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ENERGY RESEARCH

Decarbonising heating systems: evidence and options (B)

Energy sector modelling to support the second National Infrastructure Assessment

Prepared for the National Infrastructure Commission
October 2023

Glossary of terms

Section	Term	Definition
Building mapping	CB6	The UK's sixth carbon budget, which stipulates a 47-62% reduction in emissions by 2035, relative to 2019 levels
	Dimension	Characteristic element of the building stock, such as building type or level of efficiency
	EPC	Energy Performance Certificate, used to measure energy performance in buildings
	LA	Local Authority
Heating systems	(High T) ASHP	(High temperature) air source heat pump
	(High T) GSHP	(High temperature) ground source heat pump
	H2/H2B	Hydrogen/hydrogen boiler
	ER	Electric resistive heating system
	HWC	Hot water cylinder, used to provide hot water
Heat decarbonisation pathways	MHP	Max Heat Pump scenario
	HHP	High Heat Pump scenario
	BM	Balanced Mix scenario
	HER	High Electric Resistive scenario
	MER	Max Electric Resistive scenario
	Low H2	Low Hydrogen scenario
	Mid H2	Mid Hydrogen scenario
	High H2	High Hydrogen scenario

Source: Aurora Energy Research

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Executive Summary

1) Context and overview of study

- Buildings emit one fifth of the UK's total emissions therefore decarbonising this sector is critical to meeting the sixth carbon budget.
- At present, c.83% of the residential building stock is served by natural gas, with a further 5% utilising oil fuel. In the Public and Commercial sector, 43% of buildings use natural gas, with 8% using oil as fuel for heating.
- In order for emissions targets to be achieved, these building will have to be converted to low carbon forms of heating. The majority of conversion decisions taken will be down to individual households or landlords.
- Different pathways of deployment for low carbon heating technologies will result in different total system costs and costs to consumers, as well as different emissions reduction pathways.
- This report has been produced by Aurora Energy Research ("Aurora") for The National Infrastructure Commission ("NIC"). It aims to explore:
  - The options available to decarbonise heating,
  - The make up of the English building stock and why some buildings are technically unsuited to some low carbon technologies,
  - Why consumers may prefer some technologies over others,
  - The impact that the individual choices consumers make when selecting decarbonised sources of heating could have on the system.
- Aurora has modelled eight scenarios on behalf of NIC to test different decarbonisation outcomes.
- Scenarios studied as part of this report are not based on the lowest cost outcome, or on the outcome that will minimise the impact on the wider power sector. Rather, each section of the building stock is assigned a low carbon heating technology, based on suitability criteria, and provided with a decarbonisation timeline, such that all scenarios meet CB6 targets by 2035.[1] Furthermore, the impact on the power sector of the different resulting heat sectors was not assessed.
- This report follows on from Aurora's report on system flexibility in the net zero world, also produced on behalf of NIC. Wholesale power prices, commodity costs and power sector intensities used throughout this project are taken from the "Base Case" scenario produced as part of that project.

1) Scenarios meet decarbonisation targets (47-62% reduction by 2035 vs 2019 levels), assuming power sector emissions intensities and hydrogen production emission intensities can be maintained, despite high demand in some scenarios.

Source: Aurora Energy Research

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Executive Summary

2) Building stock mapping and factors affecting consumer choice

- **All building types have at least one option of low carbon heating technology which can technically be installed; however, some buildings will be significantly more expensive to decarbonise than others**
  - High efficiency, non-space constrained buildings could be the easiest to decarbonise as these properties have the most available options to choose from.
  - Highly inefficient buildings are likely to be the hardest to decarbonise as they will either require costly energy efficiency upgrades or face high running costs for electrified heating systems.
  - Many space-constrained buildings will be dependent on electric combi-boilers to decarbonise.
  - Understanding the full makeup of the English building stock is challenging due to the lack of available data at sufficient granularity. Data on buildings which have no EPC rating1 is particularly sparse. Privately owned houses are most likely to fall into this category, and these buildings are likely to have lower EPC ratings therefore there may be data gaps on the least efficient parts of the building stock.
- **Decarbonisation of heating requires individual choices from households or landlords (public or private), which may not be made on a purely economic or practical basis**
  - Costs are one of the most significant factors for consumers to take into account when selecting a decarbonised heating technology. If choosing between electrified technologies, consumers must weigh between technologies with high upfront costs and low running costs such as heat pumps, or technologies with low upfront costs but high fuel costs such as electric resistive heaters.
  - Non-financial factors, such as hassle factors, must also be considered. Consumers may be put off by technologies like heat pumps which can have significant requirements for efficiency upgrades, and that behave materially differently to their existing system. Consumers may also be influenced by perceptions on the availability of services for newer technologies or lack of education on options available.
  - Switching to hydrogen incurs low upfront costs, however running costs could be high depending on the cost of hydrogen. In addition, hydrogen could be a lower hassle option, as hydrogen behaves in the same way as natural gas, such that there may be fewer perceived barriers to switching for consumers. However, consumers will not be able to make individual decisions on whether to install a hydrogen system even if they are already connected to the gas network, but will be dependent on policy or commercial decisions taken and the timings of these.

1) Primarily buildings that have not been bought or rented in the last 20 years

Source: Aurora Energy Research

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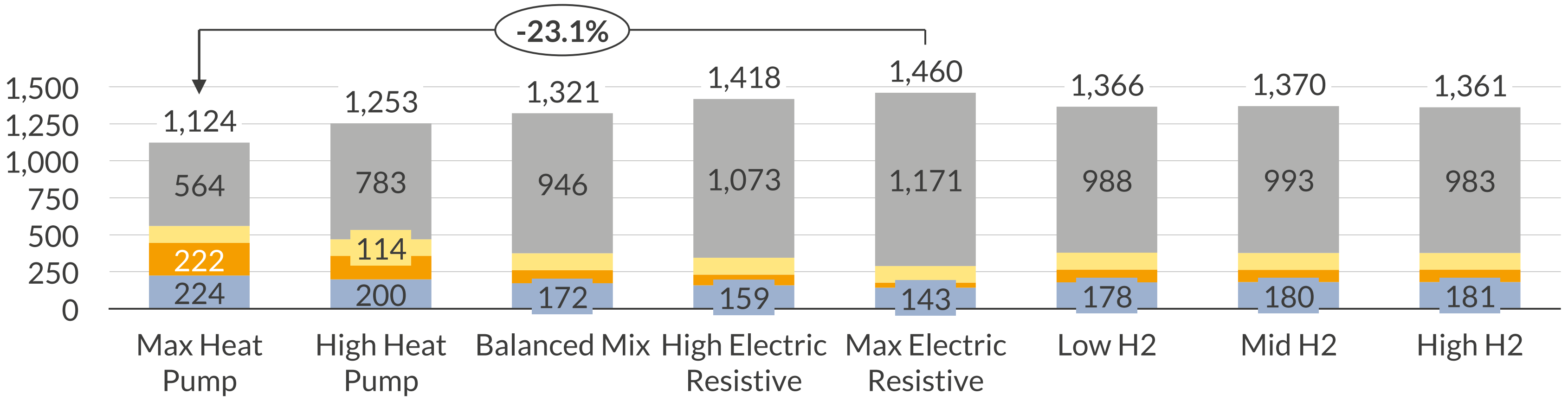
Executive Summary

3) Quantitative heat modelling outcomes

- Higher penetration of heat pumps results in reduced electricity demand and peak demand, reduced total costs and reduced emissions, whilst higher penetrations of electric resistive heating will require a significantly larger power sector in order to meet demand and peak demand, which will increase costs to consumers and will likely make decarbonisation of the power sector harder to achieve.
- Deploying hydrogen in heating could be an effective decarbonisation tool in areas where it is introduced early enough (before 2035), as it allows for the mass conversion of buildings to low carbon heating (presuming the corresponding rollout of 'hydrogen-ready' boilers). However, in areas where hydrogen is not introduced until later in the forecast, partial or even complete electrification of heating would already need to have taken place in order to meet decarbonisation targets, reducing the need for hydrogen.
- Hydrogen in heating could lead to ultimately higher emissions, due to the residual emissions resulting from blue hydrogen production, and higher system costs owing to the high fuel costs of hydrogen. The total size of the power sector would also be larger if hydrogen is deployed, owing to the additional need for electrolysis, but peak demand would be lower.

Total heat system costs, 2023-2050
£bn (real 2021)



Source: Aurora Energy Research

Aurora's report is split into four key sections, each looking to answer specific research questions posed by NIC

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Section II

What low carbon heating technologies are available? Are any heating technologies suited/unsuited to particular building types?

Heating technologies

- What low carbon heating technologies are available?
- What are their key advantages and disadvantages?

Building characteristics

- What building characteristics influence whether low carbon heating systems can be installed?
- What are the easiest buildings to decarbonise?
- What are the biggest challenges?

Section III

What does the English building stock look like?

Building stock

- What data exists on the make-up of the building stock?
- How do key building characteristics vary at a local Authority level?
- Which regions have high proportions of easy or challenging to decarbonise building archetypes?

Section IV

What additional consumer choice factors need to be considered?

- Why might consumers favour some technologies over others?

Direct financial

- Upfront costs
- Efficiency upgrade costs
- Lifetime operational costs
- Financing and subsidy options such as grants and loans

Non-financial

- Hassle factors
- levels of service
- Other behavioural or market incentives

Section V

What would different low carbon heating pathways look like?

Heat sector pathways

- What are the overall costs of each pathway by building types?
- How does heat demand for electricity, natural gas, hydrogen, and other sources of heat varies by location?
- What is the impact on the gas network?

Source: Aurora Energy Research

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Buildings emit one fifth of the UK's total emissions, therefore decarbonising this sector is critical to meeting the sixth carbon budget

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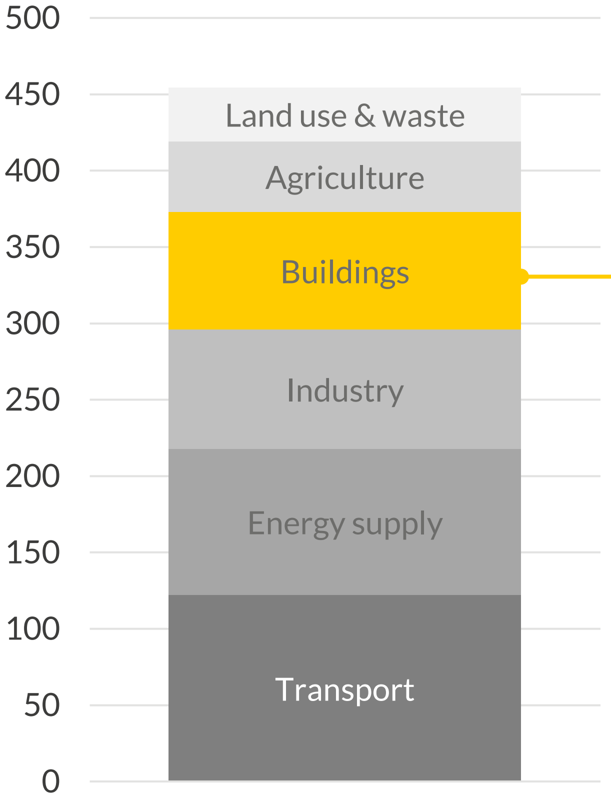
Heating is a major contributor to UK emissions

UK territorial emissions, 2019[1]
$MtCO_2e$



- Buildings accounted for 77Mt, 17% of the total of 455Mt.
- Residential buildings accounted for 69Mt, more than the whole power sector in Energy supply.
- Buildings demand includes heating, cooking and hot water.
- Emissions are heavily influenced by external temperatures. Colder temperatures result in higher emissions due to increased use of heating.

Decarbonising heat represents a major challenge

- Decarbonising buildings is challenging for several reasons:
  - Heating systems must be replaced at tens of millions of locations
  - The replacement rate for the building stock is low and heating systems have long lifetimes
  - Not all low carbon heating systems are technically suitable for all building types and even when suitable can result in significant upheavals and hassles for residents during the installation process
  - Low carbon heating systems can be more costly then traditional technologies, both in terms of upfront costs and in fuel costs
  - Decarbonisation of heating requires individual choices from households or landlords (public or private), which may not be made on a purely economic or practical basis

1) Excluding international aviation and shipping, which accounted for a further ~45 MtCO2 in 2019

Sources: Aurora Energy Research, BEIS 2020 UK Greenhouse Gas Emissions Final Figures, February 2022

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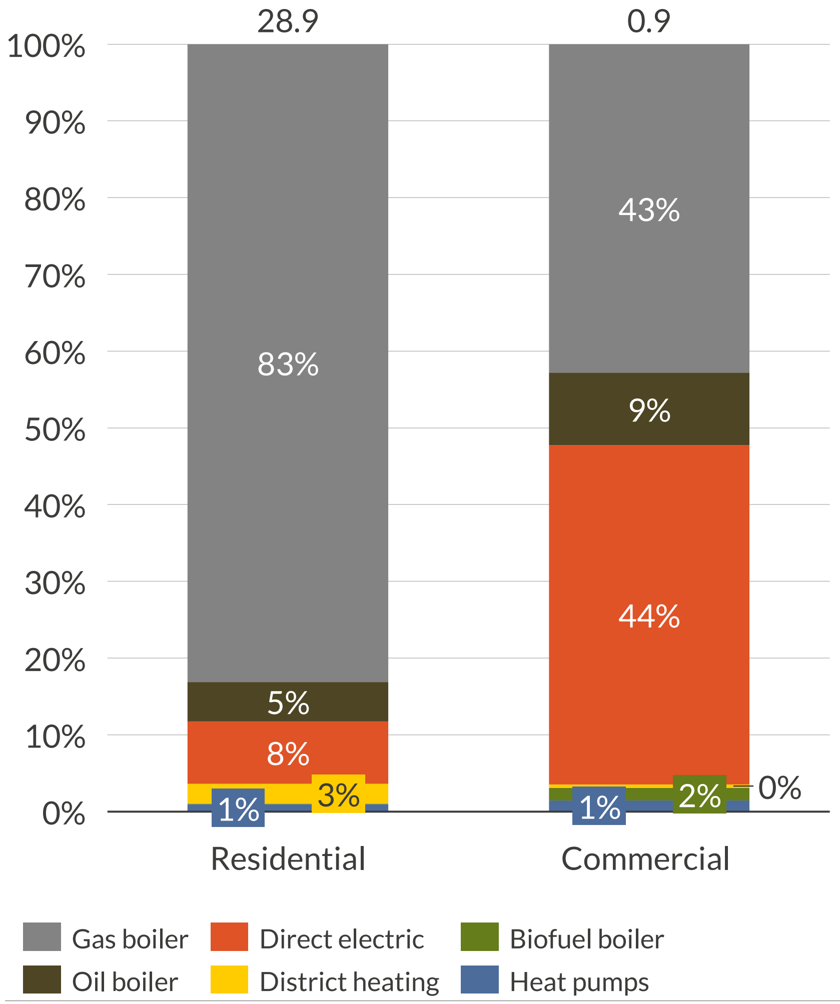
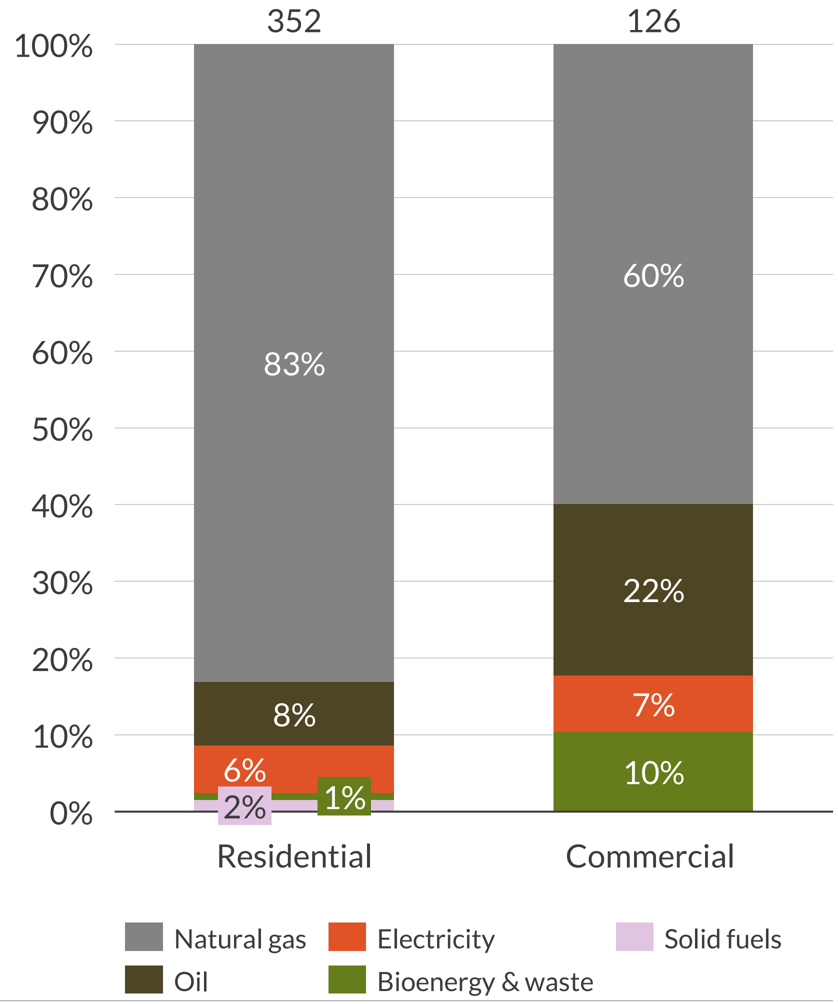
The UK's heating fuel mix is currently dominated by natural gas, which meets more than 80% of residential demand

Overall heating[1] technology mix for buildings in the UK (2021)[2]
Share of total (total amount shown in millions above bar)



Energy use for heating[1] for buildings in the UK (2021)[2]
Share of total (total amount shown in TWh above bar)



1) Heating includes space and water heating 2) Public buildings are not shown as there is insufficient data available

Sources: Aurora Energy Research, NGESO FES 2022, ECUK Energy Data Tables 2020

The decarbonisation of heat will require existing fossil based heating systems (gas/oil/solid fuels) to be replaced with low carbon technologies.

- Gas dominates the UK's heating system, serving >80% of Residential properties and meeting >80% of Residential heating demand. The Commercial sector is more diversified, but gas provides 60% of heat demand here.
- 8% of Residential buildings and 44% of Commercial buildings have electric heating, however this translates to only 6% and 7% of overall energy use for heat from electricity, assumed to be driven by buildings with electric heating tending to be smaller than those with gas heating, therefore contributing less to overall demand.
- Oil heating serves only 5% of Residential and 9% of Commercial buildings but represents 8% and 22% of fuel use, reflecting its lower efficiency.

A range of low carbon technologies could enable the decarbonisation of buildings

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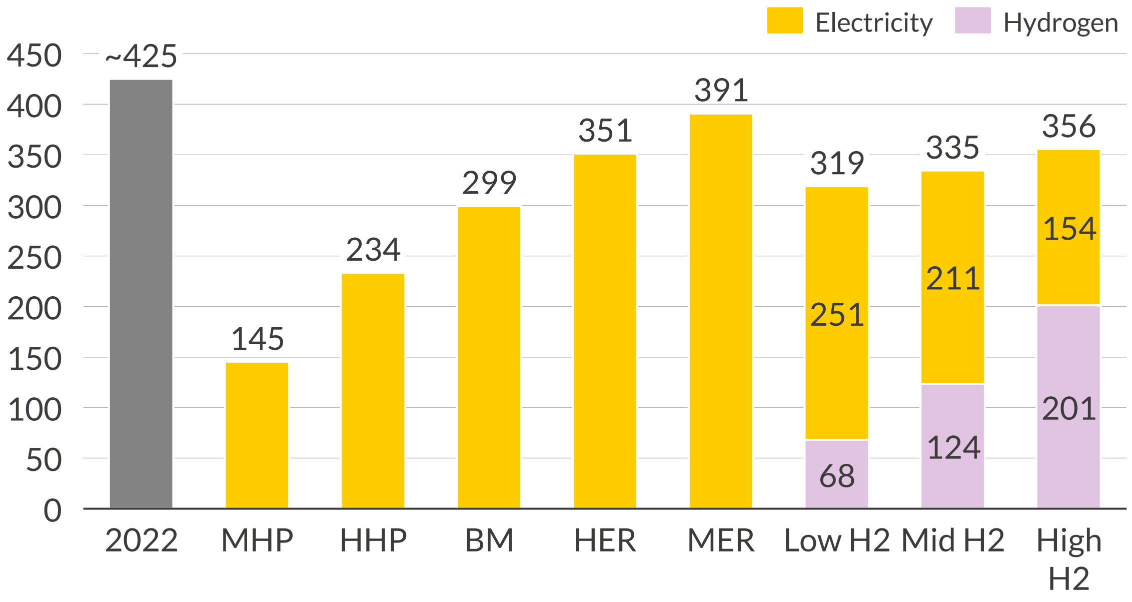
A range of technologies could contribute to a decarbonised heating system

	Overview
Electric heat pumps	An efficient electric heating technology. The Energy White Paper set a target of 600k installations per year by 2028, compared with c.27k in 2019.
Electric resistance heating	Serves c.2.8M homes today. Covers a range of options including electric combi boilers (providing heating and hot water), and electric resistance heating with a hot water cylinder.
Hydrogen	Can be burned for heat in systems similar to today's gas boilers. 100% H2 systems are now being trialled.
Heat networks	Serves c.0.5M homes today. The government plans wider deployment, using more low-carbon sources like heat pumps, biomass or solar.
Hybrid systems	Combines heat pumps with gas/H2 boiler or other forms of electric heating. Heat pumps can operate in low electricity price periods with the top-up system as back-up when economical, or in extreme cold weather.

- **Thermal storage** will become increasingly important as electrical heating becomes more widespread, given the variations in daily power prices.
- **Energy efficiency** measures will play a vital role in reducing energy demand for heat, and will be vital for homes switching to heat pumps, which tend to produce lower flow temperatures than typical gas boilers.

A broad range of outcomes is possible for heat demand in the future, depending on the path taken

Energy demand for heat in 2050 from modelled pathways[1]
TWh/year



- The future mix will depend on policy, economics, technological development, consumer choice and interactions between fuel market sectors (more information on scenario design in Section V).

1) Heat scenarios introduced in Section V of this report

Sources: Aurora Energy Research, NG FES 2022, July 2022, Energy White Paper

Low carbon technologies have several key advantages and disadvantages compared to traditional heating systems

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	Gas/ Hydrogen/ Oil/ Combi Boilers	Air source heat pump (ASHP)/ Ground source heat pump (GSHP)/ Hybrid ASHP	Electric resistive heater/electric combi-boiler	Heat network
	Fossil Fuel / Hydrogen	Electricity	Electricity	Various[1]
Overview	Burns fuel to heat up water, which then circulates through radiators to provide heating. A conventional boiler requires a hot water cylinder (HWC) while a combi boiler directly draws water from the mains, heating and suppling water on demand.	Heat is captured from air/ ground and absorbed into a fluid that passes through a heat exchanger. The temperature of the fluid is raised and circulated around the building. A hybrid ASHP system uses a heat pump alongside a fossil fuel heat source.	Electric resistance heat is supplied either by a centralised electric furnace or room heaters.	Heat is supplied from a central source to a cluster of buildings, via underground pipe networks carrying hot water.
'In home' Advantages	▪ Cheap, reliable, compatible with older heating systems. ▪ Combi boiler requires less space and provides instant hot water. ▪ Combi boilers are more energy efficient than a conventional boiler.	▪ Well-installed heat pumps have efficiency of ~300/400%[2], making them the most efficient heating technology with low ongoing costs. ▪ A hybrid system optimises cost based on fuel costs and time of day (which impacts electricity prices).	▪ Lower CAPEX and easier to install than heat pumps . ▪ Less likely to breakdown than conventional boilers. ▪ Electric combi-boilers behave in similar way to traditional boilers.	▪ Avoids the need for boilers or electric heaters in every building. ▪ Source can be changed and decarbonised with minimum disruption to the end user.
'In home' Disadvantages	▪ Conventional boiler requires additional space for HWC. ▪ Hot water supply can run out during the day. ▪ Combi boiler has no storage capacity, is reliant on mains pressure and can struggle to keep up with high demand. ▪ Use of fossil fuel creates carbon emissions.	▪ High CAPEX and high installation costs. ▪ Energy inefficient buildings need to be upgraded first. ▪ Hot water cylinder must be installed. ▪ Some outdoor space required for all heat pumps, significant space required for GSHP. ▪ Different operating behaviour to conventional system may be off-putting to some consumers.	▪ High fuel costs due to lower efficiencies. ▪ Note that high levels of electric resistive deployment can result in unfavourable dynamics at the system level, on account of their relatively poor efficiency compared to heat pumps.	▪ Expensive and complex to build. ▪ Installation requires coordination between a number of parties.

1) Including combined heat and power plants, heat pumps and biomass boilers. 2) Heat pump efficiency varies with temperature. Average efficiencies of 325% and 400% are anticipated for air source and ground source heat pumps, respectively (Ruhnau et al, 2019).

Source: Aurora Energy Research

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Some building characteristics make them technically unsuitable for certain types of heating technologies

Some building characteristics make them unsuitable for certain types of heating technologies, but all building types are *technically* able to be converted to at least one form of low carbon heating. Note the table does not reflect the full array of heating system configurations that can be employed to work around constraints arising from a given set of building characteristics.

Characteristics		Electric resistive with HWC[1]	Electric combi boiler	Hydrogen boiler (H2B)	Hybrid ASHP + H2B	Air source heat pump (ASHP)[2]	Ground source heat pump (GSHP)[2]	Community heat network
Energy efficiency	Energy inefficient	Suited	Suited	Suited	Suited	Partly suited: Unless installing a high temperature heat pump	Partly suited: Unless installing a high temperature heat pump	Suited
	Energy efficient	Suited	Suited	Suited	Suited	Suited	Suited	Suited
Gas grid connection	On-gas grid	Suited	Suited	Suited	Suited	Suited	Suited	Suited
	Off-gas grid	Suited	Suited	Unsuited	Unsuited	Suited	Suited	Suited
Space constraint	Space constrained	Unsuited	Suited	Partly suited: Except combi boilers	Partly suited: Except combi boilers	Unsuited	Unsuited	Suited
	Not space constrained	Suited	Suited	Suited	Suited	Suited	Suited	Suited
Building type	Flats	Suited	Suited	Suited	Suited	Suited	Unsuited	Suited
	All other types	Suited	Partly suited: Dependent on hot water requirements	Suited	Suited	Suited	Suited	Suited
Urban rating	Urban	Suited	Suited	Suited	Suited	Suited	Suited	Suited
	Rural	Suited	Suited	Suited	Suited	Suited	Suited	Unsuited

Energy efficiency: Inefficient buildings have higher rates of heat loss and are therefore unsuited for standard heat pumps, which provide a lower rate of heat output compared to conventional heat systems. However, they could still be suited for high temperature heat pumps which are designed to produce higher temperature heat output, but are more expensive.

Gas grid connection: Off-gas grid buildings are unsuitable for gas or hydrogen heating systems, since the future hydrogen network is assumed to be based on the extent of today's gas network, therefore these homes would not be able to be supplied with the fuel for these heating systems.

Space constraint: Space constrained buildings are unsuited for heating systems that use a hot water cylinder, such as gas/oil/electric/H2 boilers or heat pumps. However, a combi boiler with no HWC[1] could generally be installed.

Building type: Flats are typically unsuited for GSHP, since they do not tend to have sufficient outdoor space for the ground loop[3]. Combi-boilers may not be able to provide sufficient hot water to homes with a higher number of occupants which is assumed to include many detached/semi-detached houses.

Urban rating: Rural areas are unsuited for community heat networks, since these require groups of buildings to convert together.

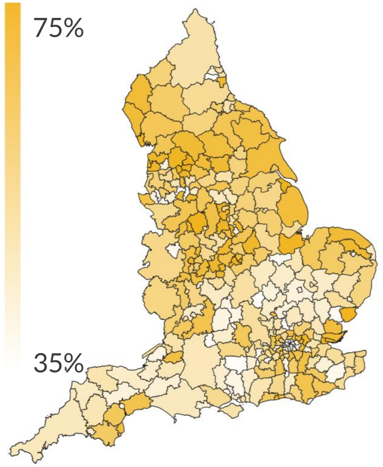
Unsuited | Partly suited | Suited

1) Hot water cylinder. 2) Heat pumps systems are assumed to provide water heating via a hot water cylinder. Heat pump systems without the use of a hot water cylinder (e.g. using electric boilers) are not considered. 3) Note there are some flats with sufficient space for ground loops, or bore holes, however these reflect only a minor portion of the total.

