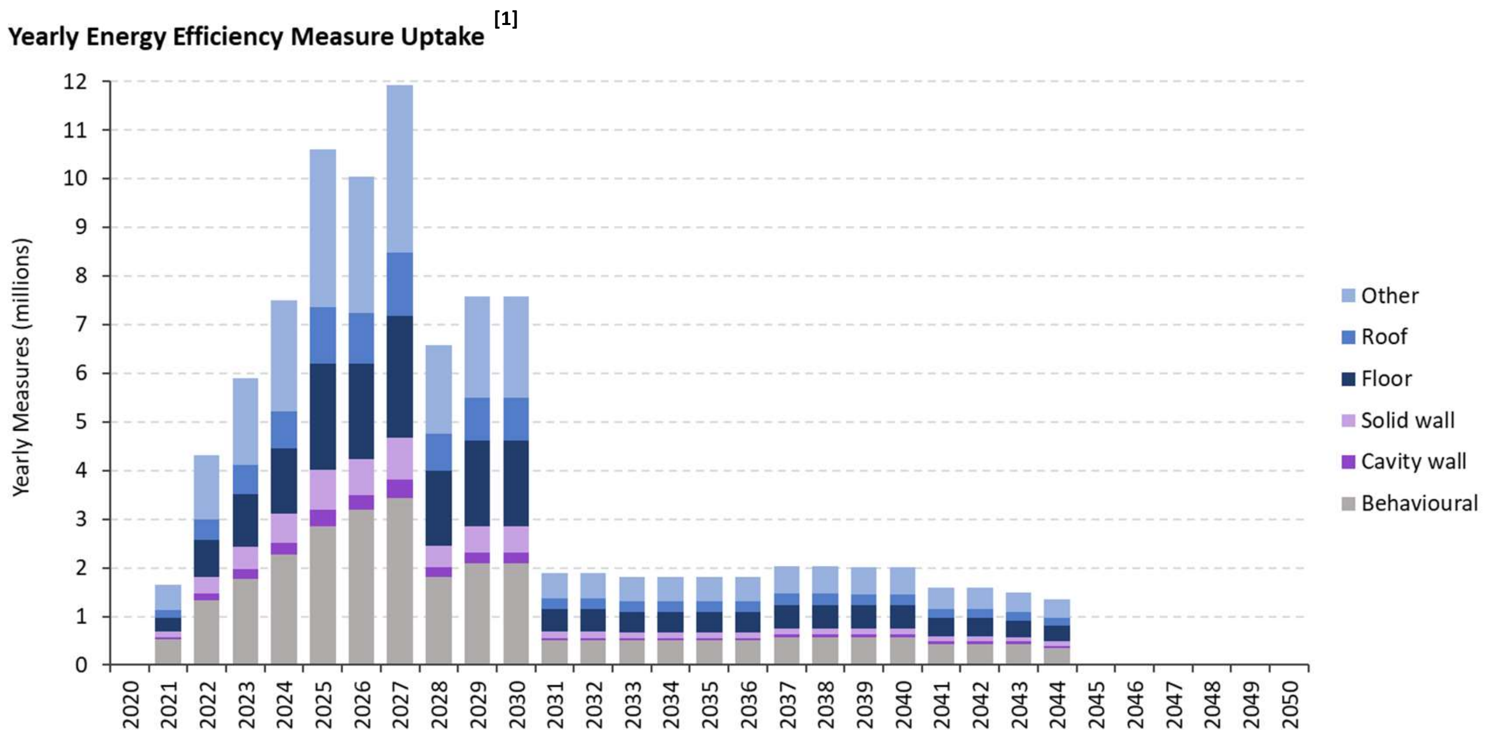
- The Tailwinds scenario deploys significantly more energy efficiency measures compared to the Balanced Pathway scenario (still based on an "energy efficiency first" approach), with a faster ramp-up in the early years.
  - The trajectory in Tailwinds implies that by 2025, cumulative new measure deployment should reach 3.1 million loft insulation measures (including top-ups), 1 million cavity walls insulated, and 2.3 million solid walls insulated[1].
  - 75% of all energy efficiency deployment in the Tailwinds scenario occurs in the first 10 years (i.e. to 2030), which is also the fossil phase-out date.
- The Tailwinds scenario represents a level of energy efficiency uptake corresponding with full economic potential, leading to the deployment of just under 100 million energy efficiency measures by 2050.



[1] Technical potential for modelling accounted for existing installations to December 2019. Installations from 2020 onwards would be counted as 'new' installations on this basis.

Tailwinds – in-year energy efficiency uptake trajectory

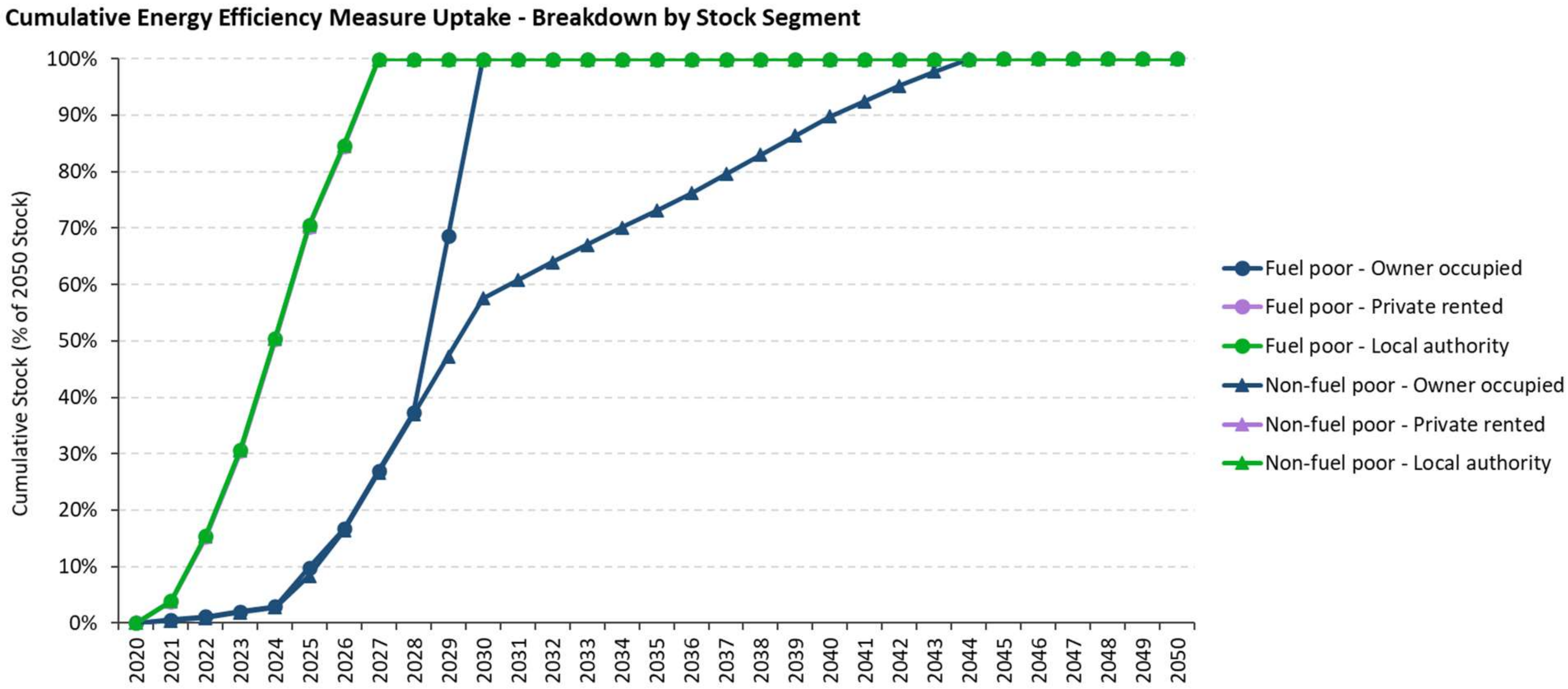
- Yearly deployment of energy efficiency measures starts at 1.6 million in 2021, and peaks in 2027, at just under 12 million.
  - The 2027 peak is due to the backstop dates, which require the completion of deployment in both social housing and private rented homes by 2027.
  - By 2025, yearly deployment of solid walls, cavity walls and loft insulation are on average more than 40 times higher than current rates of deployment, with 817,000 solid walls, 355,000 cavity walls and 1.2 million lofts deployed in 2025.
  - Deployment remains high to 2030, when the backstop date for all fuel poor homes is reached.
  - Beyond 2030, energy efficiency deployment happens solely in non-fuel poor, owner-occupied homes, with deployment levels dropping to under 2 million measures a year.



[1] Draught proofing replacements, required every 10 years, are not shown in the graph. Draught proofing is shown under 'Other' measures. All other energy efficiency measures have lifetimes exceeding 30 years and hence do not require replacement.

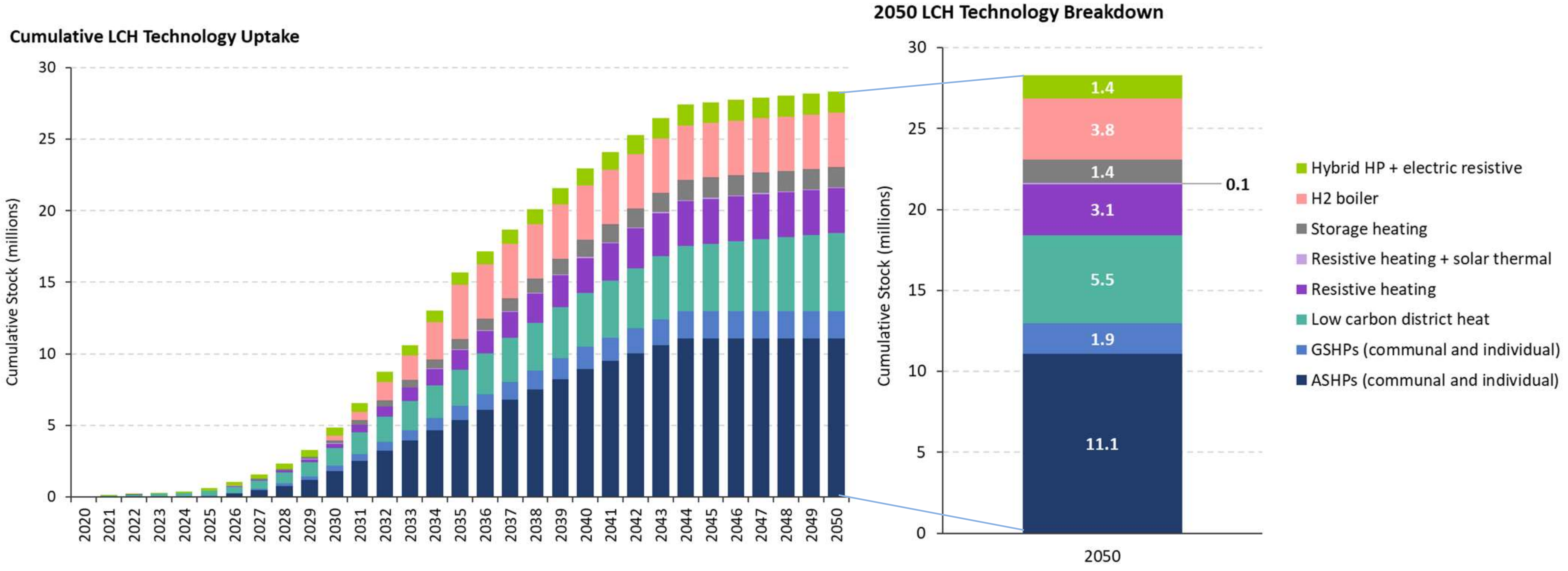
Tailwinds – energy efficiency uptake trajectory by stock segment

- The first segments to achieve 100% deployment, in 2027, are social homes and private rented homes (fuel poor and non-fuel poor).
- This is followed by owner-occupied fuel poor homes, which achieve 100% deployment by 2030.
- After 2030, the remaining 42% of non-fuel poor, owner-occupied homes are upgraded steadily.
- Full energy efficiency deployment across the stock is achieved in 2044.
- As with the Balanced Pathway, the steep ramp-ups for individual stock segments in the next decade are illustrative only; overall deployment remains within deployment constraints.



Tailwinds – cumulative low carbon heating uptake trajectory

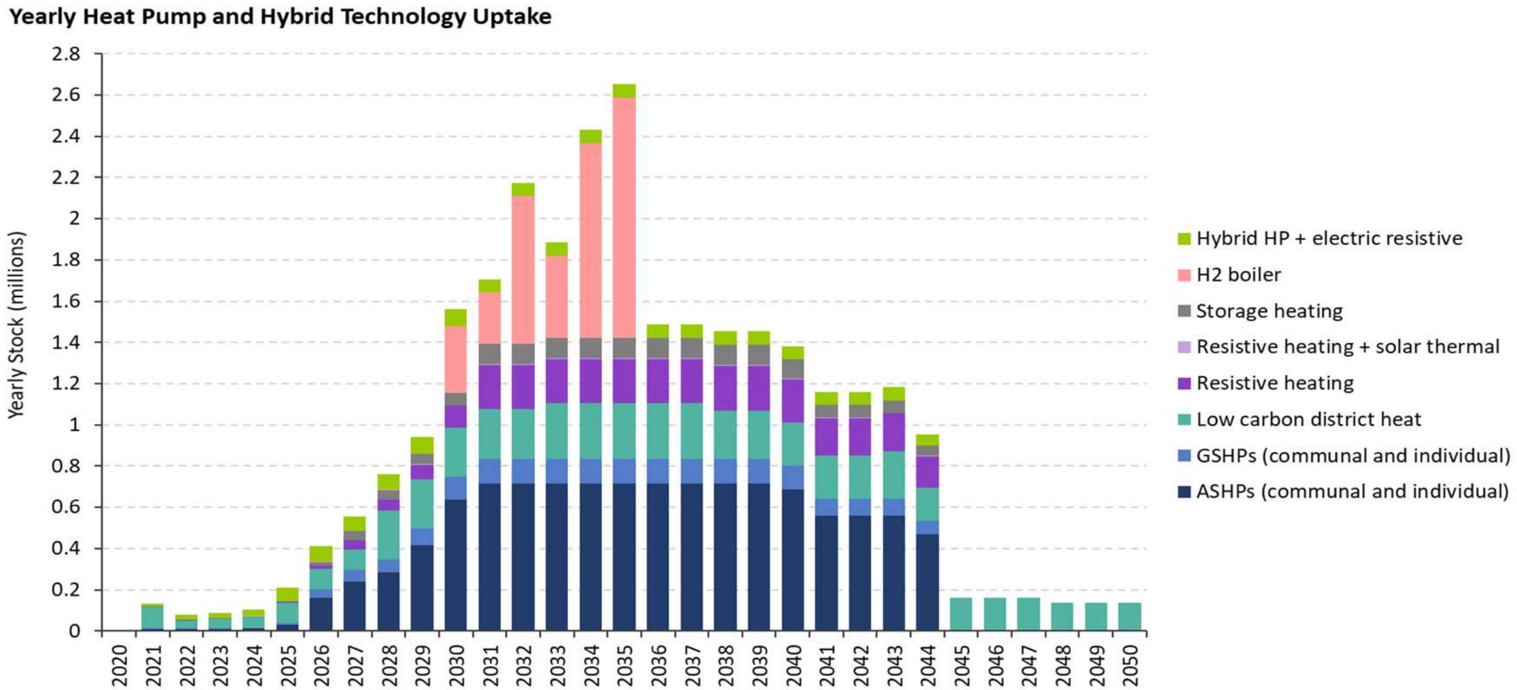
- Rapid ramp up of energy efficiency deployment prepares the stock for low carbon heating uptake.
- The low carbon heating deployment rates for the Tailwinds scenario in the early years are not noticeably faster than those for the Balanced Pathway scenario, this is because both scenarios have deployment rates close to achievable deployment constraints (i.e. significant further acceleration of deployment rates may not be feasible).
  - The scenario deploys 2.7 million heat pumps by 2030, and 7.2 million by 2035. Those figures are lower than those in the Balanced Pathway due to the presence of H_2 boilers in Tailwinds, rather than the H_2 hybrid heat pumps deployed in the Balanced Pathway[1].
- Deployment of H_2 boilers occurs over a 5-year period from 2030 (after completion of trials) to 2035 (see slide).



[1] Figures exclude deployment in new builds and replacements.

Tailwinds – in-year low carbon heating uptake trajectory

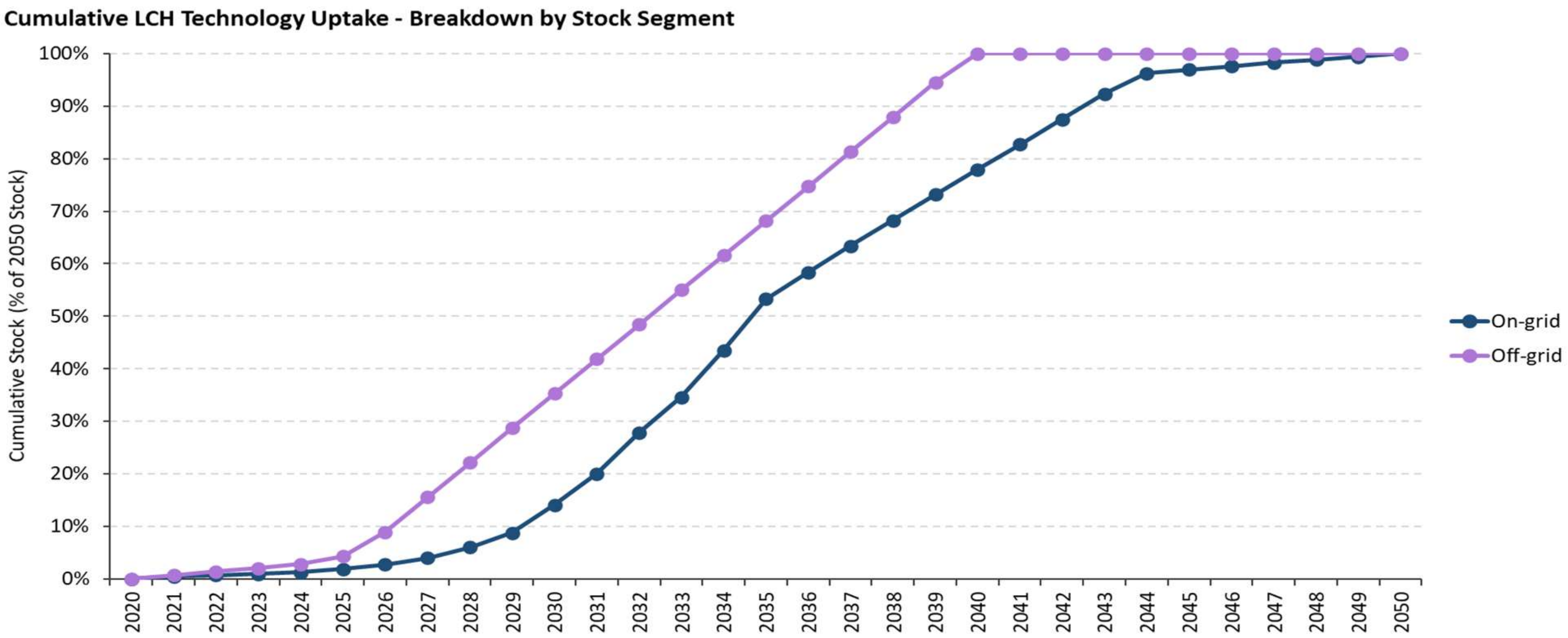
- In the early years, off-grid deployment dominates, with on-grid deployment ramping up from 2026.
  - Low carbon heat networks dominate the low carbon heating uptake up to 2025, with the relatively few heat pumps deployed primarily in off-grid homes.
- Yearly deployment increases almost eight-fold between 2025 and 2030, from 200,000 units per year to nearly 1.6 million units[1].
- Deployment of H_2 boilers begins in 2030 and completes in 2035, when radial grid conversions are assumed to stop (with peak deployment of around 1.2 million units in 2035)[1].
- Total yearly deployment of all technologies peaks in 2035 (primarily due to H_2 boilers), at just over 2.6 million units[1].



[1] Figures exclude deployment in new builds and replacements.

Low carbon heating uptake by stock segment – Tailwinds

- Deployment of low carbon heating in off-grid homes begins and ends before that in on-grid homes.
- After the fossil phase-out dates – 2026 for off-grid homes and 2030 for on-grid homes – the rate of deployment increases steadily until full deployment is reached.
  - The exceptions are technologies which deploy according to geographical conversion, namely low carbon heat networks and H_2 boilers. The slow-down in the on-grid deployment rate after 2035 is due to the completion of the deployment of H_2 boilers.
- Full deployment is achieved in 2040 for off-grid homes and 2044 for on-grid homes (with the exception of about 900,000 homes which connect to low carbon heat networks between 2045 and 2050).



Contents

Exploratory scenarios headline outputs – emissions

	Direct emissions abatement[1]				Total emissions abatement[1]			
	2035	2035	2050	2050	2035	2035	2050	2050[2]
Scenario	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%	$MtCO_2e$	%
Widespread Engagement	32.1	54%	59.9	100%	30.5	51%	59.4	99%
Headwinds	24.4	41%	59.9	100%	23.5	39%	58.4	97%
Widespread Innovation	32.9	55%	59.9	100%	32.3	54%	59.8	100%

- Of the three exploratory scenarios, Widespread Innovation achieves the most abatement by 2035, at 53% of total emissions, whereas Headwinds is the slowest, achieving only 39%.
  - The higher abatement in the Widespread Innovation and Widespread Engagement scenarios is driven by:
    - Deployment of “deep” retrofit packages in Widespread Innovation, which lead to higher heat demand savings and hence higher abatement.
    - Widespread Engagement deploying the highest level of energy efficiency of the three scenarios, with more ambitious deployment trajectories (both the private rented and social housing sectors achieve full deployment by 2027).
- The Headwinds scenario has the highest number of both hydrogen and biofuel technologies, both of which contribute indirect emissions, leading to total abatement reaching 97% only in 2050.

[1] Percentages represent yearly emissions abated as a % of baseline emissions in the specified year. [2] Total emissions abatement in 2050 varies slightly between scenarios due to the addition of indirect emissions associated with hydrogen and biofuel use.

Exploratory scenarios headline outputs – costs

			Total abatement costs (£bn)		Total net investment costs (£bn)[1]		Total net opex costs (£bn)		Total net costs (£bn)
Scenario	Average cost effectiveness (£/tCO_2)	Average abatement cost (£bn/y)	To 2035	To 2050	To 2035	To 2050	To 2035	To 2050	To 2050
Widespread Engagement	230	7.2	44.8	217	158	302	-18.2	-69.9	232
Headwinds	267	7.0	30.3	211	94.3	182	-6.4	40.7	223
Widespread Innovation	341	9.5	82.7	286	167	252	-13.2	-54.3	198

- Headwinds has the lowest total abatement costs of the three exploratory scenarios, at £211 billion, whereas Widespread Innovation has the highest costs, at £286 billion.
- Headwinds also has the lowest total net investment costs, at £182 billion, primarily due to widespread deployment of low capex H_2 boilers.
    - The low net investment costs in Headwinds are offset by the high opex costs associated with hydrogen, being the only scenario where total net opex costs are positive (i.e. increasing fuel bills).
    - When total net costs are considered (investment + opex), Widespread Innovation comes out as the scenario with the lowest costs, at £198 billion.
- Total investment costs to 2050 are £475 billion, £355 billion, and £425 billion in in Widespread Engagement, Headwinds and Widespread Innovation, respectively.
- Investment costs only account for in-year, undiscounted capex, and therefore are unaffected by the cost of capital. Abatement costs, on the other hand, incorporate annualised capex discounted by the cost of capital in addition to opex and fuel costs discounted by the discount rate. The two figures are therefore not directly comparable.
    - The cost of capital used for Widespread Innovation (7.5%) is higher than that used for the other exploratory scenarios (3.5%), overpowering more ambitious assumptions on cost reductions and leading to higher abatement costs (see slide). The higher cost of capital is applied to both low carbon heating systems and energy efficiency measures. This is a pessimistic assumption, which partially explains the higher abatement costs.

[1] Investment costs in this modelling are expected to be overestimated to some degree, due to assuming renewal costs for all household conversion items including radiators. An adjustment has been made to remove these additional renewal costs in the CCC's final Balanced Pathway. [2] Cost-effectiveness is defined as the cost of a measure per unit of emissions abated, in £ per tonne of CO_2e. The costs do not account for wider social benefits such as improved health.

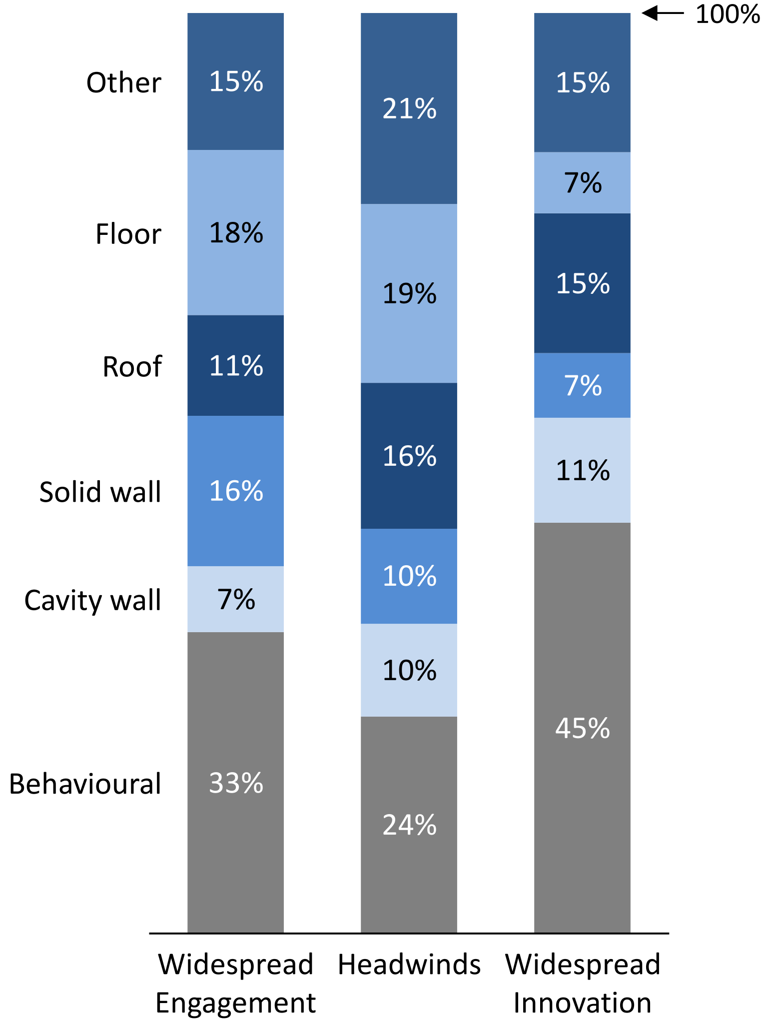
Exploratory scenarios headline outputs – behavioural

- In the exploratory scenarios, behavioural measures constitute the largest share of demand-side savings in all cases, with Widespread Engagement and Widespread Innovation boasting substantial savings relative to the other scenarios. Relative to the overall scenario savings,
  - the Widespread Engagement scenario sees a 32.7% contribution, with the highest TWh savings (aligned to Tailwinds) of all scenarios;
  - the Headwinds scenario sees a 23.6% contribution due to behavioural measures; and
  - the Widespread Innovation scenario sees 44.6% contribution, largely due to the contrast between the high behavioural engagement and low number of energy efficiency packages taken up.
- These savings are achieved differently, as each scenario accounts for a different level of behavioural engagement from consumers:

Innovation area	Widespread Engagement	Headwinds	Widespread Innovation
Pre-heating	Permitted in 50% of post-1952 homes	Permitted in 25% of post 1952 homes.	Permitted in 50% of post-1952 homes
Heat as a service	No	No	Yes [a]
Smart metering & control	Smart meter with zonal control [c]	Standard smart meter [b]	Smart meter with zonal control [c]
Reduced water temperature	Yes, 50 °C [d]	No	No
Low flow shower head	Yes	Yes	Yes

[a] Heat as a service modelled using: 7.5% cost of capital, 5% increase in heat demand, 3% financial savings, 15% increase in heat pump efficiency.
[b] Heat demand reduction based on actions including turning thermostat down and changing operating times.
[c] Heat demand reduction based on implementation of automated multizone control.
[d] 50 °C only applicable in dwellings which uptake a HP; allowance for daily legionella cycle of 1hr duration included.