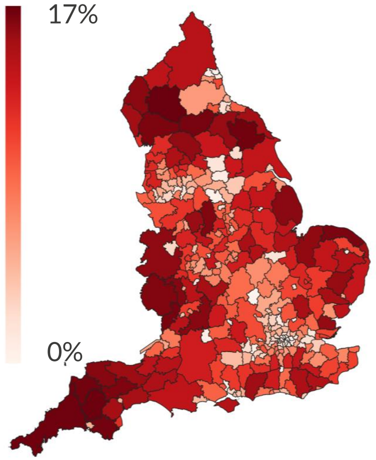
Sources: Aurora Energy Research, Element Energy

Heat pumps: Efficiency upgrades or high temp heat pumps can be needed for buildings for buildings with poor energy performance

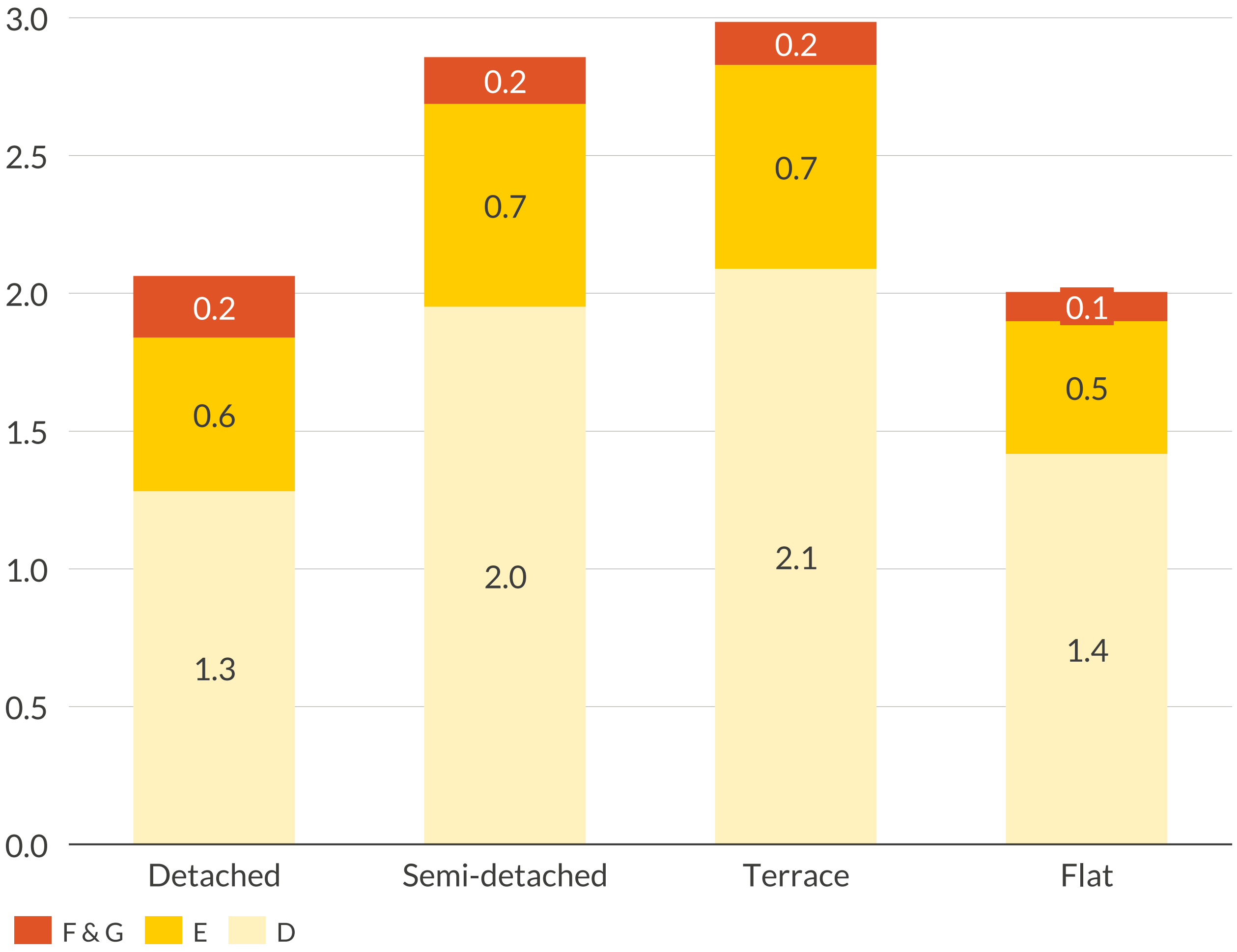
EPC D & E



EPC F & G



Total number of Residential buildings by EPC rating
Millions



Heat pumps are best suited in efficient buildings without space constraints. For buildings that are unsuitable for heat networks, heat pumps are the lowest cost option on an annualised basis.

- Standard heat pumps are often unsuitable for buildings with poor energy performance[1], as they have a low rate of heat output compared to other technologies, so cannot meet demand in inefficient buildings.
- To decarbonise using a heat pump, inefficient buildings could install a high temperature heat pump to accommodate the higher rate of heat loss, or upgrade EPC rating, increasing the cost of installing the system.

For highly inefficient buildings that are not gas grid connected, converting to heat pumps is likely to be the most viable option, unless heavily space constrained.

1) 'Poor energy performance' is considered EPC D or below for modelling purposes

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

Hydrogen for Heat: Buildings connected to the gas network may have the option to convert to a H2 boiler

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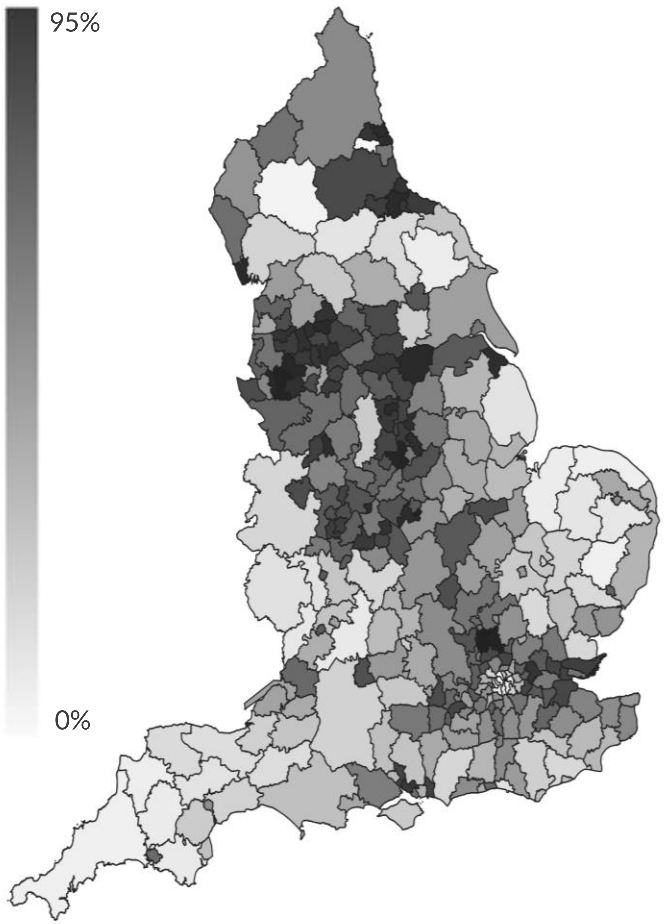
Share of buildings connected to the gas grid in each Local Authority
%



- Buildings which are currently connected to the gas network may have the option to connect to a future H2 network, which, if deployed, is expected to use the same infrastructure. This would allow conversion to hydrogen boilers or hybrid systems comprising of hydrogen boilers in tandem with air source heat pumps.
- However, any future H2 network is expected to be rolled out in stages, from potential H2 hubs, with buildings in the nearby area connected sooner, meaning this option may not be available to all consumers simultaneously.
- Very inefficient buildings face high upfront costs to convert to a standard heat pump due to the need for efficiency upgrades, and high fuel costs for electric resistive heating or high temp heat pumps. H2 presents a viable alternative for these buildings if connected to the gas grid. These buildings will be highly dependent on policy decisions surrounding the future of the gas grid.

Sources: Aurora Energy Research , non -gas map 2013, ONS 2011

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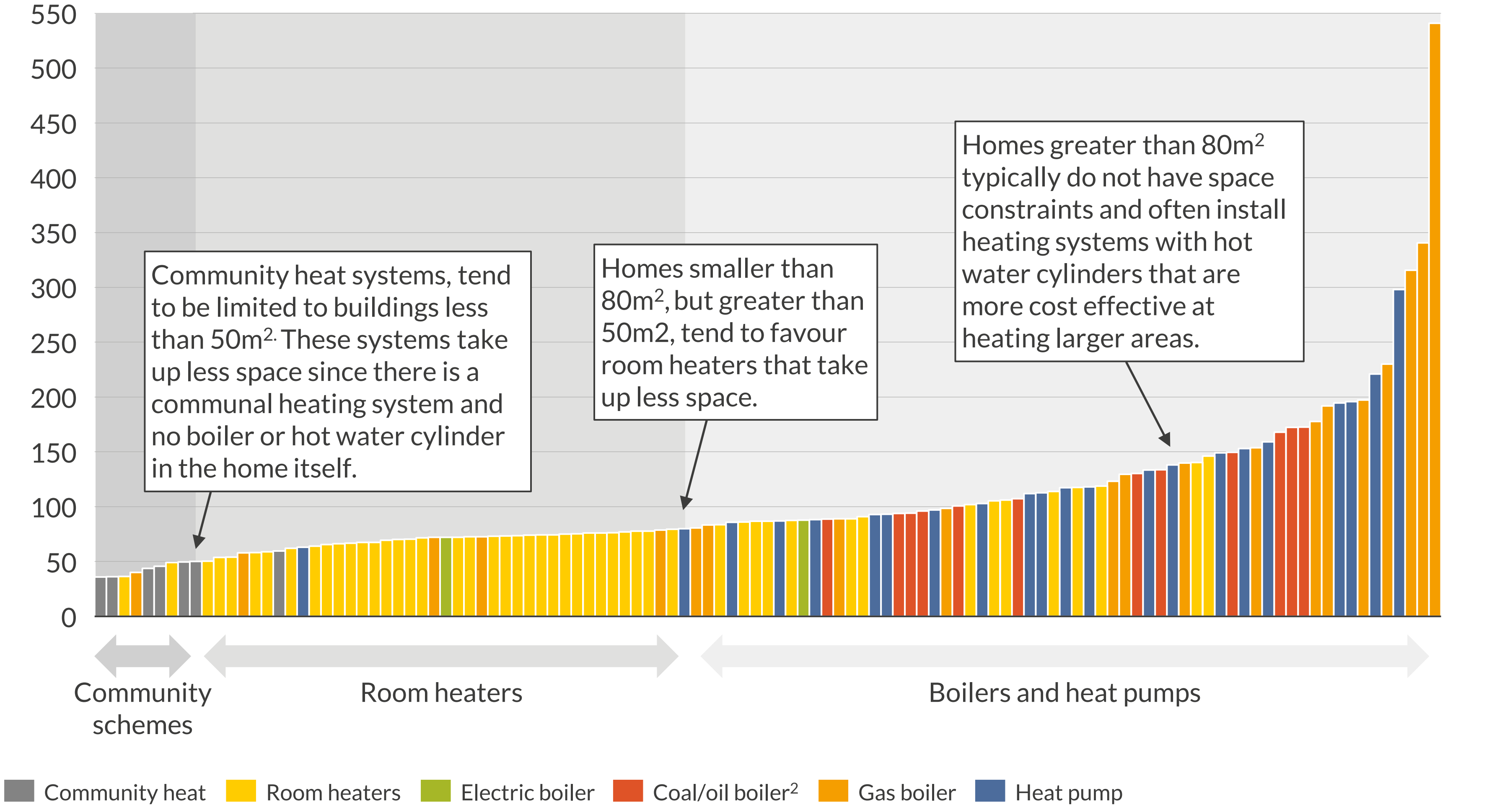
Electric resistive heating: Smaller homes are more likely to be suited to electric resistive heating, as well as community heating schemes

Average total floor area of households using different heat technologies[1]

m² (each bar represents a distinct heating technology, grouped into six main heating technologies shown in legend)



1) Data represents over 0.5 million properties in Birmingham and Cornwall, with more than 110 distinct heating systems. Bars represent the average total floor area of all properties in sample data using that particular type of heating system. Bars are coloured based on specified technology groupings shown in legend. 2) Includes LPG, dual fuel and biofuel boilers.

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

Electric resistive heating is the most expensive technology on an annualised basis, but for some buildings is likely to be the most suitable low carbon option.

- Buildings with constrained space, which cannot have a hot water cylinder, will not be able to install a heat pump but could install an electric combi-boiler.
- Other options may be to join a heat network or to convert to H2 if gas connected.

Electric combi boilers are unlikely to provide sufficient hot water to larger buildings or those with multiple occupants. A hot water cylinder can be installed, but is unlikely to be the cheapest annualised option.

To date, electric room heaters are mostly used in smaller buildings.

- A combination of room heaters and community heat systems serve the smallest buildings, while room heaters are used in homes between 50-80m².

Heat Networks: New low-carbon heat networks could be deployed, but are likely to be concentrated in areas of high heat density

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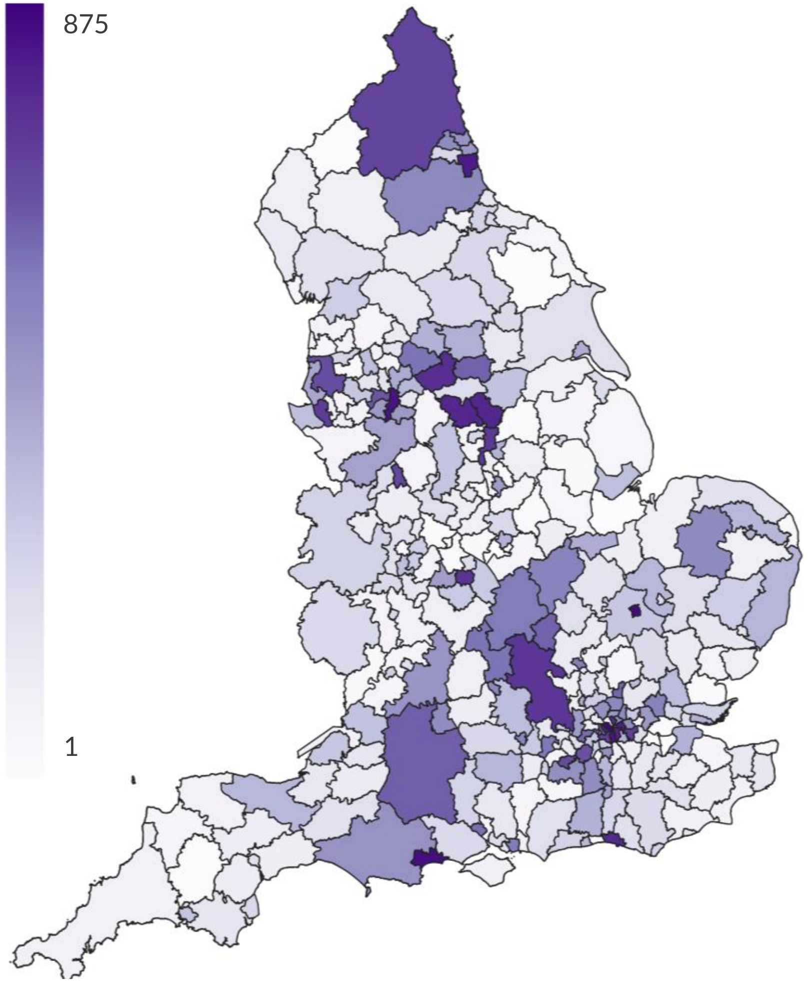
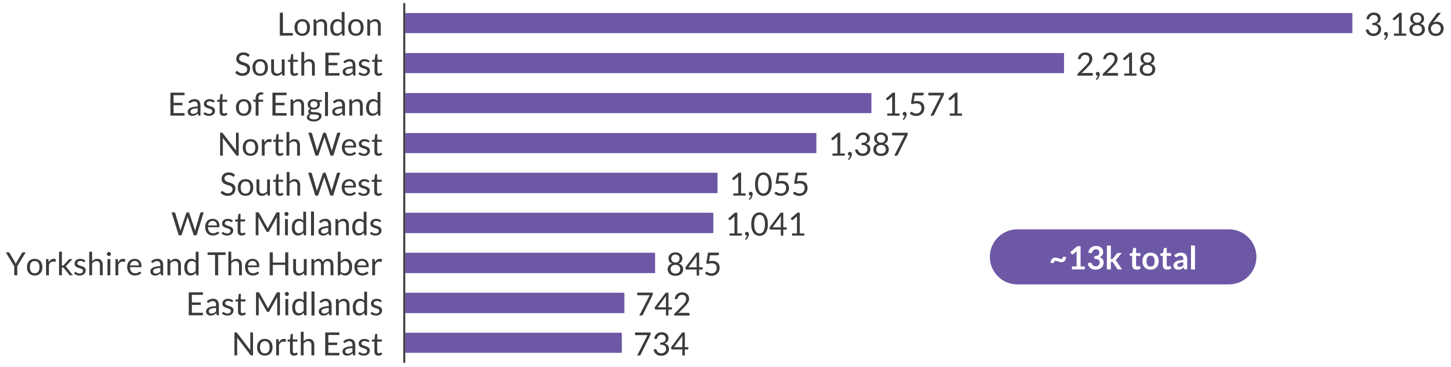
Local authority distribution of heat networks
Number of heat networks



Heat networks regional distribution
Number of heat networks



- Heat networks deliver heating to consumers from a centralised heat source. They are most typically deployed in areas of high heat density; generally in urban areas. Furthermore, they can only be deployed in suitable properties; likely flats and terraced houses in urban areas.
- Heat networks in England currently provide heating to around 54,000 Residential, 6,500 educational and 5,000 Commercial buildings, but could be further rolled-out in future, particularly in urban areas.
- The pipe infrastructure can be used to deliver heating from a range of different heat sources, and can therefore be decarbonised, by changing to a low carbon heat source, with minimum disruption to the end user.
- However, heat networks are expensive and complex to build. The installation requires organisational effort and coordination between a number of different parties. Sufficient heat demand is necessary to make an investment case hence they typically suit higher density areas.

Sources: Aurora Energy Research, BEIS Heat Network Statistics 2018

The technically easiest to decarbonise buildings are likely to be highly efficient and non-space constrained which have the most available options

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All building types have at least one option of low carbon heating technology which can technically be installed; however, some buildings will be significantly more expensive to decarbonise than others.

- High efficiency, non-space constrained buildings could be the easiest to decarbonise as these properties have the most available options to choose from, which may complicate the decision-making process, but will allow households to select low-cost options.
  - Buildings which are not gas grid connected will have to choose between electrified technologies.
  - Buildings which are gas grid connected would be able to install a hydrogen system, as well as electrified forms of heating, however for easier-to-decarbonise buildings, the timing of the deployment of the hydrogen network will be a critical factor in whether this pathway is followed, as hydrogen may not be a feasible option until after a decarbonisation decision is taken.

- Highly inefficient buildings are likely to be the hardest to decarbonise as they will either require costly energy efficiency upgrades, or face high running costs for electrified heating systems.
  - For highly inefficient buildings that are not connected to the gas grid, which can or are willing to install energy efficiency improvements, a heat pump can be installed.
  - Highly inefficient buildings that are not connected to the gas grid, which are unable to undertake efficiency improvements will be reliant on high temperature heat pumps, or electric resistive heating. These buildings will ultimately face high ongoing fuel costs.
  - Highly inefficient buildings that are gas grid connected may have the option to convert to hydrogen in the future, but will be reliant on policy decisions taken in this area.
- Many space-constrained buildings will be dependent on electric combi-boilers to decarbonise, which removes choice and simplifies the decision-making process, but will be amongst the most expensive to decarbonise on an annualized basis, and when considering ongoing running costs (on a £/MWh basis).
  - Space constrained buildings with a gas connection may have the option to convert to hydrogen, but this will depend on the deployment of the network.
  - Space constrained buildings in Urban areas may also have the option to connect to a heat network, which would reduce annualised costs.

Source: Aurora Energy Research

Summary: Heating technology suitability constraints

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1 Gas dominates the UK's heating system, serving >80% of Residential properties and meeting >90% of Residential heating demand. The Commercial building sector is more diversified, but gas still supplies two thirds of heating demand.

2 Low carbon heating technologies include heat pumps, direct electric heating, heat networks and hydrogen. Not all buildings are technically suited to each form of decarbonised heating.

3 Heat pumps are unable to operate effectively in highly inefficient buildings, necessitating efficiency upgrades to take place. Heat pumps also require space for a hot water cylinder to be installed inside the building, meaning space constrained buildings are also likely to be unsuited. Outdoor space is also required for the unit, for ground source heat pumps, sufficient space for a coil is also required. However, most buildings could install a heat pump if the necessary work was undertaken.

4 Electric resistive heating (direct electric heating, combined with a hot water cylinder for hot water provision) is technically suited for most buildings (although has high ongoing costs), however is particularly suited to space constrained buildings with few options.

5 Hydrogen heating presents a viable option for buildings that are connected to the gas network and would behave very similarly to existing gas boilers. However, consumers will be reliant on policy decisions on the rollout of the hydrogen network before individual decisions can be taken on whether to choose hydrogen or another form of electrified heating.

6 Heat networks could be installed in urban buildings, however installation requires organisational effort and coordination between a number of different parties.

Source: Aurora Energy Research

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To understand the options available to decarbonise heating, we must first understand the make-up of the building stock

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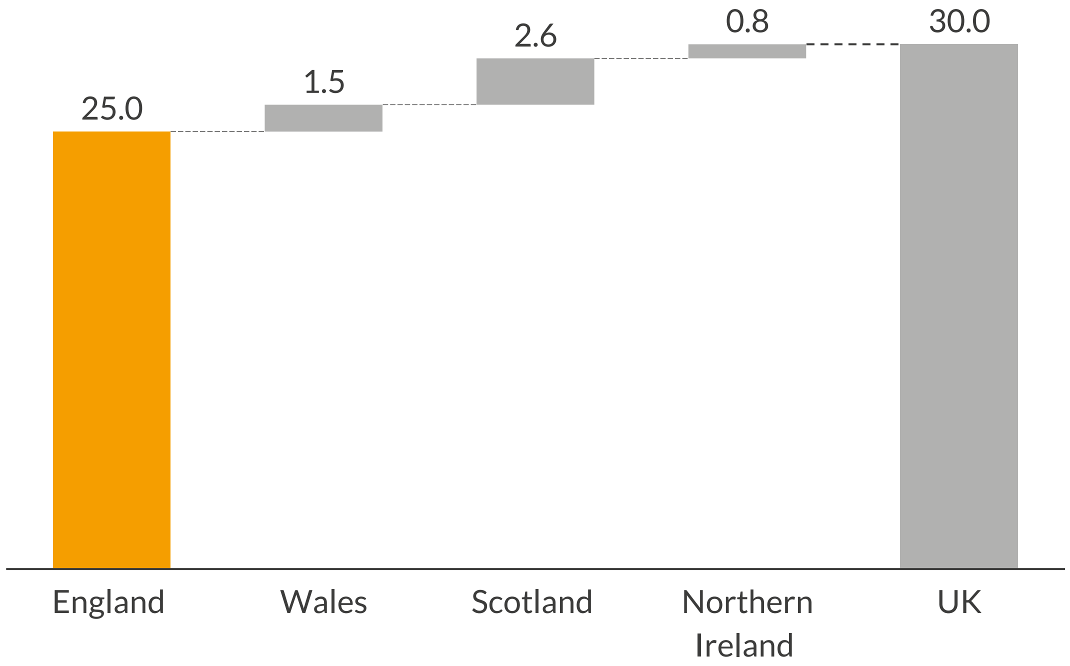
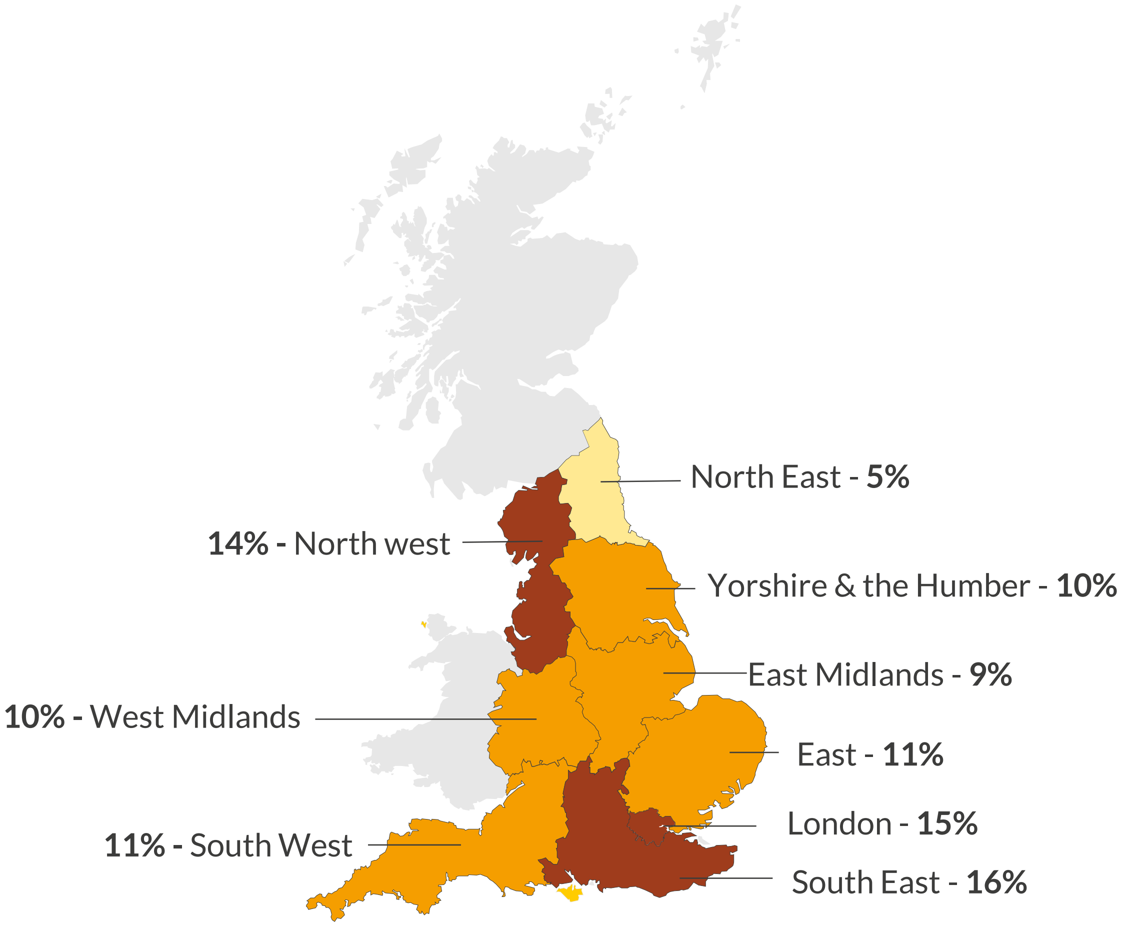
UK building stock by country[1] (as of 2020)
Millions of homes



Regional share of English building stock[1] (as of 2020)
%



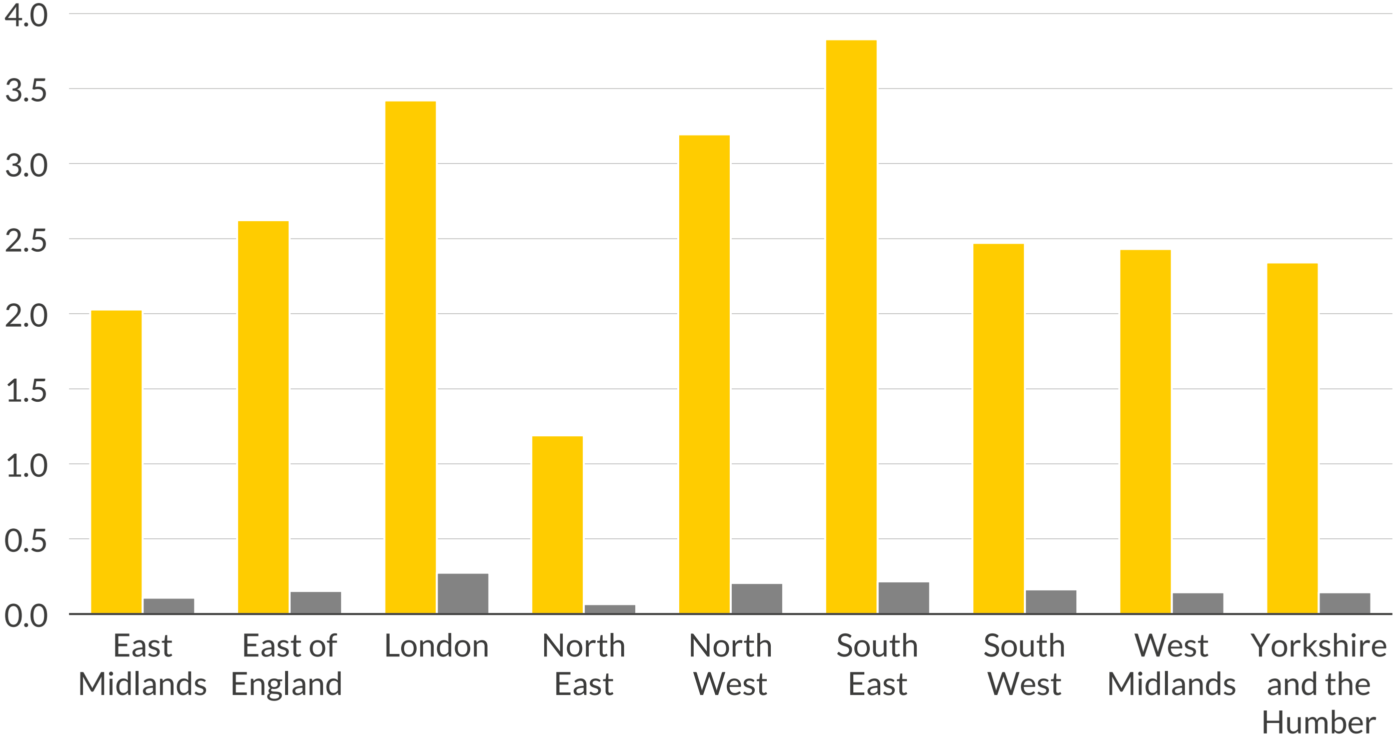
- Policy related to buildings is devolved and the National Infrastructure Commission's remit follows the UK government's competence. This report therefore focuses on the impacts of decarbonising the English portion of the UK building stock, but its learnings have relevance to the rest of the building stock more widely.
- The scope of buildings covered in this report include Residential, Commercial and Public buildings. It does not cover industrial heating.

1) Includes non-Residential buildings (but exclude industrial buildings) in England

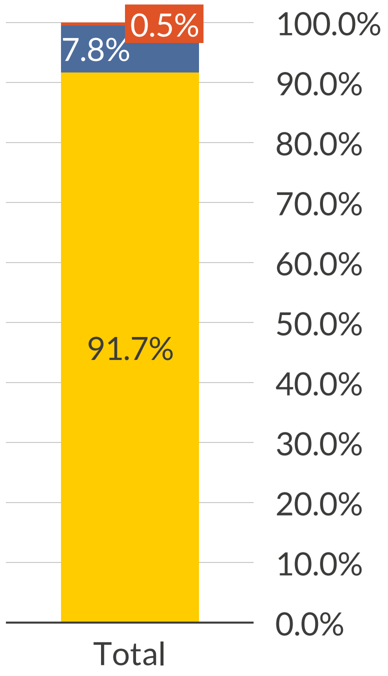
Sources: Aurora Energy Research, English Housing Survey 2021, VOA NDR 2022, ONS, Scottish House Condition Survey 2022, NGESO FES2020, NISRA 2022

Buildings can be categorised as Residential, Commercial and Public, of which c.92% are Residential

English building stock by region, sector[1]
Millions of buildings



Share of total by sector
%



- Lack of data prevents splitting non-Residential building stock into clear Public and Commercial sub-sectors at a regional level
- At the national level, Public vs Commercial split of the non-Residential building stock was derived from the VOA 2022 data set based on sectoral mapping onto these two categories[2,3]

Residential | Non-residential | Commercial[2] | Public[3]

1) Includes Commercial and Public buildings, excludes industrial buildings. 2) Commercial buildings include: stores, shops, offices, markets, car parks, private leisure centres, private educational and cultural buildings. 3) Public buildings include: Public and local authority educational and cultural buildings, medical facilities, local government offices, police stations and courts.
Sources: Aurora Energy Research, English Housing Survey 2021, VOA NDR 2022

Understanding the breakdown of building stock is important to understand the low carbon heating technologies and energy efficiency options that are available to each building and at what cost, as well as how difficult any given decarbonisation pathways might be. Buildings can be categorised as Residential, Commercial and Public.

Residential

- 91.7% of English buildings are classified as Residential, representing a total of 23.5 million buildings.

Non-Residential (Commercial & Public)

- 7.8% of buildings can be classified as Commercial, with 0.5% of buildings classified as Public. Whilst data is available on the overall breakdown between Commercial and Public buildings at country-wide level, this split is not available on a regional or LA level.

We analyse a number of key dimensions that affect the heating requirements and decarbonisation options for the building stock

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Key dimensions for analysis	Building sector		
	R Residential	C Commercial	P Public
Tenure (e.g. owner-occupied)	*Different occupants have differing incentives to update their heating technologies and different levels of responsibility/ability to do so.*	*Less important for Commercial buildings as these tend to be rented or owned by corporations rather than individuals.*	*Less important for Public buildings as these are owned Publicly and not owned by individuals.*
Building type (e.g. detached house)	*Different building types have differing heating requirements due to their different sizes and proximity to other buildings.*	*Less important for Commercial buildings as these tend to be non-Residential buildings such as offices or warehouses.*	*Different building types have differing heating requirements due to their different sizes and uses.*
Efficiency rating (EPC bands A-G)	*A building's efficiency rating impacts its heating requirements, via its heat loss rate. The heat loss rate also has bearing on the range of suitable low carbon heating technologies (for example, air source heat pumps provide a lower rate of heating and require better insulated buildings, whilst gas/H2 boilers or Electric Resistive heaters can be more effectively installed in lower efficiency properties).*		
Connection to mains gas network (yes/no)	*Whether a building is connected to the mains gas network impacts the range of low carbon heat technologies that are suitable for that building (e.g. we assume hydrogen boilers are not suited to buildings that are not on the gas grid, as we assume a future hydrogen network will be derived from the converted gas grid).*		
Urban rating (1-6 scale)	*A measure of how built up the area is surrounding a particular building; this dimension impacts the suitability of buildings or groups of buildings for conversion to low carbon heat networks.*		
Space constrained (yes/no)	*This impacts the suitability of certain low carbon heat technologies to be installed in a building. Some technologies (e.g. heat pumps requiring hot water cylinders) take up more space than others and unsuitable for space constrained buildings.*		

- We identify six key dimensions which are important to consider when investigating potential decarbonisation pathways for different types of buildings
- Each dimension will impact the low carbon heating technologies available to a building, and each is considered in more detail in the following pages

Sources: Aurora Energy Research

Data for residential buildings is relatively available at a Local Authority level…

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Data availability on Residential properties

	Tenure	Building type	Efficiency rating	Gas network connected	Urban rating	Space constraint
ONS, 2011[1]	LA level	LA level			LA level	
ONS, 2020[2]	LA level					
ONS, 2020[3]			LA level			
DLUHC, 2022[4]	Incomplete	Incomplete	Incomplete	Incomplete		Incomplete
DLHUC, 2021[5]	LA level					
DLHUC, 2021[6]	LA level	LA level				
BEIS, 2013[7]	LA level	LA level	LA level	LA level	LA level	
English Housing Survey, 2021[8]	Regional	Regional				
English Housing Survey, 2021[9]			Regional			

Data available at Local Authority level (LA level)
Regional level data available (Regional)
Incomplete data available at LA level (Incomplete)

Data gaps for Residential properties

Datasets for Residential buildings are relatively available at a Local Authority (LA) level, however there are several key data gaps within these:

- Individual datasets are compiled in different years, using different methodologies, resulting in mismatches between seemingly equivalent data
- Within some datasets, dimensions cannot all be mapped onto one another
- Datasets containing different dimensions cannot be mapped onto each other without taking assumptions and approximations
- The DLUHC dataset has the highest level of detail, but is only available for the 16M buildings which have been sold or rented in the past 20 years
  - These buildings are not a perfect representation of the overall building stock, since properties are more likely to have efficiency improvements at the point of sale or between tenancies, and certain buildings types are sold or rented more often
  - Importantly, privately owned homes are most likely to be inefficient (see page 34) and are underrepresented in this dataset, due to being sold/rented less frequently
  - Lastly, data was compiled over the past 20 years and does not reflect all changes to a building in this period, as there is no obligation to update the certificate unless a building is sold or rented and does not already have a valid certificate (from the past 10 years)

As a result, a complete set of archetypes covering all dimensions for all buildings at LA level cannot be compiled. However, extrapolations can be made. *We have been clear to note where we extrapolate from DLUHC data throughout this report.*

1) Accommodation type by type of central heating in household by tenure, 2) Subnational estimates of dwellings by tenure, England, 3) Estimated proportion of dwellings with an Energy Performance Certificate by main fuel type or method of heating used in central heating, 4) EPC open data, 5) Local authority housing statistics data returns, 6) Live tables on dwelling stock, 7) non-gas map, 8) English Housing Survey, 2020 to 2021: housing quality and condition, 9) English Housing Survey, 2020 to 2021: energy

Sources: Aurora Energy Research

…However, there is a significant lack of data on the Commercial and Public building stock at a regional and local granularity

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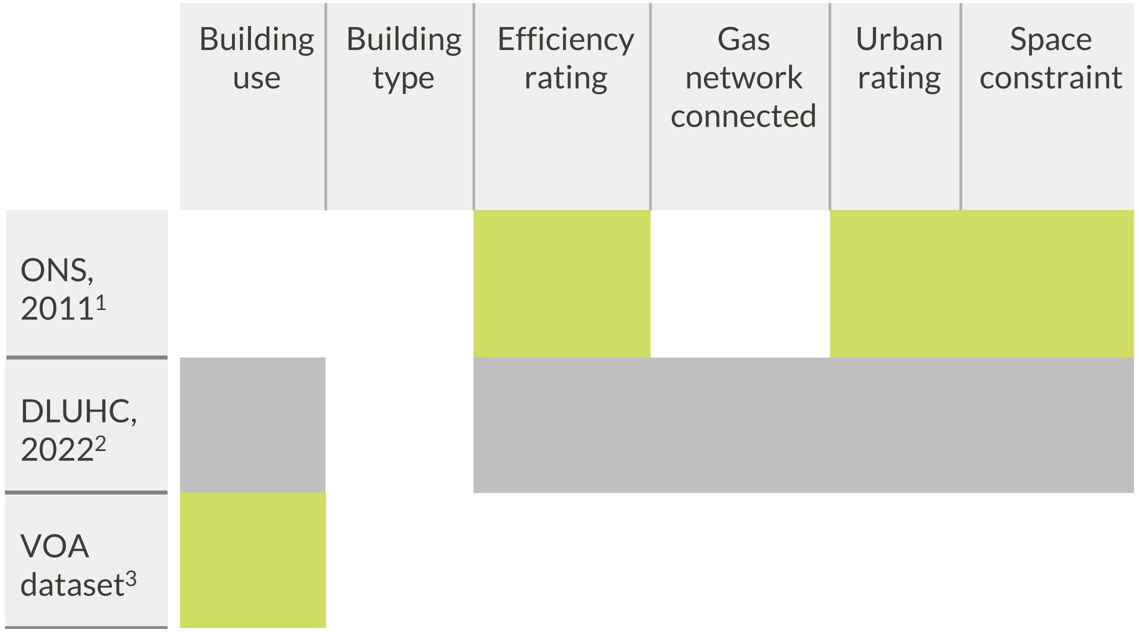
Data sources for Commercial and Public properties



Data available at Local Authority level
Regional level data available
Incomplete data available at LCA level

Data availability for Commercial and Public properties

For Commercial and Public buildings, there are significant gaps in data sources:

- Datasets do not typically distinguish between different types of non-Residential buildings
- Some dimensions cannot be mapped at a LA level
- Some dimensions cannot be mapped against each other, as data sources are compiled using different methodologies
- DLUHC data is also available for Public and Commercial buildings; see the previous slide for an overview of key issues with this dataset

As a result, a complete set of archetypes including all dimensions for all properties at LCA cannot be compiled. However, extrapolations between datasets can be made. *Throughout this deck, we have been clear to note where extrapolation have been taken.*

1) Accommodation type by type of central heating in household by tenure, 2) EPC open data, 3) Non-domestic rating: stock of properties, 2022

Sources: Aurora Energy Research

Agenda

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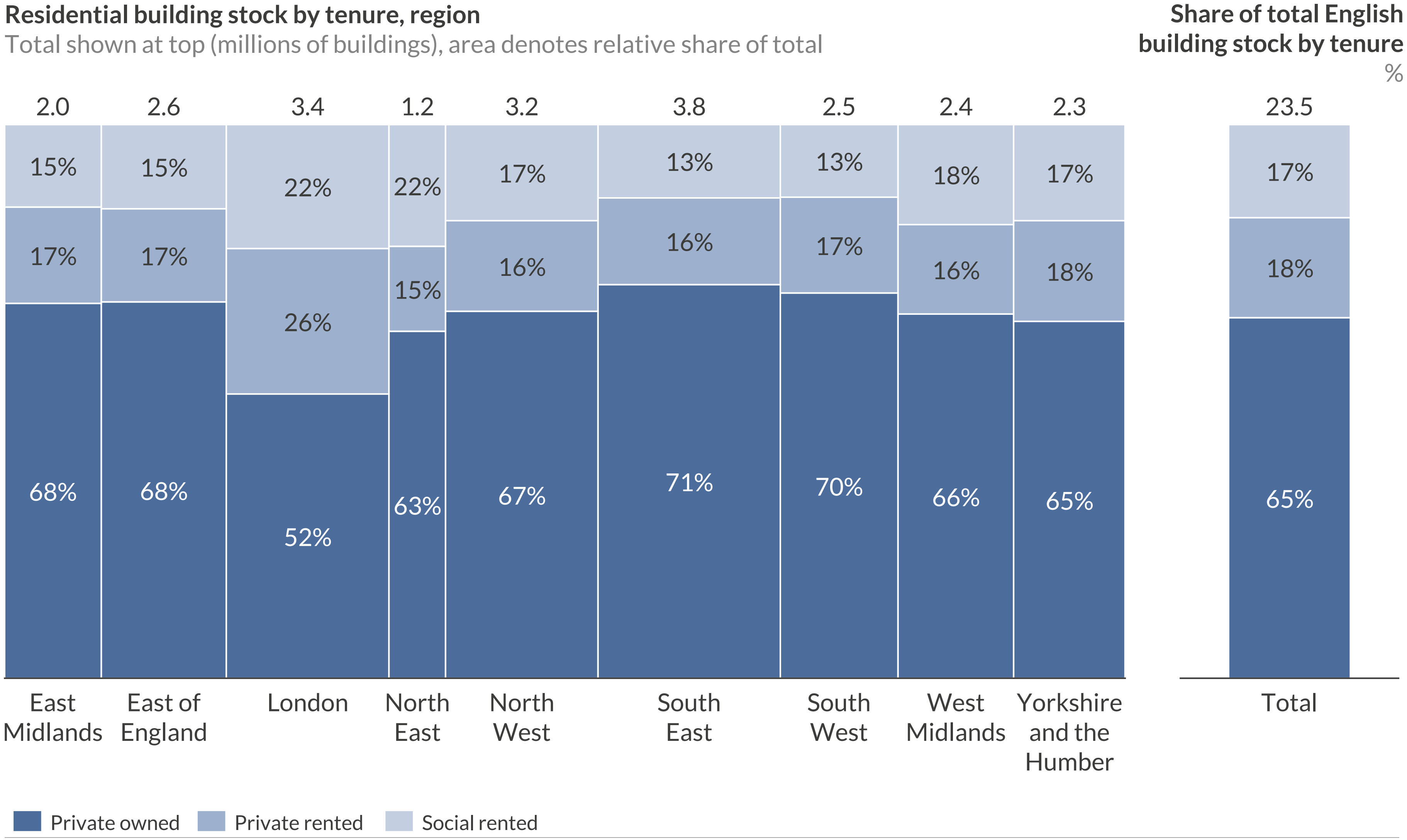
Tenure: Two thirds of Residential buildings are owner-occupied, with the remaining third shared between socially and privately rented



The tenure of a building impacts who is able to make decisions regarding its heating decarbonisation pathway.

- For **Socially rented** homes a local authority or state regulated housing association is the key decision maker.
- The decarbonisation of **Private owned** buildings would require individual decisions from millions of owners, however owners are more likely to reap the benefits of upgrading their systems, compared to landlords.
- **Private rented** buildings require landlords to make decisions about when to invest and which technology to choose, but they may not see the benefit as tenants often pay the heating bill. Renters typically have limited ability to take decisions.

If all other factors are equal, **Private rented buildings are expected to be the hardest category to decarbonise.**

Sources: Aurora Energy Research, English Housing Survey 2021

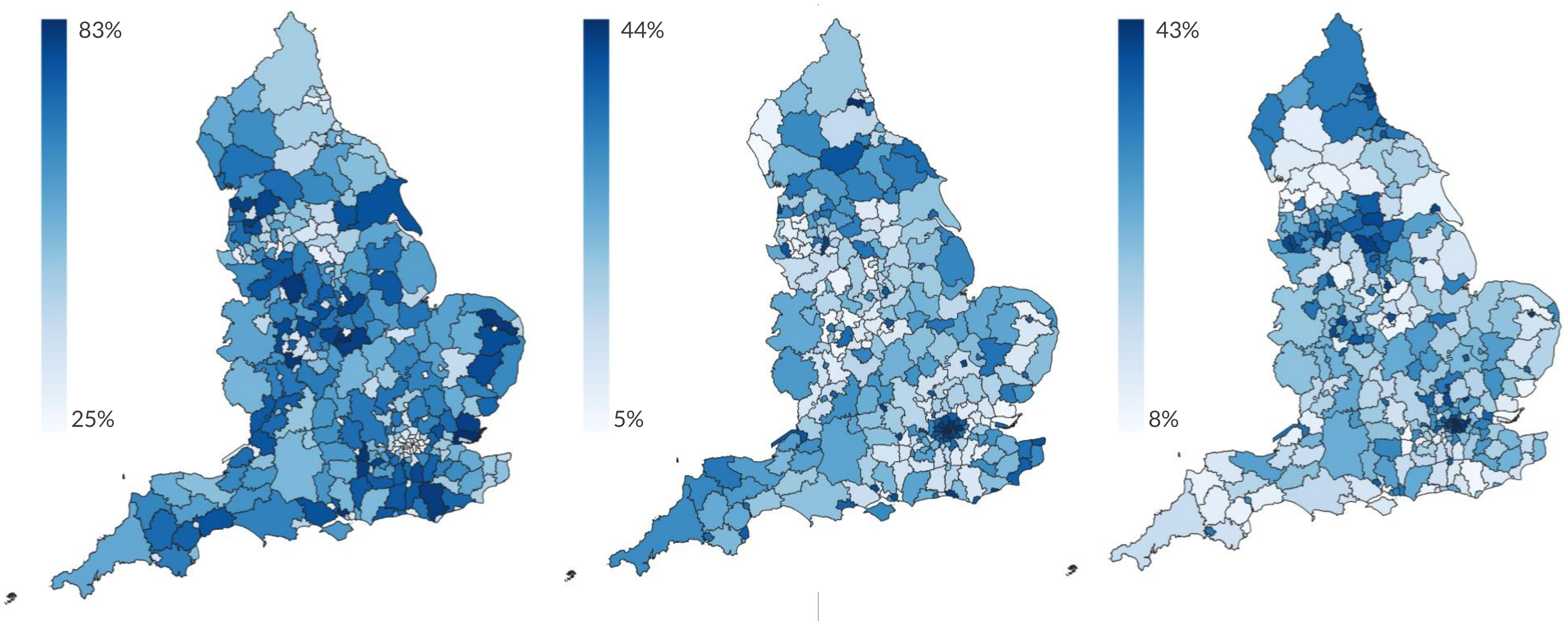
Tenure: Private ownership is common across the country, while privately rented is more prolific in the London

Share of Residential buildings by Local Authority and by tenure type[1]
%

Owner-occupied

Privately rented

Socially rented



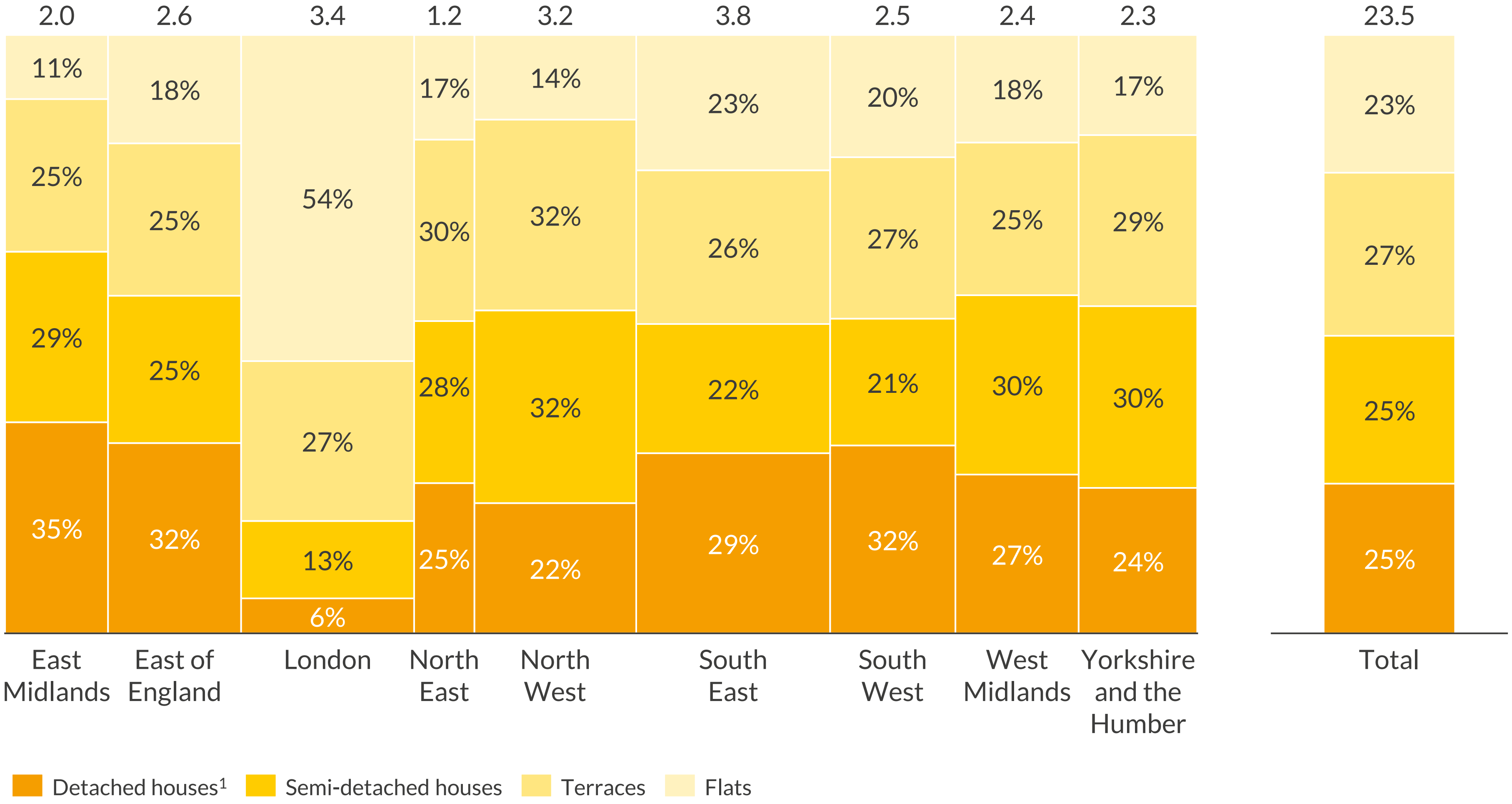
- The proportion of **Socially rented** buildings is the highest in the North West, Yorkshire & the Humber, the North east and London
- **Owner-occupied** building locations are negatively correlated with areas where socially rented houses have the highest shares
- The highest proportion of **privately rented** buildings are located in London, followed by the North East, while the South East has the lowest share of privately rented buildings

1) Note local authority level data is sourced from the ONS 2011 Census, whilst regional data shown in preceding slide is from the English National Housing Survey 2021, which is more recent but does not contain local authority data. Mismatches can be explained by the data age and methodology used.
Sources: Aurora Energy Research, ONS 2011

Building Type: Residential buildings can be broken into four building types, with similar profiles across most regions

Residential building stock by building type, region
Total shown at top (millions of buildings), area denotes relative share of total

Share of total by tenure
%



1) Includes detached houses and bungalows

Sources: Aurora Energy Research, English Housing Survey 2021

Some building types may not be suitable for all low carbon heating systems. This dimension can also be used as a proxy for the availability of outside space, which may be needed for some types of heating systems, and the number of occupants, which drives hot water requirements.

- **Detached & Semi-detached houses** are less likely to have constraints on inside and outside space. These houses are also more likely to have higher occupancies, increasing hot water requirements.
- **Flats and terraces** are most likely to be space constrained (inside and outside), but are assumed to have fewer occupants and so reduced hot water requirements.

Building types generally have to be considered alongside other dimensions in order to understand whether they will be easy or hard to decarbonise.

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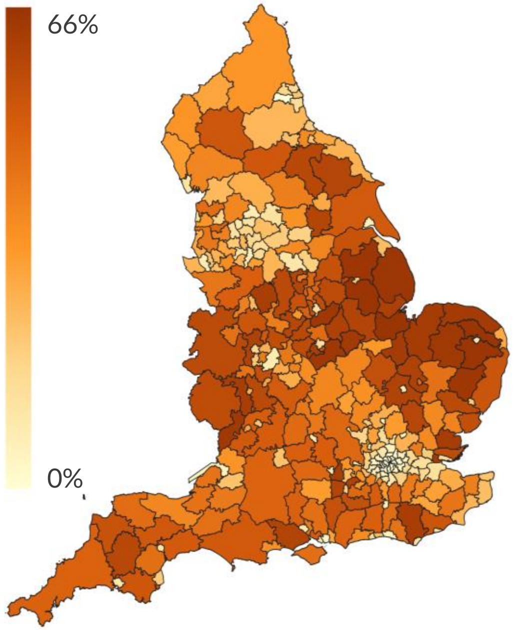
Building Type: Flats are predominantly located in major cities, while detached houses are typically found in more rural areas

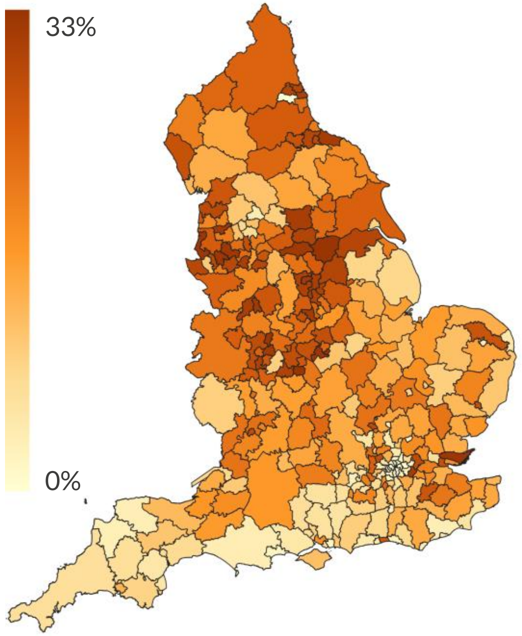
Share of Residential buildings by Local Authority and by building type[1]

%

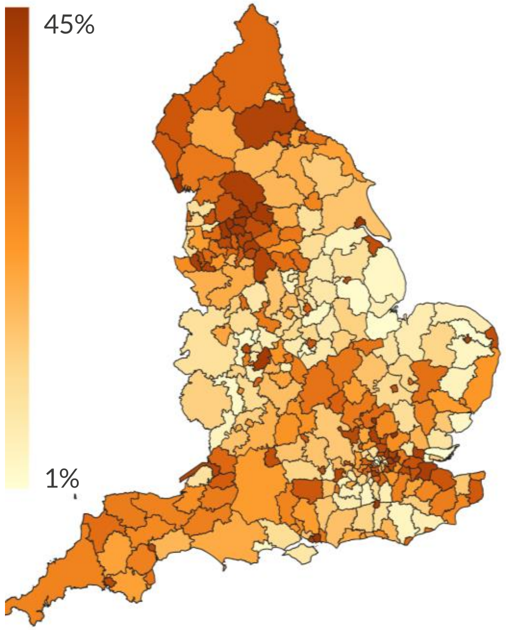
Detached house



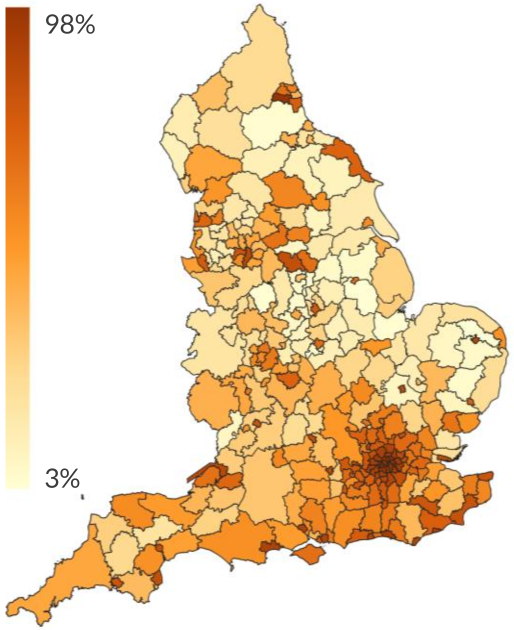
Semi-detached house



Terraced



Flat



- Detached houses make up a greater proportion of the building stock in the East Midlands (35%) and East of England (32%)
- Semi detached houses are relatively well distributed throughout England, the regional percentage varies between 13% (London) and 32% (North West)
- Terraced houses are proportionally more prevalent in the North with high terraced house shares in the North East (30%) and the North West (32%) regions
- Flats are unevenly distributed in England, 54% of London's Residential properties are flats, compared to an average of 17% for the other regions

1) Note local authority level data is sourced from the ONS 2011 Census, whilst regional data shown in preceding slide is from the English National Housing Survey 2021, which is more recent but does not contain local authority data. Mismatches can be explained by the data age and methodology used.

Sources: Aurora Energy Research, ONS 2011

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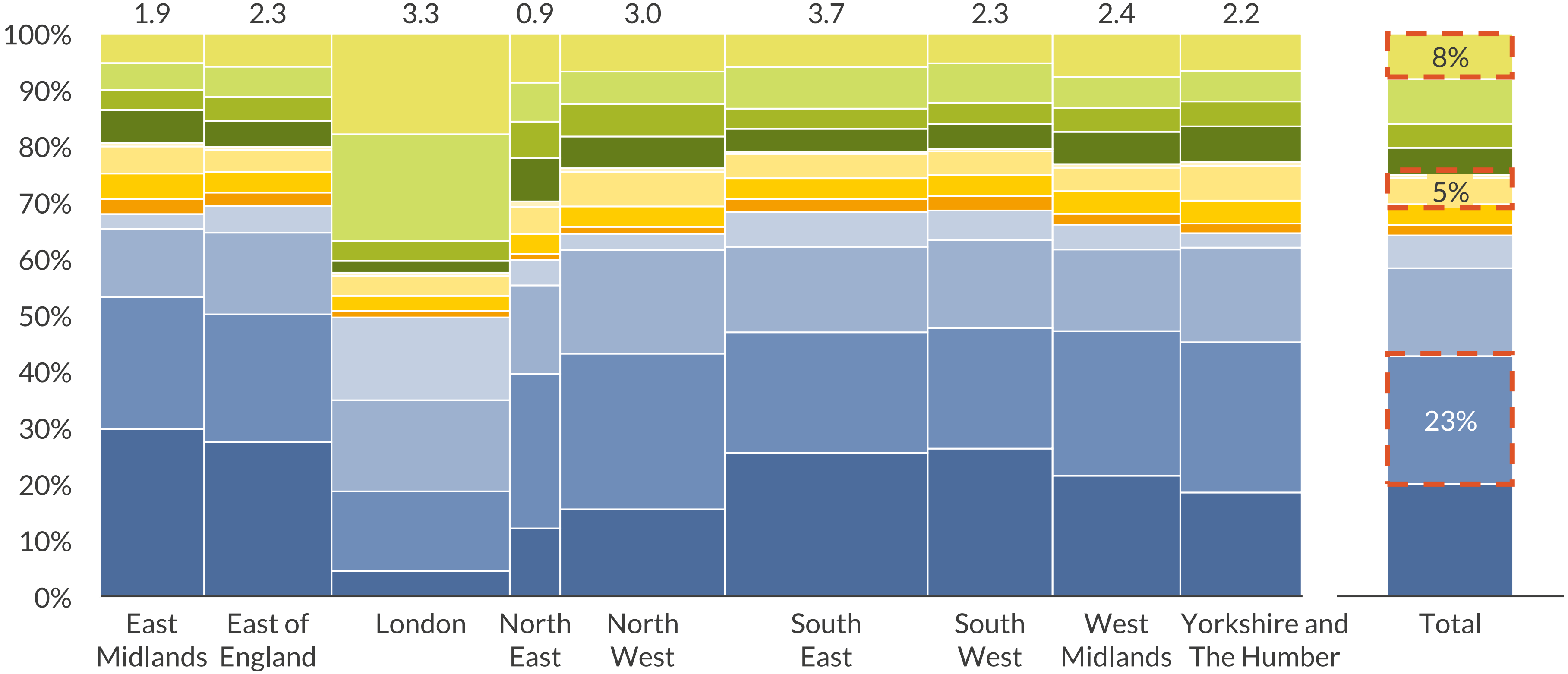
Building Type: Combining tenure and building segments identifies the most common building categories

Residential building stock by building type, tenure & region

Total shown at top (millions of buildings), area denotes relative share of total

Share of total by tenure

%



Note this chart uses 2011 data, reflecting the most recently available datasets which includes both building type and tenure data for all English properties. There may be inconsistencies with data in other slides.