% of scenario's total TWh savings from energy efficiency and behaviour change



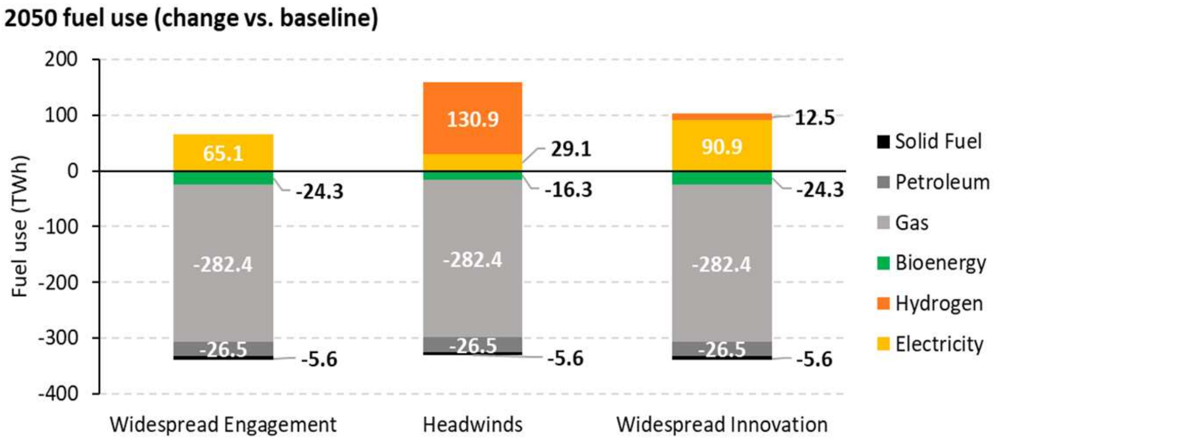
Exploratory scenarios headline outputs – energy efficiency uptake

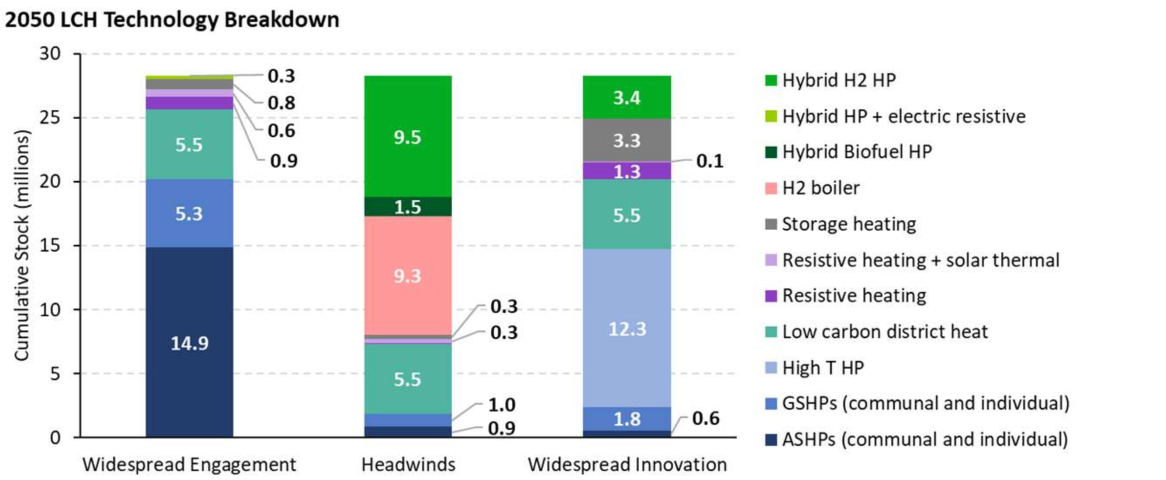
- Energy efficiency levels are driven by different factors in each scenario:
  - **Headwinds:** model permitted to optimise for the lowest lifetime cost energy efficiency + low carbon heating combination, given high H_2 prices, with no wider benefits costed for non-fuel poor homes.
  - **Widespread Engagement:** deployment of at a medium energy efficiency package in all households.
  - **Widespread Innovation:** model permitted to optimise for the lowest lifetime cost using lower-end costs, with no wider benefits costed for non-fuel poor homes; deep retrofits replace standard high packages.
- Solid walls in fuel poor homes are insulated across scenarios (implemented via the High energy efficiency package).
  - Given the high uncertainty over the achievable performance and costs of solid wall insulation, a broad range of uptake levels was modelled across the scenarios, with Tailwinds representing full economic potential (under around £700/tCO_2e).
- The overall heat demand reduction is relatively low compared to the Net Zero work due to updated assumptions (see energy efficiency modelling section), including:
  - Updated technical and economic potential (leading to lower deployment).
  - Updated cost and savings assumptions (leading to lower cost effectiveness).
- The heat demand reduction is nearly identical in Headwinds and Widespread Innovation, despite the former deploying significantly more measures, due to the use of "deep" retrofit packages which lead to much higher heat demand savings (57% on average, compared to around 30% for a home installing loft insulation, floor insulation and cavity wall insulation).

Number deployed (millions)	Headwinds	Widespread Engagement	Widespread Innovation
Measure			
Loft	9.7	10.7	6.1
Cavity wall	2.8	3.1	2.7
Solid wall	1.9	4.9	1.2
Floor	6.2	8.7	2.3
Other	25.6	27.9	8.6
Behavioural	28.3	28.3	28.3
Package			
None	2.7	0.4	19.4
Low	4.8	0.1	2.6
Medium	10.4	24.6	2.8
High	10.4	3.1	3.4
Energy demand savings (TWh/yr)	35	50	39
Total heat demand in 2017 (TWh/yr)	313		
Total heat demand in 2050 (TWh/yr)	278	263	274
Reduction in heat demand as a result of energy efficiency	11%	16%	12%

Exploratory scenarios headline outputs – fuel use change and low carbon heating uptake

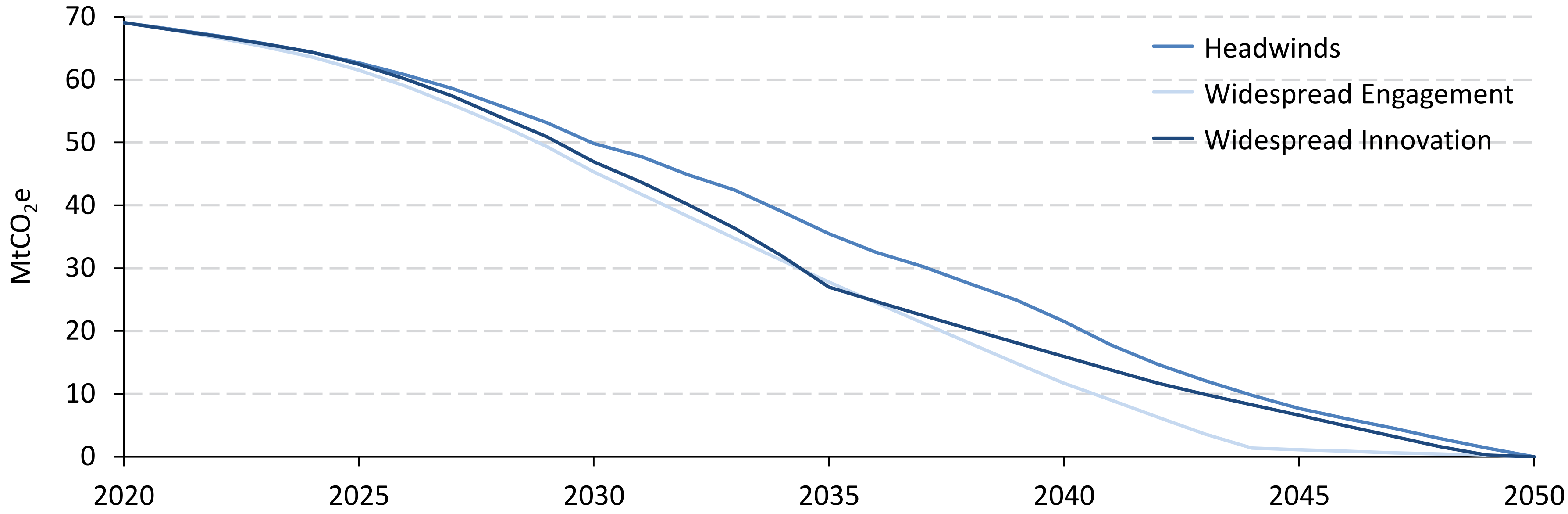
- Hydrogen fuel use is highest in Headwinds, which deploys a total of 18.8 million hydrogen-powered technologies:
  - The hydrogen technology deployment in Headwinds is informed by work done by Imperial College London for the CCC[1] (see slide) and is designed to include high levels of electrification alongside hydrogen, in-line with CCC advice.
- Heating demand from low carbon heat networks is 42.8 TWh in Widespread Engagement, 46.6 TWh in Headwinds and 45.2 TWh in Widespread Innovation.
  - The total is influenced by the levels of energy efficiency deployment in each scenario.
- Despite being fully electrified, the change in electricity use in Widespread Engagement is lower than that in Widespread Innovation, due to:
  - Deployment of less efficient high temperature heat pumps in Widespread Innovation (see slide for details on the assumptions for high temperature heat pumps).
  - Increased demand reduction associated with higher energy efficiency deployment in Widespread Engagement.





[1] Analysis of Alternative UK Heat Decarbonisation Pathways, Imperial College London for the CCC (2018).

Exploratory scenarios headline outputs – emissions trajectories

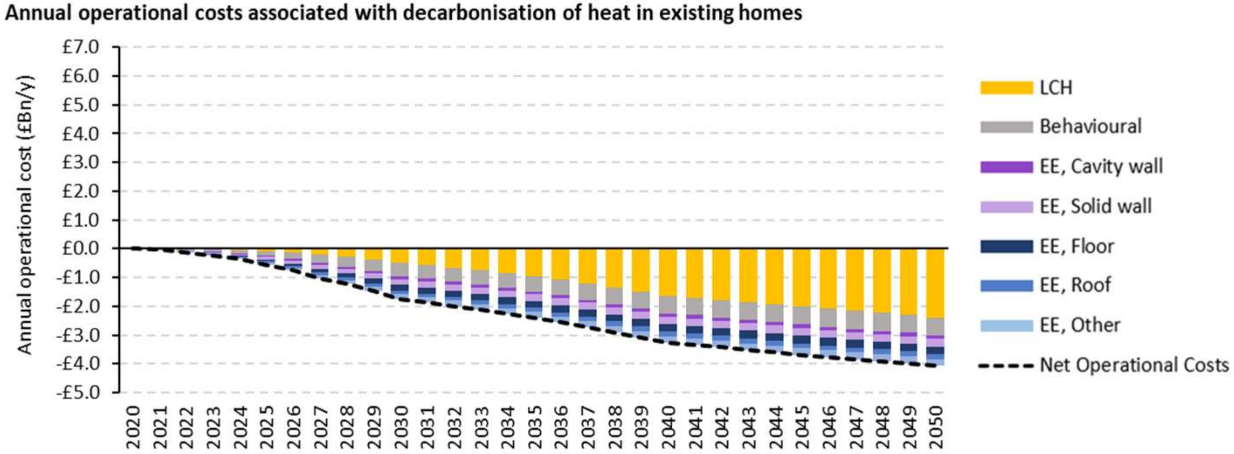


- Widespread Engagement is the fastest scenario to decarbonise, whereas Headwinds is the slowest.
- The rate of abatement for Widespread Innovation closely matches the slower rate of Headwinds in the earlier years, before accelerating from the late 2020s to 2035, then slowing down again.
  - The faster rate in those years is due to the deployment of the 3.4 million hybrid H_2 heat pumps, 3.2 million of which deploy between 2029 and 2035 (see slide for a recap of the approach to deploying hydrogen).
- Engaged People effectively reaches Net Zero in 2044, 14 years after the on-grid fossil phase-out date.
  - The residual abatement after 2044 is due to deployment of low carbon heat networks, which follows a trajectory based on geographical conversion and deploys up to 2050 (with 900,000 homes upgraded after 2044).
- Widespread Innovation and Headwinds effectively reach Net Zero in 2049 and 2050 respectively, despite both having 2035 as the on-grid fossil-phase out date, due to the slightly faster replacement rate assumed in Widespread Innovation (see slide).

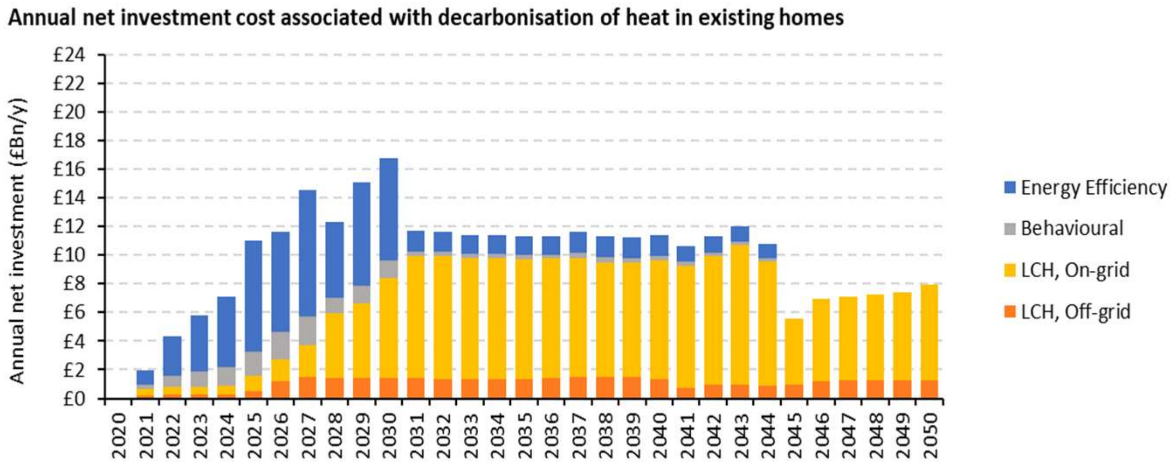
Widespread Engagement headline outputs – cost trajectories

- Widespread Engagement has the lowest net opex costs (highest savings) of the exploratory scenarios, due to:
  - High deployment of energy efficiency.
  - Absence of hydrogen technologies (with high cost H_2 fuel use).
- Net investment costs are also the highest amongst the exploratory scenarios, due to:
  - High deployment of energy efficiency.
  - Widespread deployment of heat pumps, with moderate assumptions on cost reductions.

Total opex savings £70 billion



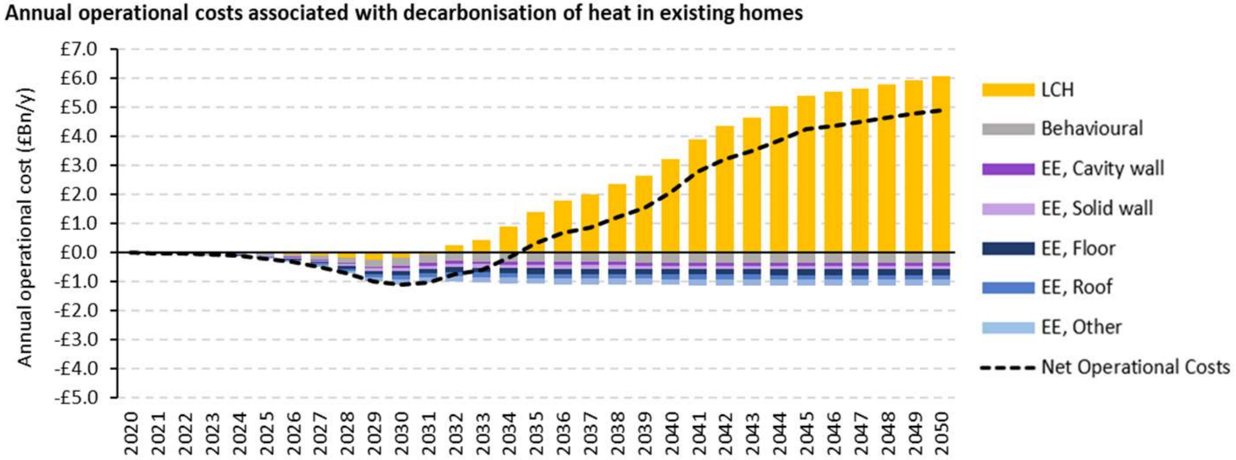
Total investment cost £302 billion



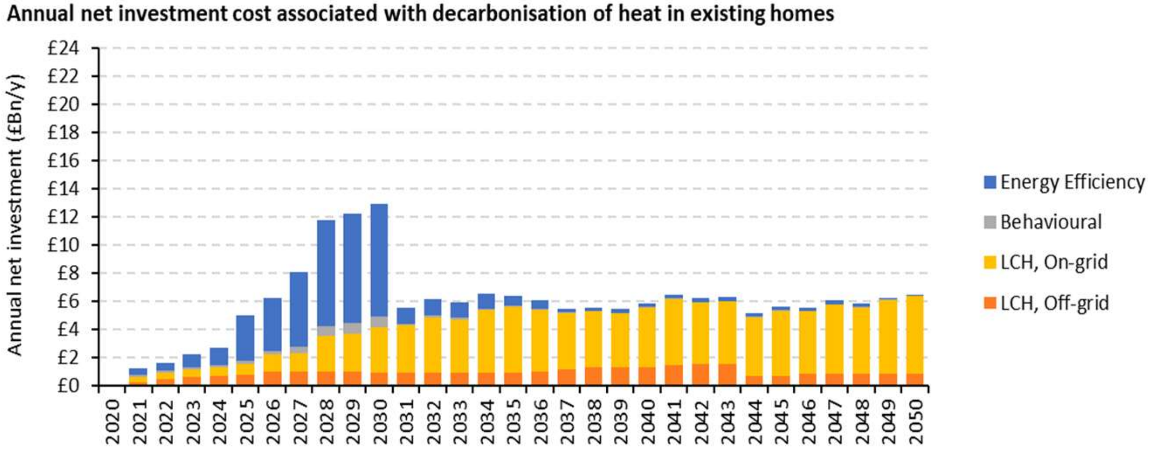
Headwinds scenario headline outputs – cost trajectories

- Headwinds has the highest net opex costs of the exploratory scenarios (leading to a net increase in fuel bills), due to:
  - Moderate savings from energy efficiency (with 2.7 million homes getting no measures).
  - Widespread deployment of hydrogen technologies, which have high fuel costs.
- Net investment costs are the lowest amongst the exploratory scenarios, due to:
  - Widespread deployment of low capex H_2 boilers.

Total opex savings £-41 billion



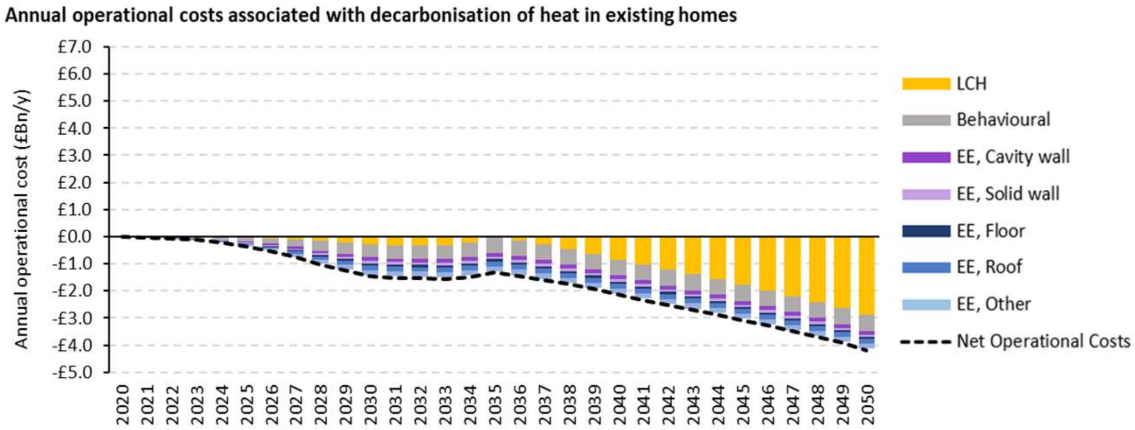
Total investment cost £182 billion



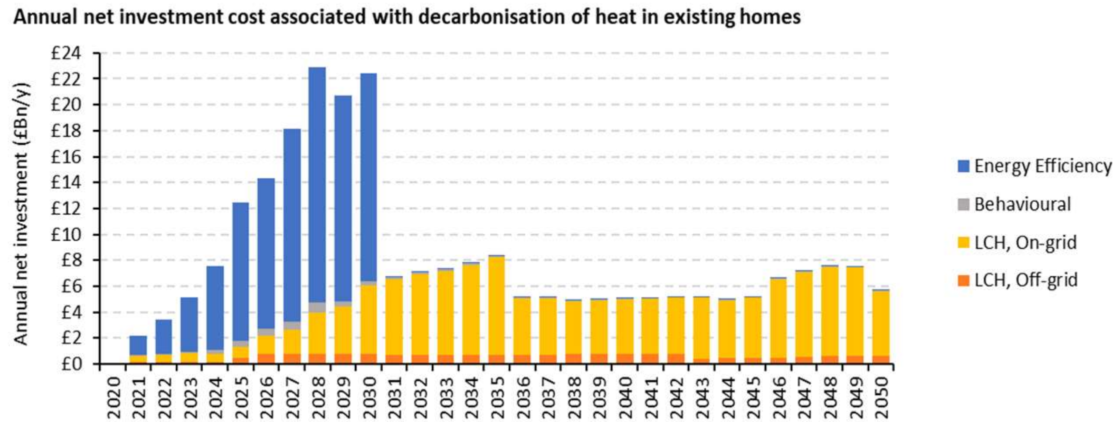
Widespread Innovation scenario headline outputs – cost trajectories

- Despite 19.4 million homes getting no energy efficiency measures, Widespread Innovation shows significant opex savings, due to:
  - High savings associated with “deep” retrofit packages.
  - Higher savings due to behavioural measures, particularly Heat as a Service.
- Net investment costs are relatively low, despite widespread deployment of high temperature heat pumps and high costs associated with “deep” retrofit packages. This is primarily due to more ambitious assumptions on technology cost reductions.
- The very high upfront investment associated with the deployment of “deep” retrofit packages also contributes to lower low carbon heating costs in later years, by reducing the average heating system size in the scenario (see slide).

Total opex savings £54 billion



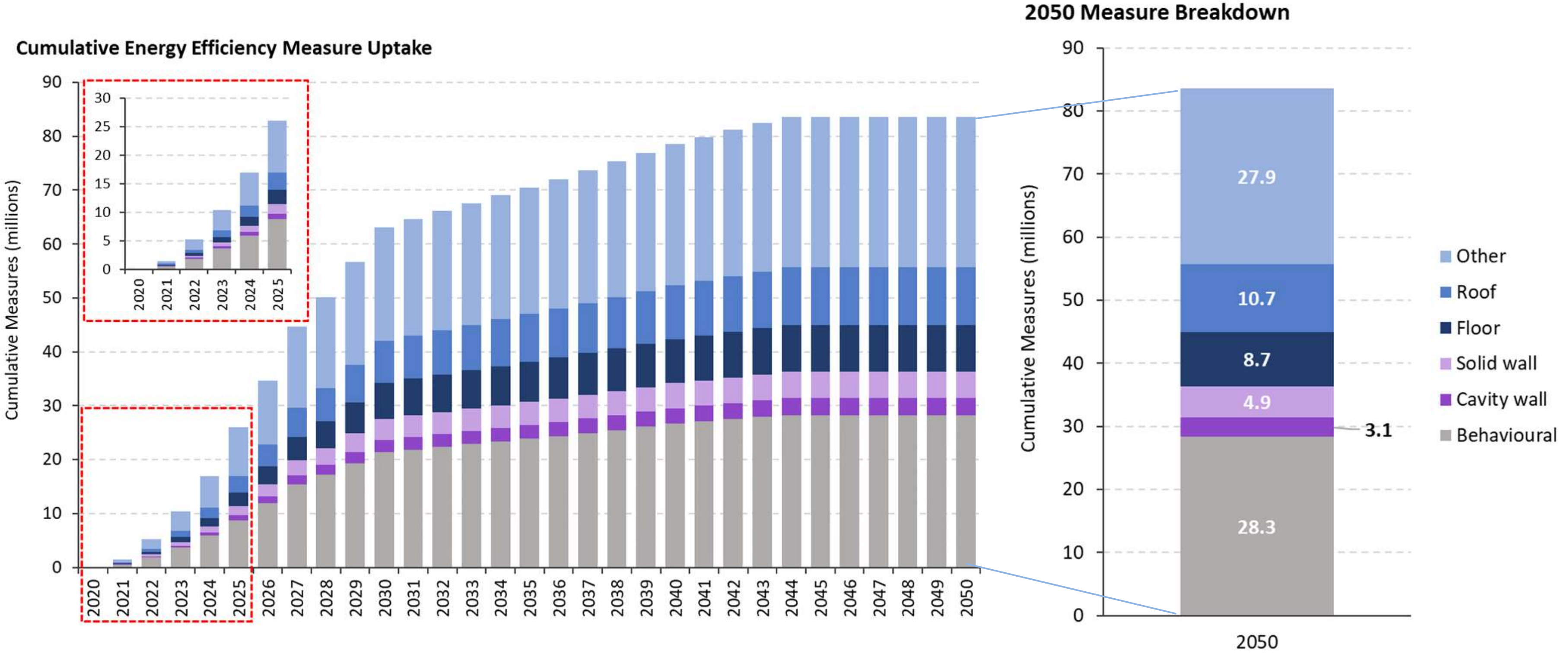
Total investment cost £252 billion



Contents

Energy efficiency uptake trajectory – Widespread Engagement

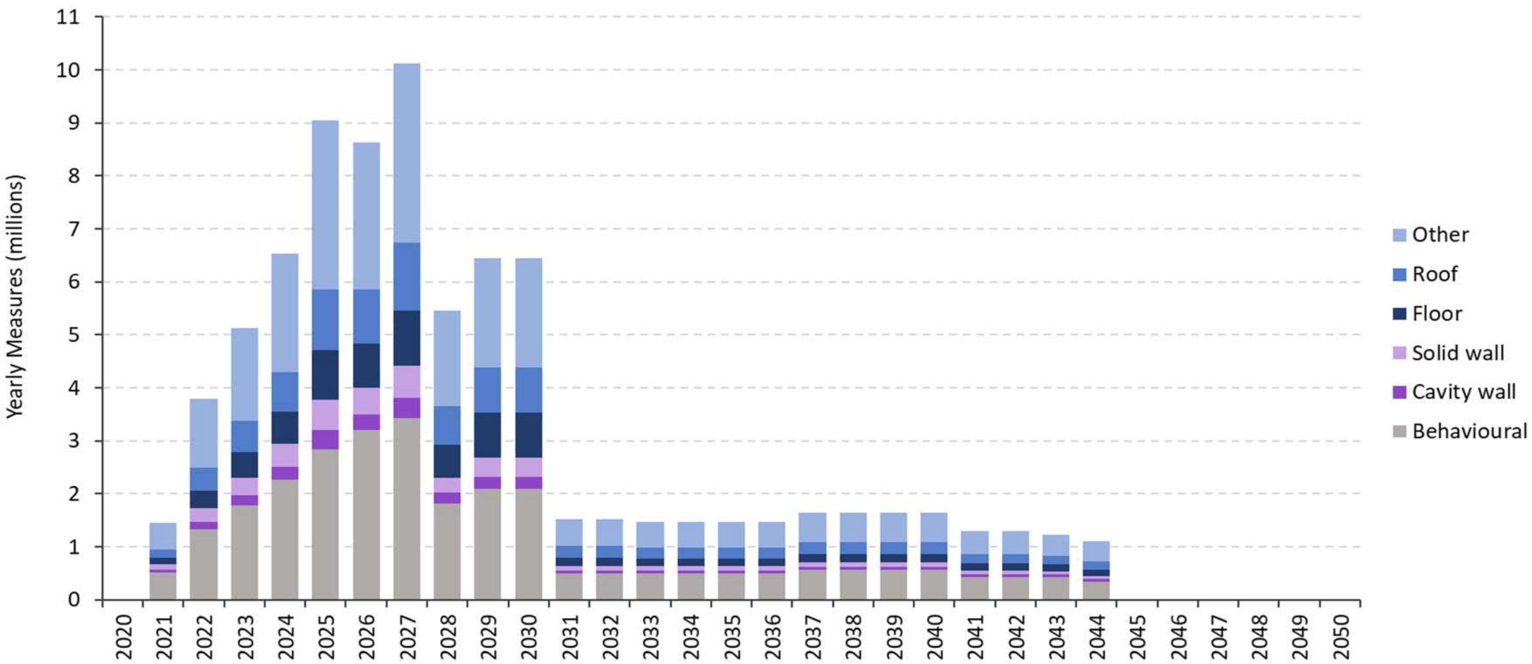
- As with the Central scenarios, all exploratory scenarios are based on an "energy efficiency first" approach, with a view to preparing the stock for low carbon heating technology uptake and reducing emissions and fuel bills in the near term. Therefore, rapid ramp-up of energy efficiency uptake is required.
- The Widespread Engagement scenario deploys the largest number of energy efficiency measures of the three exploratory scenarios.
  - 76% of all energy efficiency deployment in the scenario happens in the first 10 years (i.e. to 2030), which is also the fossil phase-out date.
- The Widespread Engagement scenario represents a level of energy efficiency uptake corresponding with all homes across the UK stock getting some combination of measures.