1) Flats include maisonettes, apartments in a purpose-built block of flats, apartments that are part of a converted or shared house, apartments in a Commercial building, or mobile/temporary accommodation

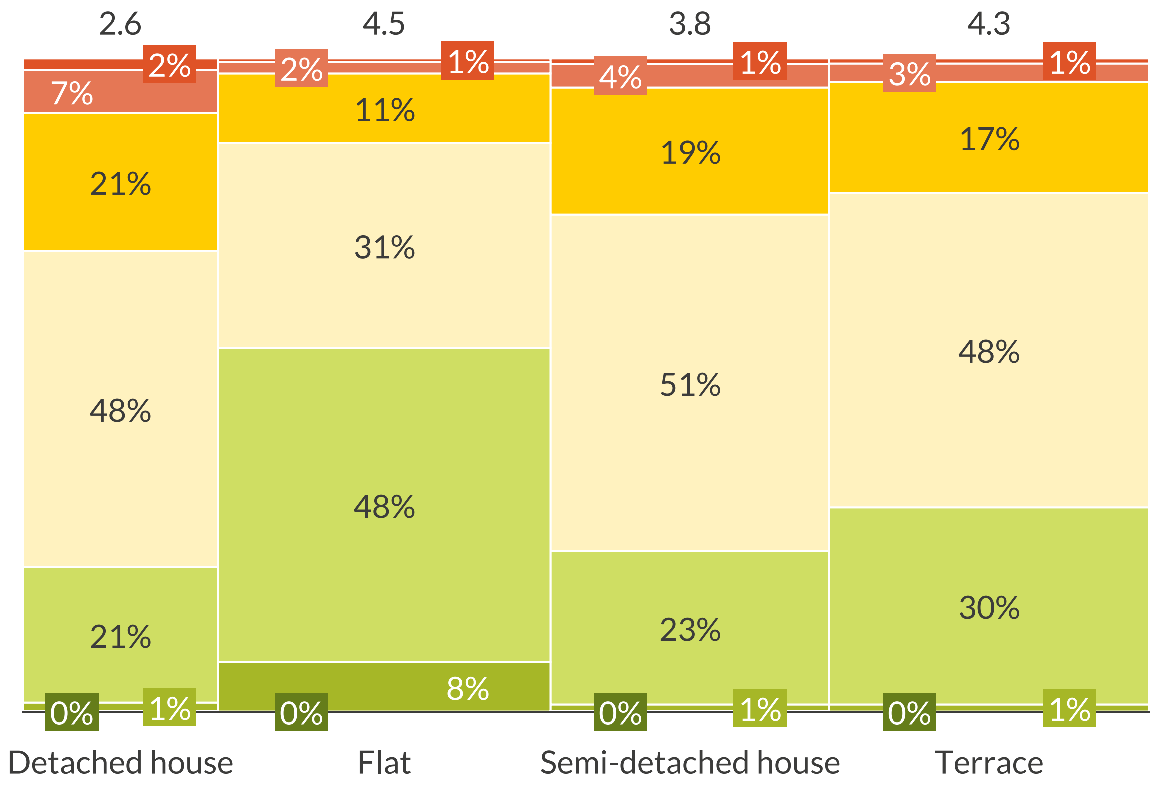
Sources: Aurora Energy Research, ONS Census 2011

- By comparing tenure and building type we see the dominate English building types. These, highlighted in red, are:
  - Owner-occupied: semi-detached house (23%)
  - Privately rented: terrace (5%)
  - Socially rented: flat (8%)
- Data used here is from ONS Census 2011; the most recent data available for both dimensions for all properties. Compared to the newer English National Housing Survey 2021, used to compile regional building type and tenure data, the ONS data has a lower proportion of privately rented buildings. Conflicts between datasets result from different methodologies and from differences in housing stock from 2011-2021.
- **The mismatch between datasets highlights the difficulty in understanding the overall make-up of the building stock.**

AURORA

Efficiency: The EPC rating of a building gives a snapshot of its overall energy efficiency

Residential building stock by building type, EPC rating
Total shown at top (millions of buildings)



The overall energy efficiency of a building can impact the types of low carbon heating technologies that are available, as well as the upfront and operating costs of any given heating system.

- An building with an EPC rating of C is typically considered energy efficient (see appendix)
- The majority of buildings (90-95%) are classified as EPC ratings C, D and E across all building types
- Between 3-9% of all building types have ultra-low ratings (F-G), however only <c1% of buildings across all categories have A and B efficiency ratings
- **Detached and semi-detached houses** are on average the least efficient building type and so would require the highest level of investments in energy efficiency upgrades to reduce overall energy demand, and to support the installation of some heating technologies
- **Flats** are generally the most efficient building types, likely reflecting reduced heating losses from proximity to other units.

Higher EPC ratings indicates a building might have more low carbon heating options, without having to undertake any additional energy efficiency improvements.

Note that data is based on available EPC data and may not fully represent the entire building stock

A B C D E F G

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

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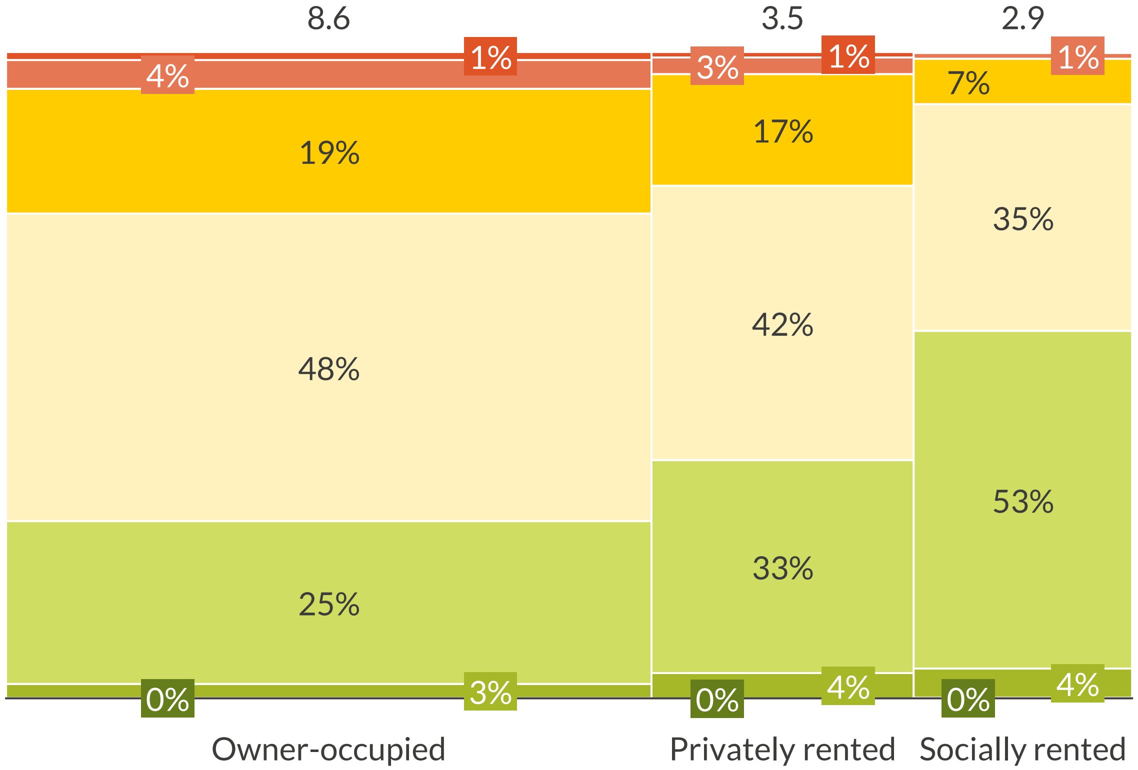
Efficiency: Over half of socially rented houses achieve EPC C or above, while just one quarter of owner-occupied houses achieve the same standard

Residential building stock by tenure, EPC rating

Total shown at top (millions of buildings)



Note that data is based on available EPC data and may not fully represent the entire building stock

A B C D E F G

Buildings of different tenures also have different average EPC ratings.

- **Socially rented** buildings have the highest EPC ratings, with more than 55% achieving EPC C or above, driven by the higher availability of government funding. In any given area they are often managed by a single entity, making it easier to perform bulk energy efficiency upgrade measures as fewer parties have to decide to undertake the work.
- Over one third of **privately rented** houses achieve EPC C or above.
- Only one quarter of **owner-occupied** houses achieve EPC C or higher, making this the tenure segment performing least well for energy performance.

As an EPC certificate is only required when buildings are sold or rented when the building does not already have an EPC certificate dated within the preceding 10 years, the data available here may not fully represent the entire building stock.

- Owner-occupied buildings are particularly under-represented, as according to the English National Building survey 2021, there are around 15.3 million owner occupied buildings in England, with only 9.1 million EPC certificates registered.
- According to the English National Building survey 2021, there are 4.2 million privately rented and 4.0 million socially rented buildings in England, for which there are 3.7 million and 3.1 million EPC certificates registered.

Thus, inefficient buildings may be under-represented as there is a lack of data for typically worse performing owner-occupied buildings. As home improvements often happen as buildings are bought and sold or rented, buildings without EPC certificates might also have worse efficiencies then those with certificates, however the lack of data prevents certainty here.

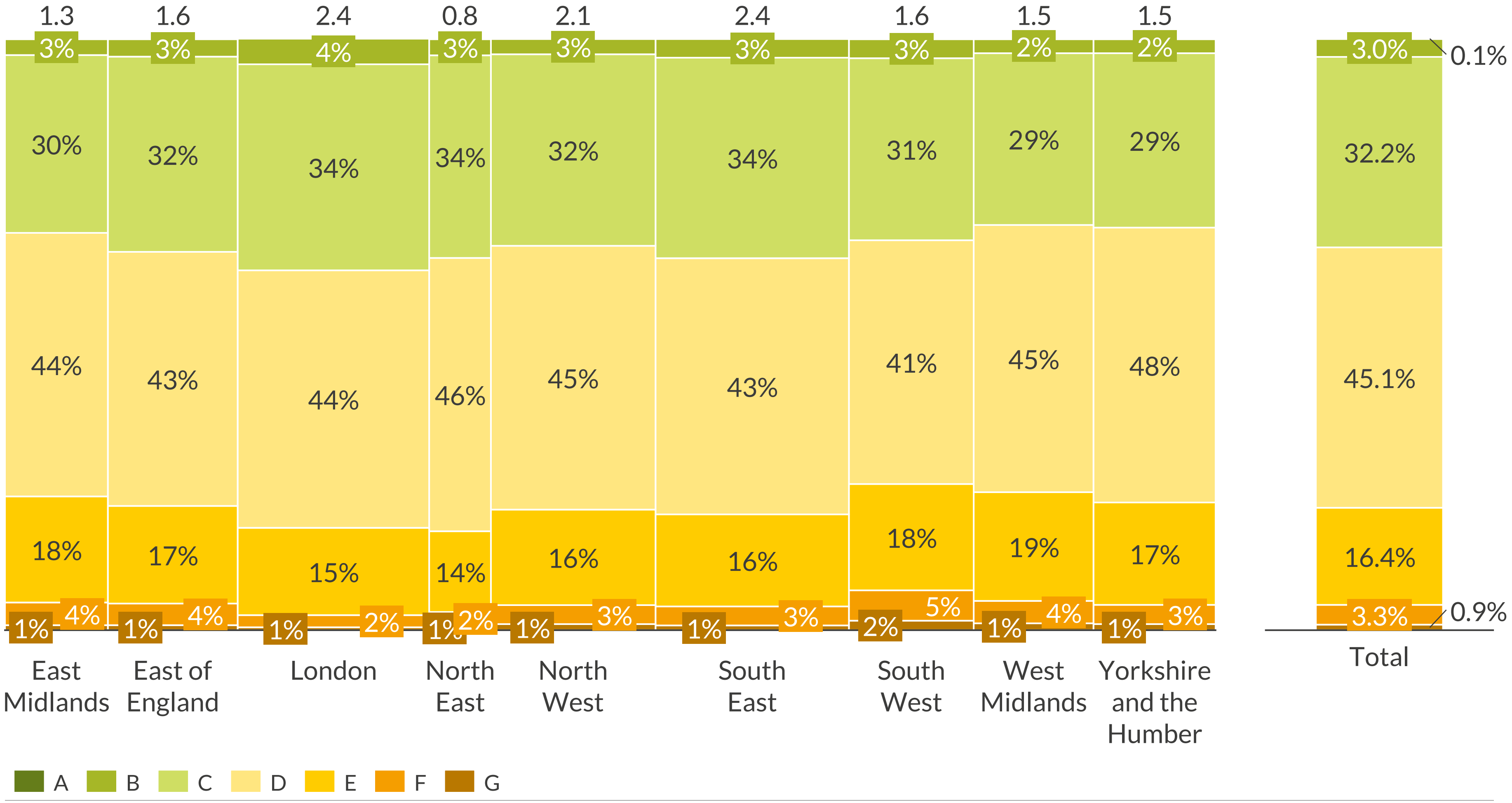
Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

AURORA

Efficiency: West Midlands has the largest share of Residential energy inefficient buildings with 69% of total properties are below EPC C

Residential building stock split by energy efficiency rating

EPC levels A-G. Total shown at top (millions of buildings)



High Efficiency

- All regions have a negligible share of EPC A buildings. The regions with the highest share of EPC A to C buildings are London(39.15%), South East (37.12%) and North East (37.08%).

Low Efficiency

- The regions with highest share of EPC D to G buildings are West Midlands (68.53%), Yorkshire and the Humber (68.06%), and East Midlands (67.17%).

Note that data is based on available EPC data and may not fully represent the entire building stock

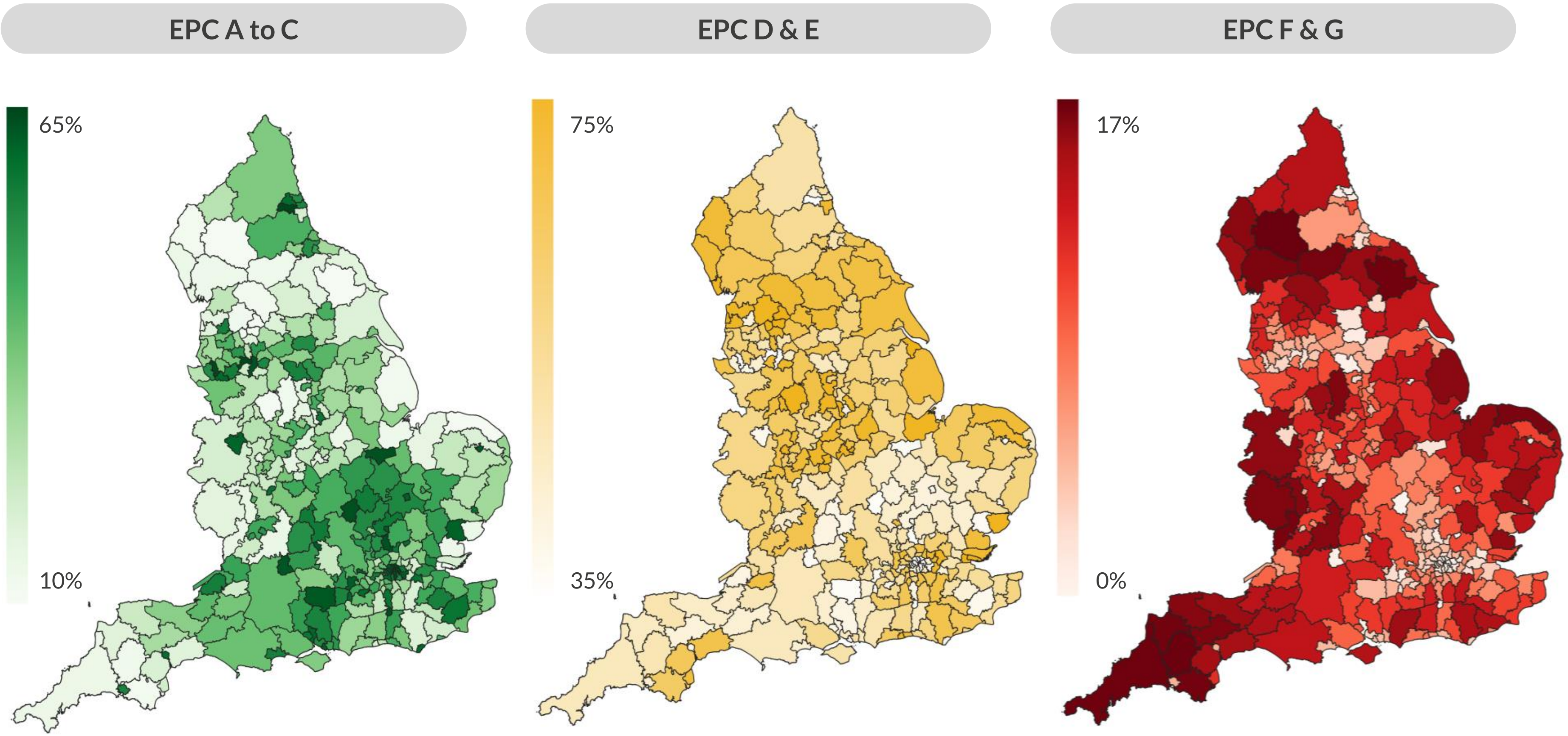
Source: Aurora Energy Research , Department for Levelling Up, Housing & Communities 2022

AURORA

Efficiency: Homes with EPC A to C occur primarily in the south of the country, but are particularly prevalent in London

Share of Residential buildings by Local Authority

%



Note that data is based on available EPC data and may not fully represent the entire building stock

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

High Efficiency

- The regions with the highest share of energy efficient buildings have a high share of socially rented houses and they are also predominantly urban.
- Tower Hamlets (65%) and City of London (55%) are the local authorities with the highest number of housing rated between EPC A and C.

Low Efficiency

- Birmingham (75%), Leeds (72%) and Manchester (52%) have the highest share of EPC D and E buildings.
- The local authorities with the highest share of EPC F and G are Eden (17%) in the North West, West Devon (16%) and Cornwall (15%) in the South West.

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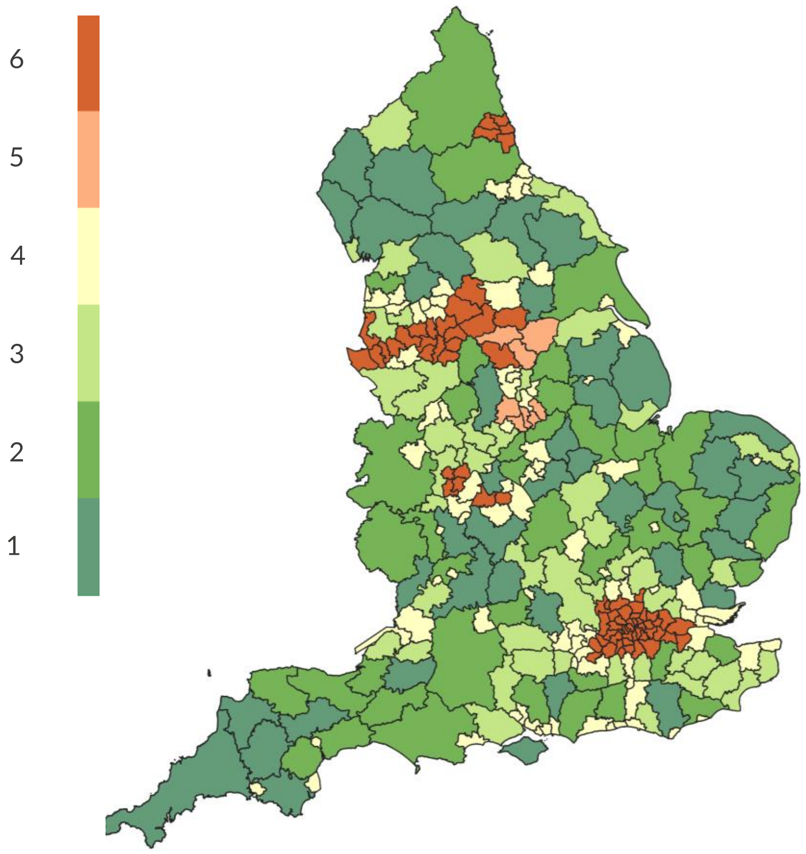
Urban Rating: The Urban Rating can be used as a proxy for heat density of the area a building is situated in

Rural vs Urban Local authorities

1-6 rating (1 = highly rural, 6 = highly urban)



The Urban Rating Classification categorises districts and unitary authorities on a six point scale, based on the share of the resident population that resides in rural areas. The six categories are:

- Mainly Rural (80% or more of the population resides in rural areas),
- Largely Rural (Between 50% and 79% of the population resides in rural areas),
- Urban with Significant Rural (Between 26% and 49% of the population resides in rural areas),
- Urban City and Town,
- Urban with Minor Conurbation,
- Urban with Major Conurbation.

- The Urban rating can be used as a proxy for heat density. Areas with high heat densities may be more suitable for networked heating. This may be an option in Greater London, The Northwest, the West Midlands & around Tyne and Wear.
- **Other factors must also be taken into consideration before it can be determined whether rural or urban areas are easier to decarbonise.**

Sources: Aurora Energy Research, ONS 2011

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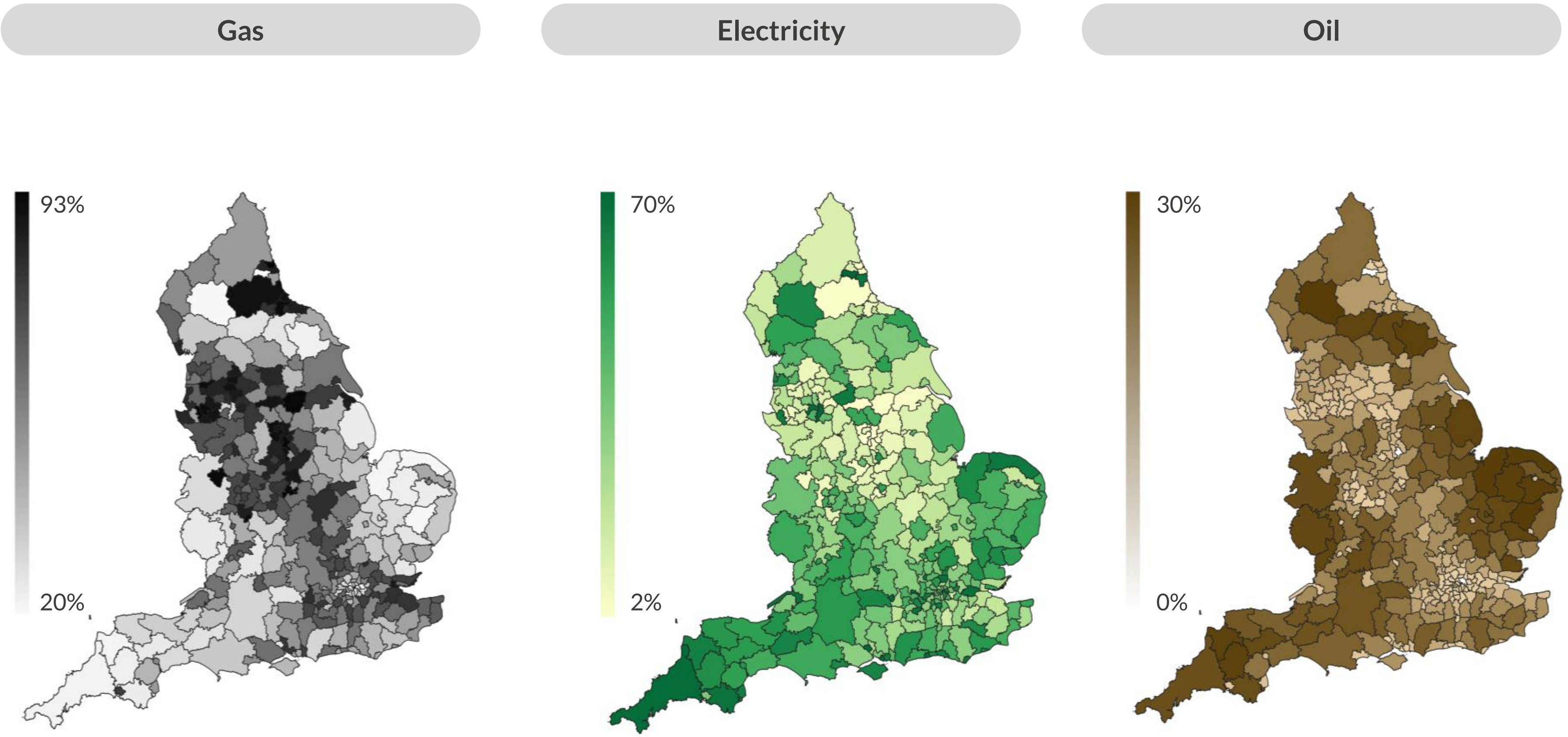
Gas networks: The spatial distribution of heat technologies reflects the extent of gas and power networks and the local building stock

Share of Local Authority Residential buildings with certain heat technologies[1]
%



- Gas, oil and electricity together meet the majority of the UK's heat demand and boiler systems using these fuels are the conventional heating systems employed across the country today
- The distribution of gas-fired heating systems shows the extent of the gas network, and is concentrated around England's most populated region
- Oil- and electric-fired heating systems meet most of demand that is not met by gas, and these techs are often found in more rural areas
- Electric heat systems are also common in highly urban areas where gas is not in use but there is easy access to the power network

Sources: Aurora Energy Research, ONS Energy Efficiency 2021

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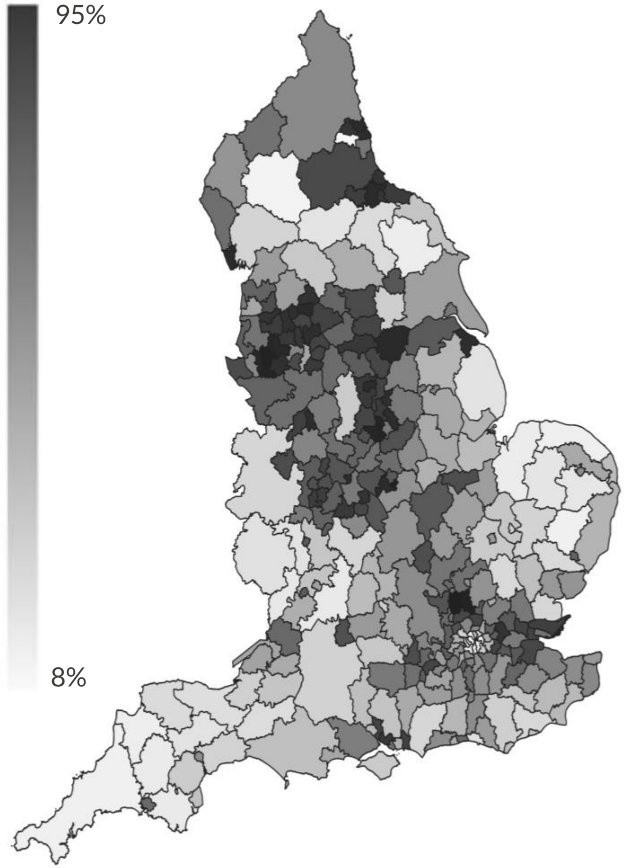
Gas Networks: A higher proportion of low efficiency buildings are not connected to the gas grid, although their overall number is less

Share of buildings connected to the gas grid in each Local Authority
%



Gas connected properties by EPC rating
% (total shown on top in millions of buildings)

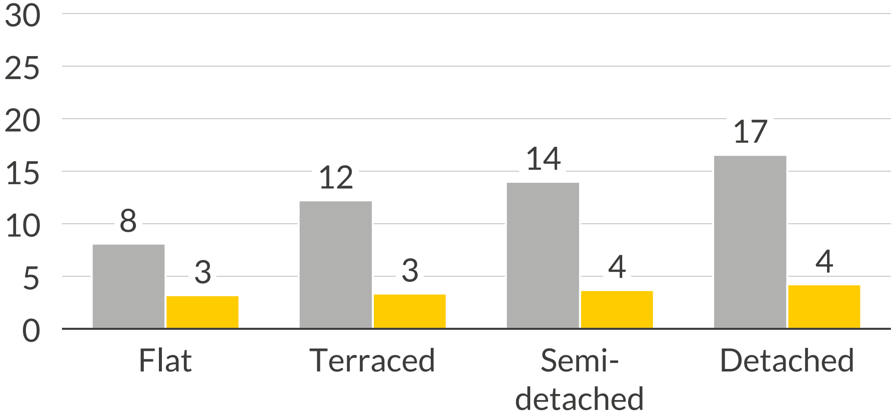
Note that data is based on available EPC data and may not fully represent the entire building stock

- Natural gas is the dominant heating fuel in the UK; c.83% of Residential buildings in England are connected to the gas grid.
- Buildings without a gas supply may use electricity or other high carbon fuels. These properties are often located in rural areas where the gas grid is uneconomic, or in urban areas, where flats may not be connected due to issues with gas pressure and routing pipes via multiple households.
- The proportion of buildings in the EPC dataset that are gas grid connected is proportional to the total number of gas grid connected buildings in England.
- More than half of the lowest efficiency buildings (EPC F-G) are not connected to the gas grid. However, very inefficient buildings are more likely to be owner-occupied buildings that are underrepresented in the EPC dataset on account of their lower turnover (see page 25).

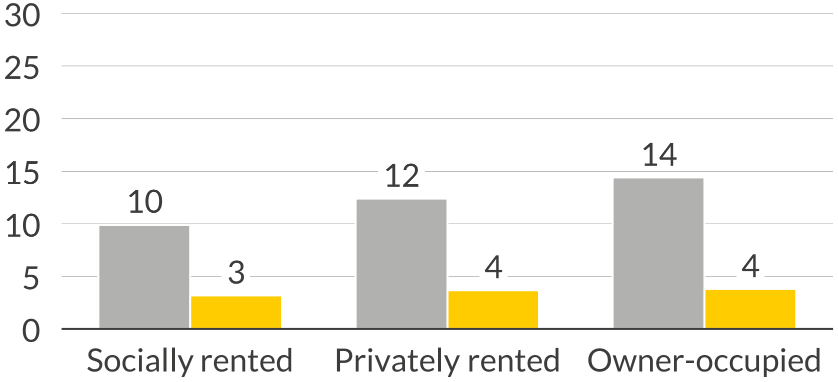
Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022, ONS Energy Efficiency 2021, NGESO FES 2022, ECUK Energy Data Tables 2020

Gas Networks: A building's gas demand is typically 3-4x larger than its electricity demand

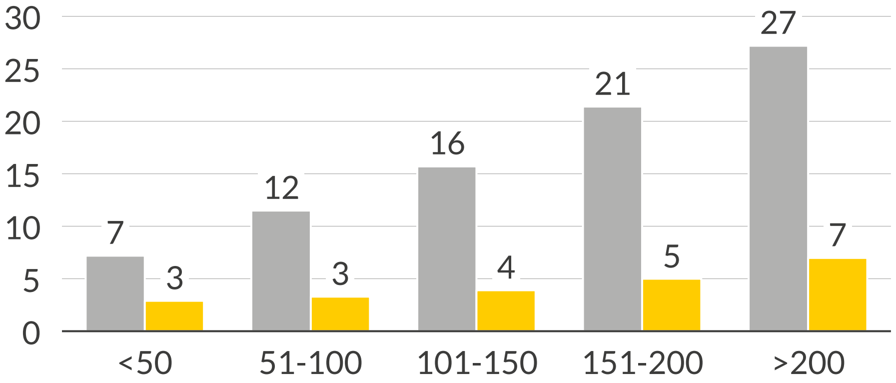
Mean gas and electricity consumption by building type[1]
MWh



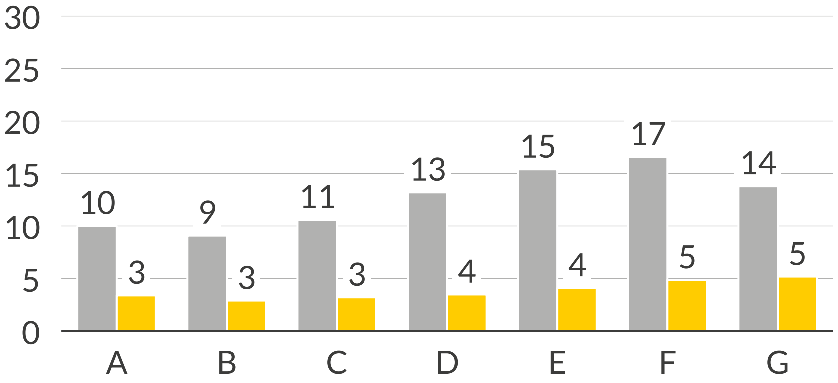
Mean gas and electricity consumption by tenure[1]
MWh



Mean gas and electricity consumption by floor area (m^2)[1]
MWh



Mean gas and electricity consumption by EPC rating[1]
MWh



Mean gas consumption   Mean electricity consumption

Note that data presented is taken from the NEED 2019 report, where the pool of buildings used for analysis is all domestic properties in England and Wales. 1) Data displays gas and electricity demand for the entire property, not only for heating

Sources: Aurora Energy Research, NEED 2019

Owner-occupied detached houses with large floor areas have the highest gas and electricity consumption. This is also likely linked to the wealth and number of occupants of a building. As electricity is more expensive than gas, these buildings would face the largest increase in ongoing fuel gas if fully electrified.

- **Building type:** A detached house consumes 104% more gas than a flat, likely linked to **Floor Area**. Heat demand scales with floor area, resulting in large changes in demand.
- **Tenure:** fuel use is less sensitive to tenure, the increase for an owner-occupied building likely reflects higher usage for houses.
- **EPC rating:** fuel usage generally increases for less efficient buildings. Higher and lower use for Bands A and G may reflect household ability to pay for fuel. However, smaller sample sizes for these properties may also be impacting this trend.

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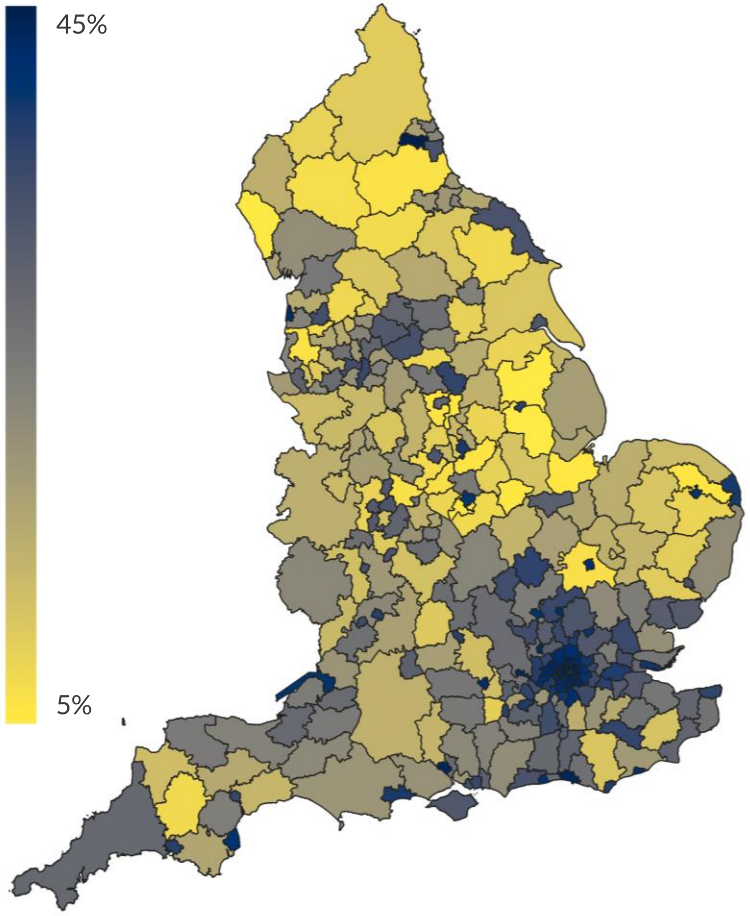
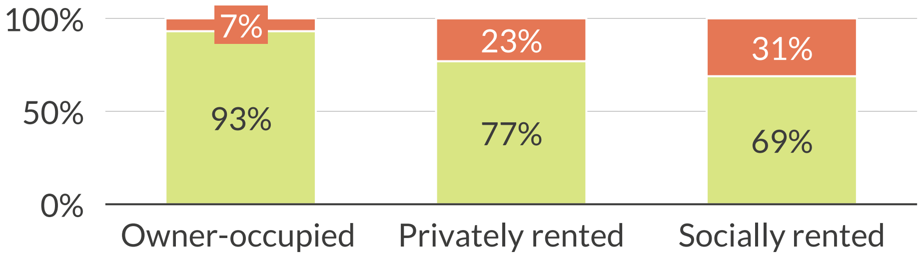
Space Constraint: Buildings with space constraints are unsuitable for some types of low carbon heating systems

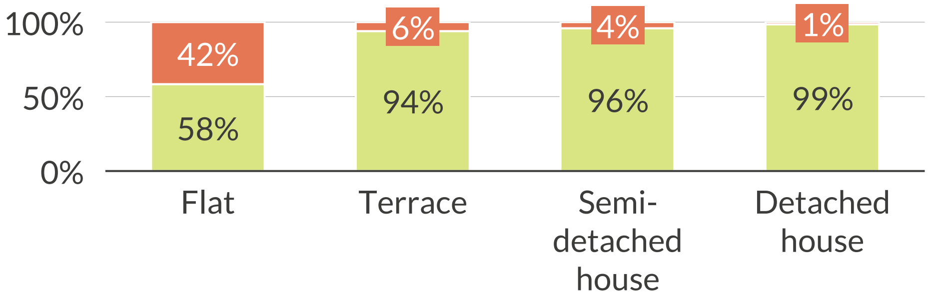
Share of space constrained buildings (<50m² total floor area) by local authority, %



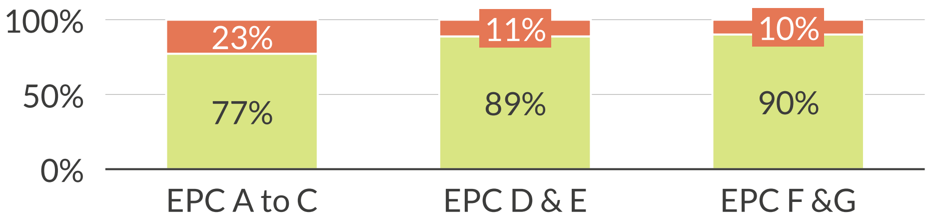
Space constrained properties by tenure
%



Space constrained properties by building type
%



Space constrained properties by EPC rating[1]
%



Space constrained Not space constrained

Space constrained buildings refer to buildings of <50 sq m. This does not refer to available outside space, which is also an important metric for some types of heating systems.

- **Tenure:** socially rented homes have the highest share of space constrained buildings, while owner-occupied buildings are almost all not space constrained.
- **Building type:** Space constraints are not limited to a single type of building, however they are much more prevalent in flats and terraces than in detached and semi-detached houses.
- **EPC rating:** buildings with EPC rating A-C have a higher proportion that are space constrained than lower efficiency buildings.

Note that data is based on available EPC data and may not fully represent the entire building stock

1) Only data available for Residential building with an EPC rating

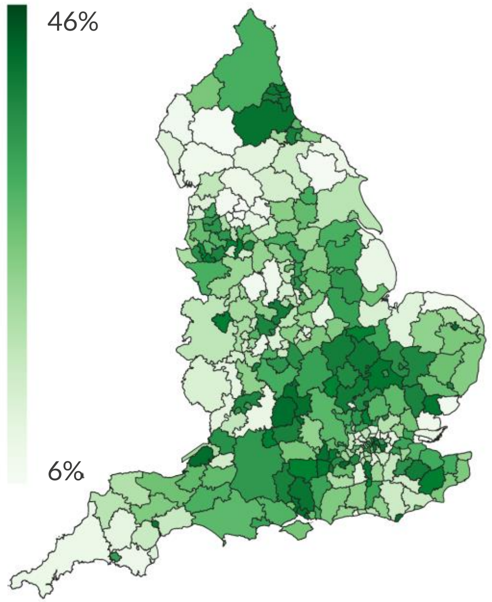
Sources: Aurora Energy Research, English Housing Survey 2020-2021, Department for Levelling Up, Housing & Communities 2022

AURORA

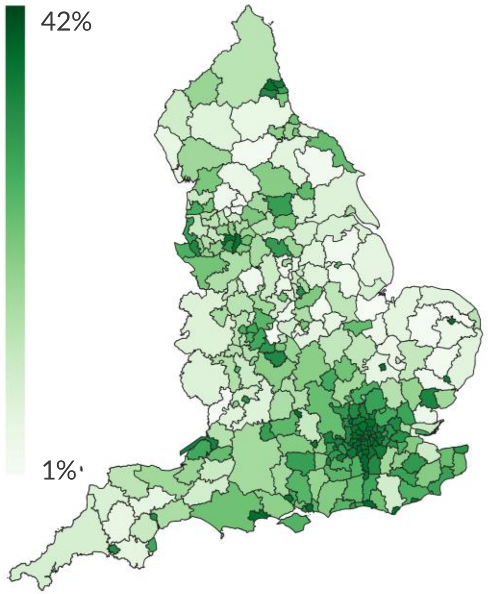
Energy Efficient | Off Gas Grid | Non-Space Constrained: These easier-to decarbonise archetypes are most prevalent in the Southeast and East Anglia

Share of Residential buildings by Local Authority
%

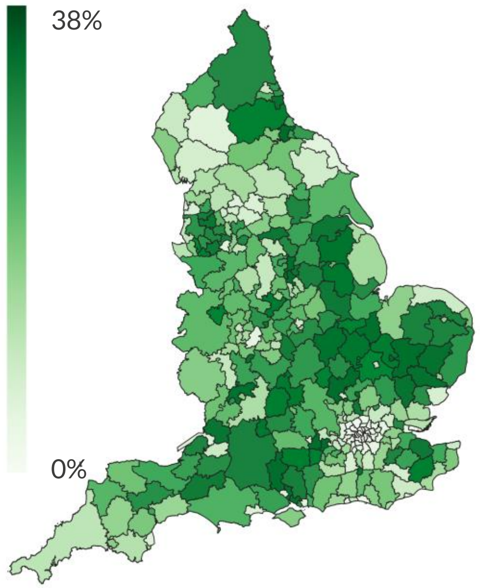
Total
2.8% of residential buildings



Flats
2.2% of residential buildings



All other types[1]
0.6% of residential buildings



Note that data is based on available EPC data and may not fully represent the entire building stock

- Energy efficient, non-space constrained, off gas grid buildings are expected to be easy-to-decarbonise as they have a range of electrified heating technologies to choose from
- These building archetypes are most prevalent in the South East and East Anglia, as well as London for flats, and the East Midlands for other building types

10 Includes terraces, semi-detached houses and detached houses

Source: Aurora Energy Research

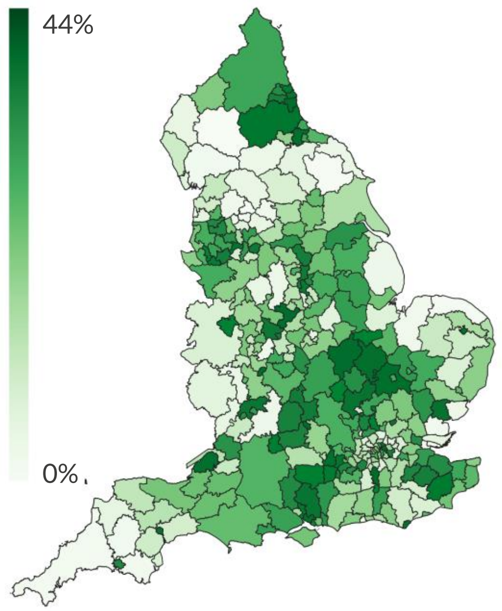
R Residential: easy-to-decarbonise

Energy Efficient | On Gas Grid | Non-Space Constrained: These easier-to decarbonise archetypes are most prevalent in the Southeast and East Anglia

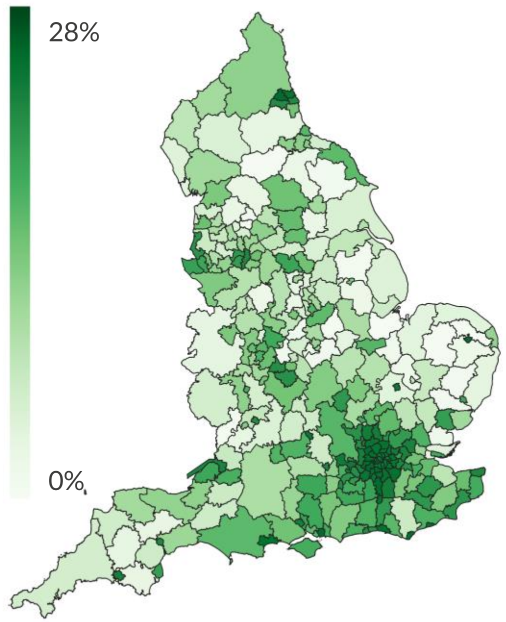
AURORA

Share of Residential buildings by Local Authority
%

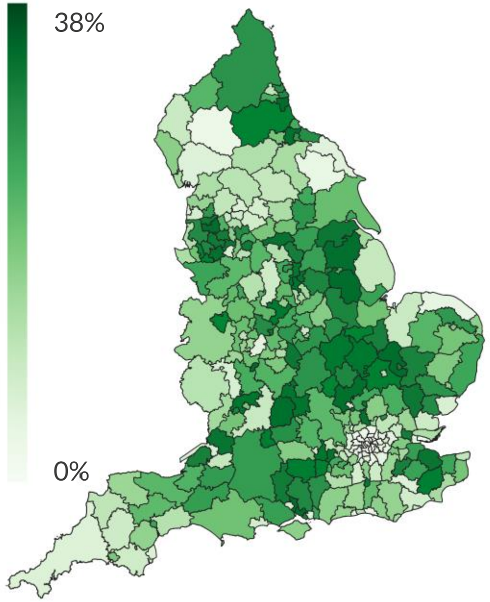
Total
24.4% of residential buildings



Flats
7.0% of residential buildings



All other types[1]
17.4% of residential buildings



Note that data is based on available EPC data and may not fully represent the entire building stock

- Energy efficient, non-space constrained, on gas grid buildings are expected to be easy-to-decarbonise as they have a range of electrified heating technologies to choose from. These buildings could also install a hydrogen system, should the network be converted, increasing the options available.
- These building archetypes are most prevalent in the South East and East Anglia, as well as London for flats, and the East Midlands for other building types.

1) Includes terraces, semi-detached houses and detached houses

Source: Aurora Energy Research

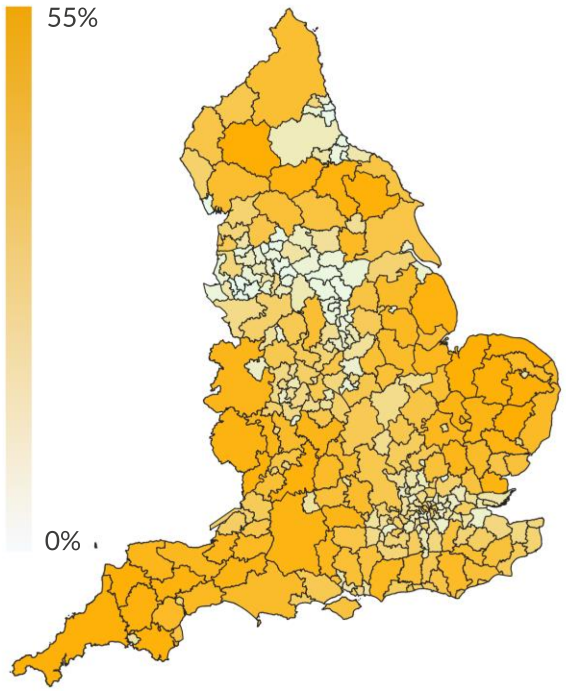
R Residential: harder-to-decarbonise

AURORA

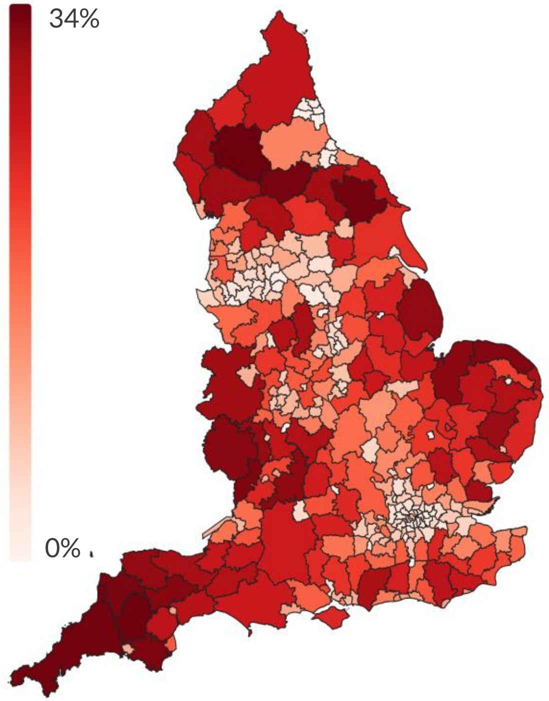
Energy Inefficient | Off Gas Grid: These harder to decarbonise archetypes are typically located in more rural Local Authorities

Share of Residential buildings by Local Authority
%

EPC D & E
9.3% of residential buildings



EPC F & G
2.4% of residential buildings



Note that data is based on available EPC data and may not fully represent the entire building stock

- Inefficient, off gas grid properties have few decarbonisation options, unless efficiency upgrades are first undertaken. These buildings are typically located away from Urban areas, with the most inefficient off-gas grid buildings typically located in highly rural areas such as in Cornwall.

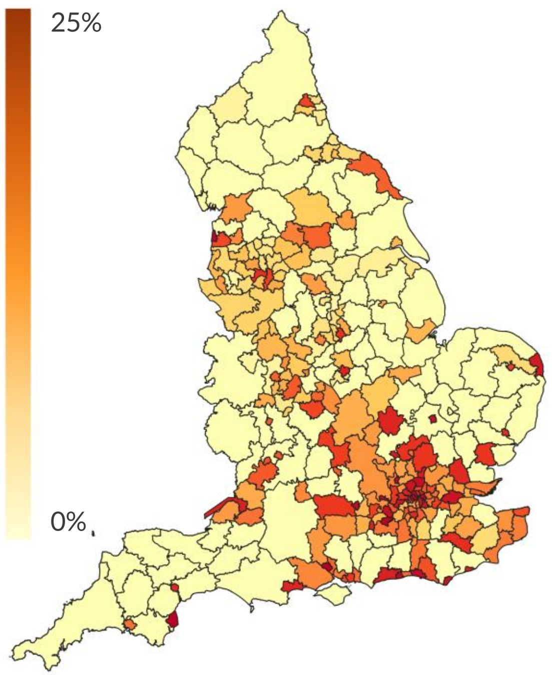
Source: Aurora Energy Research

R Residential: harder-to-decarbonise

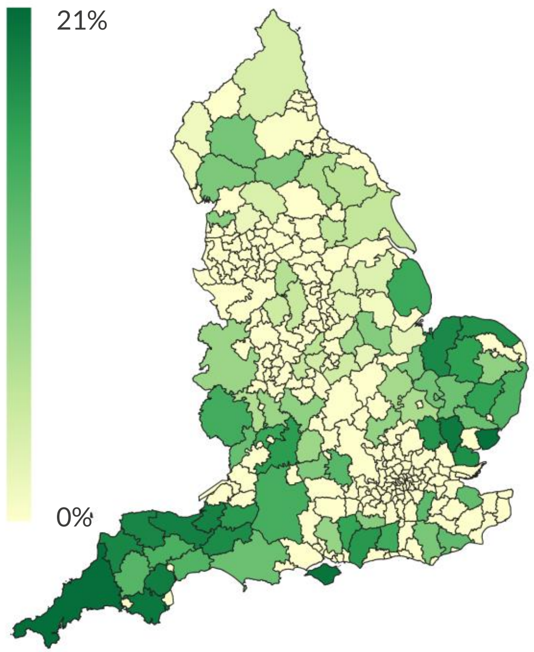
Space Constrained | Off Gas Grid: These harder to decarbonise archetypes are typically located around London or in extremely rural Local Authorities

Share of Residential buildings by Local Authority
%

Urban
4.2% of residential buildings



Rural
1.0% of residential buildings



Note that data is based on available EPC data and may not fully represent the entire building stock

- Space constrained, off gas grid properties also have few decarbonisation options, other than direct electric heating. In Urban areas, these buildings may be able to install heat networks, which may be an option particularly for buildings in and around London.
- The highest prevalence of space constrained off gas grid properties in rural areas is seen in Cornwall and Devon, as well as in East Anglia.

Source: Aurora Energy Research

Agenda

Tenure & Space Constraint: There is no clear trend of energy consumption by tenure or floor space across the Commercial building stock

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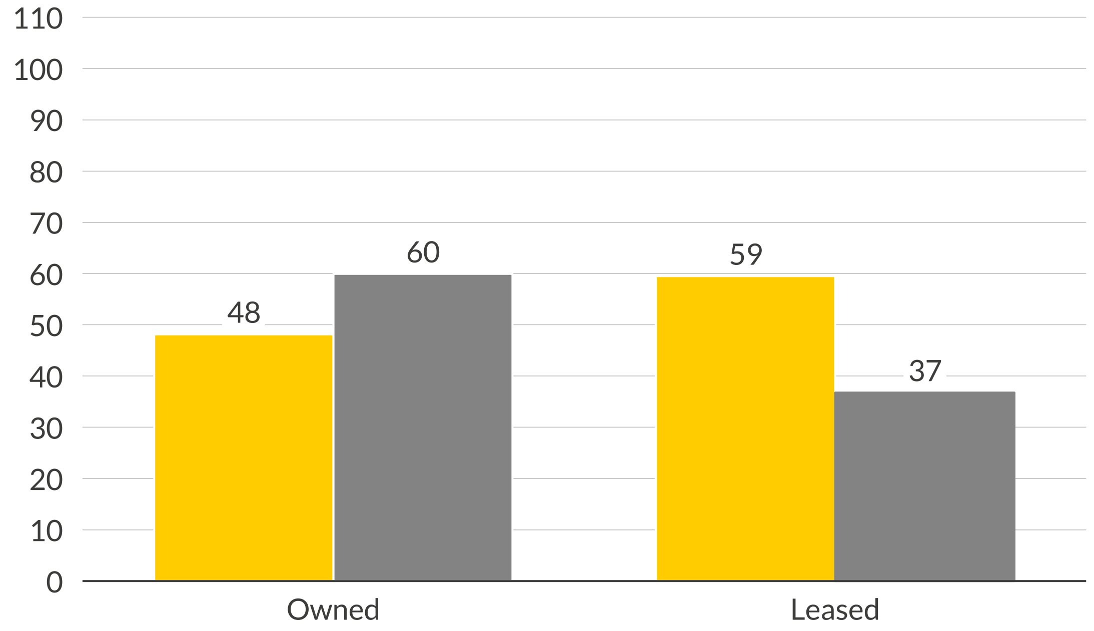
Tenure

Energy consumption by tenure type, normalised average[1]
MWh/m^2

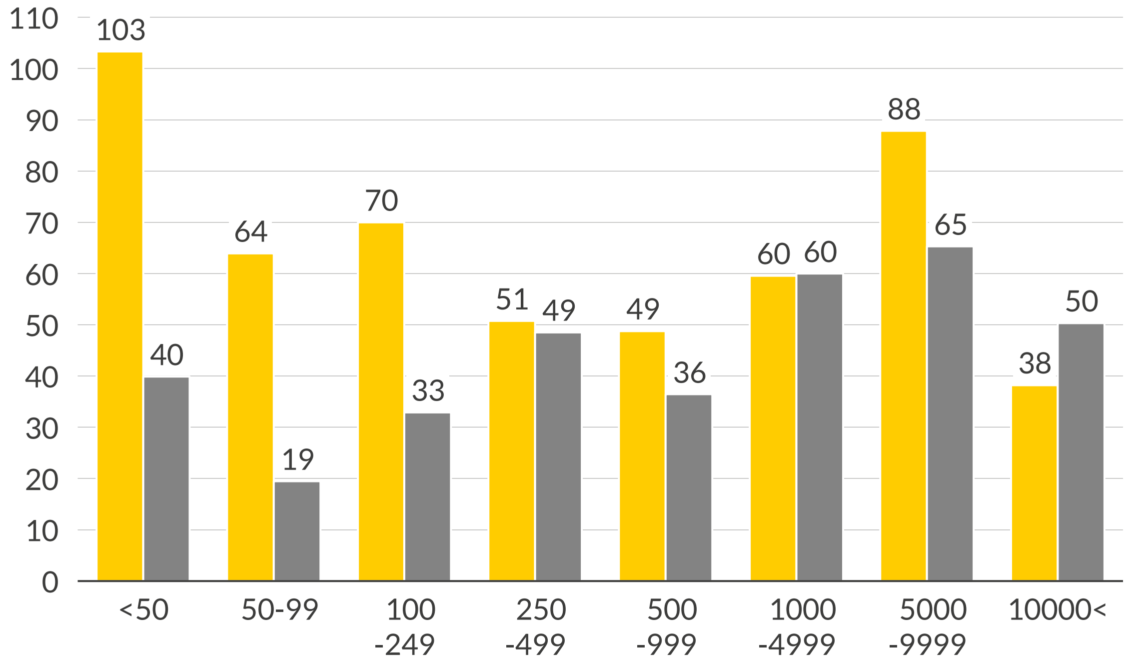


- It is unknown whether a substantial of the buildings in the dataset are owned or leased
- Non-electrical forms 55% of the total energy consumption in owned buildings, and 38% in leased buildings

Electrical Non-electrical

Floor space

Energy consumption by floor area (m^2), normalised average[1]
MWh/m^2 (normalised by the total floor area within each category)



- Buildings between 50 and 4999m^2 have similar consumption levels, with an average of 97MWh/m^2
- No clear trends in non-electrical consumption across building sizes can be determined

1) Total energy consumption, not only for heating purpose

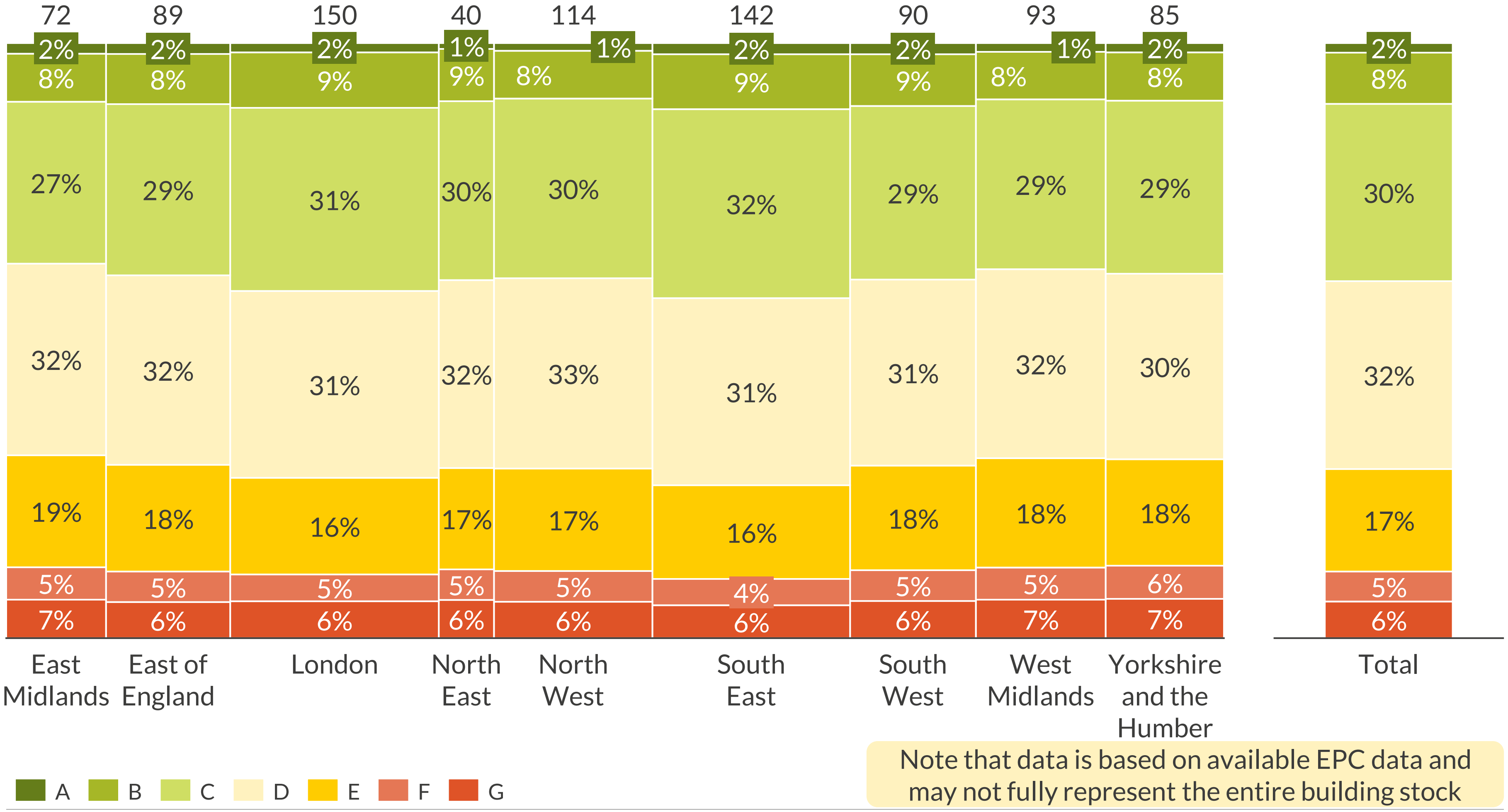
Sources: Aurora Energy Research , BEIS 2014-2015

AURORA

Efficiency: All regions have a similarly high proportion of buildings with EPC ratings below C, with 60% of total stock rated D-G

Commercial building stock split by energy efficiency rating

EPC levels A-G. Total shown at top (thousands of buildings)



Note that data is based on available EPC data and may not fully represent the entire building stock

Compared to Residential buildings, the Commercial sector has higher shares of extremely efficient properties (EPC A & B) and higher shares of extremely inefficient ones (EPC F & G).