Energy efficiency uptake trajectory – Widespread Engagement

- Yearly deployment of energy efficiency measures starts at 1.5 million in 2021, and peaks in 2027, at just over 10 million.
  - By 2025, yearly deployment of solid walls, cavity walls and loft insulation are on average more than 30 times higher than current rates of deployment, with 581,000 solid walls, 355,000 cavity walls and 1.1 million lofts deployed in 2025.
  - The 2027 peak is due to the backstop dates, which require the completion of deployment in both social housing and private rented homes by 2027.
  - Deployment remains high to 2030, when the backstop date for all fuel poor homes is reached.
  - Beyond 2030, energy efficiency measures are deployed solely in non-fuel poor, owner-occupied homes, with deployment levels dropping to under 2 million measures a year.

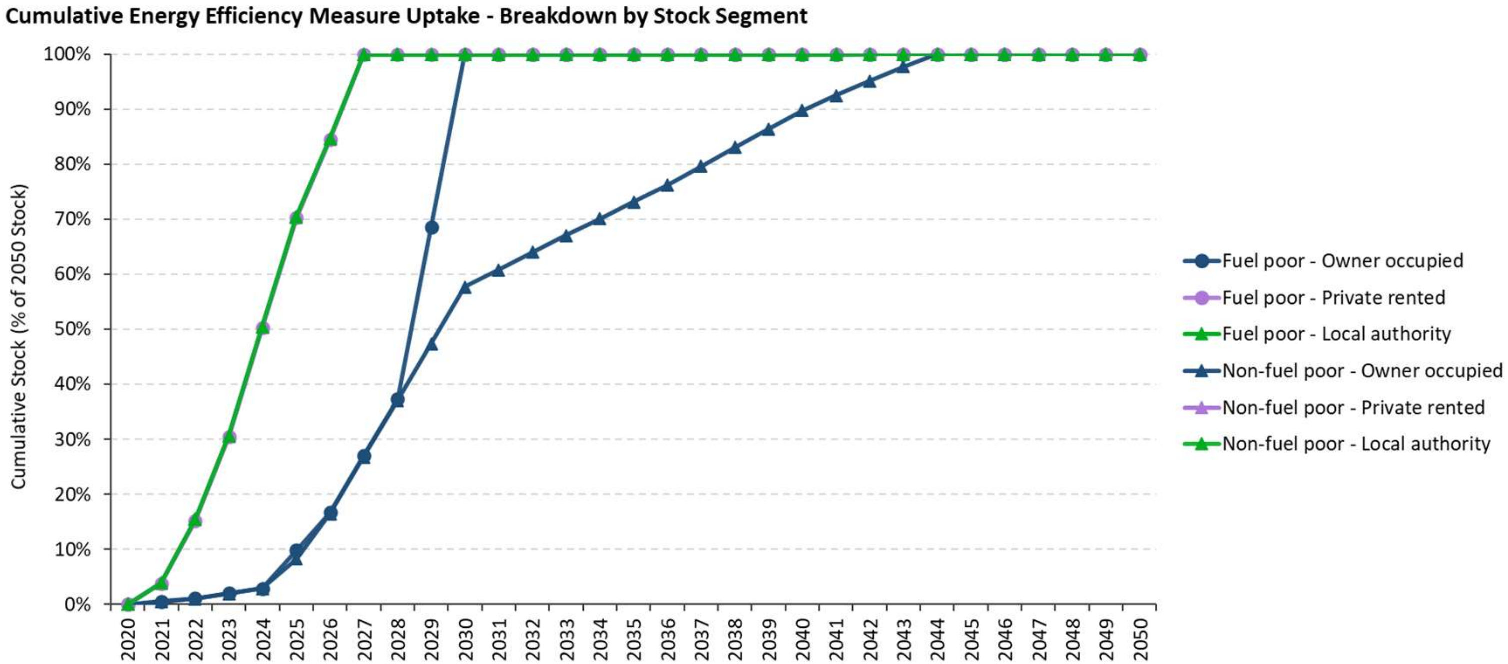
Yearly Energy Efficiency Measure Uptake [1]



[1] Draught proofing replacements, required every 10 years, are not shown in the graph. Draught proofing is shown under 'Other' measures. All other energy efficiency measures have lifetimes exceeding 30 years and hence do not require replacement.

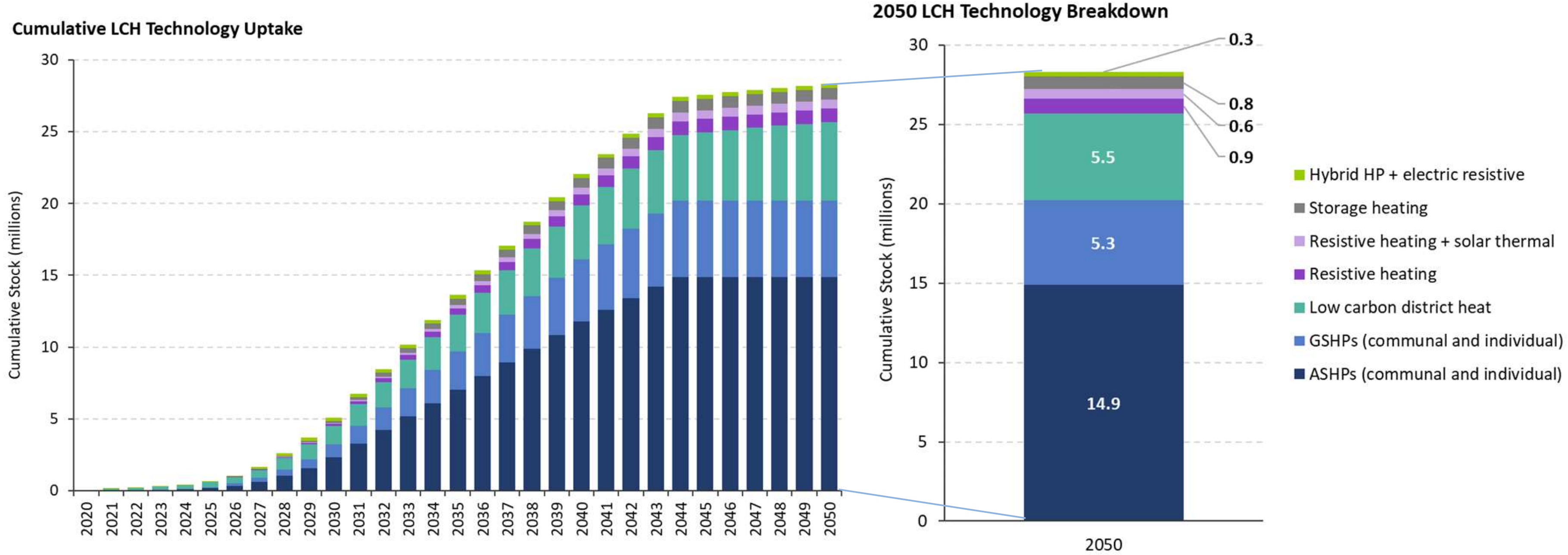
Energy efficiency uptake by stock segment – Widespread Engagement

- The first segments to achieve 100% deployment, in 2027, are social homes and private rented homes (both fuel poor and non-fuel poor).
- This is followed by owner-occupied fuel poor homes, which achieve 100% deployment by 2030.
- After 2030, the remaining 42% of non-fuel, owner-occupied homes are upgraded steadily.
- Full energy efficiency deployment across the stock is achieved in 2044.
- Whilst the ramp-ups in deployment are steep over the next decade, particularly for fuel poor owner-occupied homes, overall deployment rates remain within deployment constraints. The focus of this analysis was on ensuring overall ramp-up across the stock remains within deployment constraints and represents a reasonable profile of growth. As such, profiles for individual stock segments should be taken to be illustrative only, with reprofiling between segments viable.



Low carbon heating uptake trajectory – Widespread Engagement

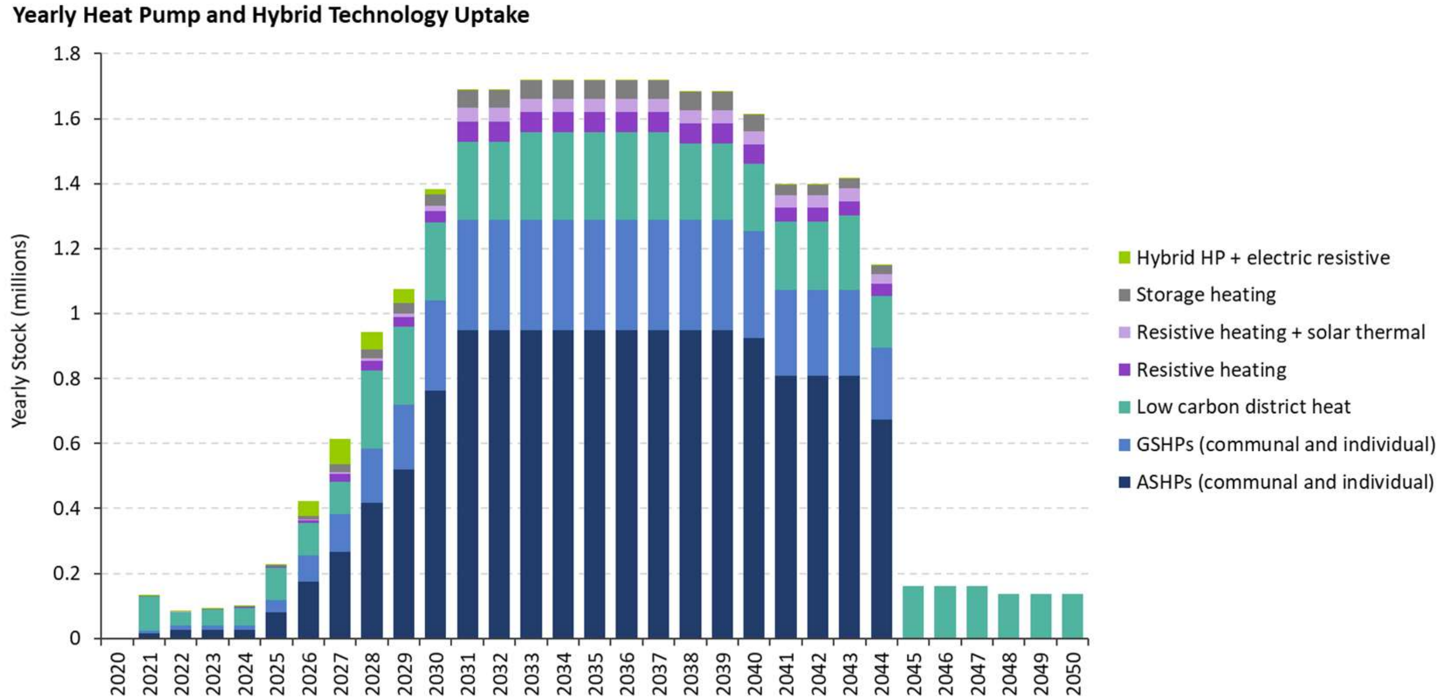
- Rapid ramp up of energy efficiency deployment prepares the stock for low carbon heating uptake.
- The low carbon heating deployment rates for the Widespread Engagement scenario in the early years are not noticeably faster than those for the Balanced Pathway scenario, as both scenarios are close to achievable deployment constraints.
    - 3.5 million heat pumps are deployed by 2030, and 10 million by 2035[1].
- As a fully electrified scenario, Widespread Engagement does not have any hydrogen- or biofuel-powered technologies.



[1] Figures exclude deployment in new builds and replacements.

Low carbon heating uptake trajectory – Widespread Engagement

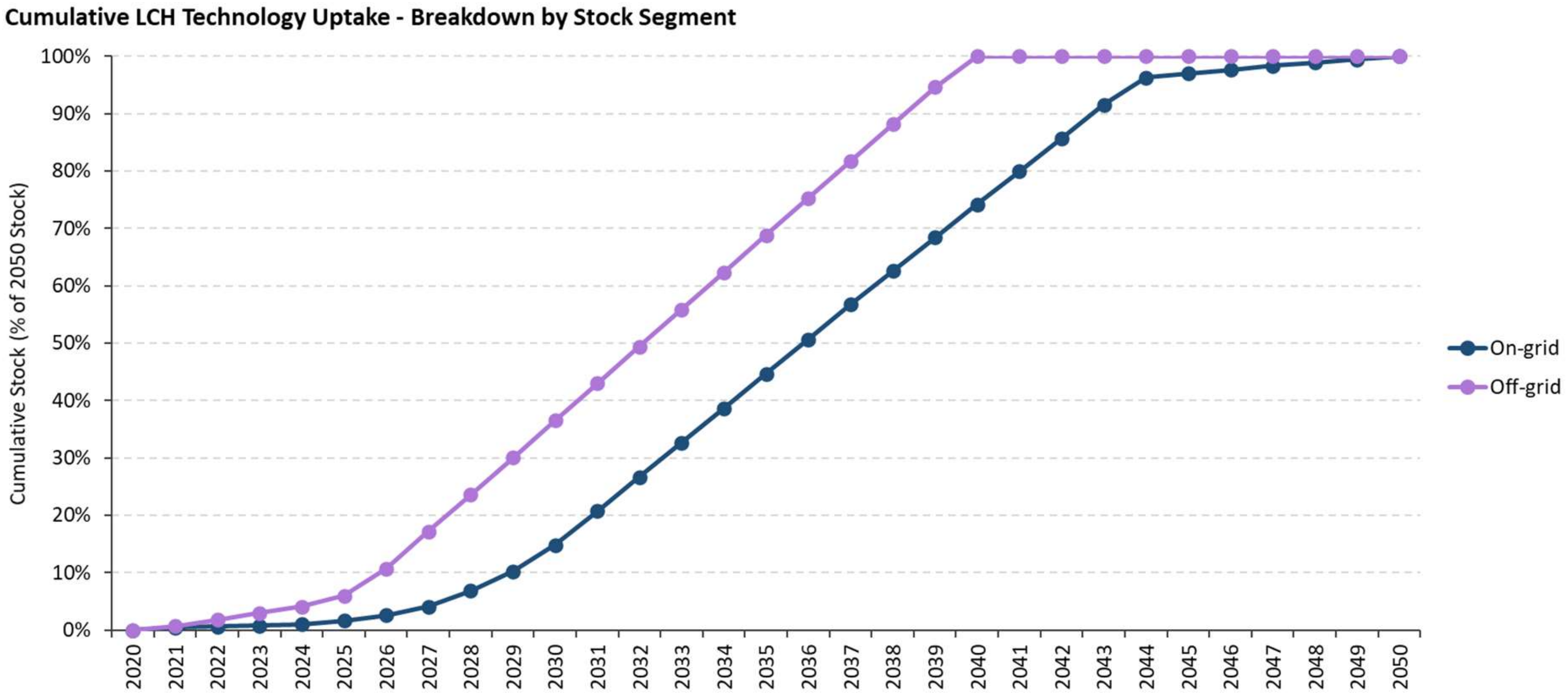
- In the early years, off-grid deployment dominates, with on-grid deployment ramping up from 2026.
  - Low carbon heat networks dominate the low carbon heating uptake up to 2025, with the relatively few heat pumps deployed primarily in off-grid homes.
- Yearly deployment increases almost seven-fold between 2025 and 2030, from just over 200,000 units per year to just under 1.4 million units[1].
- With no hybrid H_2 heat pumps, heat pump deployment follows trajectories dictated by fossil-phase out dates, leading to consistent uptake of nearly 1.3 million units per year after 2030, when both off-grid and on-grid fossil phase-out dates have come into effect[1].



[1] Figures exclude deployment in new builds and replacements.

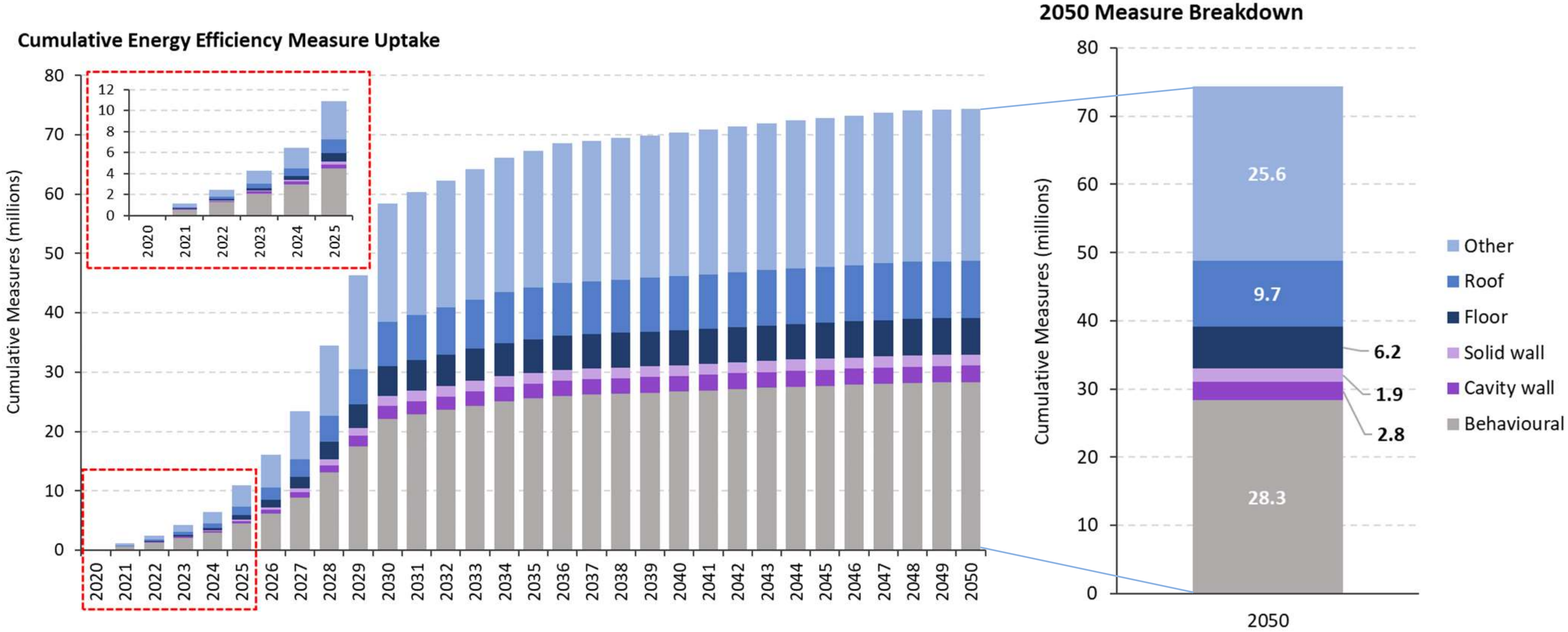
Low carbon heating uptake by stock segment – Widespread Engagement

- Deployment of low carbon heating in off-grid homes begins and ends before that in on-grid homes.
- After the fossil phase-out dates – 2026 for off-grid homes and 2030 for on-grid homes – the rate of deployment increases steadily until full deployment is reached.
  - The exceptions are technologies which deploy according to geographical conversion, namely low carbon heat networks (there is no hydrogen in the Widespread Engagement scenario).
- Full deployment is achieved in 2040 for off-grid homes and 2044 for on-grid homes (with the exception of about 900,000 homes which connect to low carbon heat networks between 2045 and 2050).



Energy efficiency uptake trajectory – Headwinds

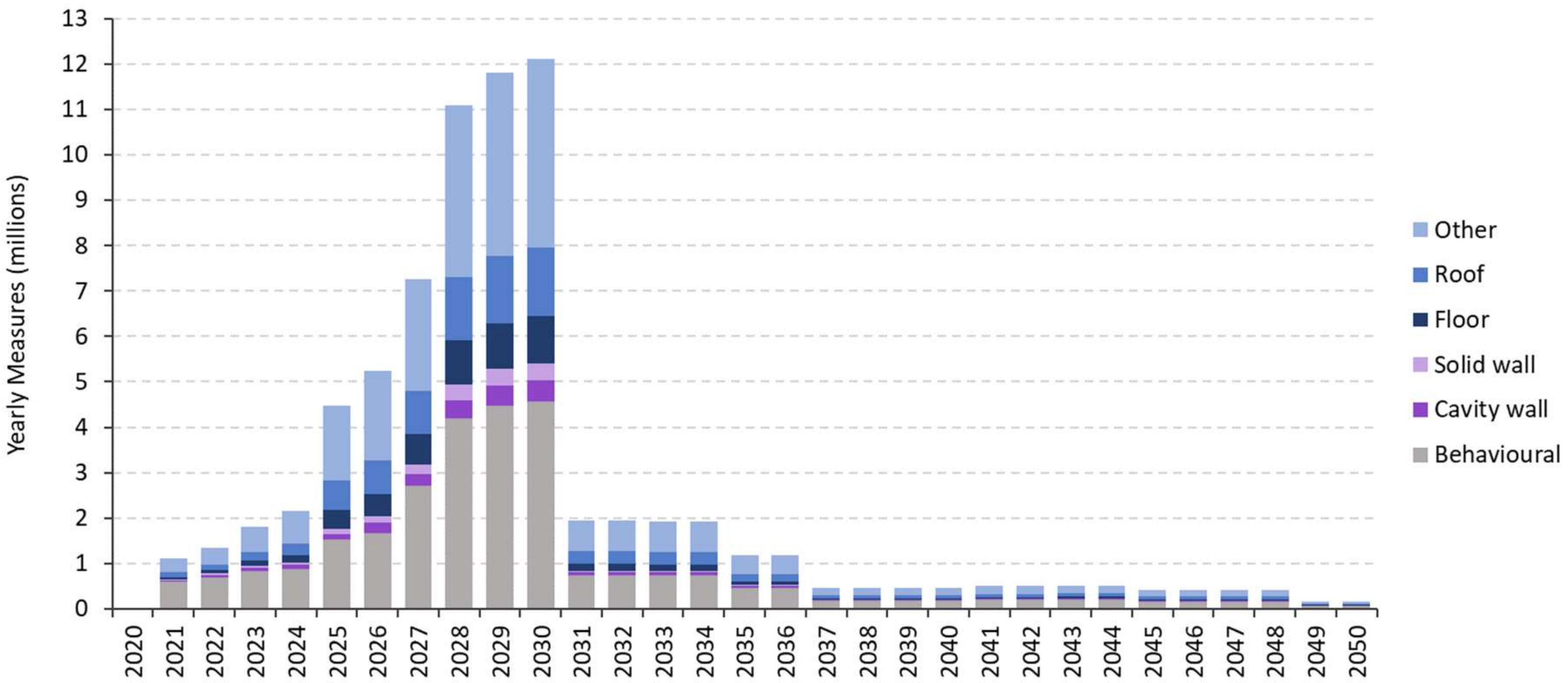
- The Headwinds scenario includes energy efficiency levels optimised for the lowest lifetime cost energy efficiency + low carbon heat combination (see slide for a recap of the "cost-effective" definition used in the modelling), given high H_2 prices, with no wider benefits costed for non-fuel poor homes. As with other scenarios, deployment is based on an "energy efficiency first" approach.
  - 78% of all energy efficiency measures are installed in the first 10 years (i.e. to 2030), with 90% installed by the fossil phase-out date of 2035.
- 2.7 million homes (10% of the total stock) receive no energy efficiency measures.
  - These are primarily more insulated dwellings, with most (58%) in the owner-occupied sector.



Energy efficiency uptake trajectory – Headwinds

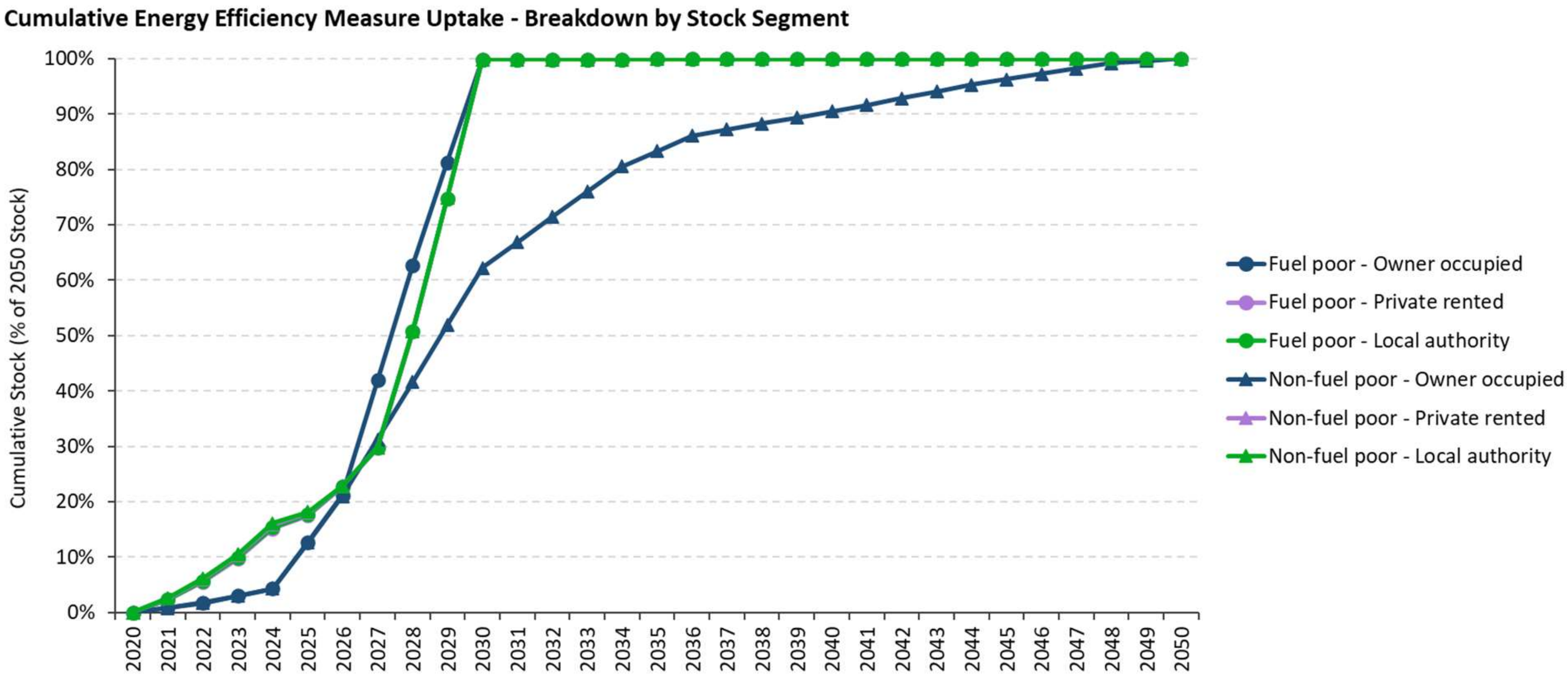
- Yearly deployment of energy efficiency measures starts at 1.1 million in 2021, and peaks in 2030, at just over 12 million.
  - By 2025, yearly deployment of solid walls, cavity walls and loft insulation are on average more than 10 times higher than current rates of deployment, with 105,000 solid walls, 133,000 cavity walls and 642,000 lofts deployed in 2025.
  - The 2030 peak is due to the backstop dates, which require the completion of deployment in social housing, private rented homes and all fuel poor homes by 2030.
  - Deployment rates fall significantly after 2030, when only non-fuel poor, owner-occupied homes get uptake.
  - Deployment levels in those years drop to under 2 million measures a year.

Yearly Energy Efficiency Measure Uptake



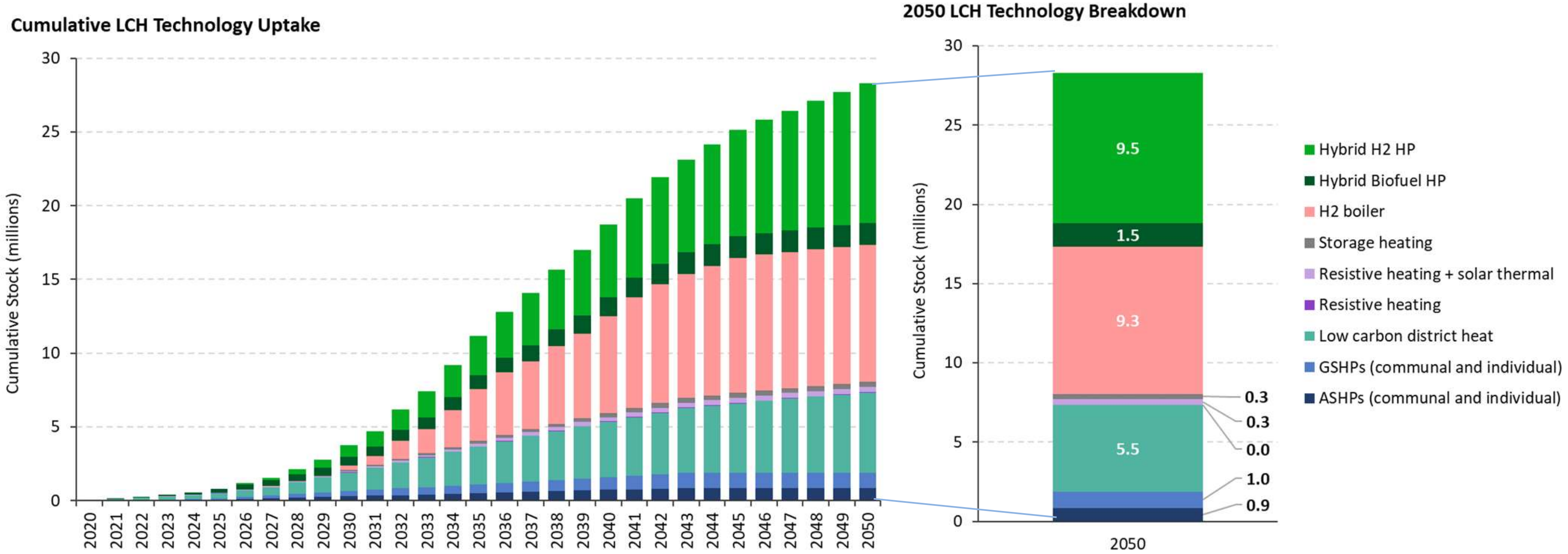
Energy efficiency uptake by stock segment – Headwinds

- The first segments to achieve 100% deployment, in 2030, are social homes, private rented homes and all fuel poor homes.
  - The slight slow-down in the deployment rate for social housing and private rented homes after 2024 is necessary to ensure deployment constraints are not breached, given the rapid acceleration of deployment in owner-occupied fuel poor homes from 2025.
  - As with the other scenarios, the steep ramp-ups for individual stock segments in the next decade are illustrative only; overall deployment remains within deployment constraints.
- After 2030, the remaining 38% of non-fuel, owner-occupied homes are upgraded steadily.
- Full energy efficiency deployment across the stock is achieved in 2050.



Low carbon heating uptake trajectory – Headwinds

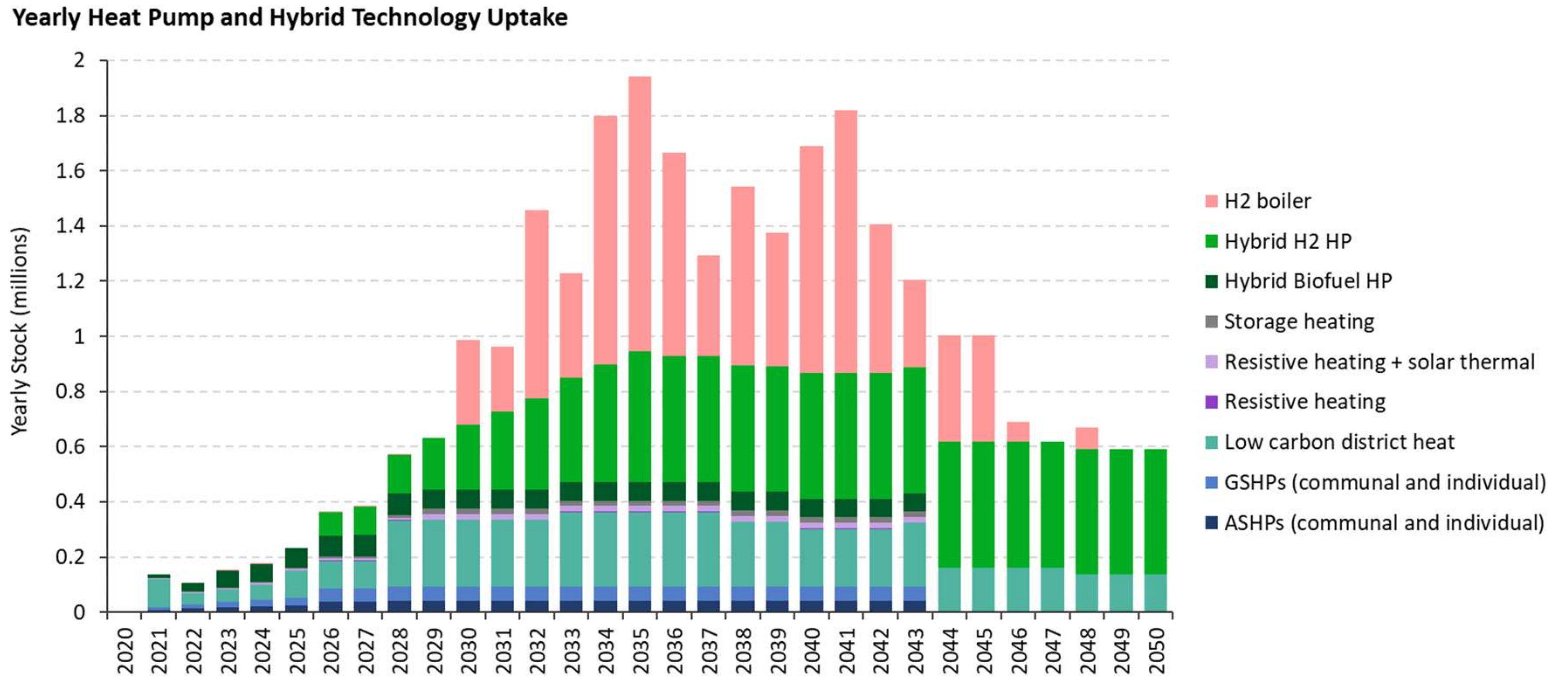
- Ramp up of low carbon technologies is relatively slower in the Headwinds scenario compared to the other exploratory scenarios, primarily due to the widespread deployment of H_2 boilers, which – in accordance with the hydrogen conversion trajectory (see slide) – do not begin deploying at scale until 2030.
- The technology uptake is dominated by hydrogen technologies, split nearly 50/50 between hybrid H_2 heat pumps and H_2 boilers.
  - With hydrogen technologies and low carbon heat networks together deploying 24.3 million units, and some deployment of hybrid biofuel heat pumps, the Headwinds scenario deploys less than 2 million conventional heat pumps[1].



[1] Figures exclude deployment in new builds and replacements.

Low carbon heating uptake trajectory – Headwinds

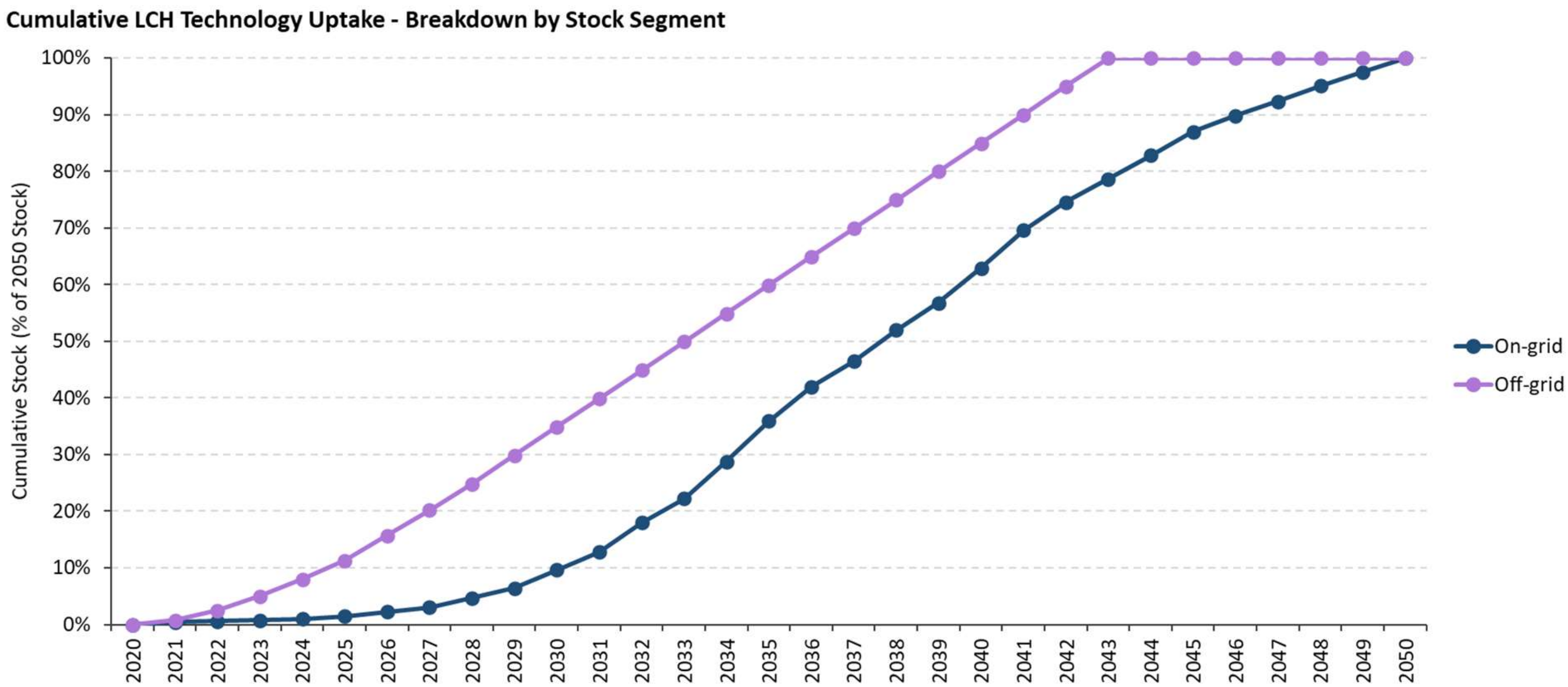
- In the early years, off-grid deployment dominates, with on-grid deployment ramping up from 2026.
  - Low carbon heat networks and hybrid biofuel heat pumps dominate the low carbon heating uptake up to 2025.
- Yearly deployment increases almost seven-fold between 2025 and 2030, from about 140,000 units per year to just under 1 million units[1].
- Yearly heat pump deployment stabilises at about 600,000 per year after the 2035 on-grid fossil phase-out date[1].
- Due to the hydrogen boiler deployment being governed by a trajectory based on geographical conversion (see slide), the overall yearly deployment rates for the scenario do not show a consistent pattern, peaking at around 1.9 million in 2035, falling thereafter, then rising again to a second peak of just over 1.8 million in 2041[1].



[1] Figures exclude deployment in new builds and replacements.

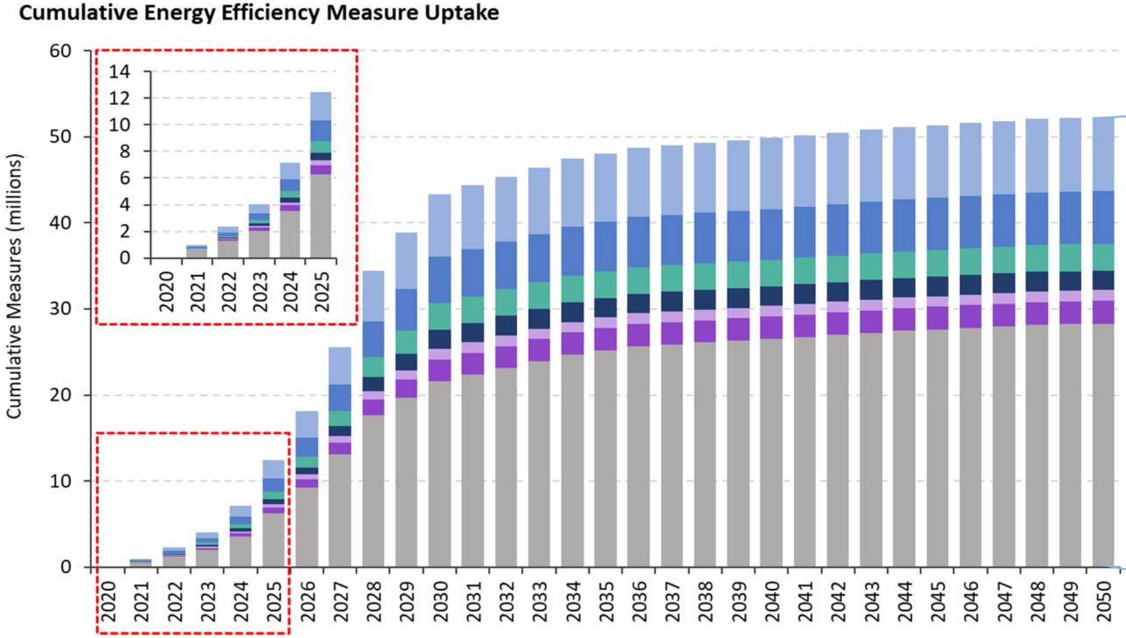
Low carbon heating uptake by stock segment – Headwinds

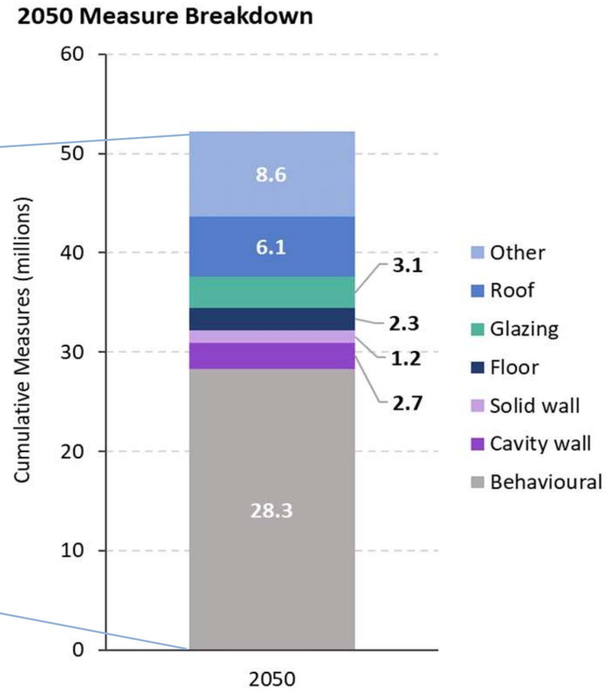
- Deployment of low carbon heating in off-grid homes begins and ends before that in on-grid homes.
- After the fossil phase-out dates – 2028 for off-grid homes and 2035 for on-grid homes – the rate of deployment increases steadily until full deployment is reached.
  - Due to the influence of the H_2 boiler deployment trajectory, the on-grid deployment rate fluctuates slightly between years.
- Full deployment is achieved in 2043 for off-grid homes and 2050 for off-grid homes.



Energy efficiency uptake trajectory – Widespread Innovation

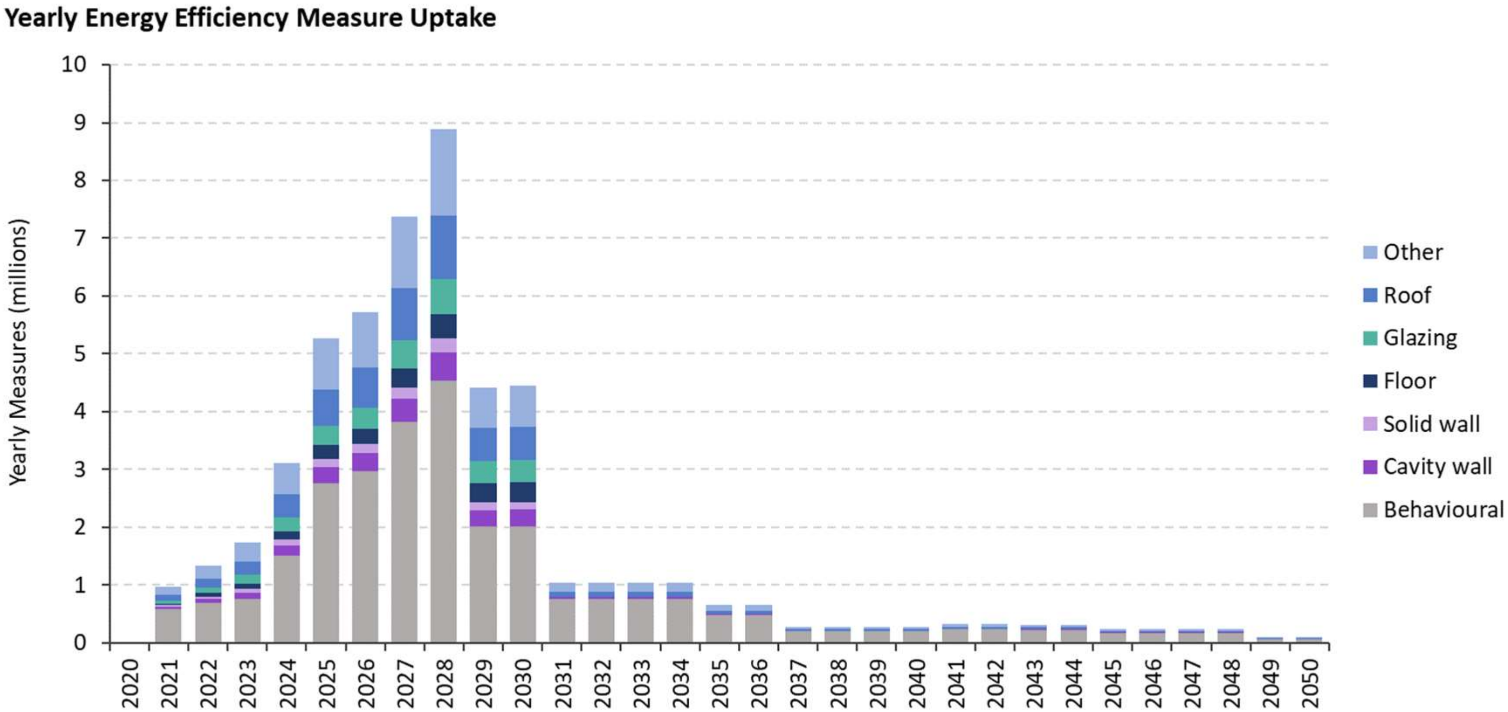
- The Widespread Innovation scenario includes energy efficiency levels optimised for the lowest lifetime cost using lower end costs (see slide for a recap of the "cost-effective" definition used in the modelling), with no wider benefits costed for non-fuel poor homes; deep retrofits replace standard high packages. The scenario is based on an "energy efficiency first" approach, as other scenarios are.
  - 83% of all energy efficiency measures are deployed in the first 10 years (i.e. to 2030), with 92% deployed by the fossil phase-out date of 2035.
- Most homes (19.4 million) do not get any energy efficiency measures, leading to Widespread Innovation having the lowest total deployment of energy efficiency measures amongst the exploratory scenarios, at 52.3 million (28.3 million of which are behavioural measures).
  - Despite the low overall deployment, savings remain high because of the relatively high savings from "deep" retrofit packages.





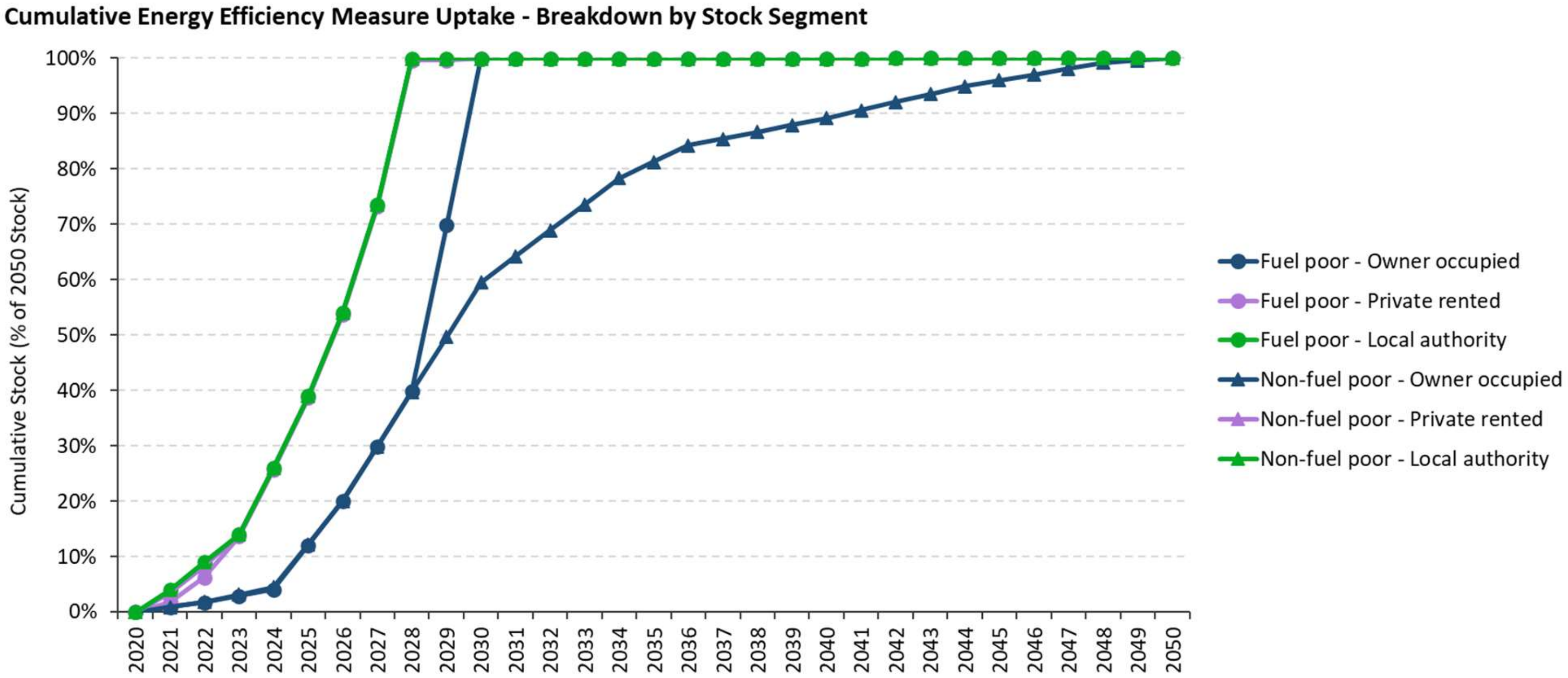
Energy efficiency uptake trajectory – Widespread Innovation

- Yearly deployment of energy efficiency measures starts at 1 million in 2021, and peaks in 2028, at just under 9 million.
  - By 2025, yearly deployment of solid walls, cavity walls and loft insulation are on average more than 10 times higher than current rates of deployment, with 139,000 solid walls, 279,000 cavity walls and 633,000 lofts deployed in 2025.
  - The 2028 peak is due to the backstop dates, which require the completion of deployment in both social housing and private rented homes by 2028.
  - Deployment remains high to 2030, when the backstop date for all fuel poor homes is reached.
  - Beyond 2030, energy efficiency measures are deployed solely in non-fuel poor, owner-occupied homes, with deployment levels dropping to under 1 million measures a year.



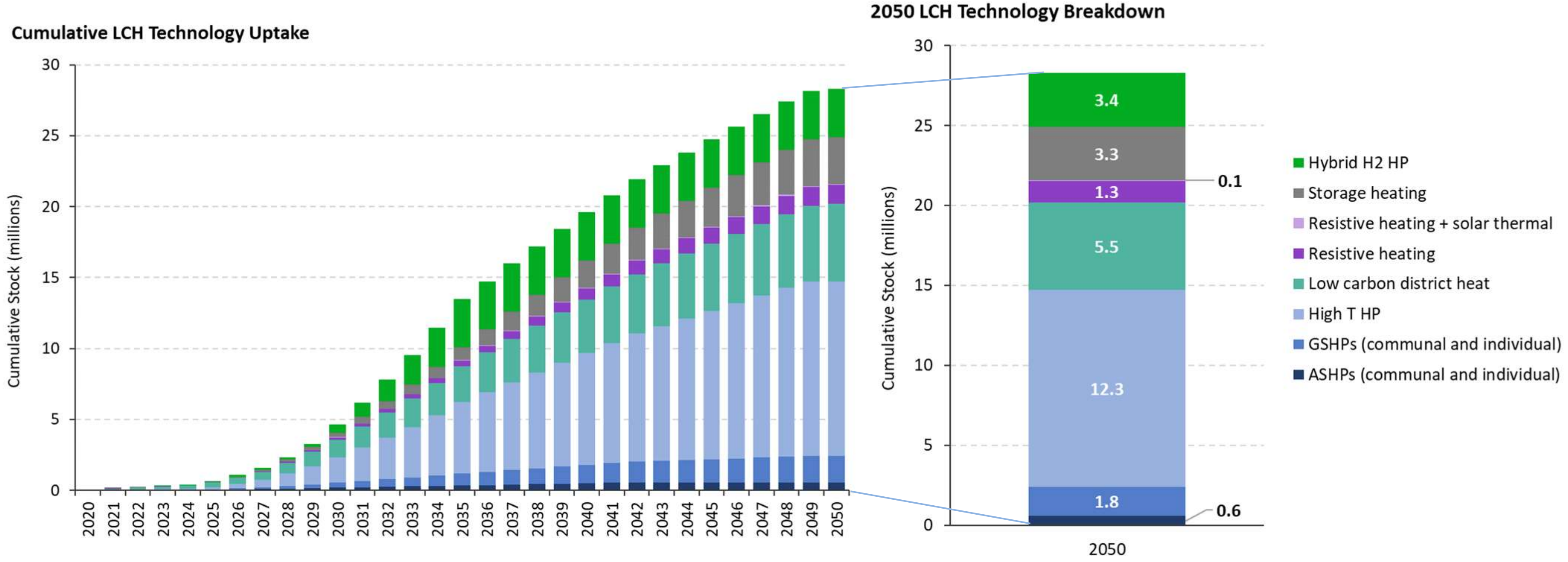
Energy efficiency uptake by stock segment – Widespread Innovation

- The first segments to achieve 100% deployment, in 2028, are social homes and private rented homes (both fuel poor and non-fuel poor).
- This is followed by owner-occupied fuel poor homes, which achieve 100% deployment by 2030.
- After 2030, the remaining 40% of non-fuel, owner-occupied homes are upgraded steadily.
- Full energy efficiency deployment across the stock is achieved in 2050.
- As with the other scenarios, the steep ramp-ups for individual stock segments in the next decade are illustrative only; overall deployment remains within deployment constraints.