High Efficiency

- The regions with the highest share of EPC from A to C are South East (43%), London (42%) and North East (40%). This could be explained by the fact that these regions have more new build Commercial buildings which have slightly higher EPC ratings.

Low Efficiency

- All regions have a high share of inefficient buildings. However London and South East have the lowest share of buildings rated D-G.

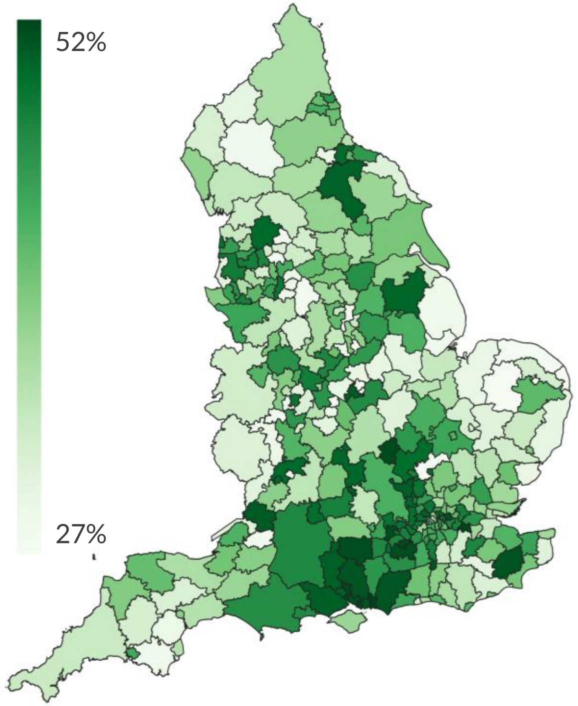
Source: Aurora Energy Research , Department for Levelling Up, Housing & Communities 2022

AURORA

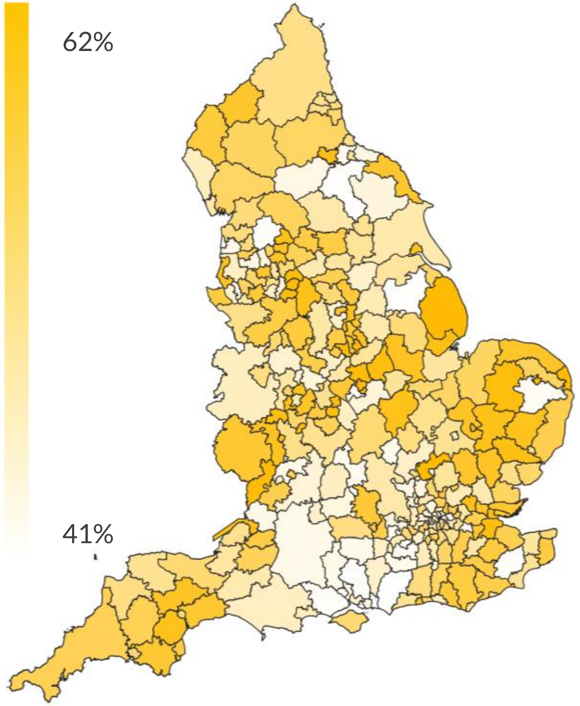
Efficiency: Low energy efficiency buildings, rated below C, occur across the country, but are particularly prevalent in the East Midlands

Share of Commercial buildings by Local Authority
%

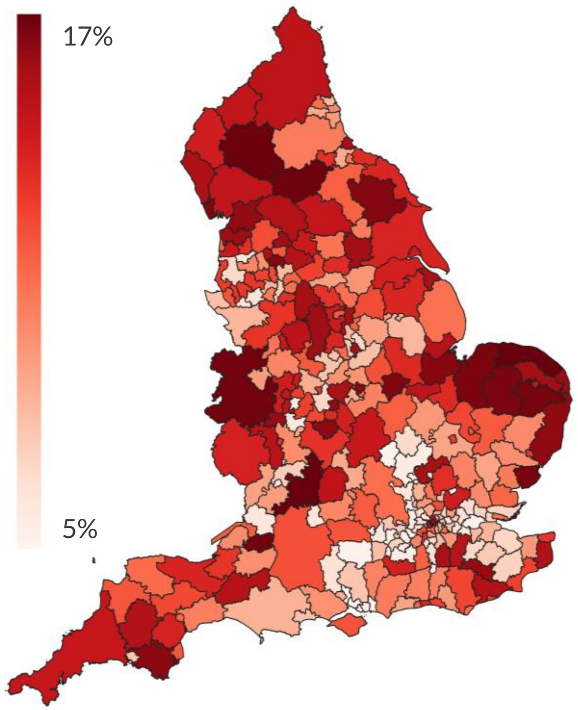
EPC A to C



EPC D & E



EPC F & G



Note that data is based on available EPC data and may not fully represent the entire building stock

High Efficiency

- Only 40% of Commercial buildings in England have an EPC rating between A to C
- Havant (52%) and Dartford (50%) are the Local authorities with the largest share of efficient buildings

Low Efficiency

- 49% of Commercial buildings have EPC ratings between D and E, and 11% are below F
- The region with the highest share of EPC rated buildings between D and G is the East midlands (63%) region
- Buildings in Oadby and Wigston, Leicester, and Wellingborough has the lowest EPC ratings of (74%-69%) between D and G

Source: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

C Commercial: area type, mains gas

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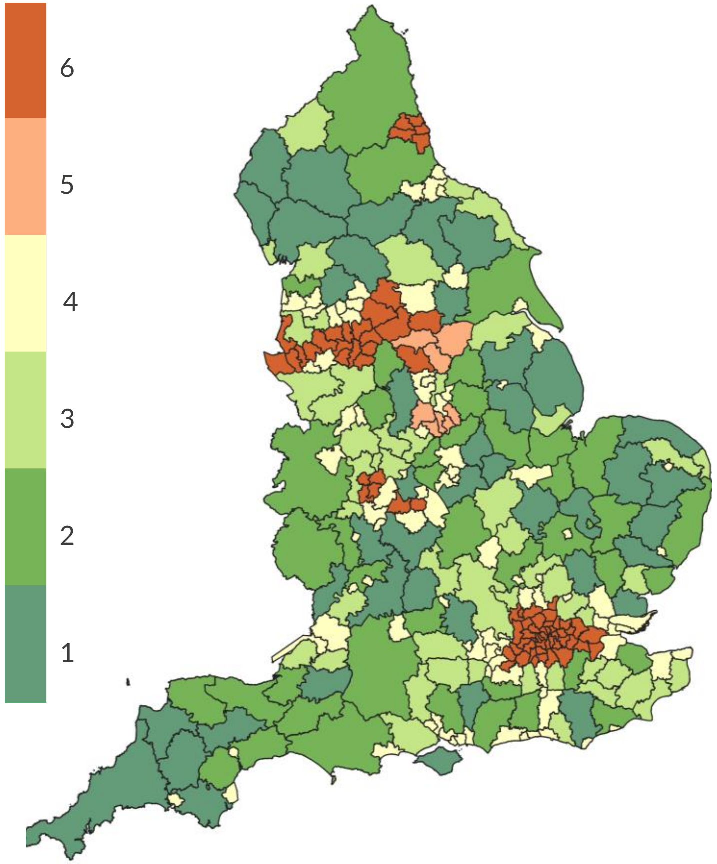
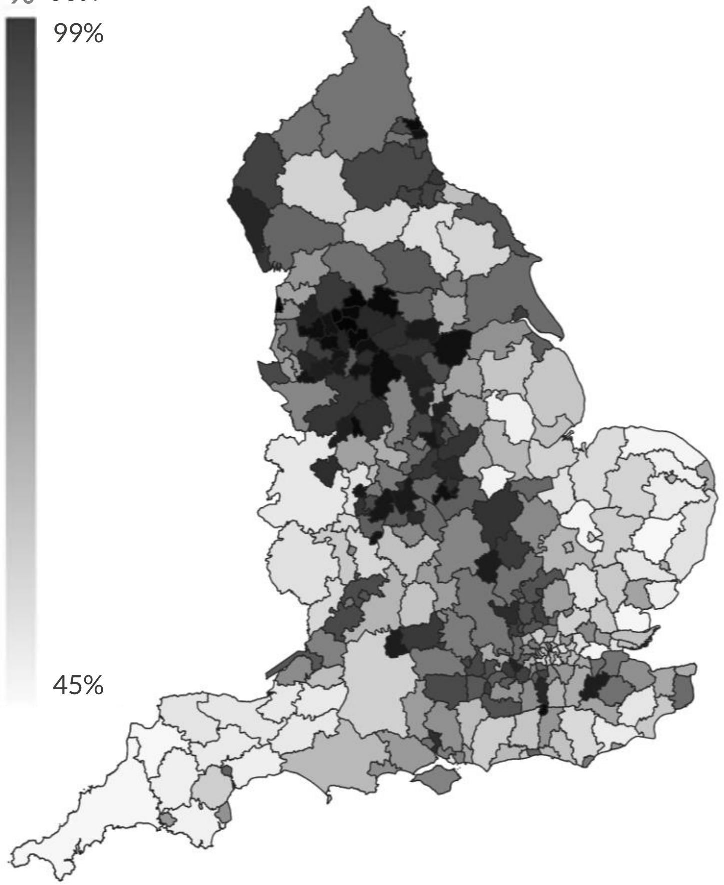
Gas Networks: Commercial off-gas grid properties tend to be located in highly rural areas such as the East of England and South West

Rural vs Urban Local authorities[1]
%



Share of buildings connected to the gas grid in each Local Authority
%



- Natural gas is the dominant heating fuel in the UK, however, more than 61% of Commercial buildings in England are not connected to the gas network
- The local authorities with the highest share of non-gas properties are Isles of Scilly (99%) and Torridge (81%)
- These properties are typically located in highly rural areas where it is not economically favourable to extend the network to serve a small number of households
- Off-gas properties which are not already electrified may have fewer low carbon heat technologies available to them

Note that data is based on available EPC data and may not fully represent the entire building stock

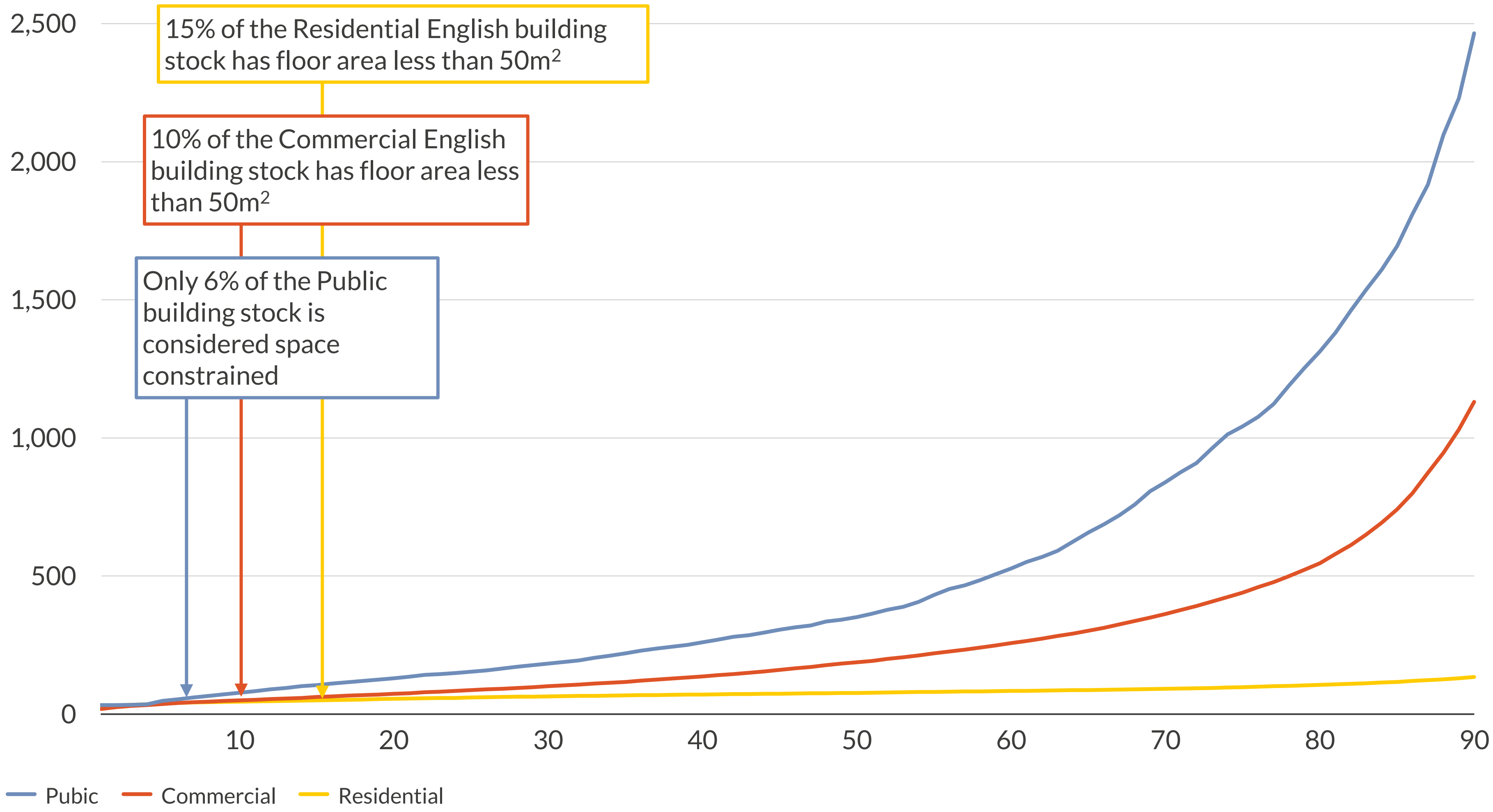
Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

AURORA

Space Constraint: The portion of English buildings below 50m² is 10% for Commercial properties and 6% for Public buildings

Cumulative distribution of total floor area across the Residential , Commercial and Public building stock[1]

000's m²



1) Based on data from one urban and one rural Local Authority (Birmingham and Cornwall, respectively)

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022, EPC data

- Buildings smaller than 50m² are classified as 'space constrained,' and these buildings are unlikely to install larger heating systems such as (non-communal) heat pumps and boiler systems.
- As Public and Commercial buildings are typically significantly larger than Residential housing. Respectively, only 6% and 10% of Public and Commercial properties are considered space constrained compared to 15% for the Residential sector.

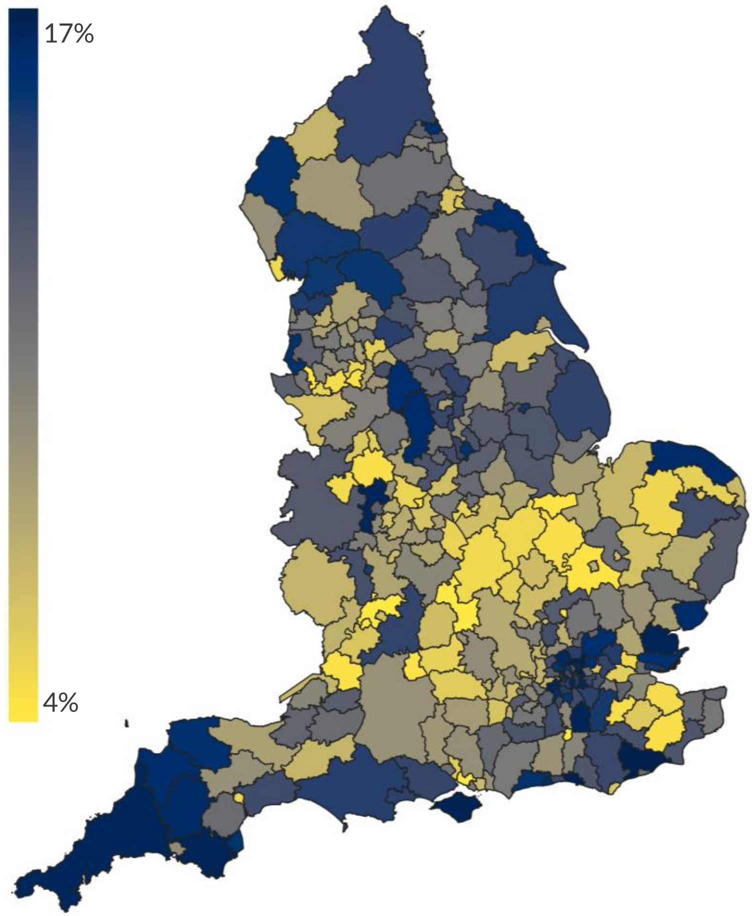
Standalone (detached) non-residential buildings less than 50m² can apply for an EPC exemption, so data for these buildings may be missing even when buildings are bought or rented.

Note that data is based on available EPC data and may not fully represent the entire building stock

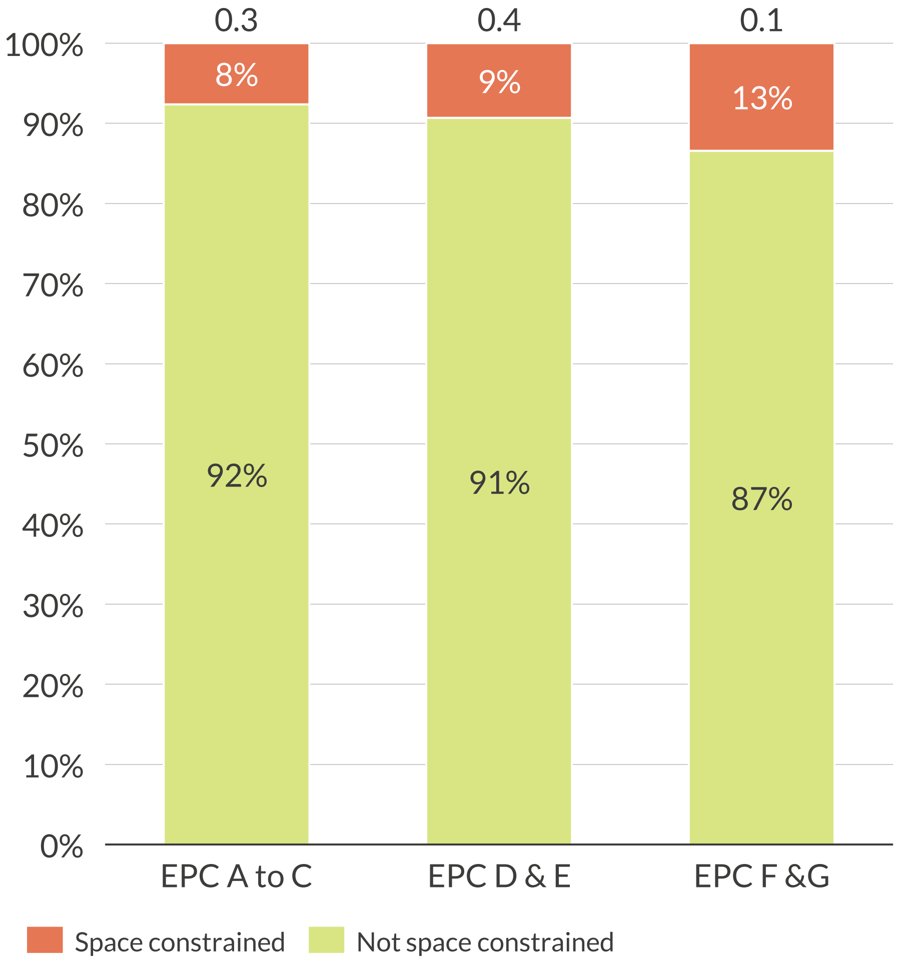
AURORA

Space Constraint: Could be a barrier to new heat technology deployment in areas such as London and Yorkshire and the Humber

Share of space constrained properties[1]
%



Space constrained properties by EPC rating
% (total shown on top in millions of buildings)



- Compared to the Residential building stock, a smaller proportion of buildings are space constrained within each efficiency group.
- The regions with the highest percentage of space constrained properties per local authority in England are London (12%) and Yorkshire and the Humber (10%). The centre of England has the lowest amounts of space constrained properties.
- A higher proportion of Commercial buildings with EPC ratings F&G are space constrained than higher efficiency buildings.

Note that data is based on available EPC data and may not fully represent the entire building stock

1) Only data available for Residential building with an EPC rating

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

Agenda

AURORA

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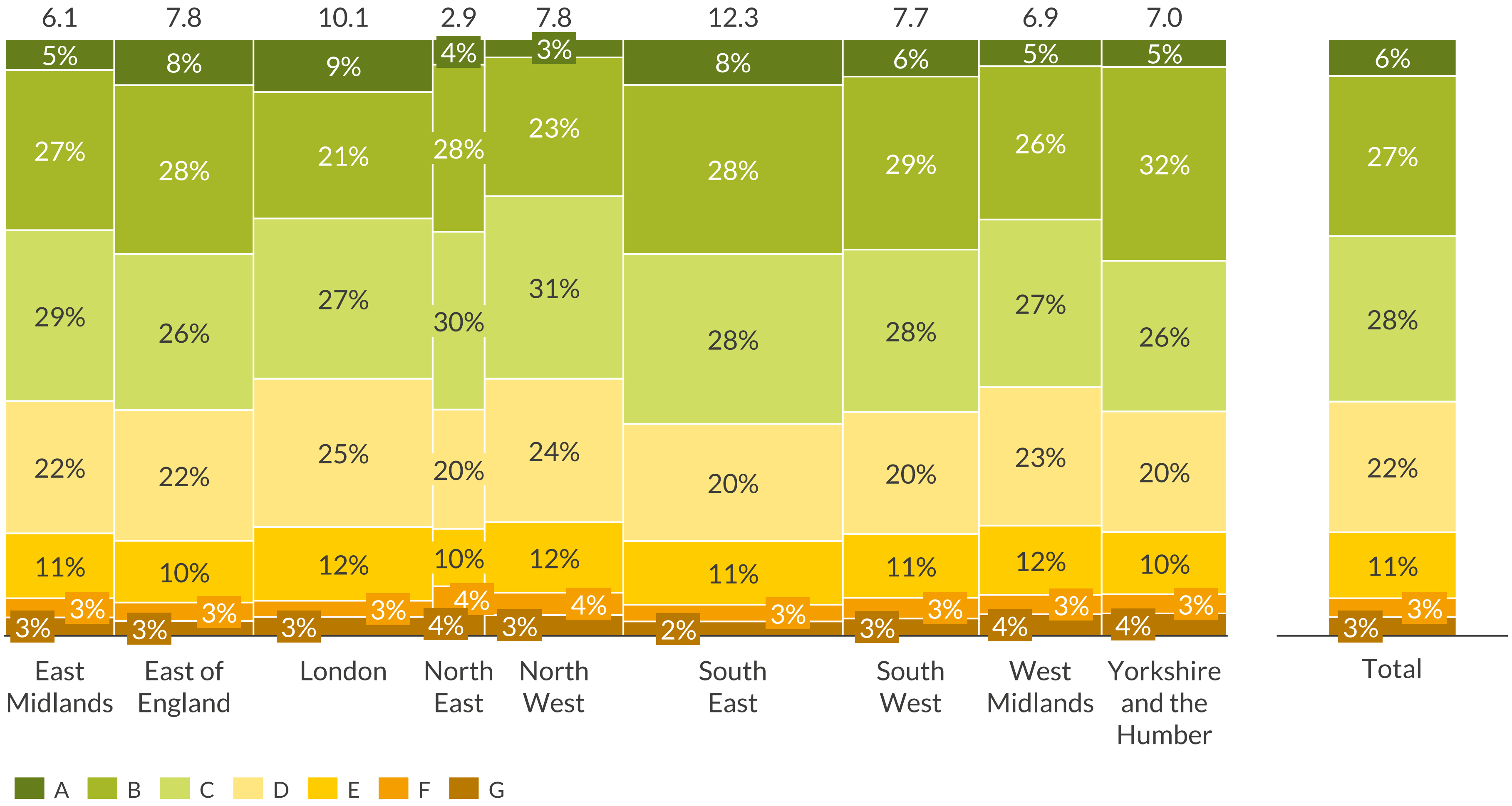
Efficiency: London and North West have the largest share of energy inefficient Public buildings, with % of properties rated below C

Public building stock split by energy efficiency rating

EPC levels A-G. Total shown at top (buildings in thousands)



	East Midlands	East of England	London	North East	North West	South East	South West	West Midlands	Yorkshire and the Humber	Total
Total	6.1	7.8	10.1	2.9	7.8	12.3	7.7	6.9	7.0	
A	5%	8%	9%	4%	3%	8%	6%	5%	5%	6%
B	27%	28%	21%	28%	23%	28%	29%	26%	32%	27%
C	29%	26%	27%	30%	31%	28%	28%	27%	26%	28%
D	22%	22%	25%	20%	24%	20%	20%	23%	20%	22%
E	11%	10%	12%	10%	12%	11%	11%	12%	10%	11%
F	3%	3%	3%	4%	4%	3%	3%	3%	3%	3%
G	3%	3%	3%	4%	3%	2%	3%	4%	4%	3%

High efficiency

- Public buildings have a considerable higher share of EPC A buildings than the Residential and Commercial building stock
- Regions with the highest proportion of buildings with EPC A to C are South East(64%), South West(62%), and Yorkshire and the Humber(62%)