Low carbon heating uptake trajectory – Widespread Innovation

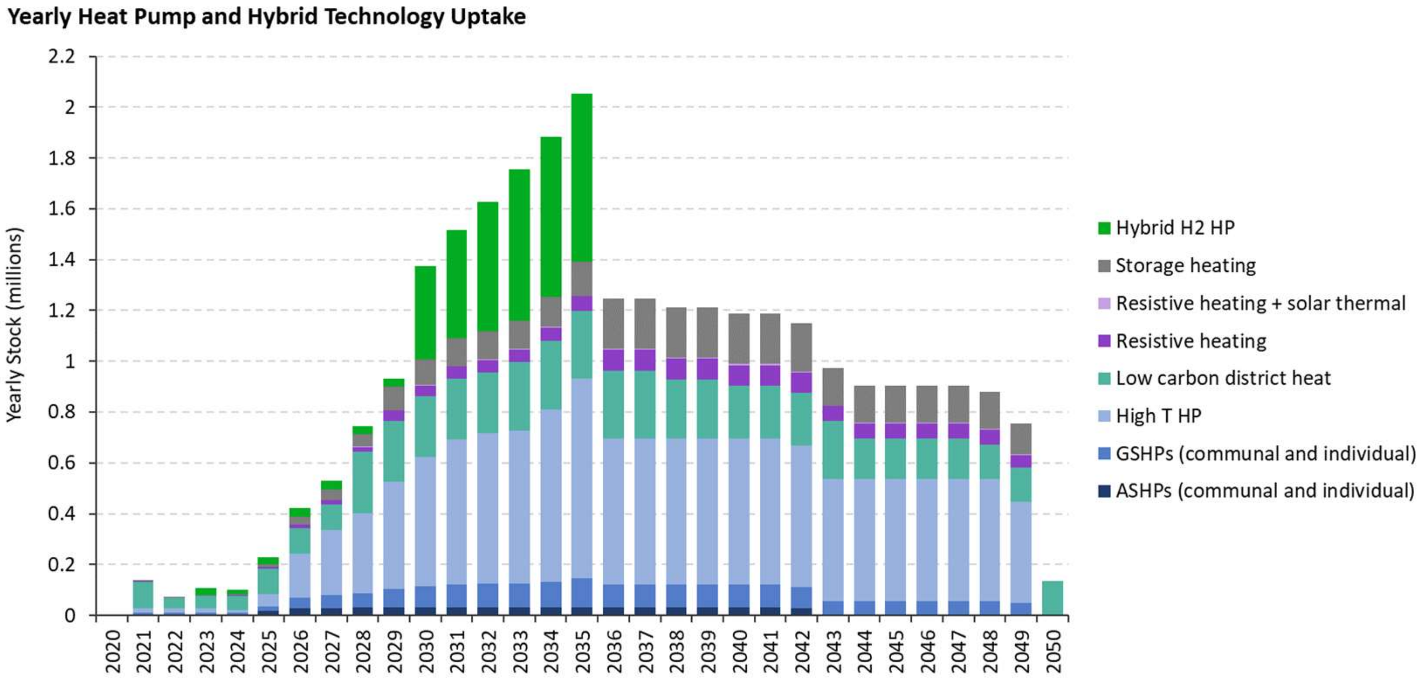
- Rapid ramp up of energy efficiency deployment prepares the stock for low carbon heating uptake.
- As the only scenario where high temperature heat pumps are modelled, Widespread Innovation is dominated by the technology, which is deployed in 54% of the stock not suitable for low carbon heat networks (in both air-source and ground-source configurations).
- 2.9 million heat pumps are deployed by 2030, and 9.6 million by 2035[1].
- The scenario also has significant deployment of electric storage heating, at 3.3 million units[1].
- The deployment of 3.4 million hybrid H_2 heat pumps is consistent with the approach for hydrogen deployment in the scenario (see slide).



[1] Figures exclude deployment in new builds and replacements.

Low carbon heating uptake trajectory – Widespread Innovation

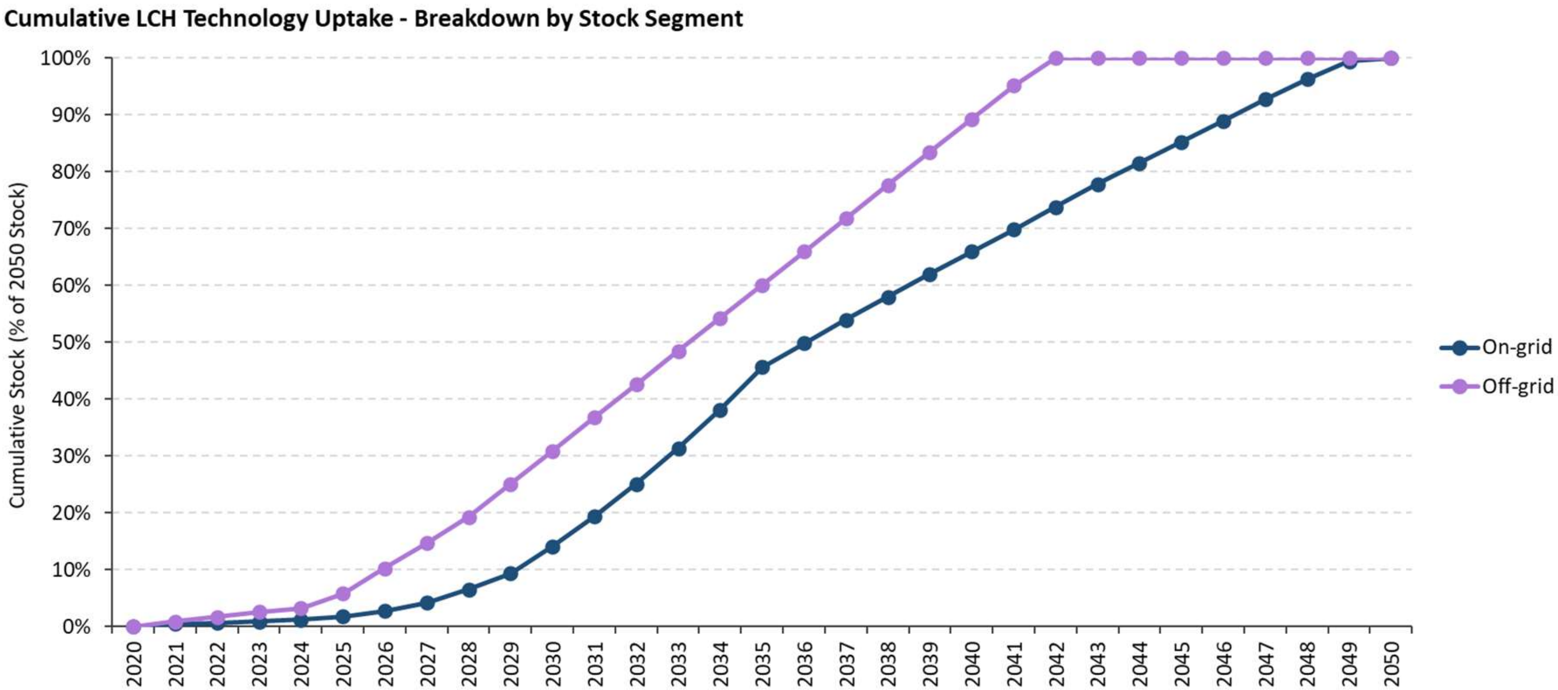
- In the early years, off-grid deployment dominates, with on-grid deployment ramping up from 2026.
  - Low carbon heat networks dominate the low carbon heating uptake up to 2025, with the relatively few heat pumps deployed primarily in off-grid homes.
- Yearly deployment increases almost seven-fold between 2025 and 2030, from just over 200,000 units per year to just under 1.4 million units.
- Deployment of hybrid H_2 heat pumps primarily occurs between 2030 and 2035 (see slide).
- Total yearly deployment of all technologies peaks in 2035 at just over 2 million units[1].
- After 2035, when deployment of hybrid H_2 heat pumps is complete and the on-grid fossil phase-out date is reached, deployment of heat pumps stabilises at around 700,000 units per year[1].



[1] Figures exclude deployment in new builds and replacements.

Low carbon heating uptake by stock segment – Widespread Innovation

- Deployment of low carbon heating in off-grid homes begins and ends before that in on-grid homes.
- After the fossil phase-out dates – 2028 for off-grid homes and 2035 for on-grid homes – the rate of deployment increases steadily until full deployment is reached.
  - The on-grid deployment rate slows down after the fossil phase-out date; whilst possibly counterintuitive, this is due to the effect of hybrid H_2 heat pump deployment, where 3.4 million units are deployed in the 5-year period between 2030 and 2035, accelerating the deployment rate.
- Full deployment is achieved in 2042 for off-grid homes and 2049 for on-grid homes (with the exception of 140,000 homes which connect to low carbon heat networks between 2049 and 2050).



Contents

Sensitivities - overview

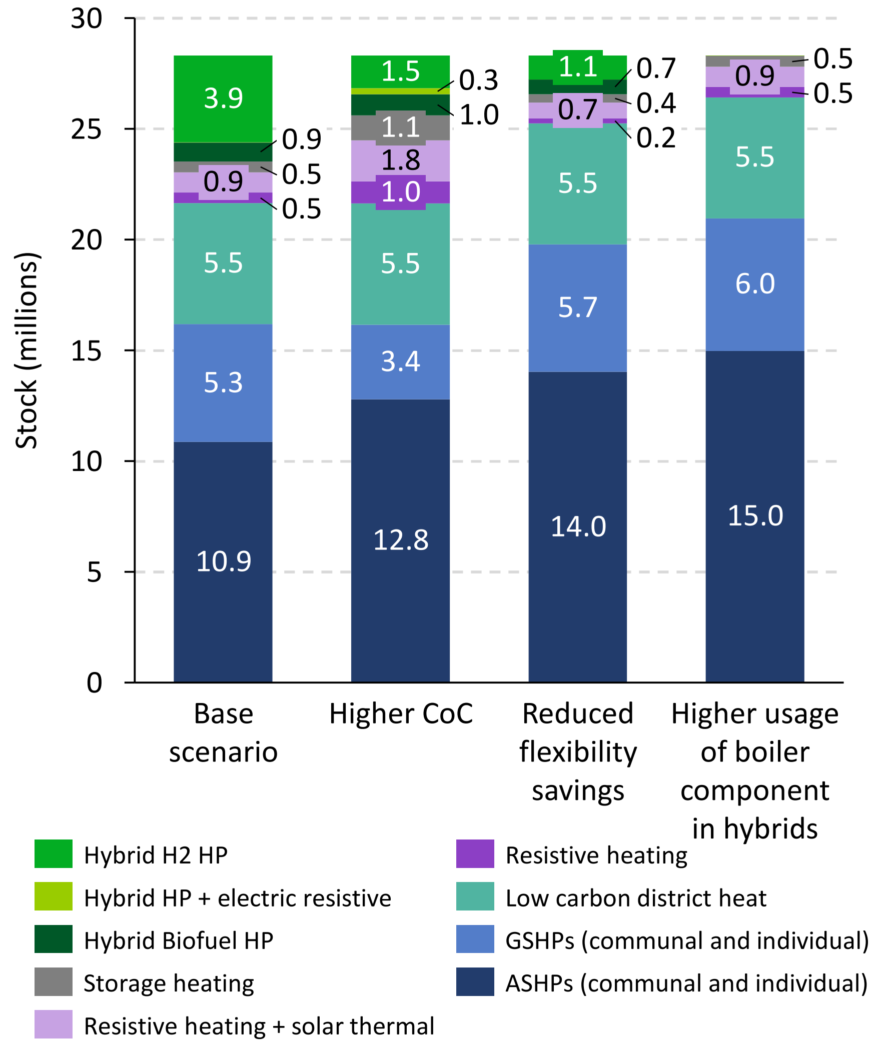
- Several sensitivities were run to investigate the effect of varying assumptions in areas where there may be high uncertainty.
  - The approach taken for the sensitivity analysis (in most cases) involved changing a particular input assumption and noting the effect on the end-state technology mix and total costs.
  - All sensitivities were tested on the Balanced Pathways[1] scenario, except where specified in the below table.
- It has only been possible to test a limited number of sensitivities within the scope of this analysis; further work to test the influence of the much wider range of uncertainties in this analysis would be valuable.

Sensitivity	Description
High cost of capital	Cost of capital – applied to both low carbon heating and energy efficiency – is increased to 7.5% (from 3.5% in the Balanced Pathway scenario)
Reduced opportunities for savings from flexibility	Difference between the flexible and inflexible long-run variable costs for electricity halved
Maximum energy efficiency reflecting full economic potential (tested on Widespread Engagement scenario)	High energy efficiency packages applied in all homes where technically feasible
Alternative hybrid HP operating mode	Share of heating demand met by the boiler component in hybrid heat pump systems increased from 20% to 50%
2022 Hy-ready mandation[2] (tested on both Balanced Pathway and Headwinds scenarios)	Date when Hydrogen ready boilers are mandated moved forward from 2026 to 2022
No Hy-ready mandation[2] (tested on both Balanced Pathway and Headwinds scenarios)	Hydrogen ready boilers never mandated

[1] Balanced Pathway sensitivities tested on an earlier version of the scenario, which had minor differences from the final scenario (primarily in the deployment trajectories of hybrid H_2 heat pumps). [2] Sensitivity tested on trajectories, with end-states fixed.

Balanced Pathway sensitivities – low carbon heating deployment

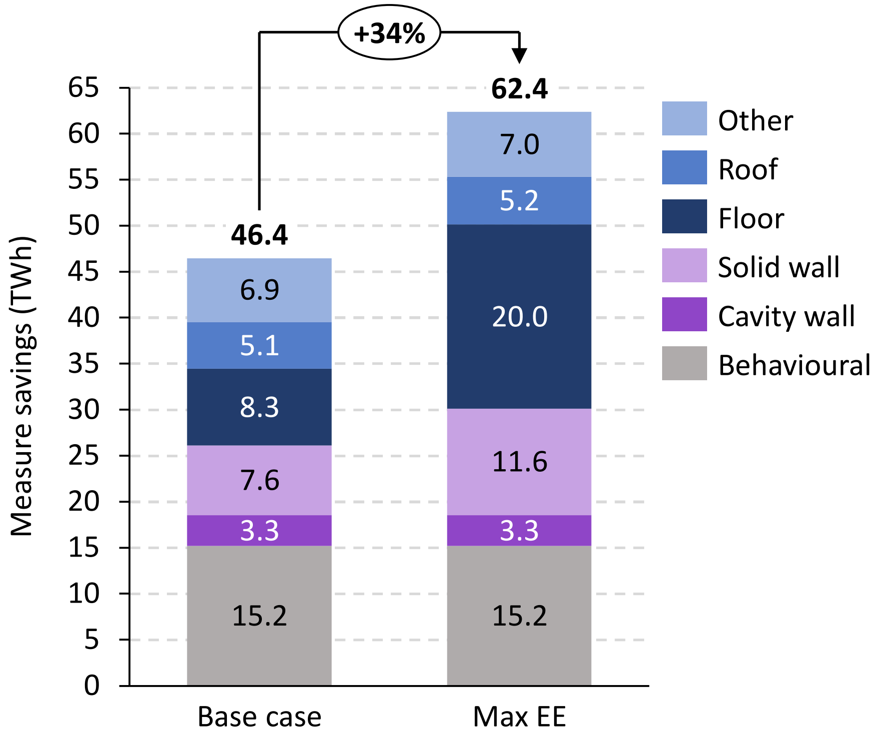
- The effects of varying three different assumptions on the final low carbon heating uptake are shown in the graph on the right (see Appendix for further graphs on cost impacts) [1]:
  - **Cost of capital (CoC):** A higher cost of capital increases annualised capex (see slide and slide). With the discount rate fixed, the share of capex as a percentage of total costs increases. A higher cost of capital therefore favours lower capex technologies, leading to reduced deployment of hybrid H_2 heat pumps and increased deployment of electric resistive heating.[2] Air-source heat pumps also become more favourable than ground-source heat pumps.
  - **Gains from flexible operation:** There is high uncertainty over the savings which could be gained from flexible operation of low carbon heating technologies. With lower savings (modelled as relatively higher costs for flexible electricity), deployment of hybrid heat pumps – both biofuel and H_2 – reduces significantly in favour of higher deployment of pure air-source heat pumps.
  - **Hybrid heat pump operation:** The operation of hybrid heat pumps – the percentage of time during which they operate in heat pump mode versus hybrid mode – is also subject to uncertainty, with trials suggesting it can vary significantly between homes. Modelling operation in hybrid mode 50% of the time (compared to 20% in the baseline case) leads to the cost-effective uptake of hybrid heat pumps falling from nearly 5 million in the baseline case to zero. The hybrids are replaced by conventional heat pumps, both air-source and ground-source.

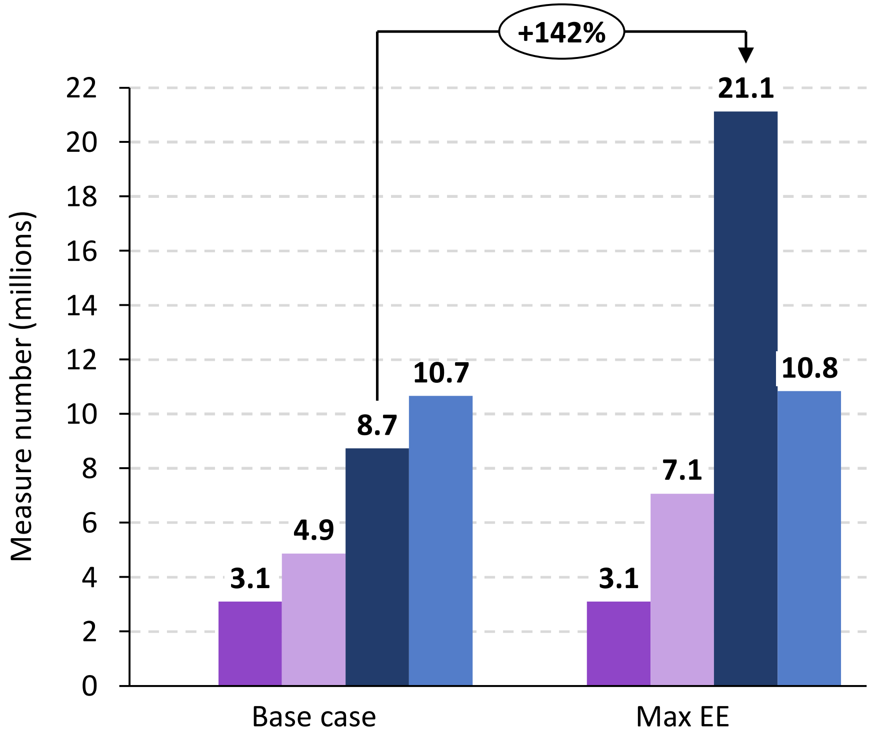


[1] Energy Efficiency uptake remained highly constrained in the Balanced Pathway sensitivities, and so was not subject to significant change. [2] This reflects the fact that the heating system capex of a hybrid heat pump is higher than that for a full heat pump in most cases (although for some homes the energy efficiency costs and additional costs can be higher).

Widespread Engagement sensitivity – energy efficiency measure deployment and savings

- Deploying maximum energy efficiency (reflecting full economic potential) in the Widespread Engagement scenario increases the number of solid walls deployed from 4.9 million to 7.1 million, and the number of floor insulation measures deployed from 8.7 million to 21.1 million.
  - The sensitivity was used as a basis for setting the energy efficiency uptake seen in the Tailwinds scenario.
- The total number of measures deployed (excluding Behavioural and Other measures, which are deployed across the stock in both the base case and the sensitivity) rises from 27.4 million to 42.1 million.
- The associated increase in savings is 16 TWh, or 34% from the base case.





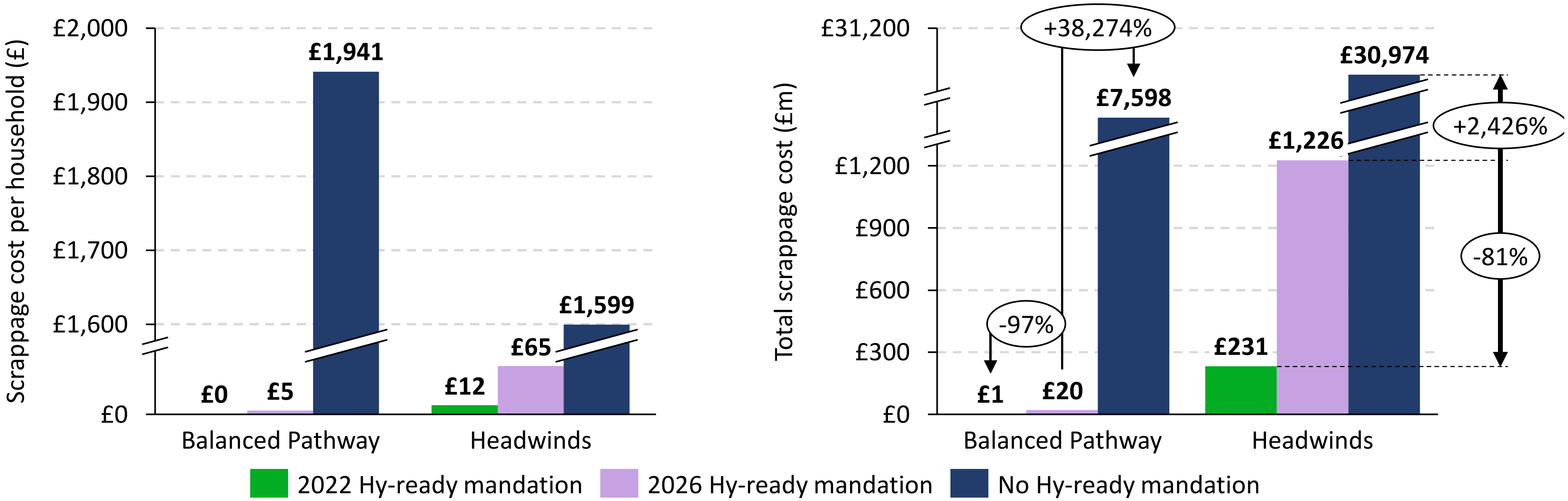
Scrappage cost analysis

- All scenarios assume 2026 as the date when hy-ready boilers will be mandated. There remains optionality over this date, with possibilities ranging from mandating Hy-ready boilers early/for all households in order to minimise scrappage to mandating later/for a smaller number of homes in order to minimize the number of households exposed to inflated boiler costs.
- There is effectively a trade-off between widespread early deployment of hy-ready boilers, such that all households are subject to a small premium in terms of boiler costs and scrappage costs are minimised, or later/more targeted mandation, whereby fewer household would be subject to a premium but scrappage costs risk being higher.
- A scrappage cost sensitivity was run to investigate this trade-off, with 2 cases tested:
  - Earlier mandation, in 2022: This would minimise scrappage costs but would subject all households to a premium in boiler costs. As per the low carbon heating cost modelling assumptions (see slide), the cost premium for a hy-ready gas boiler compared to a conventional gas boiler was assumed to be £100. Past evidence[1] suggests that this cost premium may disappear at production volumes exceeding 100,000 per manufacturer. On the other hand, low manufacturing volumes (10,000 per year per manufacturer) can lead to significant cost premiums of more than 100% of the price of a conventional gas boiler.
  - No mandation: This maximises scrappage costs but allows households to avoid paying the premium associated with installing hy-ready boilers.
- Total scrappage costs were estimated by summing the scrappage costs for deployment of H_2 boilers and hybrid heat pumps with H_2 boilers.
  - Before the hy-ready standards apply, all homes deploying hydrogen systems incur scrappage costs.
  - After the date hy-ready standards come into force, only a proportion of homes deploying hydrogen systems incur scrappage costs. This proportion is governed by the replacement rate and reduces to zero 15 years after mandation.

[1] Hydrogen supply chain evidence base, Element Energy for BEIS (2018) [1]

Scrappage cost sensitivities – total costs and household costs

- The Hy-ready mandation date strongly influences the scrappage costs paid by households:
  - In the base case (2026 Hy-ready mandation date), total scrappage costs are around £20 million in the Balanced Pathway and £1.2 billion in Headwinds. By comparison, making all existing gas boilers hy-ready (assuming a conversion cost of £100) would cost £2.4 billion.
  - An earlier mandation date of 2022 reduces scrappage costs significantly, to £0.55 million in the Balanced Pathway and £231 million in Headwinds.
  - By contrast, not mandating Hy-ready boilers at all leads to extremely high scrappage costs of £7.6 billion in the Balanced Pathway (3% of the baseline total investment cost) and £30 billion in Headwinds (17% of the total investment costs).
- Trends in scrappage costs per household do not exactly mirror those for total scrappage costs due to the different number of hydrogen systems deployed in the two scenarios (3.9 million in the Balanced Pathway compared to 18.8 million in Headwinds) being deployed at different rates [1].



[1] Because scenario deployment trajectories and hydrogen conversion trajectories differ, the scrappage cost per household differs. As an example, in the “no hy-ready mandation” case, for the Headwinds scenario, the unused lifetime of a non-hy-ready hybrid boiler is on average lower than the unused lifetime of on in the Balanced Pathway by its required replacement date; as such, this type of scrappage cost, per household, is lower in Headwinds.

Contents

Fuel bill analysis – overview

- In order to examine the impact of installing energy efficiency measures and low carbon heating on household fuel bills, additional analysis was carried out.
- Model outputs[1] – primarily fuel use – were combined with retail fuel prices (as opposed to Long-Run Variable Costs (LRVC) used in the model) to determine heating bills households would likely pay.
- Fuel use from cooking, lighting and appliance use, from ECUK end-use data tables[2], was also taken into account.
- Fuel use for all end-uses, combined with retail fuel prices, was then used to provide an overall picture of household fuel bills and how these might change after installing energy efficiency and low carbon heating, using the CCC's fuel price assumptions.
- The counterfactual case (i.e. before installing any measures) is different for different scenarios due to different retail prices for fuels in 2020.
- The fuel bill assessments resulting from this analysis will differ from those which might result from using the SAP/BREDEM methodology and so cannot be directly compared. In particular, this analysis uses different assumptions for baseline heat demands and savings associated with measures (containing also only a subset of the measures which are included in SAP); it incorporates fuel use associated with lighting and appliances based on ECUK (whilst SAP ratings are based on energy costs associated with space heating, water heating, ventilation and lighting only); and it is based on CCC retail price projections (rather than SAP fuel prices and standing charges). The fuel bill assessments in the following slides have been undertaken for 2050 only and different profiles would be expected over the course of the trajectory.