Low efficiency

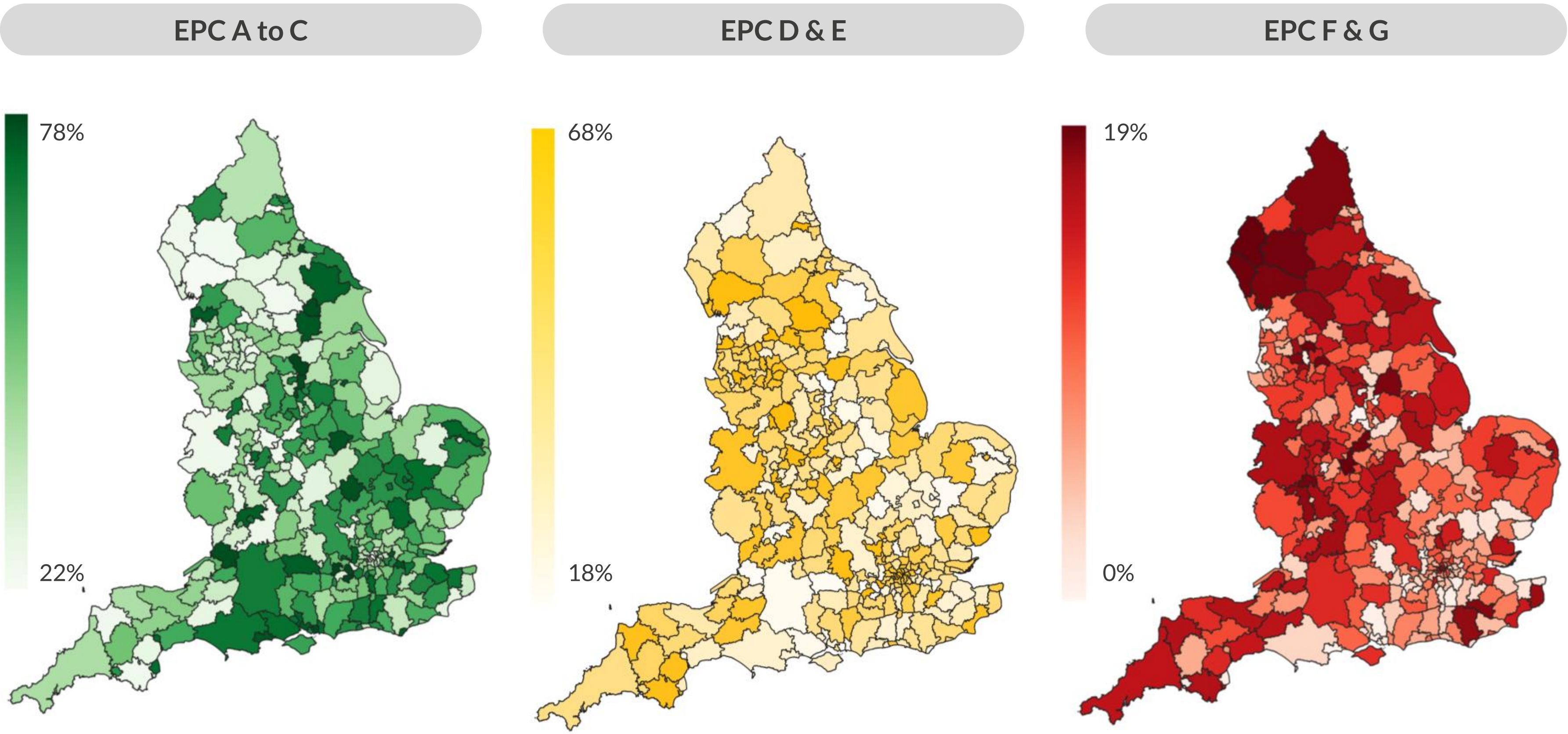
- North West (43.1%) and London (43.1%) are the regions that have the highest proportion of buildings that have EPC ratings below C

Note that data is based on available EPC data and may not fully represent the entire building stock

Source: Aurora Energy Research , Department for Levelling Up, Housing & Communities 2022

Efficiency: Low energy efficiency buildings occur across the country, but are particularly prevalent in the Yorkshire and the Humber

Share of Public buildings by Local Authority
%



Note that data is based on available EPC data and may not fully represent the entire building stock

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

61% of the Public buildings have an EPC rating between A to C, 33% between D and E and 6% below F on a national level

High Efficiency

- The regions with the highest share of EPC from A to C are South East (64%) and North East (62%). Bracknell Forest (78%) and Sheffield (78%) are the local authorities with the largest share of efficient buildings

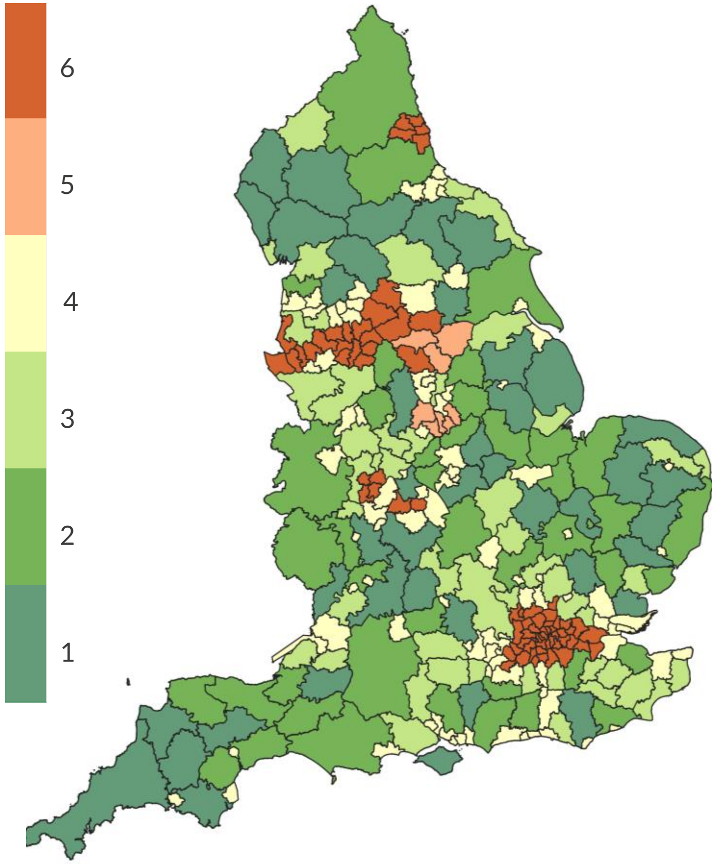
Low Efficiency

- The regions with the highest share of EPC F and G are Yorkshire and The Humber (8%) and North West (8%)
- Allerdale has the lowest EPC ratings, with 19% of buildings rating between F and G and North Warwickshire with 16%

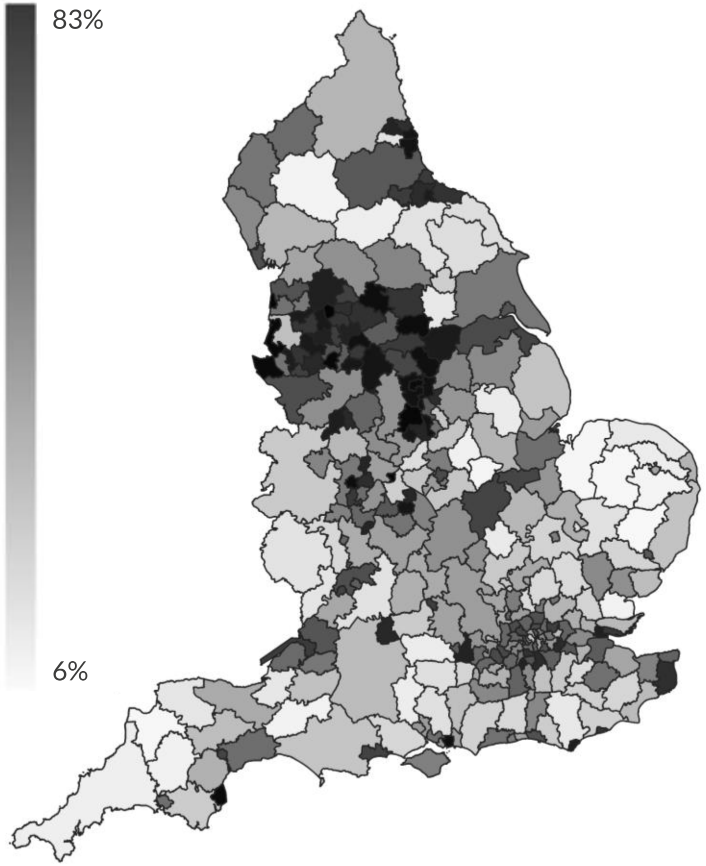
AURORA

Gas Networks: Public off-gas grid properties tend to be located in highly rural areas such as the South West and East of England regions

Rural vs Urban Local authorities
%



Share of buildings connected to the gas grid in each Local Authority
%



Natural gas is the dominant heating fuel in the UK, however, more than 31% of Public buildings in England are not connected to the gas network

- The local authorities with the highest share of non-gas properties are Isles of Scilly (83%) and Mid Suffolk (59%)
- These properties are typically located either in highly rural areas where it is not economically favourable to extend the network to serve a small number of households

Note that data is based on available EPC data and may not fully represent the entire building stock

Sources: Aurora Energy Research, Department for Levelling Up, Housing & Communities 2022

Space Constraint: Few Public buildings are space constrained

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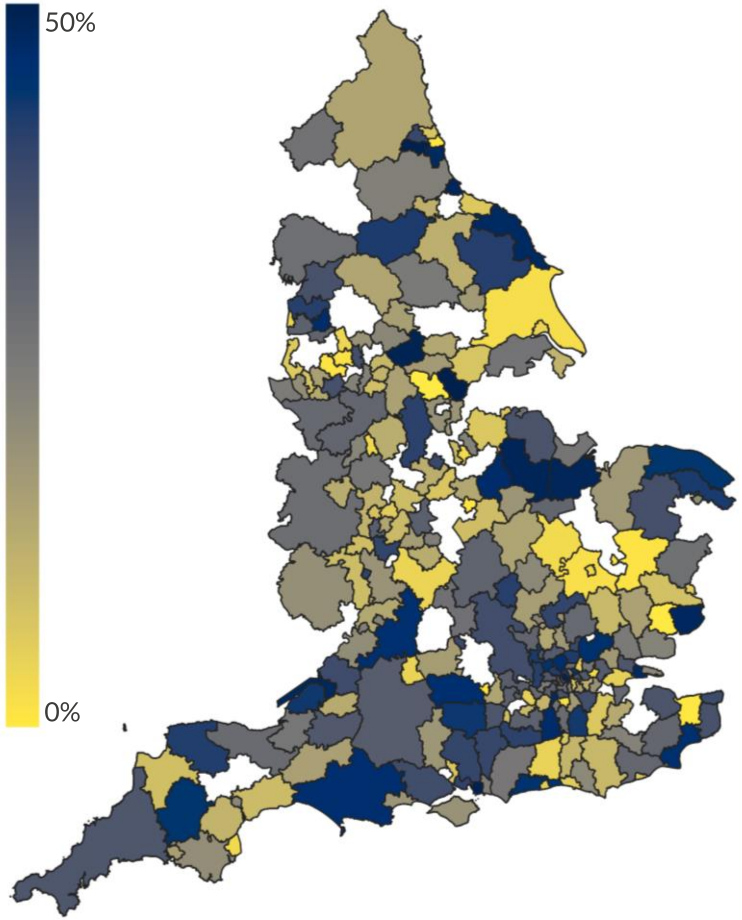
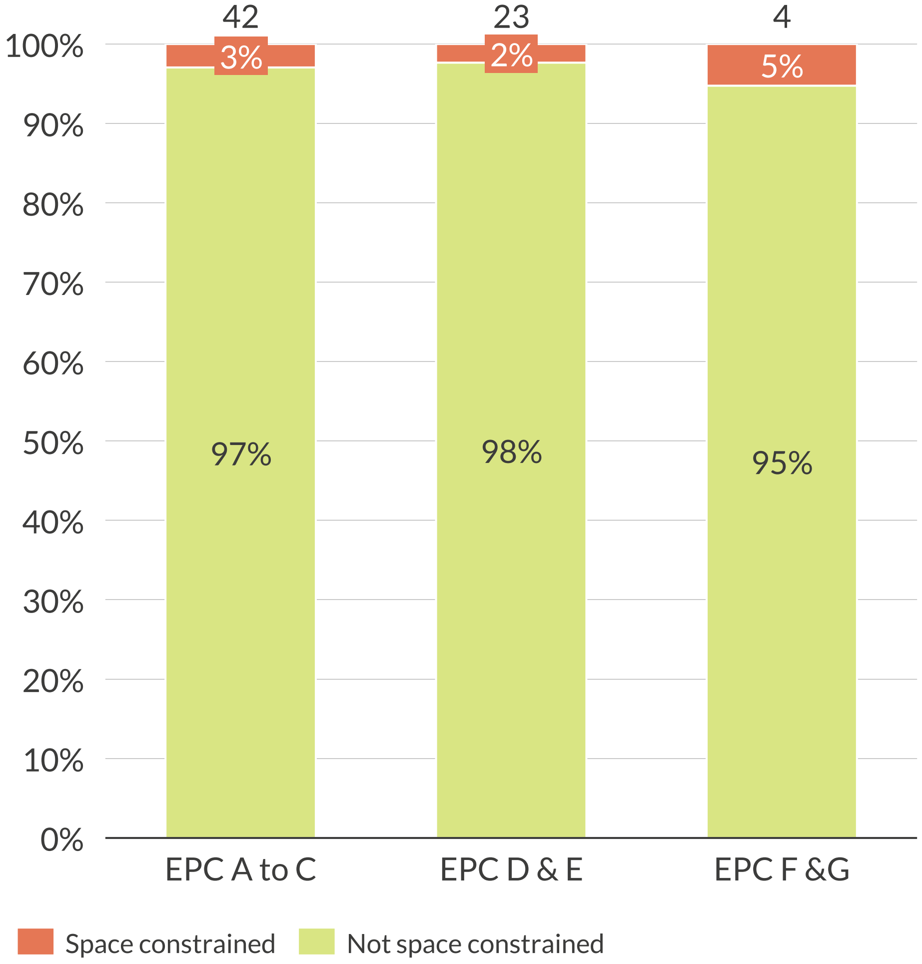
Share of space constrained properties[1]

%



Space constrained properties by EPC rating

% (total shown on top in thousands of buildings)



- Compared to the Residential and Commercial building stock, a smaller proportion of buildings are space constrained within each efficiency group
- The regions with the highest percentage of space constrained properties per local authority in England are Yorkshire and the Humber, followed by London and the Southeast region
- A slightly higher proportion of Public buildings with EPC ratings F&G are space constrained than higher efficiency buildings

Standalone (detached) non-residential buildings less than 50m^2 can apply for an EPC exemption, so data for these buildings may be missing even when buildings are bought or rented

Note that data is based on available EPC data and may not fully represent the entire building stock

1) Where Local Authority data is unavailable, these regions are left uncoloured

Source: Aurora Energy Research

Summary: Building stock

AURORA

1. The largest data gaps for residential buildings are for properties that have not been bought or rented in the last 20 years and so do not have an EPC certificate registered. For this reason, privately owned buildings are underrepresented in this dataset. Since these buildings are also most likely to have poor efficiencies, the dataset is expected to underrepresent the most inefficient buildings in the stock. Changes that have taken place since an EPC certificate was recorded are also not available.

2. There is a significant lack of data available for Public and Commercial buildings in general.

3. Where complete datasets are available for different dimensions of the building stock, these cannot always be mapped directly onto each other. Datasets of different ages, or collected under different methodologies, often contain inconsistent data. Anyone looking to understand the make-up of the building stock must weigh between prioritising between data recency and data completeness.

4. More than 90% of the English building stock are Residential buildings, 8% are Commercial and fewer than 1% are Publicly owned. The most common building type for owner-occupied homes is a semi-detached house, while for privately rented homes it is a terraced house. Flats are the most common socially rented building.

5. Most space constrained buildings are flats. Public buildings tend to be larger than Commercial buildings, while Residential buildings are the smallest.

6. The owner-occupied residential sector performs the worst in terms of energy efficiency, while socially rented buildings perform best. Flats also typically have higher energy efficiencies, with detached and semi-detached houses having lower efficiencies. The Commercial building stock has slightly better energy performance compared with Residential buildings, with 41% of buildings achieving EPC C or higher, compared to 35% of Residential buildings. Roughly one fifth of Residential buildings are not connected to the mains gas network. These buildings are likely to perform worse in energy efficiency.

Source: Aurora Energy Research

Agenda

Decarbonisation of the heat sector is heavily dependent on consumer choice, which is impacted by both direct and non-direct financial factors

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- More than 90% of the English building stock is composed of Residential buildings. Many building archetypes have multiple options for low carbon heating systems available and so decarbonising these buildings relies on the individual decisions of millions of consumers.
- Therefore it is important to understand how different economic and behavioural factors can influence the choices consumers may make is switching heating technology and how they might impact different consumer groups.
- Pathways for the decarbonisation of Public buildings is also likely to be impacted by decisions made considering the factors laid out in this section, but decisions will be taken by government authorities. For Commercial buildings, there is a lack of data on the relative proportion of owned vs leased buildings, and responsibilities for decision making can depend on the length ad terms of the lease, however owners and landlords will have to consider many of the same factors laid out in this section.

Direct Financial Factors

Technology costs:

Upfront costs:
- The cost involved in purchasing and installing the low carbon heating tech

Operational costs:
- The cost involved in running the low carbon heating tech during its lifetime

Efficiency upgrades:
- The cost involved in upgrading homes to energy efficiency rating EPC C or above

Policy options:

Financing options:
- The way in which a consumer finances their low carbon heating tech

Subsidies:
- Financial support, usually provided by the government, to lower the costs

Non-Direct Financial Factors

Levels of service:
- The performance and ease of service of low carbon heating technologies over their lifetime

Hassle factors:
- Inconveniences, typically non-economic, related to installing a new heating technology, such as choosing a supplier or having the correct paperwork or planning permission

Other:
- Consumer behaviour and psychology that are not captured by the other factors

Source: Aurora Energy Research

Agenda

AURORA

Between 45-70% of consumers identify high upfront costs as a barrier to switching to a low carbon heating system

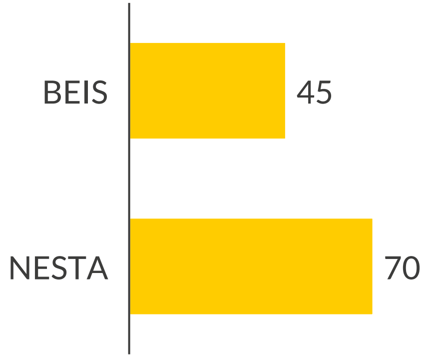
1 **Upfront cost:** The cost involved in purchasing and installing the low carbon heating technologies

£ **Impact mechanism:** Economical

- The upfront cost is a key determinant of a consumer's heating technology choice[1]
- Upfront cost relates to the CAPEX of the new heat technology, but also covers any installation costs or costs associated with home improvements that may be required
- These components all have a bearing on how likely consumers are to switch to new, low-carbon heat technologies

Element	Description
CAPEX	▪ The high cost of certain heat technologies can be prohibitive to certain consumers, particularly those with lower incomes, with between 45-70% of consumers identifying upfront costs as a barrier to making a technology switch
Installation and decommissioning costs	▪ The installation of low carbon heat technologies can cost up to 10-15% of CAPEX costs, depending on the technology, particularly if planning permissions are required ▪ Decommissioning of old appliances may also be required is switching from a gas system
Efficiency improvement cost	▪ This can be required in order for the new heating system to function properly. ▪ However, even if efficiency improvements are not required for the installation of a system, they will reduce ongoing operational costs as less fuel will be needed to operate the system ▪ These improvements can come at significant expense to the consumer

Share of consumers for whom high installation cost is a barrier, %



1) Public Attitudes Summer 2022 - BEIS PAT Summer 2022 Heat & Energy in the Home reveals that 56% of the owners surveyed wouldn't opt for a new heating system; 45% of them said it was due to installation cost barrier

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

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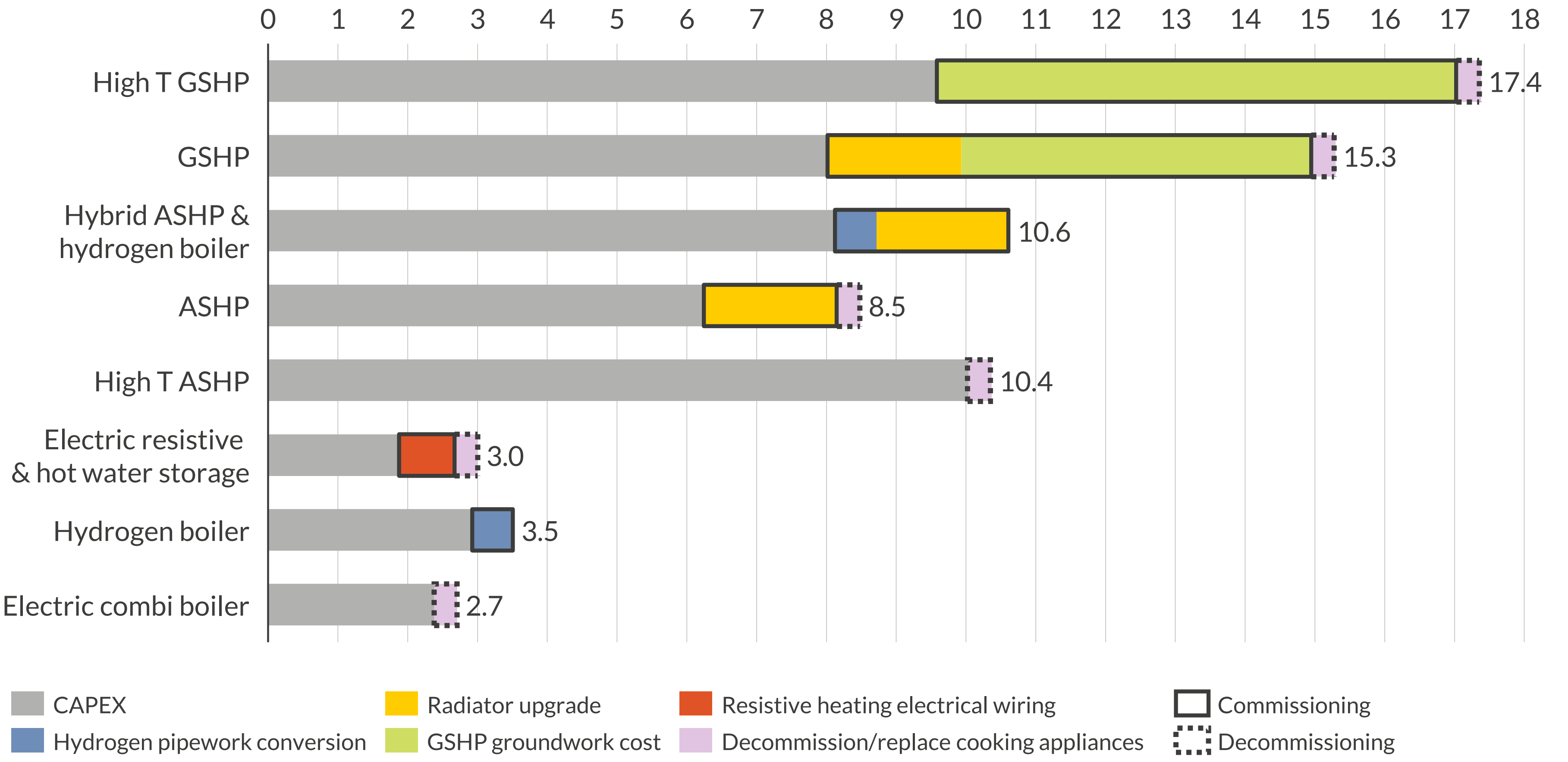
Upfront expenditure reflects the CAPEX and transition costs, which includes the costs of installation and decommissioning

Note that the costs presented represent average costs and actual costs will vary depending between households depending on the specific characteristics of each building.

Upfront costs for converting from a gas boiler to various technologies in 2023
£000's (real 2021)



- Electric resistive heating (either with hot water storage or a combi-boiler) or a hydrogen boiler have the lowest upfront costs when converting from a gas boiler. Consumers who see upfront costs as a barrier may be more likely to switch to these technologies.
- Ground Source Heat Pumps (GSHP) have the highest upfront costs owing for the need for groundworks, followed by Air Source Heat Pumps.
- Low efficiency homes installing heat pumps are likely to require either a high temperature heat pump, which provides a higher heating output, or an energy efficiency upgrade package, adding further to the upfront costs.
- Although high temperature heat pumps are up to 40% more expensive than standard heat pumps, they tend to be cheaper than the average cost of upgrading a building's energy efficiency.

Sources: Aurora Energy Research, Element Energy, CCC

Buildings with different dimensions may be differently impacted by high upfront technology costs

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Dimensions	Consumer behaviour
Tenure	• Tenants are not allowed to make upgrades, therefore upfront costs fall on landlords, whilst ongoing fuel costs are paid for by tenants. • Private landlords are expected to be more likely to choose cheaper technologies to install, and may not install efficiency upgrades, even if resulting technologies are more expensive to operate. However Social landlords are expected to be more likely to take a holistic approach, and Public sector buildings could be expected to take full lifetime costs into consideration, even if upfront costs are higher. • The decision taken by an owner occupier is less clear; the owner would see the benefit from any trade off between upfront costs and ongoing costs for technologies with higher upfront costs but lower running costs, but new technologies' payback periods can exceed the time a household stays in one building. Any decision is also likely to be driven by the access to finance the owner has.
Gas connection	• Gas connected buildings will face costs to decommission gas appliances, which may deter or delay electrification. However, any future H2 conversion would also need appliances to be converted.
EPC rating	• Inefficient homes would have to implement higher cost efficiency upgrades to be able to install heat pumps, which may deter owners of these buildings from selecting this option. However, whilst electric resistive heating/hydrogen would not require upgrades, these technologies would be significantly more expensive to operate without efficiency upgrades. For owner-occupiers, social landlords and public sector buildings, the benefit of efficiency upgrades on bills reduction may outweigh the costs.

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

Agenda

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Between 25-70% of consumers identify high operational costs as a barrier to switching to a low carbon heating system

AURORA

2 **Operational cost:** The cost involved in running the low carbon heating technology during its lifetime

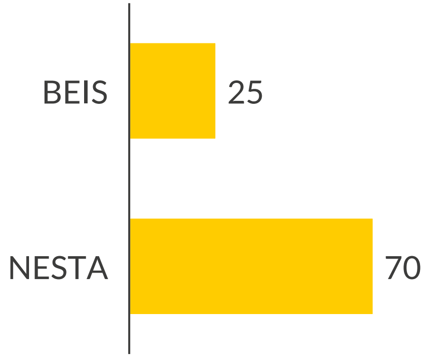
£ **Impact mechanism:** Economical

Description

- Running costs, unlike CAPEX, are a recurring cost that can represent a large percentage of the annualised cost of the heating technology. Operational costs primarily include maintenance and fuel costs.
- Running costs vary per heating technology and are highly impacted by both the heating technology and the building's energy efficiency. Studies estimate the percentage of owners who would not choose a new heating technology due to its running cost varies from 25% (BEIS, 2022) to 70% (BI, 2022).

Element	Description
Fuel costs	▪ Fuel costs are a source of uncertainty for consumers, which has been accentuated in the current market environment of very volatile commodities markets since 2021 . ▪ Total fuel costs are highly correlated to the building size and efficiency.
Heating technology efficiency	▪ The efficiencies of electrified heating range from 100% (electric resistive heating) to 300-400% (heat pumps), with H2 boilers achieving 85-90% efficiencies (end-use only, round trip efficiency is significantly lower). Therefore, the ongoing fuel costs for a heat pump are significantly lower than for an electric resistive heater.
Maintenance cost	▪ Maintenance costs are also an important component of ongoing costs.

Share of consumers for whom operational costs is a barrier,
%



1) How to reduce the cost of heat pumps, NESTA

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

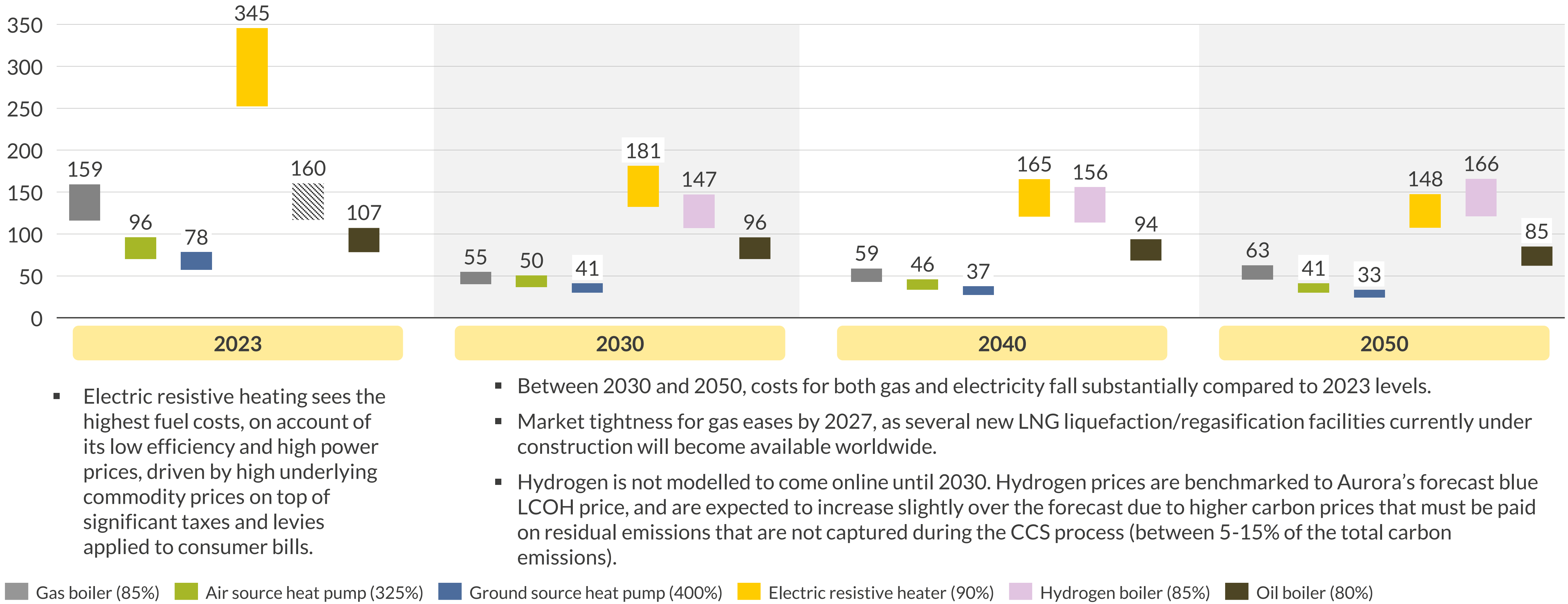
Although electricity is expected to be the most expensive fuel, high efficiencies results in heat pumps having the lowest fuel costs

AURORA

Fuel costs are shown accounting for the efficiency of different heating technologies, and normalised by heating demand, in order to be comparable.