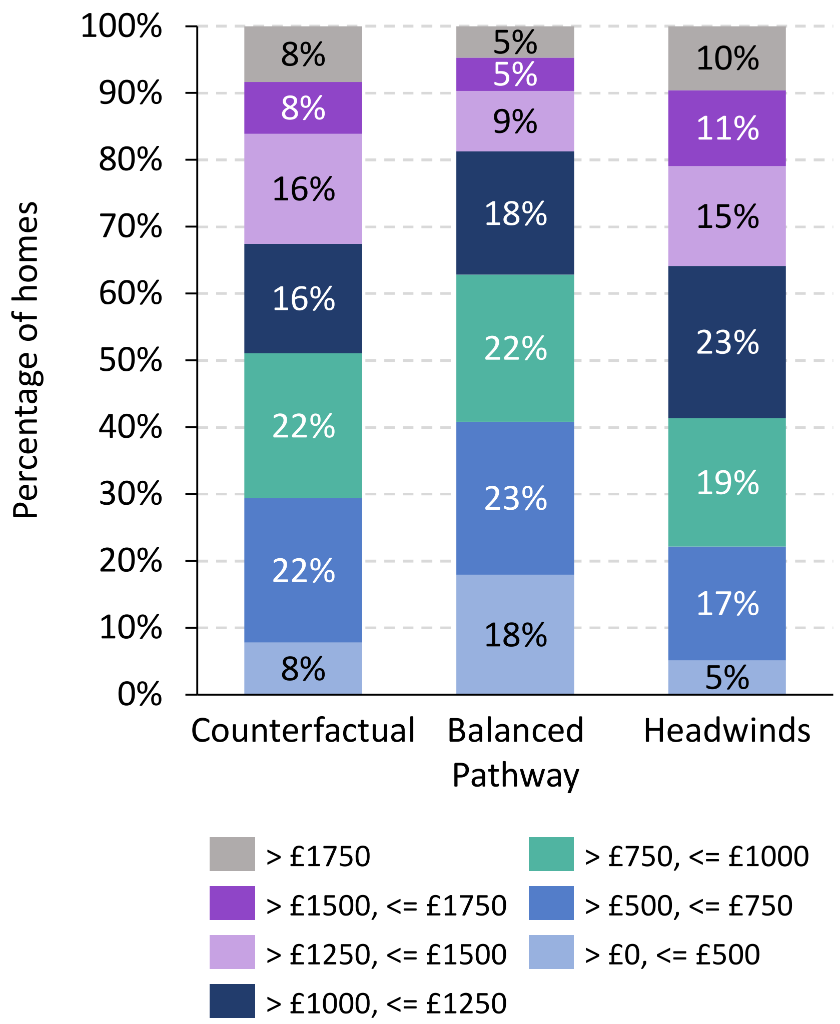
	2050 fuel price in the Balanced Pathway (p/kWh)	
Fuel	**LRVC**	**Retail**
Electricity for SH – Inflexible	10.9	15.4
Electricity for SH – Flexible	7.3	11.7
Electricity for SH – Highly flexible	6.9	11.2
Electricity for HW – with storage	7.3	11.7
Electricity for HW – without storage	13.5	18.1
Electricity – residential	8.3	12.6
Hydrogen	8.2	9.8
Heat (applicable for low carbon heat networks)	6.3	7.8

[1] Sensitivity tested on trajectories, with end-states fixed. [2] Energy Consumption in the UK, 2018, Table U3

Fuel bill analysis – Balanced Pathway and Headwinds

- Compared to the counterfactual case (i.e. before installing any energy efficiency or low carbon heating systems), the Balanced Pathway sees:
  - The proportion of homes paying the lowest fuel bills (up to £500/year) increasing from 8% to 18%.
  - The proportion of homes with bills below £1000/year rising from 52% to 63%.
- The Headwinds scenario has a detrimental effect on fuel bills, decreasing both the proportion of homes paying the lowest fuel bills (from 8% to 5%) and the proportion paying less than £1000/year (from 52% to 41%). Conversely, the proportion paying the highest costs – above £1250 a year – significantly increases (from 19% to 36%).
  - This is due to the widespread deployment of hydrogen-powered technologies, which have higher fuel costs and lower efficiencies compared to heat pumps.

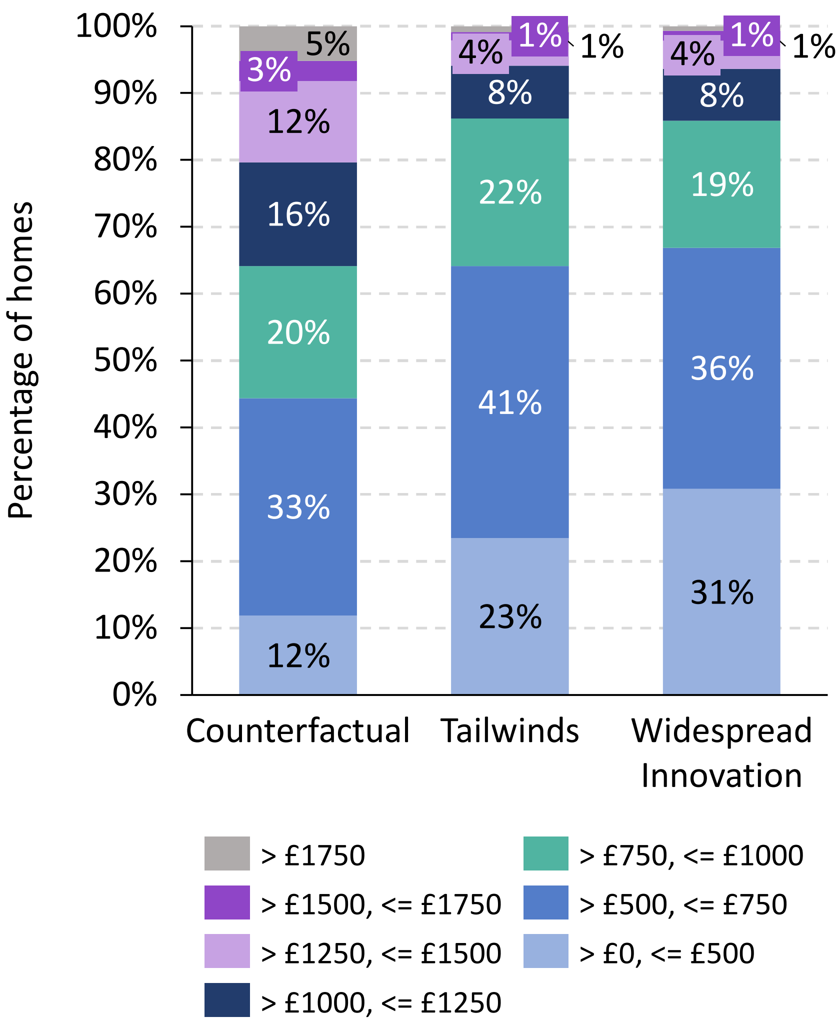
Distribution of homes by annual fuel bill bracket (£/y) in 2050



Fuel bill analysis – Tailwinds and Widespread Innovation

- Compared to the counterfactual case (i.e. before installing any energy efficiency or low carbon heating systems), Tailwinds sees:
  - The proportion of homes paying the lowest fuel bills (up to £500/year) nearly doubling, from 12% to 23%.
  - The proportion of homes with bills below £1000/year rising from 66% to 86%.
- The Widespread Innovation scenario shows a similar picture to Tailwinds, with the proportion of homes paying less than £1000/year also rising to 86%.
  - The main difference compared to Tailwinds is a higher proportion of homes paying the lowest fuel bills of less than £500/year, where the increased share is due to the deployment of hybrid H_2 heat pumps as the hydrogen technology of choice, as opposed to H_2 boilers in Tailwinds.

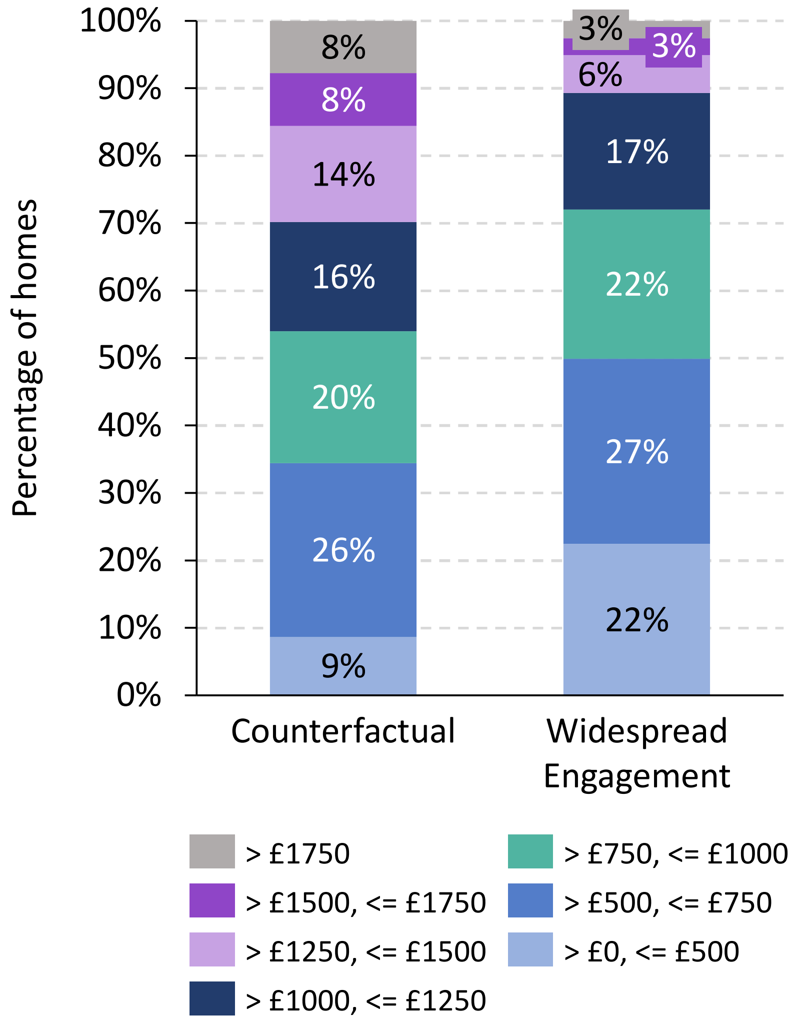
Distribution of homes by annual fuel bill bracket (£/y) in 2050



Fuel bill analysis – Widespread Engagement

- Compared to the counterfactual case (i.e. before installing any energy efficiency or low carbon heating systems), the Widespread Engagement scenario sees:
  - The proportion of homes paying the lowest fuel bills (up to £500/year) increasing from 9% to 22%.
  - The proportion of homes with bills below £1000/year rising from 55% to 71%.
- The savings are due to a combination of electrification and the widespread installation of energy efficiency measures.
- The proportion of homes with bills between £1000 and £1250 per year remains practically constant, whilst that for homes paying the highest fuel bills (£1250/year and above) reduces from 30% to 12%.

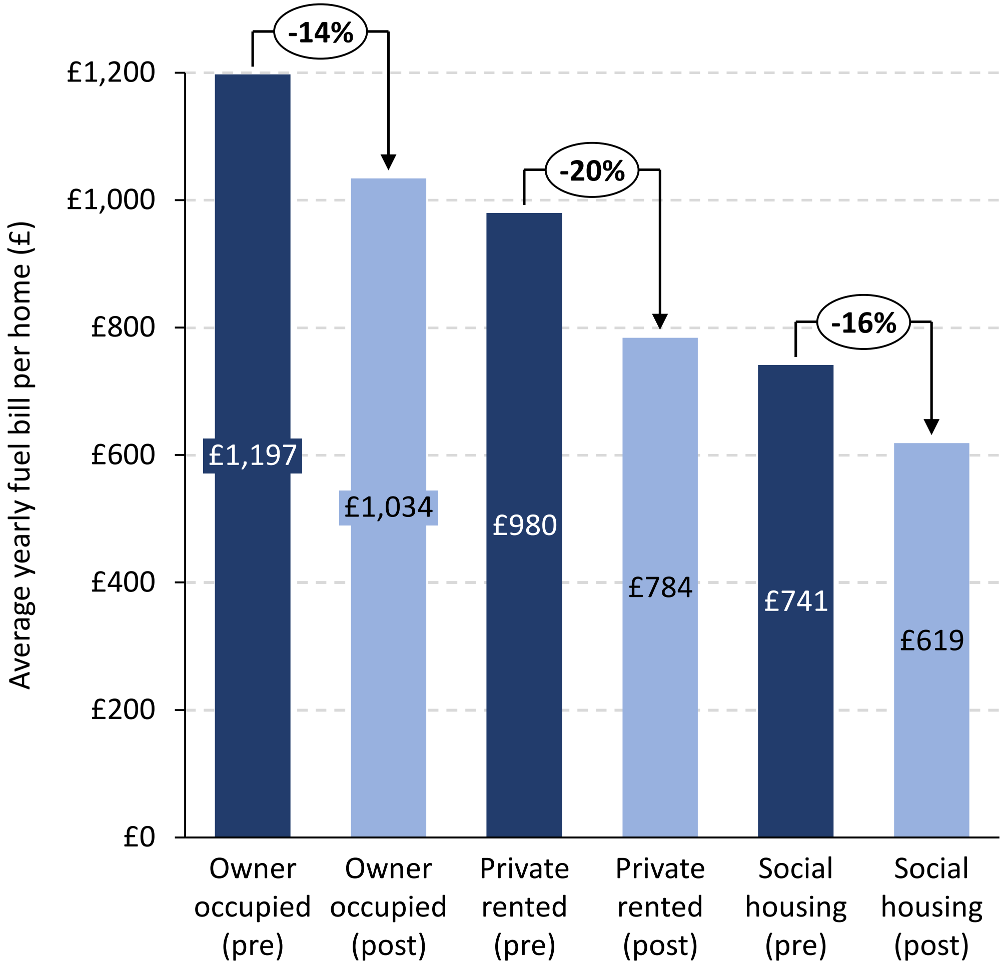
Distribution of homes by annual fuel bill bracket (£/y) in 2050



Fuel bill analysis – absolute reduction in bills for the Balanced Pathway

- Installing energy efficiency and low carbon heating leads to a significant reduction in fuel bills for households in the Balanced Pathway.
  - The largest saving is seen in the private rented sector, where average yearly fuel bills decrease by 20%, or just over £200.
  - The smallest saving is in the owner occupied sector, where bills decrease by 14%, or about £160.
- Given that the average energy demand savings in the scenario due to installing energy efficiency measures are 12% (see slide), the bulk of the reduction in fuel bills can be attributed to energy efficiency installation, with additional savings in terms of technology running costs constituting a smaller share.
- This modelling does not include cooking or lighting and appliance efficiency which would be expected to drive additional savings.
  - The CCC's scenarios estimate additional savings in the order of £1.2 billion per year across the existing stock by 2050 associated with lights and appliances.

Average yearly fuel bills[1] for homes before and after energy efficiency + low carbon heating installation, by tenure type



[1] Includes costs not associated with space or water heating, including cooking, lighting and appliances.
Non-heating fuel use estimated from ECUK end-use data tables (2018 values)

Contents

Limitations of the modelling [1/3]

Summary of limitations of the modelling and suggestions for further work

- The scenarios for residential heat decarbonisation set out in this report represent a significant advancement on the previous work in this area (namely the 2019 analysis on abating direct emissions from 'hard-to-decarbonise' homes). They are based on a wholesale review of assumptions, making use of the latest and best-available evidence, and incorporating expanded stakeholder input and testing. They incorporate a range of additional analytical components including new measures and technology configurations, and improved modelling of flexibility, scrappage, and potential adaptation costs. This work is the first to model detailed trajectories for residential heat decarbonisation to 2050 for the purposes of a UK net zero target.
- As with all modelling exercises, assumptions and simplifications have been made, commensurate with the time available and the limitations of the modelling framework. Below, are summarised a range of modelling limitations and gaps in the evidence base identified, and areas where further work would be valuable are suggested.
- **Solid wall insulation.** Uncertainties remain over the achievable savings from solid wall insulation, given the unknown number of partial solid wall insulation measures in the NEED sample. There would be value in further research to examine the costs and benefits of solid wall insulation in more detail in this context. More broadly there is scope to build on the existing evidence base for energy efficiency savings and costs, including the additional costs which can be associated with energy efficiency upgrades but which do not form part of the costings in this work.
- **Heat pump efficiencies and sizing.** The 5th Carbon Budget assumptions on heat pump efficiency were informed by field trials and monitoring for the Renewable Heat Premium Payment (RHPP) scheme, leading to conservative assumptions in the near term. While deficiencies in this data are widely acknowledged, in the absence of large-scale new published evidence, the 6th Carbon Budget assumptions have used these conservative assumptions as a starting point. The assumptions have then been updated to seek to reflect the higher efficiencies that might be achieved at lower flow temperatures, where radiators are replaced. The evidence for these assumptions remains limited and subject to uncertainty. The Metering and Monitoring Service Package data is expected to provide an updated and expanded evidence base on in-situ heat pump performance which will support future analysis. There would also be merit in further work to build on the evidence to date on heat pump sizing.
- **Flow temperatures and radiator upgrades.** This analysis deploys radiator upgrades widely in order to achieve the lowest possible flow temperatures and highest heat pump efficiencies across the stock. Given the high costs and disruption which can be associated with radiator upgrades, and the material impacts on efficiency that are associated with higher flow temperatures, there is merit in further testing the appropriate balance here and the knock-on impacts of varied assumptions.

Limitations of the modelling [2/3]

Summary of limitations of the modelling and suggestions for further work

- **Performance gap.** A representation of some closure of the performance gap for retrofit energy efficiency measures in existing homes has been included. There remains a high level of uncertainty over the precise scale and variance of the performance gap although a large body of evidence points to it being substantial. The CCC has previously recommended a large-scale study to provide robust quantification and benchmarking of the performance gap for energy, water and ventilation. There is also uncertainty around the efficiencies which might be achieved where a whole-house approach to retrofit is pursued. New evidence here would be of value in future work.
- **Refined energy efficiency modelling**. Measures included in energy efficiency packages were predefined, and are identical across all archetypes, as opposed to being optimised for individual archetypes. The analysis could be extended by identifying cost optimal packages at individual archetype level and varying costs at a finer resolution (e.g. based on floor areas rather than property size categories). This modelling represented a first step in examining deep retrofits, and took a top-down approach to valuing wider benefits. There would be merit in building on the analysis in both of these areas.
- **Heat networks and communal heating.** Heat network uptake is based on previous analysis for the 5th carbon budget and is not co-optimised based on the costs of other technology options (see slide). There is scope for wider system cost analysis for a more consistent comparison of low carbon heat networks versus heat pumps and H_2 technologies. Assumptions for communal configurations, particularly for ground-source heat pumps, are subject to high uncertainty due to limited publicly available evidence on the topic. This is an area that would benefit from further research.
- **Storage.** Only thermal storage options are included in the model, with electrical storage options not considered. Thermal storage sizing is not calculated based on archetype-specific demand and heating system sizing. An improved representation of storage options could help inform future policy thinking on household level flexibility.
- **Hard to decarbonise features**. There remains scope to improve modelling of hard to decarbonise homes in the stock, including better reflecting the additional costs that can be associated with traditional homes more widely (as opposed to those with a heritage classification), modelling of both external and internal space constraints, as well as of wider suitability constraints faced by homes e.g. in coastal areas.
- **Temporal granularity.** Heating demand for each building archetype was modelled only on a yearly basis, with no further temporal breakdown. Incorporating hourly simulations of heating demand would be useful in order to more accurately estimate the amount of storage required for the lowest cost heating system (in terms of both capital costs and fuel costs).

Limitations of the modelling [3/3]

Summary of limitations of the modelling and suggestions for further work

- **Technology transitions.** Heating system uptake trajectories are based on final 2050 end-states and do not allow the explicit modelling of multiple technology transitions over time (e.g. a home transitioning from a fossil fuel heating system to a hybrid heat pump, then transitioning to a conventional heat pump at a later date). Technology transitions could nonetheless have a valuable role to play in the path to net zero.
- **Adaptation measures.** The modelling includes some high level ranges of the costs that could be associated with ventilation and overheating measures accompanying retrofits. A holistic approach to retrofit remains key to delivering homes which are low-carbon, comfortable to live in and better for health, and on this basis future work should continue to build on the analysis undertaken in this area.
- **System interactions.** System impacts and benefits of electric heating options (e.g. to make use of potential renewable curtailment) are not explored. There is scope for integrated analysis of wider system benefits associated with decarbonisation of heat, including:
  - Increased utilisation of renewable generation.
  - Reduction in peak network demand and use of dispatchable generation.

  There is also scope for further work on cross sectoral interactions, e.g. with household level electric vehicle charging.
- **More detailed assessment of the local/spatial infrastructure impacts.** There would be value in more detailed spatial analysis of network cost upgrades for heat, electricity and hydrogen networks (see next slide).

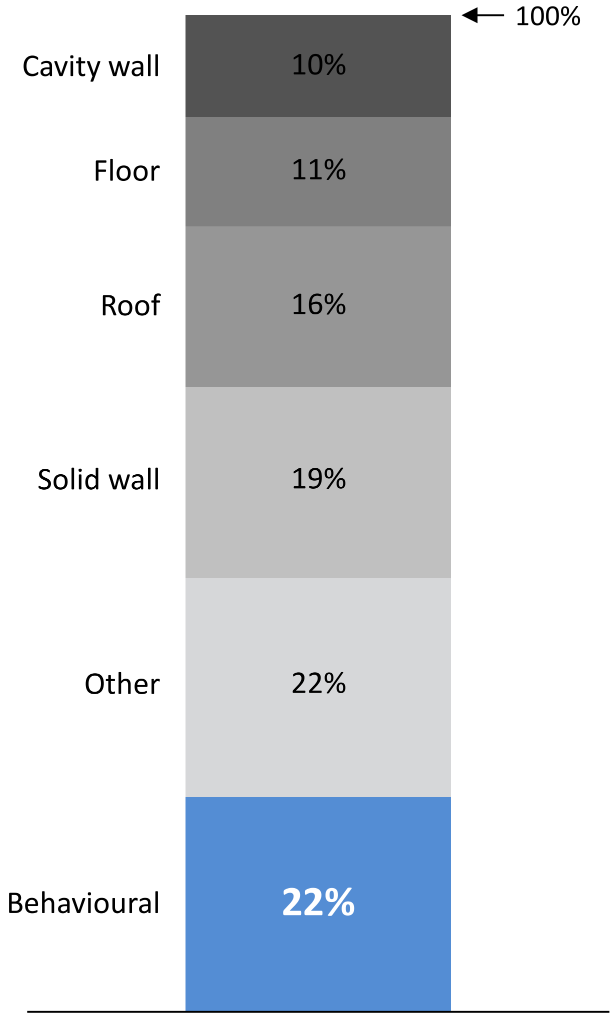
Modelling limitations – suggestions for more detailed spatial analysis

- The current analysis uses a single set of Long-Run Variable Costs (LRVCs) for electricity, fuel for district heat and hydrogen for UK-wide analysis. To aid potential future modelling works, additional spatially resolved data on the cost of upgrading and maintaining the electricity network under various levels of penetration of electric heating technologies (i.e. various levels of electricity demand – peak and annual), and how this cost could vary depending on (i) the timescales of deployment and (ii) the approach taken to grid upgrade (piecemeal/reactive or coordinated/strategic) would be useful.
- To provide some more detail, the following presents some of the potentially required data points including a higher spatial resolution of LRVC costs, as well as a more detailed breakdown of costs including:
  - Breakdown of electricity cost into components:
    - Generation (e.g. wholesale £/MWh).
    - Transmission and distribution network capex (e.g. £/kW_e/y).
  - Breakdown of hydrogen cost into components:
    - Generation (£/MWh).
    - Transmission and distribution network capex (e.g. total capex or marginal capex £/meter).
    - Storage cost (e.g. marginal capex £/kWh).
  - Breakdown of district heating fuel cost into components:
    - Generation (£/kWh).
    - Network capex (£/kW).
    - Waste heat availability (e.g. annual GWh for each spatial region).
    - Network cost scalars (e.g. to differentiate urban and rural costs of a heat network).
- All the above inputs can be differentiated across geographies by, for instance, local authority, government office region or local distribution zone to allow a more detailed comparison of total fuel production costs. This includes e.g.:
  - Electricity network upgrade cost (£/kW) for each DNO.
  - H2 network repurpose cost (£m) for each LDZ.
  - H2 production and storage by GOR.

Contents

Key areas requiring behaviour change

- As seen throughout this report, behavioural measures can constitute a significant share of the overall demand-side savings in all scenarios, varying from 22% to 45% of all savings achieved (N.B. this relative ratio is largely dependent on the level of energy efficiency take up).
  - In all scenarios, of all measure categories, the highest or second-highest relative savings are achieved by behavioural measures.
  - This translates directly to a reduction in emissions which, for the majority of cases, can be obtained now, prior to installing energy efficiency or switching to low carbon heating.
- Simple measures such as pre-heating one's home or installing a smart meter and using its feedback to ensure temperatures are lowered in the house when possible can stack up to large savings.
  - As these measures can be done relatively easily, early-on, on a wide-scale, and with minimal investment, they illustrate what the average householder can do immediately, and the level of impact it could make.
- Additionally, the cost benefits of many of the measures can be seen directly via lowered fuel bills.
  - This can be particularly important in higher operational cost scenarios, such as Headwinds, where lowered demand would effectively lower H_2 fuel use, which can be a significant cost reduction in the long-term.
  - For example, a household which simply uses the feedback from their smart meter (e.g. to turn down heating or otherwise) and installs a low flow shower head would save 3% off their heating bill and 5% off their hot water bill.



% of Scenario's Total TWh Savings from Energy Efficiency in the Balanced Pathway

Contents

Policy recommendations [1/4]

The ‘critical path’ and a timeline for policy decisions

Low carbon heating

- The natural replacement cycle of heating systems is of the order 15-20 years. If scrappage is to be minimised, this implies the need for all new heating systems to be low carbon from the mid-2030s in order to achieve net zero by 2050.
- The scenarios have been developed to work within this natural replacement cycle as far as possible. The Balanced Pathway scenario is therefore based on a fossil fuel phase out date of 2033 for on-gas homes (with a range 2030 – 2035 across scenarios) and 2028 for off gas homes (with a range of 2026 – 2028 across scenarios). Whilst alternative regulatory approaches could be possible, they would need to deliver similar levels of ambition.
- The date chosen for on-gas homes in the Balanced Pathway scenario reflects a balance between minimising scrappage risks, remaining within supply chain constraints, and leaving time for energy efficiency deployment to be maximised in advance of fossil phase out. The earlier date for off-gas homes recognises Government ambition, and the fact that low carbon heating is more cost-effective and delivers higher carbon savings in these properties. The smaller number of such homes means the supply chain should also be able to deliver this at an earlier date.
- Whilst these phase out dates are assumed to apply to much of the stock in the Balanced Pathway scenario, there are some technologies (notably hydrogen and district heat) where uptake must necessarily be driven by geographically targeted switchovers rather than phase out dates. These technologies therefore follow geographically-led switchovers in the scenarios. On this basis, the scenarios imply that any homes in areas designated for hydrogen or district heat would need to be exempt from any regulated fossil fuel phase out before the switchover to hydrogen or district heat occurs. This in turn implies a need for areas to be designated as suitable for those solutions ahead of the fossil fuel phase out dates.

Policy recommendations [2/4]

The ‘critical path’ and a timeline for policy decisions (continued)

Energy efficiency

- An approach which works with replacement cycles for low carbon heating necessarily requires that homes have a sufficient and appropriate level of energy efficiency to ensure that low carbon heating is viable at reasonable cost by the time new fossil fuel systems are phased out.
- This defines the timeline for regulatory drivers relating to minimum standards of energy efficiency in the scenarios, as described on the next slide.
- The proposed fossil fuel phase out and regulations on minimum standards for energy efficiency would need to be set well in advance of the dates they will come into force, to provide a clear signal to the market and sufficient time to plan ahead.
- It will also be crucial for a comprehensive suite of support to be in place ahead of those dates to ensure affordability for every household.

Hydrogen and the gas grid

- Decisions on the future of gas grid across regions are expected to be required from the mid 2020s. Trialling, evidence gathering and analysis must progress in advance of this to facilitate these decisions.
- Fossil fuel phase out dates in the early 2030s mean that any areas to be converted to hydrogen (with conversion taking place from the 2030s) would need to be designated for hydrogen conversion well ahead of time. This is necessary for infrastructure planning and delivery. It also provides clarity over where any exemptions would be in place for fossil fuel phase out, in turn enabling effective planning for both energy efficiency and low carbon heat at a household level.
- Optionality exists over the role that Hy-ready boiler mandation could play in the transition. The scenarios assume mandation in the mid-2020s on a UK-wide basis, to minimise the potential cost of scrappage of gas boilers in areas of hydrogen conversion, but also in recognition of the economies of scale and cost reduction that would accompany widespread uptake.

Policy recommendations [3/4]

Regional and local approaches to decision-making

- Several components of the Balanced Pathway scenario will rely on a coordinated approach to decision making on the future of low carbon heat.
- Identification of areas suitable for deployment of heat network infrastructure, and the implementation of heat networks, will rely on coordination and decision-making at a local level.
- The decision on the future of the gas grid will likely need to be taken at a regional level. As described on the previous slide, the Balanced Pathway scenario assumes that some areas are designated for conversion to hydrogen before 2033, such that homes in those areas can be exempted from the mandation for low carbon heating systems from that date.
- It is also evident that the rollout of heat pumps would benefit from a detailed, coordinated plan for rollout at a highly local level, in order to plan and deliver required network upgrades without this becoming a constraint on deployment.

Policy recommendations [4/4]

Key regulatory levers and supporting policy measures

- Private and social rented homes are well suited to regulatory levers in the form of minimum standards for energy efficiency and/or carbon emissions, as is recognised by Government policy ambition – the Balanced Pathway scenario is based on a 'backstop' date of 2028 for all such homes to have a sufficient and appropriate level of energy efficiency to ensure that low carbon heating is viable and cost-effective.
- Owner occupiers are more challenging to reach using such levers.
- For owner occupied homes with mortgages, the Balanced Pathway scenario envisages strong incentives for lenders to drive a similar minimum level of energy efficiency by 2033.
- For outright owners of homes, the Balanced Pathway scenario is based on a regulation around minimum energy efficiency at the point of sale from 2028. This approach is already being considered in Scotland[1]
- As described on the previous slide, the scenario proposes a fossil fuel phase out date for all tenures, from which time all new heating systems must be low carbon – this is 2028 for off-gas homes and 2033 for on-gas homes.
- The intention of the scenarios is not to be prescriptive about how the regulations would look in practice (for example, whether minimum standards would be based on EPC rating, energy intensity per square metre, or the equivalent carbon based metrics) but rather to frame the level of ambition that is needed to meet legally binding targets.
- It should also be noted that, while not modelled explicitly, it is expected that a suite of policy measures to accompany these regulatory levers would be introduced. This includes financial incentives, price signals such as levies on fossil fuels and carbon pricing and a comprehensive package of support for supply chain and investment in skills and training.

[1] Energy Efficient Scotland: Improving energy efficiency in owner occupied homes

Distribution of final attribute values across the existing UK stock (1/4)

The below table presents the insulation level/fabric measure distribution in the UK stock (before the application of any energy efficiency measures). Insulated cavity walls and insulated lofts are more common in the current stock, whereas the majority of floors are uninsulated.

Measure category	Measure subcategory	UK stock	% of UK stock
Wall	Cavity uninsulated extra-hard-to-treat	2,774,351	10%
	Cavity uninsulated hard-to-treat	979,095	3%
	Cavity uninsulated easy-to-treat	2,115,298	7%
	Cavity insulated	14,219,975	50%
	Solid uninsulated (internal)[1]	4,929,203	17%
	Solid uninsulated (external)[1]	2,483,132	9%
	Solid insulated	803,004	3%
Roof	No roof	3,908,280	14%
	Less than 100mm extra-hard-to-treat	721,210	3%
	Less than 100mm hard-to-treat	649,353	2%
	Less than 100mm easy-to-treat	2,521,154	9%
	100-199mm extra-hard-to-treat	1,746,204	6%
	100-199mm hard-to-treat	1,572,223	6%
	100-199mm easy-to-treat	6,104,258	22%
	200mm or more	11,081,376	39%
Floor	Solid uninsulated	16,009,093	57%
	Solid insulated	1,129,342	4%
	Suspended uninsulated	7,389,412	26%
	Suspended insulated	236,688	1%
	None	3,539,523	13%

[1] The split between internal and external solid wall insulation is aligned with the 5th Carbon Budget technical potential split (i.e. 1/3 external, 2/3 internal).

Distribution of final attribute values across the existing UK stock (2/4)

The below table presents the insulation level / fabric measure distribution in the UK stock, split by tenure type[1] (prior to the application of energy efficiency measures). In the owner occupied and social housing (local authority) sectors, most cavity walls are insulated, but insulated cavity walls are less common in privately rented homes.

		UK stock by tenure					
Measure category	Measure subcategory	Owner occupied stock	% of owner occupied stock	Private rented stock	% of private rented stock	Local authority stock	% of local authority stock
Wall	Cavity uninsulated extra-hard-to-treat	1,717,411	10%	590,194	10%	466,745	10%
	Cavity uninsulated hard-to-treat	612,851	3%	203,768	4%	162,476	3%
	Cavity uninsulated easy-to-treat	1,322,581	7%	439,857	8%	352,859	7%
	Cavity insulated	9,133,265	52%	2,075,793	36%	3,010,917	61%
	Solid uninsulated (internal)	2,930,984	17%	1,571,710	28%	426,508	9%
	Solid uninsulated (external)	1,554,979	9%	726,214	13%	201,940	4%
	Solid insulated	424,291	2%	103,732	2%	274,981	6%
Roof	No roof	1,058,124	6%	1,336,020	23%	1,514,136	31%
	Less than 100mm extra-hard-to-treat	463,872	3%	213,676	4%	43,662	1%
	Less than 100mm hard-to-treat	410,155	2%	202,559	4%	36,639	1%
	Less than 100mm easy-to-treat	1,456,732	8%	859,453	15%	204,969	4%
	100-199mm extra-hard-to-treat	1,273,930	7%	267,558	5%	204,716	4%
	100-199mm hard-to-treat	1,153,789	7%	237,001	4%	181,433	4%
	100-199mm easy-to-treat	4,300,532	24%	1,044,261	18%	759,465	16%
	200mm or more	7,579,229	43%	1,550,739	27%	1,951,407	40%
Floor	Solid uninsulated	10,404,170	59%	2,997,217	52%	2,607,706	53%
	Solid insulated	821,775	5%	117,567	2%	190,000	4%
	Suspended uninsulated	5,309,909	30%	1,325,983	23%	753,520	15%
	Suspended insulated	175,490	1%	21,736	0%	39,462	1%
	None	985,019	6%	1,248,765	22%	1,305,739	27%

[1] The distribution of tenure type was applied on a building archetype level, sourced from the housing condition surveys for each Devolved Administration. However, there is limited available public data regarding the real-world distribution of easy-to- treat / hard-to-treat / extra-hard-to-treat; as such, this has been assumed to be uniform across tenures and should not be taken as a precise reflection of the true stock distribution

Distribution of final attribute values across the existing UK stock (3/4)

The below table presents the insulation level / fabric measure distribution in the UK stock, split by fuel poverty status[1] (prior to the application of energy efficiency measures). Fuel poor homes tend to have lower levels of insulation.

		UK stock by fuel poverty status			
Measure category	**Measure subcategory**	**Fuel poor stock**	**% of fuel poor stock**	**Not fuel poor stock**	**% of not fuel poor stock**
Wall	Cavity uninsulated extra-hard-to-treat	286,757	9%	2,487,594	10%
	Cavity uninsulated hard-to-treat	95,217	3%	883,878	4%
	Cavity uninsulated easy-to-treat	207,850	6%	1,907,448	8%
	Cavity insulated	1,314,535	41%	12,905,440	51%
	Solid uninsulated (internal)	908,932	28%	4,020,271	16%
	Solid uninsulated (external)	366,823	11%	2,116,309	8%
	Solid insulated	45,441	1%	757,563	3%
Roof	No roof	636,043	20%	3,272,237	13%
	Less than 100mm extra-hard-to-treat	70,908	2%	650,302	3%
	Less than 100mm hard-to-treat	57,425	2%	591,928	2%
	Less than 100mm easy-to-treat	376,124	12%	2,145,030	9%
	100-199mm extra-hard-to-treat	133,224	4%	1,612,980	6%
	100-199mm hard-to-treat	117,266	4%	1,454,957	6%
	100-199mm easy-to-treat	668,037	21%	5,436,221	22%
	200mm or more	1,166,527	36%	9,914,849	40%
Floor	Solid uninsulated	1,903,177	59%	14,105,916	56%
	Solid insulated	61,755	2%	1,067,587	4%
	Suspended uninsulated	728,001	23%	6,661,411	27%
	Suspended insulated	9,005	0%	227,683	1%
	None	523,616	16%	3,015,907	12%

[1] Fuel poverty status was determined from post-code level UK EPC data, with the distribution applied to the stock on an archetype level.

Distribution of final attribute values across the existing UK stock (4/4)

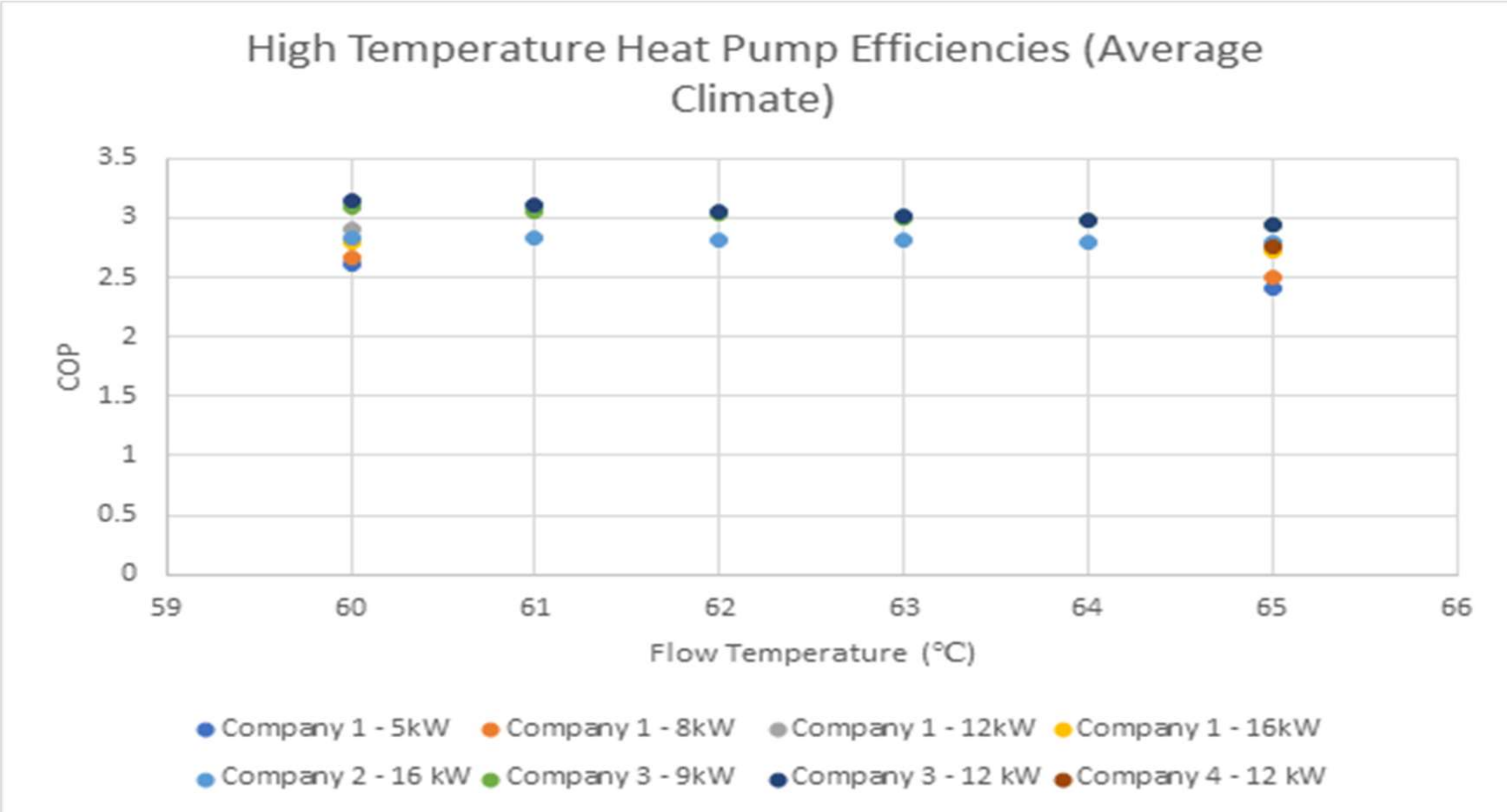
The below table presents the insulation level/fabric measure distribution in the UK stock, split by Devolved Administration[1] (before the application of any energy efficiency measures. England has a smaller proportion of insulated cavity walls compared to other Devolved Administrations, but a higher proportion of insulated floors.

		UK stock by Devolved Administration							
Measure category	Measure subcategory	England stock	% of England stock	Scotland stock	% of Scotland stock	Wales stock	% of Wales stock	Northern Ireland stock	% of Northern Ireland stock
Wall	Cavity uninsulated extra-hard-to-treat	2,491,720	10%	164,292	8%	87,877	8%	30,461	5%
	Cavity uninsulated hard-to-treat	884,710	4%	55,809	3%	28,553	2%	10,024	2%
	Cavity uninsulated easy-to-treat	1,904,329	8%	123,446	6%	63,663	6%	23,861	4%
	Cavity insulated	11,739,178	48%	1,339,403	62%	670,064	59%	471,330	76%
	Solid uninsulated (internal)	4,413,190	18%	293,408	13%	172,757	15%	49,848	8%
	Solid uninsulated (external)	2,247,310	9%	137,129	6%	78,822	7%	19,871	3%
	Solid insulated	683,139	3%	60,202	3%	42,600	4%	17,062	3%
Roof	No roof	3,209,201	13%	588,000	27%	84,942	7%	26,137	4%
	Less than 100mm extra-hard-to-treat	691,382	3%	8,530	0%	16,994	1%	4,304	1%
	Less than 100mm hard-to-treat	608,785	2%	23,131	1%	13,976	1%	3,460	1%
	Less than 100mm easy-to-treat	2,378,081	10%	44,181	2%	74,674	7%	24,218	4%
	100-199mm extra-hard-to-treat	1,598,084	7%	68,897	3%	43,966	4%	35,257	6%
	100-199mm hard-to-treat	1,453,410	6%	60,770	3%	38,575	3%	19,468	3%
	100-199mm easy-to-treat	5,388,470	22%	305,979	14%	192,151	17%	217,659	35%
	200mm or more	9,036,164	37%	1,074,202	49%	679,057	59%	291,954	47%
Floor	Solid uninsulated	13,412,586	55%	1,188,790	55%	962,554	84%	445,163	72%
	Solid insulated	936,312	4%	109,068	5%	57,187	5%	26,775	4%
	Suspended uninsulated	6,791,021	28%	395,005	18%	76,083	7%	127,302	20%
	Suspended insulated	207,482	1%	21,595	1%	2,308	0%	5,302	1%
	None	3,016,175	12%	459,231	21%	46,203	4%	17,915	3%

[1] The distribution of measures by Devolved Administration was sourced directly from the detailed split from the housing condition surveys for each Devolved Administration.

High temperature heat pumps – manufacturer data[1] [1/3]

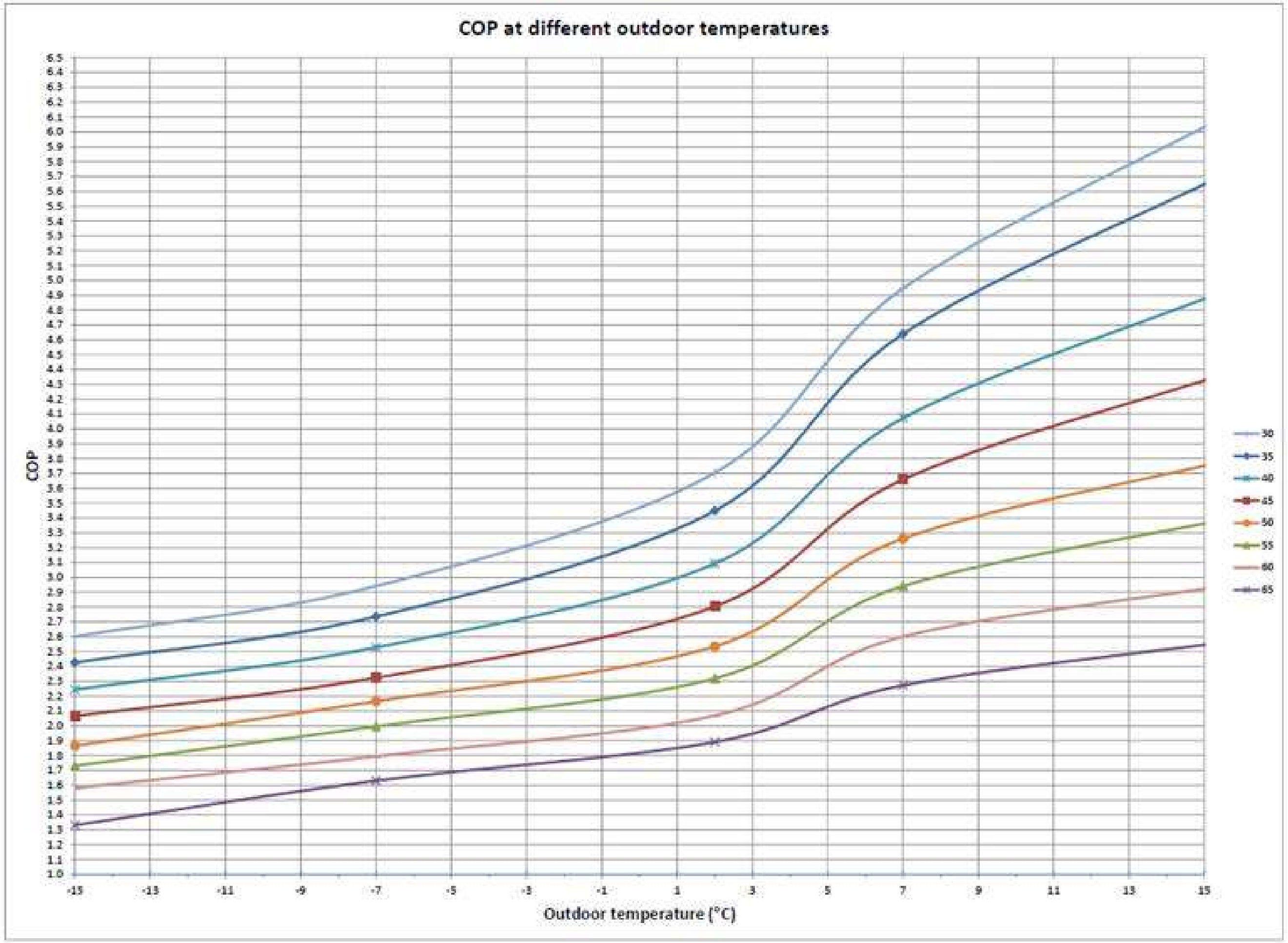
The below presents some graphical performance data relating to heat pumps. Whilst COP reduces at as flow temperature increases, the effect is marginal and smaller than the variation in performance between different manufacturers at the same flow temperatures.



[1] Provided by members of the Heat Pump Association (HPA)

High temperature heat pumps – manufacturer data[1] [2/3]

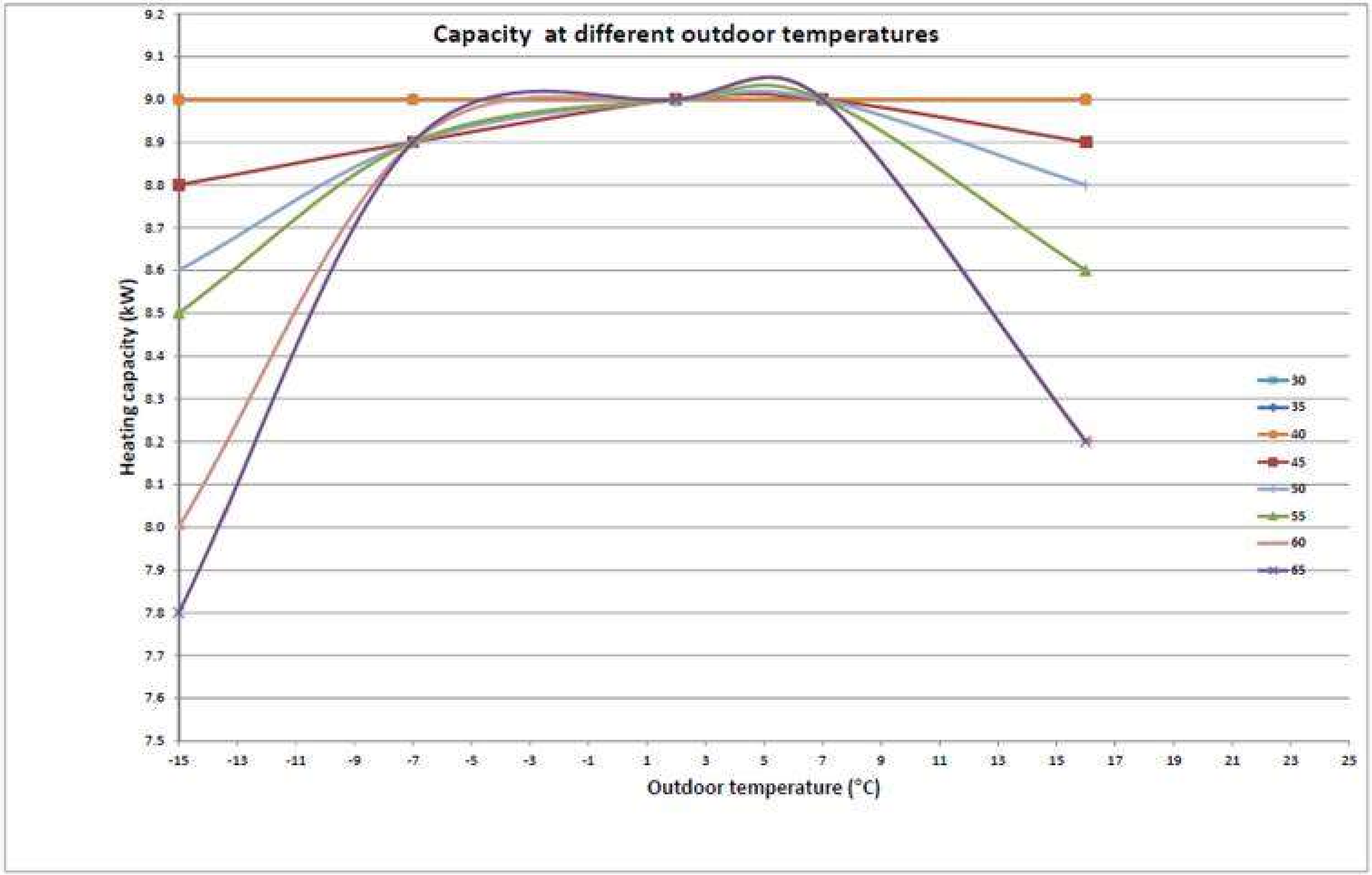
The below presents some graphical performance data relating to heat pumps. Even at extremely cold external temperatures, high temperature heat pumps maintain a COP higher than 1.



[1] Provided by members of the Heat Pump Association (HPA)

High temperature heat pumps – manufacturer data[1] [3/3]

The below presents some graphical performance data relating to heat pumps. For high temperature heat pumps, heating capacity can decrease by nearly 15% at extremely cold external temperatures



[1] Provided by members of the Heat Pump Association (HPA)

Low carbon heat network assumptions – heat produced by fuel type

- Gas and hydrogen only contribute to low carbon heat networks in the Headwinds scenario, with the fuel consumption per kWh for each fuel shown in the top table.
- The values for gas and hydrogen reflect the transition to hydrogen over time assumed in the Headwinds scenario.
  - In the early years, hydrogen does not contribute.
  - As the grid converts to hydrogen, the gas contribution decreases whilst the hydrogen contribution increases.
  - By 2050, with the grid fully converted, the gas contribution falls to zero.
- In all other scenarios, only electricity contributes to low carbon heat networks, with the fuel consumption per kWh of heat shown in the middle table. This does not vary across scenarios.
- The total heat demand met by low carbon heat networks is shown in the bottom table.
- See the accompanying published Assumptions Log for details of the costs of heat and emissions modelled for low carbon heat networks.

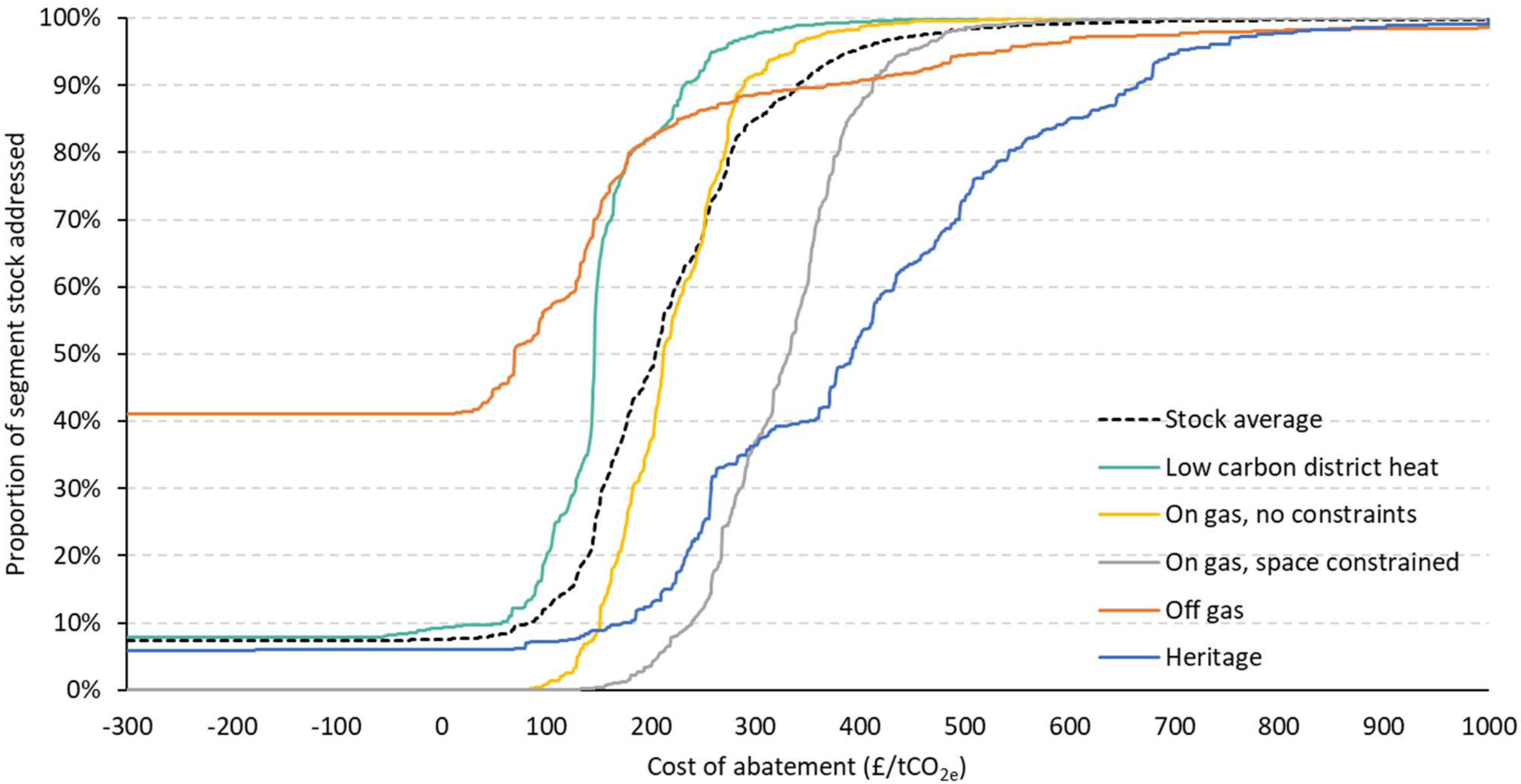
	Fuel consumption per kWh of heat (kWh) by heat source in the Headwinds scenario						
Fuel	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity	0.30	0.31	0.32	0.34	0.35	0.36	0.37
Gas	0.29	0.27	0.25	0.21	0.13	0.03	0.00
Hydrogen	0.00	0.00	0.00	0.00	0.09	0.22	0.28

		Fuel consumption per kWh of heat (kWh) by heat source						
Scenario	**Fuel**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Balanced Pathway	*Electricity*	0.30	0.31	0.32	0.34	0.35	0.36	0.37
Tailwinds								
Widespread Engagement								
Widespread Innovation								

Scenario	Heat demand met by low carbon heat networks (TWh)
Balanced Pathway	45.2
Tailwinds	40.7
Headwinds	46.6
Widespread Engagement	42.8
Widespread Innovation	45.2

Balanced Pathway scenario abatement cost curve

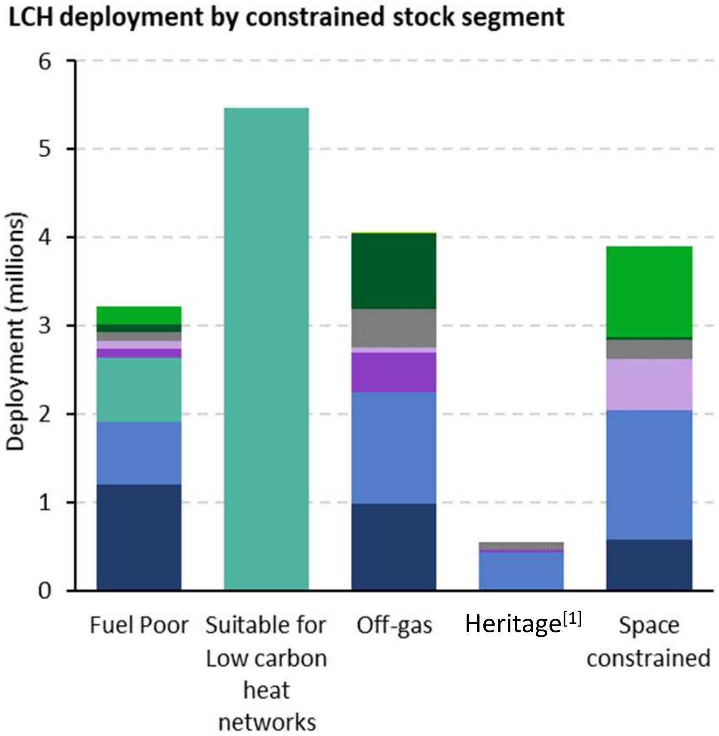
On average, more than 90% of the stock can be addressed by measures with abatement costs less than £300/tCO_2e.



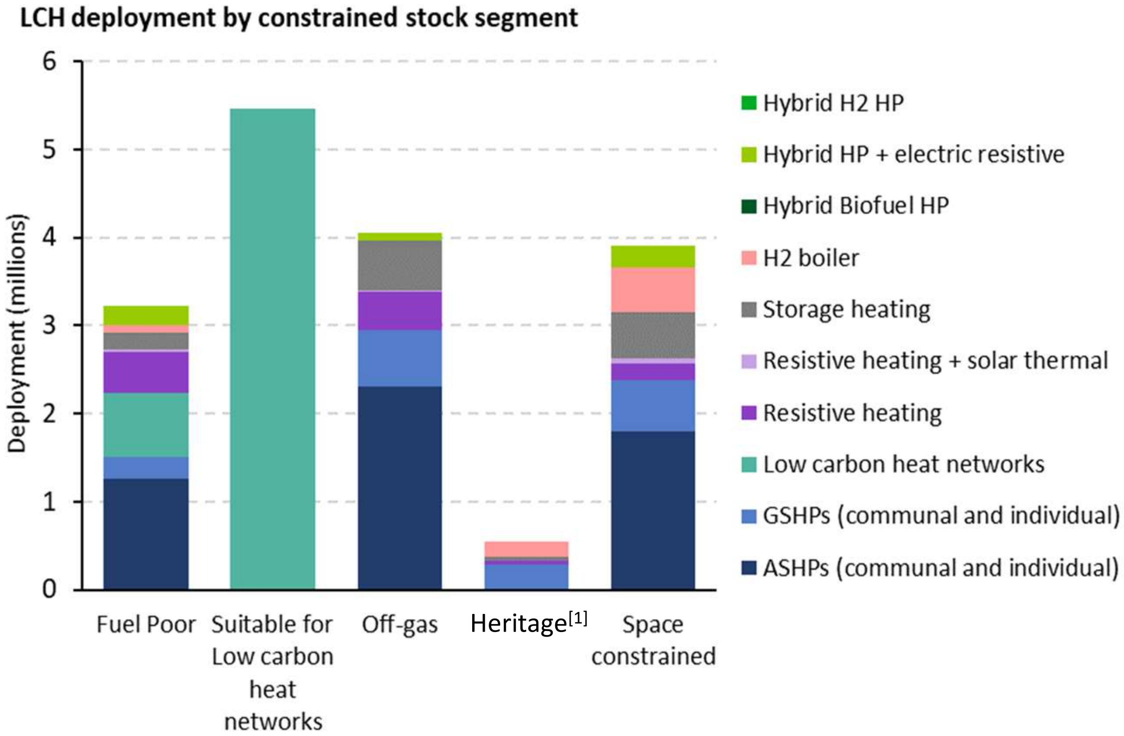
Balanced Pathway and Tailwinds low carbon heating by constrained stock segment

Differences in technology uptake across constrained stock segments between the Balanced Pathway and Tailwinds scenarios are primarily due to differences in permitted technologies (e.g. biofuel technologies not modelled in Tailwinds)

Balanced Pathway



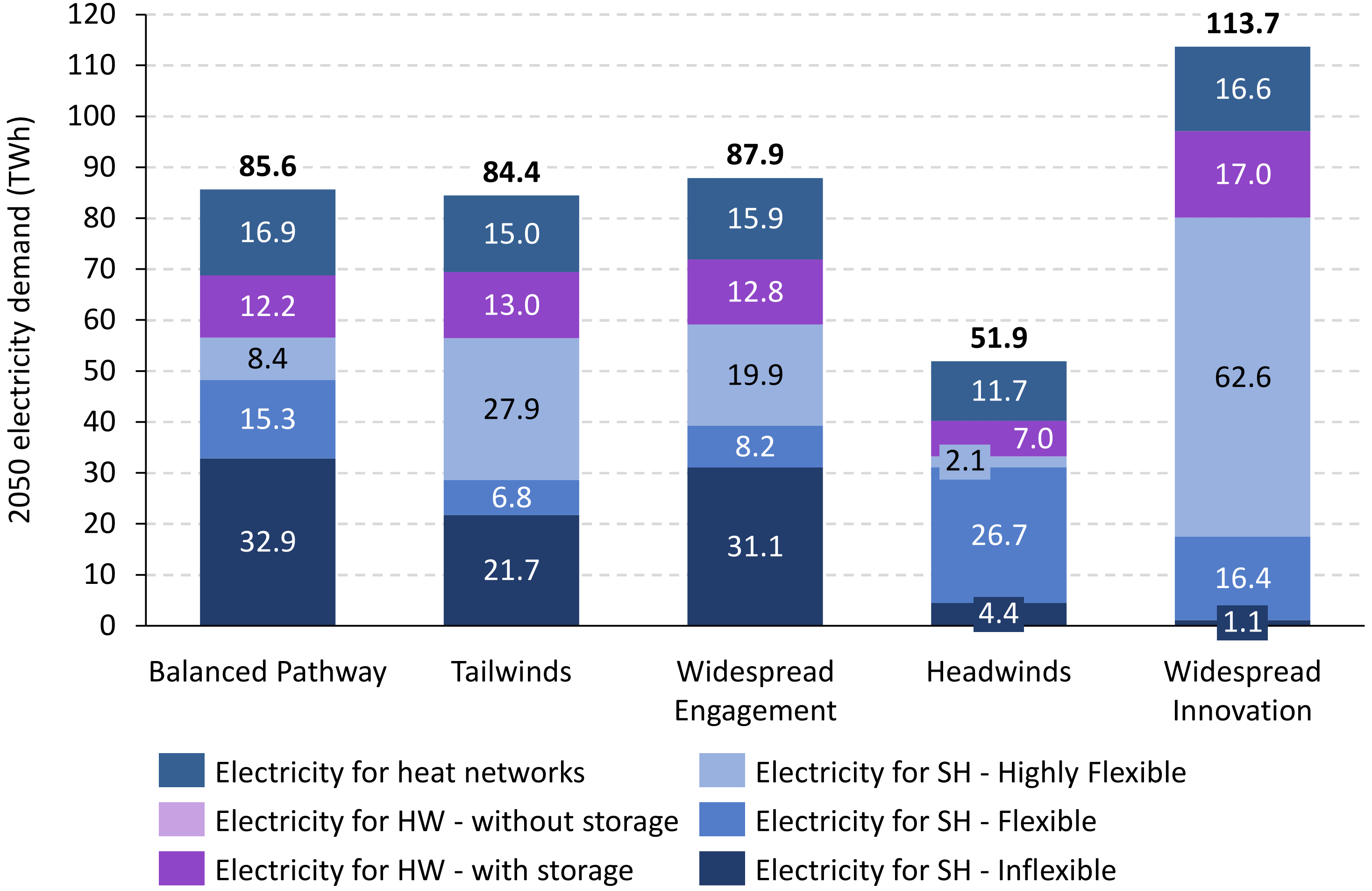
Tailwinds



[1] Includes listed homes and homes in conservation areas.

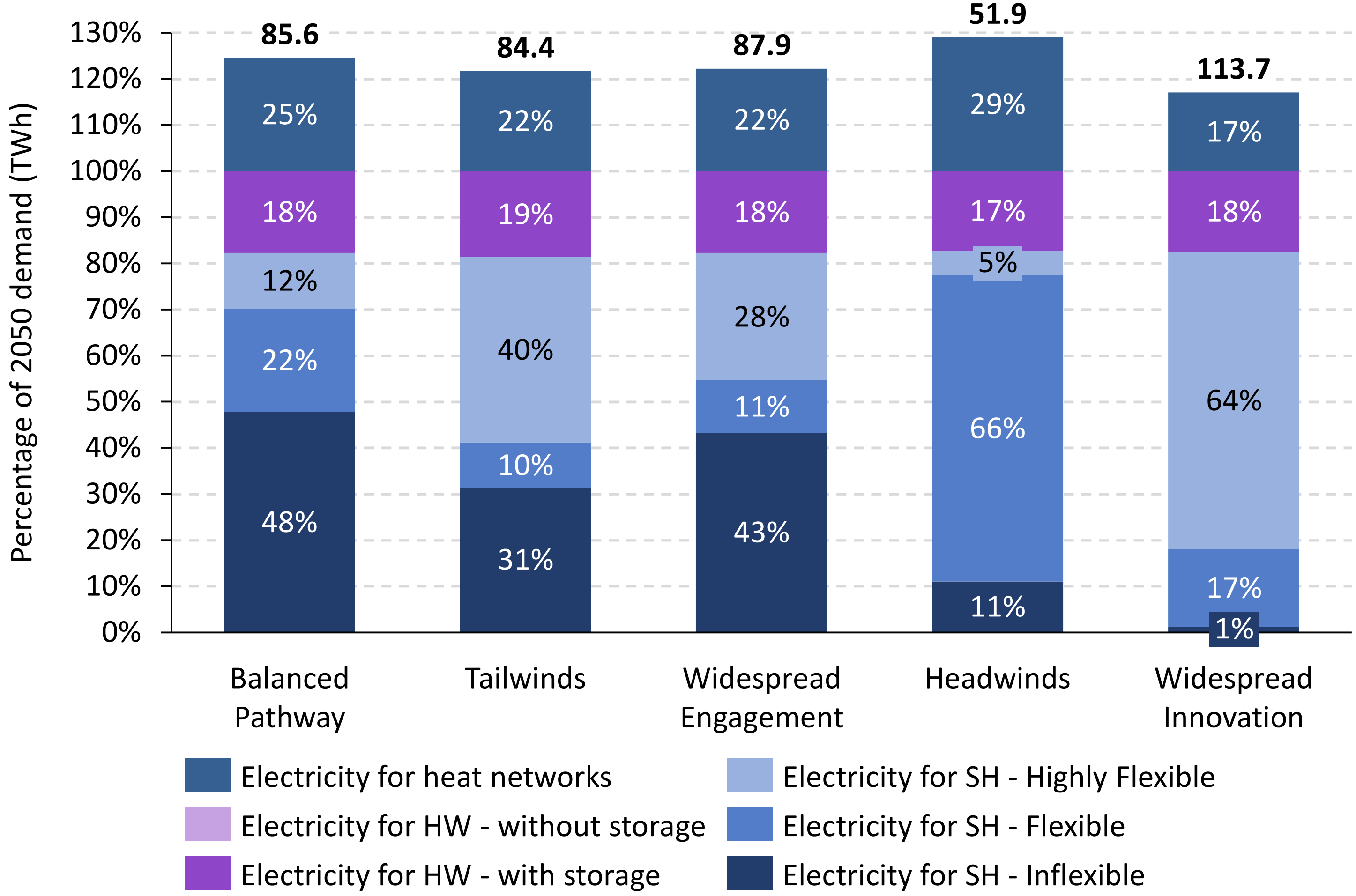
2050 electricity demand split by electricity type across all scenarios

Headwinds has the lowest total electricity demand due to widespread deployment of hydrogen technologies, whereas Widespread Innovation has the highest demand due to widespread use of high temperature heat pumps



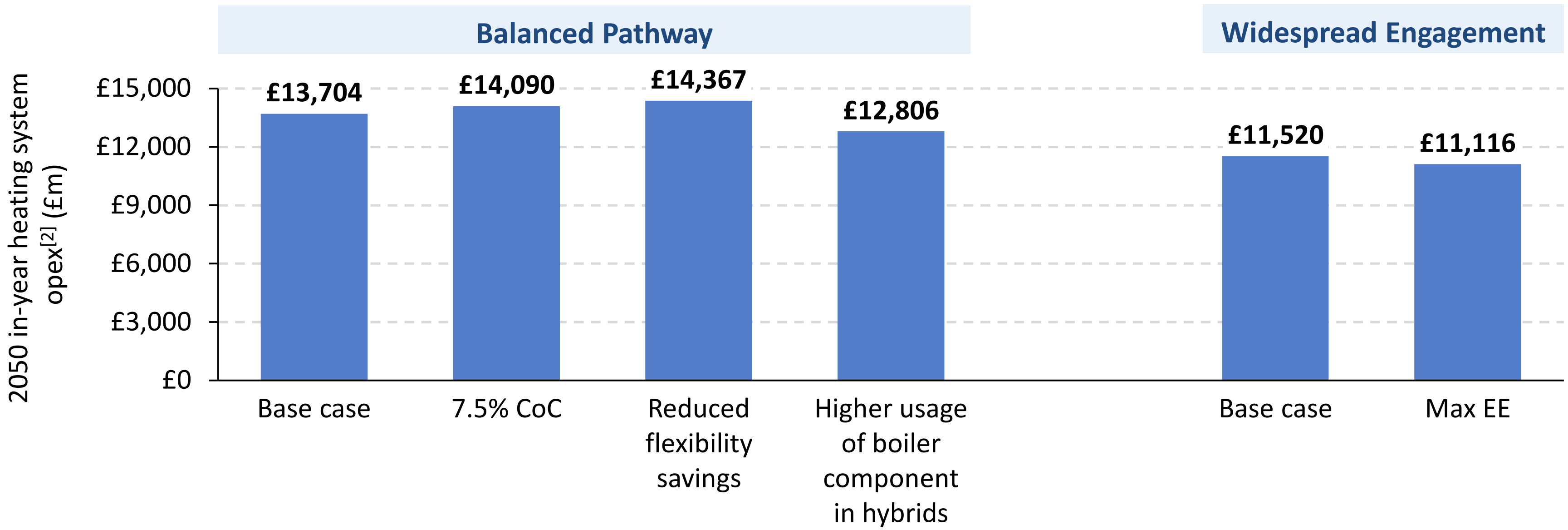
2050 electricity demand split by electricity type across all scenarios

The electricity type split across scenarios is determined by the technology mix e.g. in Widespread Innovation, where additional storage is widespread (>14 million homes), "Highly Flexible" space heating electricity dominates



Summary of heating system opex across sensitivities

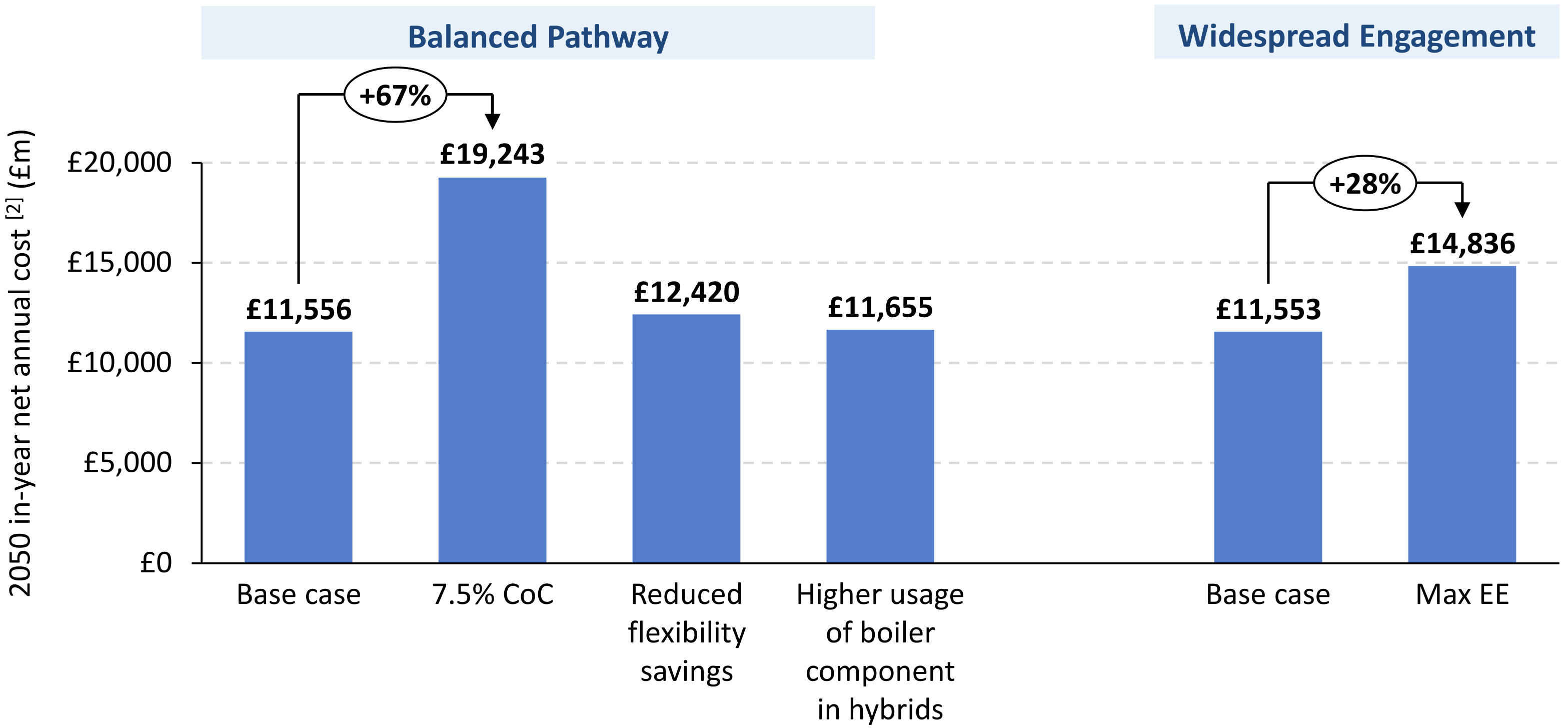
- As noted in the main body, the approach followed for the sensitivity analysis (in most cases) involved changing a particular input assumption and analysing the effect on the end-state technology mix and total costs.
- For the Balanced Pathway sensitivities[1]:
  - A higher cost of capital has a minor, indirect effect on opex, due to its influence on the technology mix (more pure heat pumps, less biofuel hybrids).
  - Reduced flexibility savings lead to an increase in opex, due to more expensive fuel costs.
  - Higher usage of the boiler component in hybrids leads to a reduction in overall opex, due to more pure heat pumps being deployed than hydrogen hybrids. This leads to a significant reduction in the use of relatively expensive hydrogen fuel and reduction in more expensive maintenance costs (i.e. from the hybrid systems to the pure heat pumps).
- For the Widespread Engagement sensitivity:
  - Deploying more ambitious energy efficiency reduces opex due to reduced fuel costs associated with heating better-insulated homes. The reduction remains limited as heating system maintenance costs and hot water costs remain constant and a material proportion of the costs presented.



[1] Balanced Pathway sensitivities tested on an earlier version of the scenario, which had minor differences from the final scenario (primarily in the deployment trajectories of hybrid H_2 heat pumps). [2] Opex includes both maintenance costs and fuel costs.

Summary of net annual cost across sensitivities

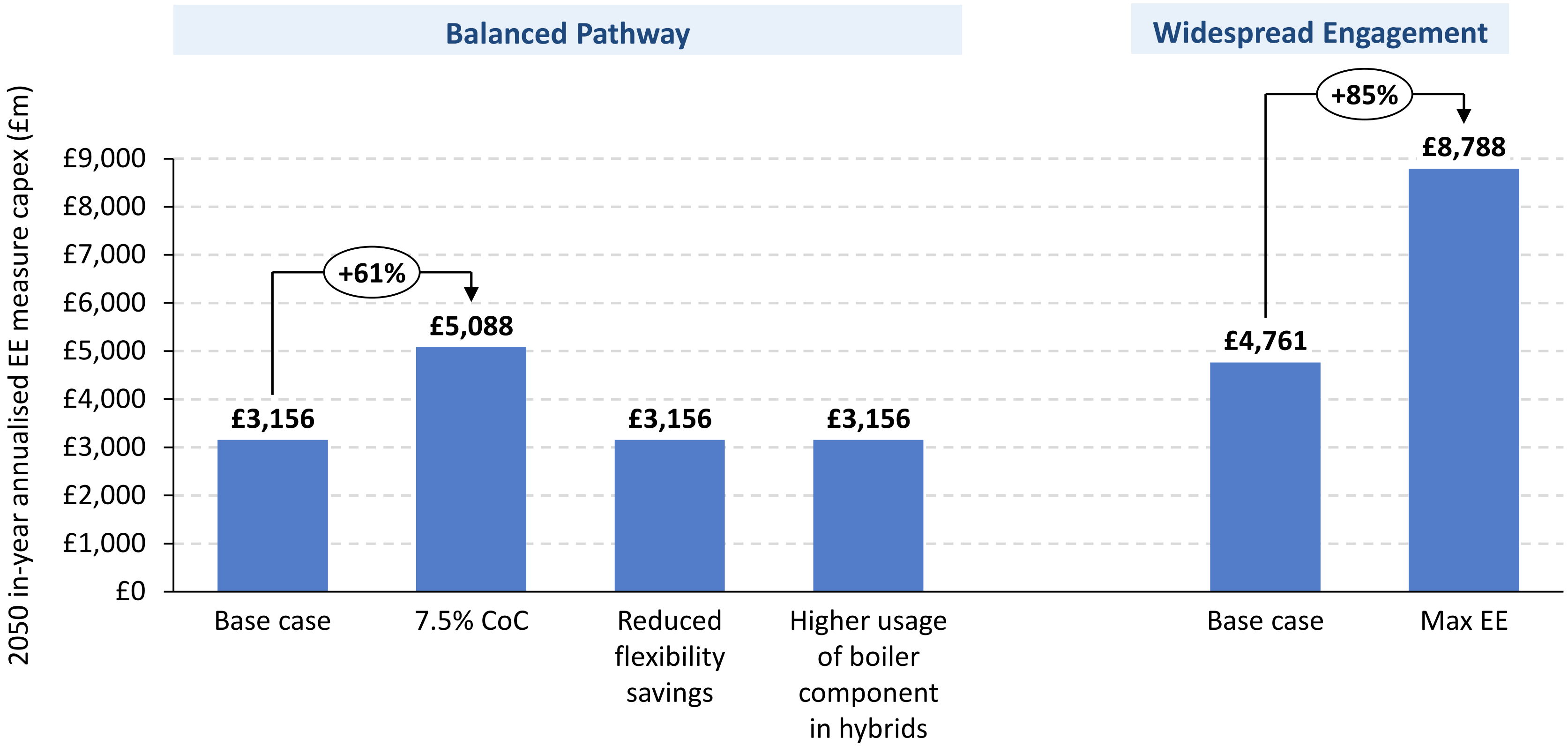
- As noted in the main body, the approach followed for the sensitivity analysis (in most cases) involved changing a particular input assumption and noting the effect on the end-state technology mix and total costs.
- For the Balanced Pathway sensitivities[1]:
  - A higher cost of capital increases the annualised capex component of the net annual cost, driving up the total.
  - Reduced savings from flexibility and higher usage of the boiler component in hybrid heat pumps only increase fuel costs, leading to only a minor increase in net annual costs.
- For the Widespread Engagement sensitivity:
  - Increasing energy efficiency deployment increases annualised capex, leading to higher net annual costs.



[1] Balanced Pathway sensitivities tested on an earlier version of the scenario, which had minor differences from the final scenario (primarily in the deployment trajectories of hybrid H_2 heat pumps). [2] The net annual cost is the sum of discounted, annualised capex, discounted opex and discounted fuel costs for the LCH and EE package combination, less the same for the counterfactual heating system.

Summary of annualised measure capex across sensitivities

- As noted in the main body, the approach followed for the sensitivity analysis (in most cases) involved changing a particular input assumption and noting the effect on the end-state technology mix and total costs.
- For the Balanced Pathway sensitivities[1]:
  - Only the higher cost of capital affects energy efficiency measure costs, leading to an increase of 61% when the cost of capital rises from 3.5% to 7.5%.
- For the Widespread Engagement sensitivity:
  - Deploying more ambitious energy efficiency increases the measure capex by 85%.



[1] Balanced Pathway sensitivities tested on an earlier version of the scenario, which had minor differences from the final scenario (primarily in the deployment trajectories of hybrid H_2 heat pumps).