Average fuel costs for different heating technologies[1], normalised by heat demand

£/MWh(thermal)/year (average efficiencies assumed for technologies shown in legend in brackets)



- Electric resistive heating sees the highest fuel costs, on account of its low efficiency and high power prices, driven by high underlying commodity prices on top of significant taxes and levies applied to consumer bills.

- Between 2030 and 2050, costs for both gas and electricity fall substantially compared to 2023 levels.
- Market tightness for gas eases by 2027, as several new LNG liquefaction/regasification facilities currently under construction will become available worldwide.
- Hydrogen is not modelled to come online until 2030. Hydrogen prices are benchmarked to Aurora's forecast blue LCOH price, and are expected to increase slightly over the forecast due to higher carbon prices that must be paid on residual emissions that are not captured during the CCS process (between 5-15% of the total carbon emissions).

1) Fuel costs are calculated using representative, average efficiencies of each heating technology. The range denotes differences in fuel costs that are observed in buildings with differing energy efficiencies.

Source: Aurora Energy Research, NEED 2019

Different consumers may be differently impacted by high ongoing fuel costs

AURORA

According to NESTA 2021, the most motivating incentive for consumers to switch to low carbon heating technology is a 25% energy bill reduction. Whilst this is consistent across all demographics, including social class, household size, and building tenure and type, not all consumer segments will be able to make decisions to achieve this goal.

Dimensions	Consumer behaviour
Tenure	▪ In privately rented buildings, tenants are responsible for paying fuel costs, however, are not responsible for choosing the system installed. With landlords paying upfront cots and tenants paying fuel costs, landlords could be incentivised to install cheaper systems, even if it means the tenants paying more. ▪ Social landlords and public buildings are more likely to take ongoing costs into account whilst decisions on which technology to install are taken. ▪ Owner-occupiers will have to trade off between reduced upfront costs and reduced ongoing costs, and decisions taken will also be impacted by their access to finance and their assumptions on whether they would stay in the property long enough to benefit from reduced bills.
Building type/ space constraint	▪ The building type can impact heat demand size and variability, impacting fuel costs. Larger buildings have higher operational costs and will see more benefit from selecting technologies with low operating costs.
Gas connection	▪ Gas boilers have the lowest operational costs of any technology and buildings with gas heating are likely to be disincentivised to select a higher cost option until forced to.
EPC rating	▪ Fuel costs are highly affected by the home's efficiency level. Low EPC rated homes will have higher fuel requirements and so may be incentivized to select technologies with lower fuel costs, provided the bill payer is able to take this decision. Private landlords may not take EPC ratings into consideration.

Sources: Aurora Energy Research, BEIS 2022, Element energy 2017, Nesta 2021

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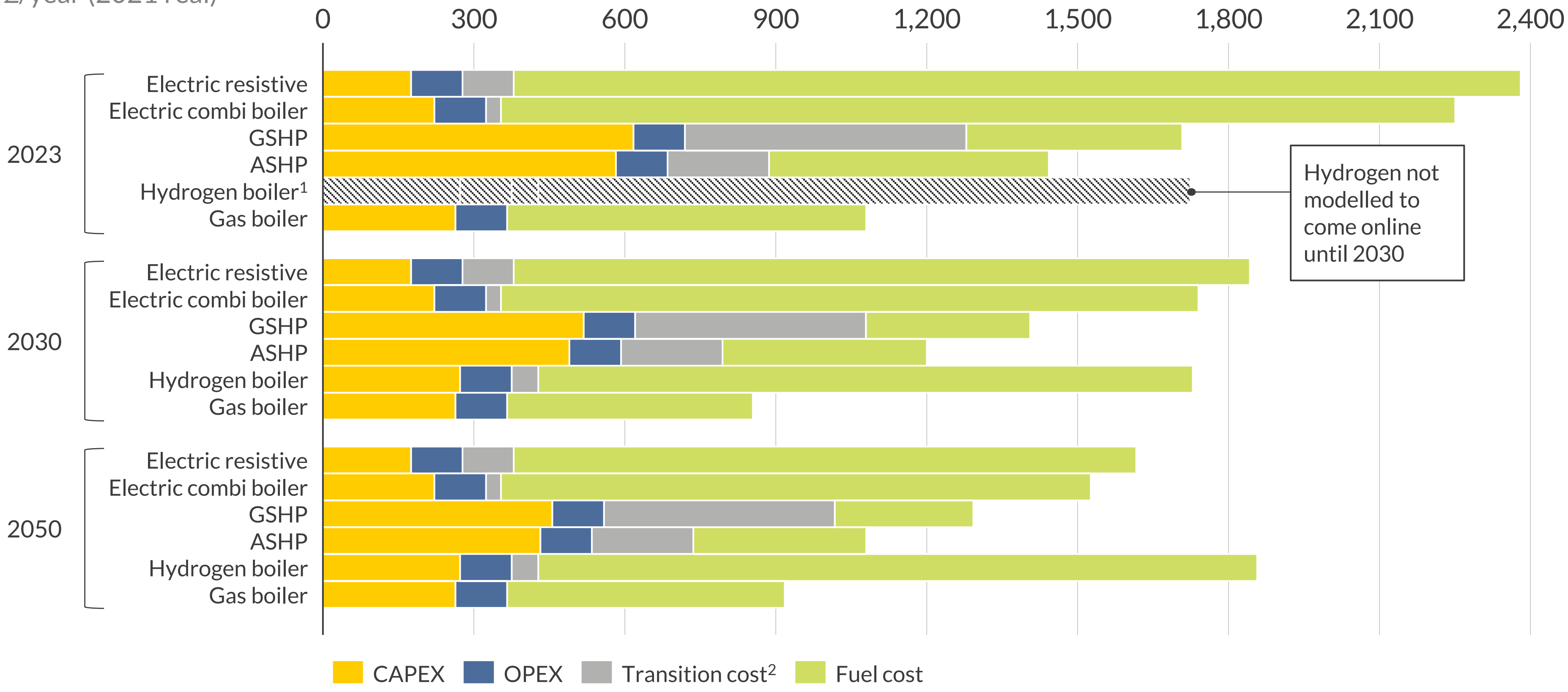
Annualised costs enable the full lifetime cost of different technologies to be directly compared

Annualised cost of new heating technologies, when switching from a gas boiler in an efficient, owner-occupied terrace
£/year (2021 real)



Key cost parameters	Discount rate (%)	Annual heat demand (MWh)	Technology efficiencies (%)	Technology lifetime (years)	Fuel costs (£/MWh)
Value	4.5	8.15	Found in data book	15	Found in appendix

1) H_2 boilers are only accessible for homes connected to a hydrogen network in our modelling 2) Transition costs include the cost of decommissioning the old heating technology and preparing the building for the new technology (commissioning cost).
Sources: Aurora Energy Research, Element Energy, CCC

- Gas boilers have the lowest annualised costs across the forecast horizon and so consumers who see costs as a key part of their decision making may continue to choose to replace gas boilers with like-for-like replacements unless they are unable to do so.
- In 2030 a hydrogen-ready boiler would be the lowest cost low carbon technology to install in advance of a hydrogen network being deployed. However, as no hydrogen network has yet been announced this may not be a viable low carbon option.
- Air source heat pumps have the lowest annualised costs of all electrified heating systems and so represent the cheapest overall technology for households that are technically able to install one (assuming a hydrogen system is unavailable). However, owing to their high upfront cost, consumers may not take this decision.

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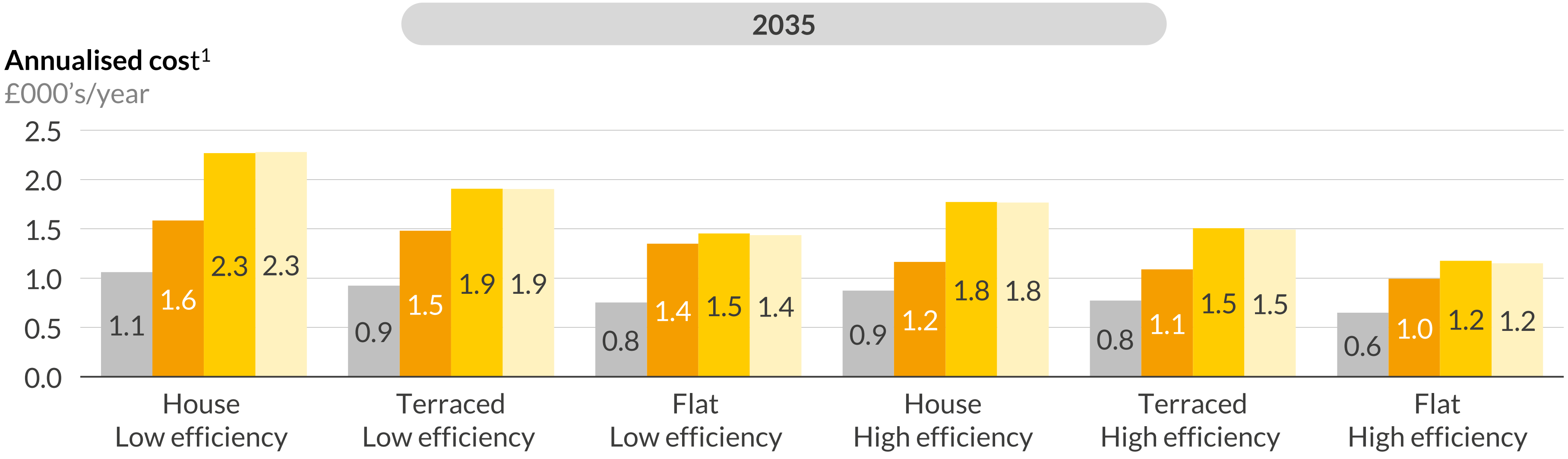
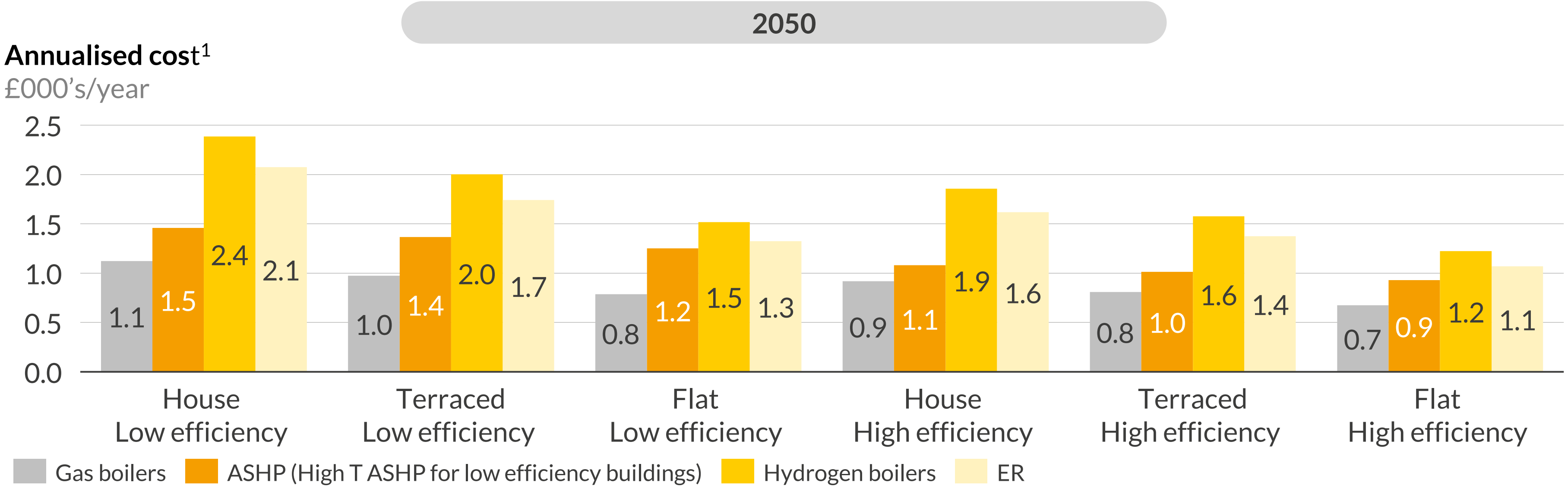
The total annualised cost of heating systems varies by building type, efficiency and year of installation





- **Building type**: The total annualised cost of each technology varies by £0.3-0.6k/year between building types, due to their differing heating demands.
- **Efficiency:** The cost for low efficiency buildings is greater than for high efficiency buildings, due to their higher heating demand (and requirement for more powerful heat pumps) leading to higher fuel costs[2].
- **Time:** Annualised cost of heat pumps falls between 2035-2050, driven by declining CAPEX and falling power costs, which also causes costs for electric resistive heating systems to fall. Costs for hydrogen systems increases slightly due to higher hydrogen fuel costs towards the end of the forecast, due to higher carbon costs incurred on residual emissions produced during blue hydrogen production.

1) The annualised data includes upfront and operational costs, 2) Note that low efficiency homes are able to use the same gas, hydrogen or electric boiler system as high efficiency homes, since the heating output of these types of boiler is high enough to accommodate the higher rate of heat loss. However, standard heat pumps provide a lower rate of heating and must be higher powered ('high temperature') in order to adequately meet the heating demand in low efficiency homes.

Source: Aurora Energy Research

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Improving the energy efficiency of the building stock is one way to reduce building sector emissions

AURORA

For some heating technologies to be effective, a minimum level of energy efficiency is needed. Efficiency upgrades will therefore be required to allow the installation of some technologies in some buildings. Improving building stock efficiency is also an effective standalone measure to reduce, but not eliminate, emissions from heating.

What are energy efficiency upgrades and why are they important in the context of decarbonising the building sector?

- Installation of low carbon heating systems alone will not reduce heat energy that is wasted; for this, we need to consider energy efficiency upgrades.
- Energy efficiency has a bearing on how well (or poorly) a building retains heat. Energy efficiency upgrade measures are aimed at improving a building's insulation such that it keeps heat in or out more effectively, reducing the overall amount of energy required to heat (or cool) the building, thereby reducing heating energy that is wasted and reducing carbon emissions.
- The government aspires for as many homes as possible to be EPC Band C by 2035 where practical, cost-effective and affordable.
- Employed in tandem with low carbon heat technologies, energy efficiency upgrades have significant potential to aid decarbonisation of England's buildings, and will be required in some circumstances if lower efficiency buildings are to adopt certain heating technologies. Here, we consider EPC band C to be the threshold that needs to be reached in these cases.

Common challenges surrounding energy efficiency measures

- Energy efficiency upgrades vary in cost from a few hundred to several thousand pounds. Common measures include cavity wall insulation, loft insulation, double or triple glazing, draught-proofing, hot water tank jackets. The more costly measures, such as a wall or loft insulation, often have larger energy-saving impacts than cheaper and less intrusive measures.
- For rented buildings there is generally a mismatch between the entity who is paying for the upgrades (the landlord) and the entity who is benefitting from the upgrades (the tenant).

- A key barrier to widespread installation of energy efficiency upgrades is their long payback periods, since the energy saving benefits are incremental and often small compared to the upfront cost of installation. However, in an environment where energy prices are higher, this has a positive impact on payback periods by increasing the relative value of energy savings.

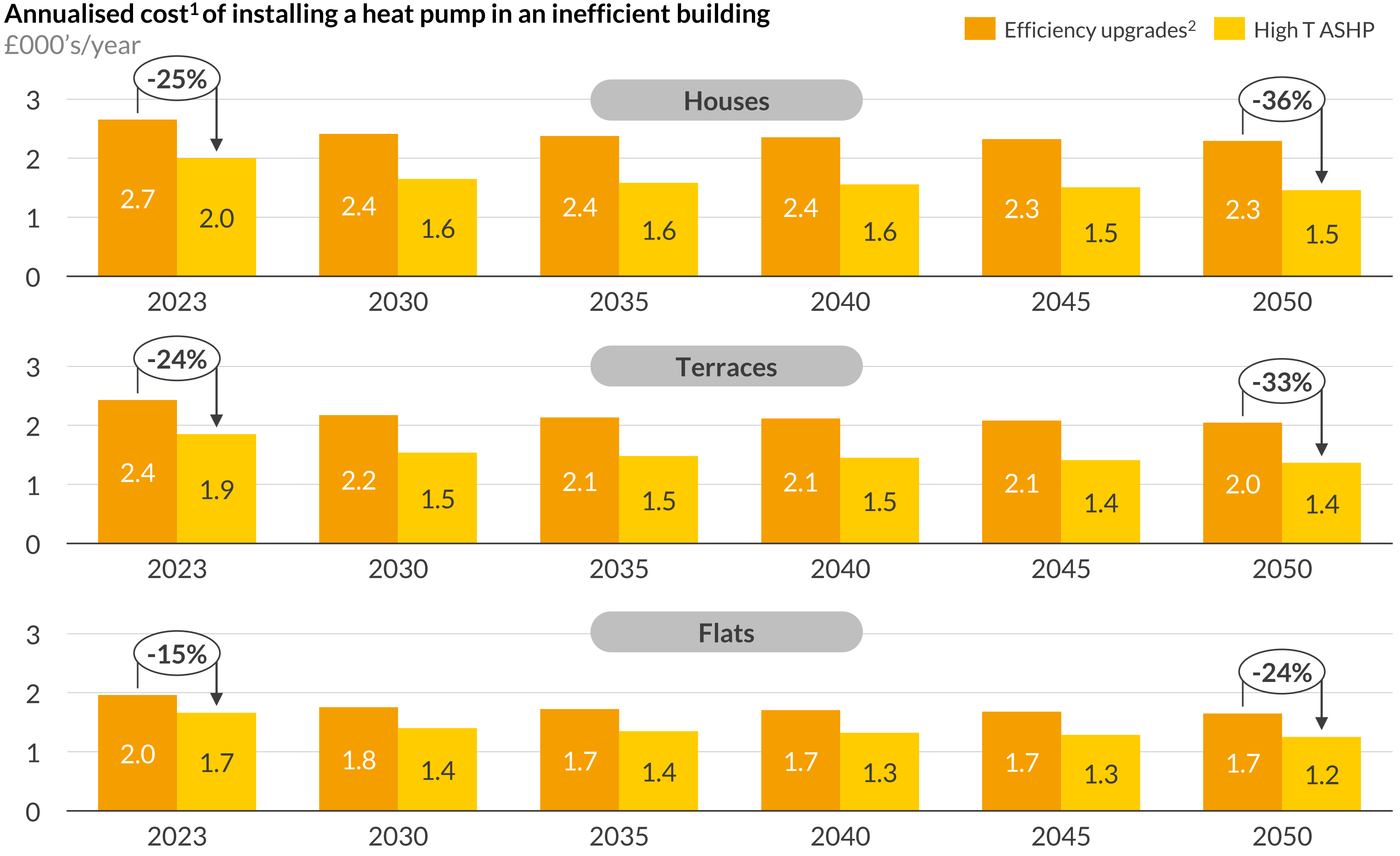
- Furthermore, it is typically more expensive to retrospectively fit energy efficiency measures in existing homes (also called retrofitting), since one must work within the confines of the existing architecture. As the majority of the building stock is made up of existing buildings, this materially adds to the cost of improving the energy efficiency of England's buildings.

Source: Aurora Energy Research

High temperature heat pump installation is 15-25% cheaper than energy efficiency improvements to buildings in 2023

AURORA

Annualised cost[1] of installing a heat pump in an inefficient building
£000's/year



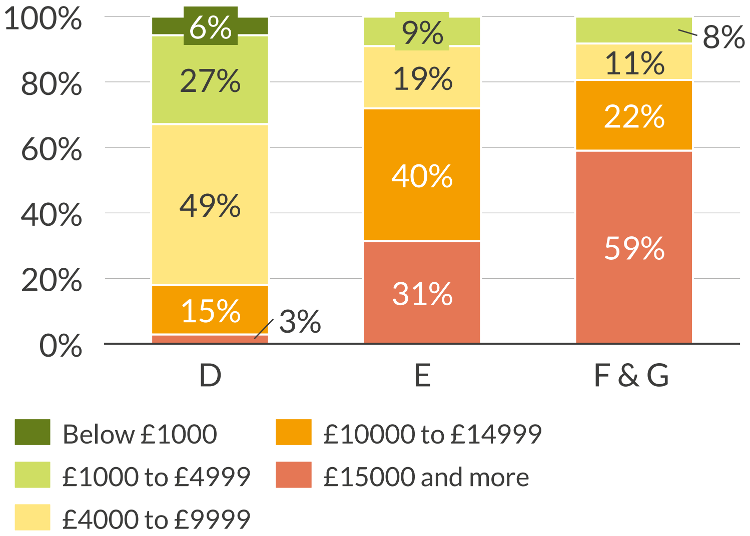
- Low efficiency buildings looking to install standard heat pumps could be required to improve home efficiency, via an efficiency upgrade package, otherwise the heat provision might not be sufficient for the building. Alternatively, consumers could install more expensive high temperature heat pumps to cater for the building's higher rate of heat loss.
- The costs for efficiency upgrades vary based on building types, with houses having the most expensive cost on account of their larger size.
- The cost gap between installing a high temperature heat pump and installing a standard heat pump alongside energy efficiency upgrades increases through time, as falling power costs lowers the impact of higher fuel costs in poorer efficiency buildings.

1) Includes all cost components: CAPEX, transition cost, OPEX and fuel cost. 2) We model the cost of a generic energy efficiency upgrade package, representing the average cost of improving a building's energy performance from its current level up to EPC C.
Source: Aurora Energy Research

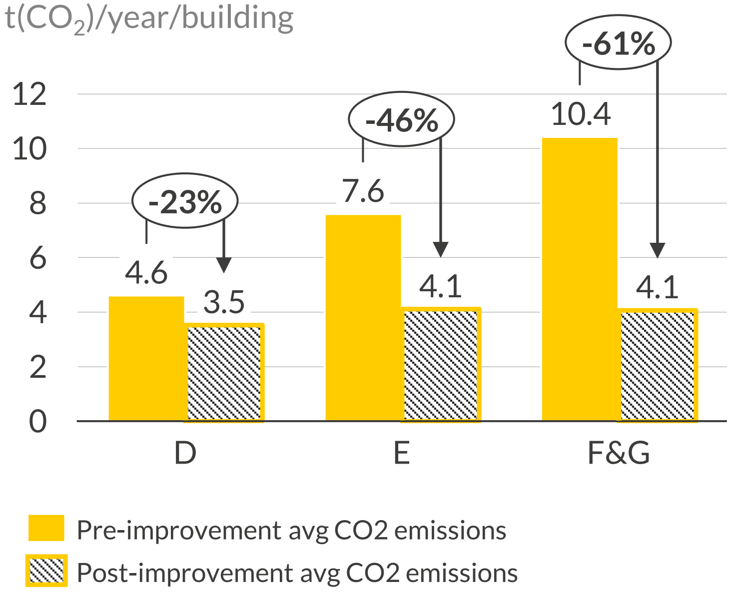
However, energy efficiency improvements lowers emissions, allowing the government to meet targets and long term benefits for consumers

AURORA

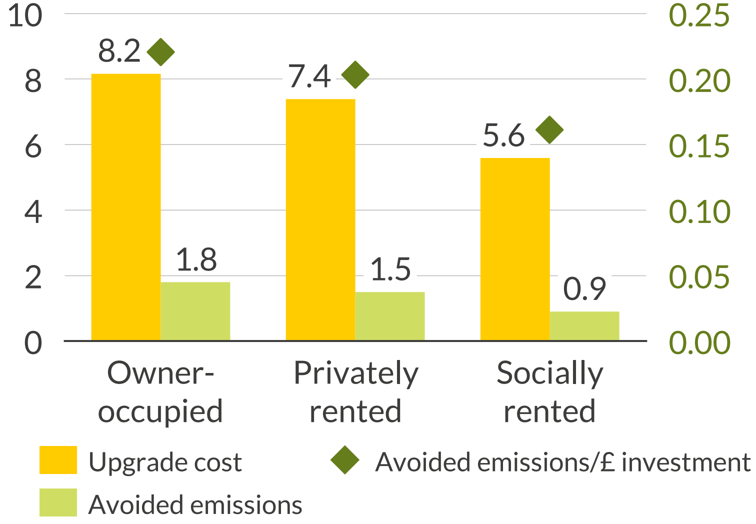
Distribution of costs to improve rating to EPC C, by EPC rating
%



CO_2 emissions pre and post-improvement to EPC C
$t(CO_2)$/year/building



Cost to improve rating to EPC C **Avoided emissions**
£000's/building , $t(CO_2)$/year/building
$t(CO_2)$/£/year



- The costs of improving a building's energy performance rating to EPC C are higher where buildings have a lower EPC rating. More than half of homes with EPC F or G would require investments of over £15k to improve to EPC C.
- For buildings at EPC D; just 3% would cost over £15k to improve to EPC C, and over 30% would cost less than £5k.

- Average costs of improvement to EPC C are positively correlated with CO_2 emissions reductions that could be achieved.
- On average, improving buildings from EPC F or G to EPC C would reduce their carbon emissions by 61%, while improvement from EPC D to C saves just 23%.

- Analysis of the cost of energy performance improvement on a tenure basis reveals that owner-occupied buildings have the highest cost and resulting avoided emissions, but also offer the most cost-effective improvement in terms of emissions reduction per £ investment. This is likely due to this tenure group performing the poorest in terms of energy performance, therefore offering the greatest improvement in emissions reduction.

Sources: Aurora Energy Research, English Housing Survey, Energy Report, 2020-21

The categories of low energy efficiency, detached house and private owned buildings have the largest share of costly energy efficiency improvements

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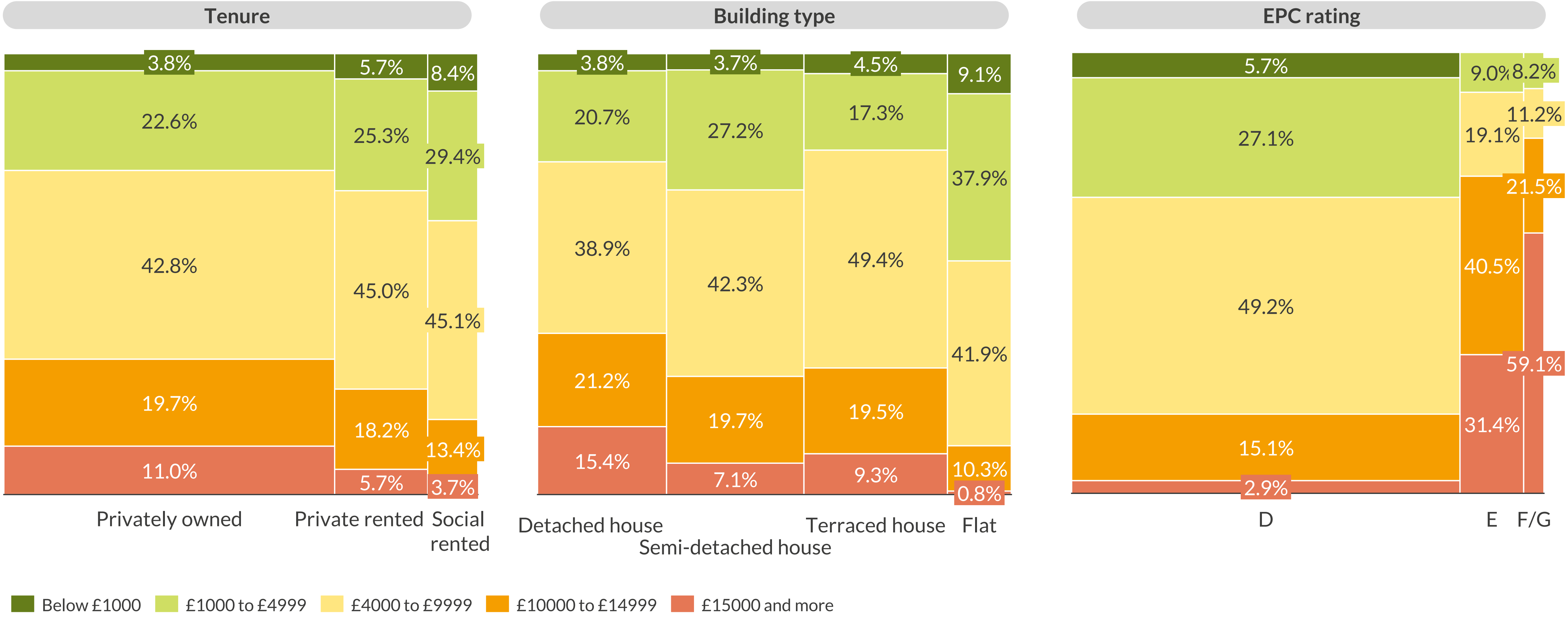
The cost of improving dwellings to an energy efficiency rating band C, by tenure, building type and EPC rating, 2020

% by £/property



Source: Aurora Energy Research, English Housing Survey, Energy Report, 2020-21

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Financing options could incentivise consumers to adopt low carbon technologies, by effectively lowering the investment cost

AURORA

3 **Financing options:** The way in which a consumer finances their low carbon heating technology

£ **Impact mechanism:** Economical

Description

- Financing options offer solutions to paying for systems that would otherwise be prohibitively expensive to many consumers. Existing or past schemes include green mortgages, standalone personal loans, government schemes, and heat as a service.
- Home Energy Scotland advises on funding options including grants and interest free loans. Loans were very influential in encouraging the uptake of renewable technologies: nearly half (46%) of installations would not have occurred without the support, and the majority (88%) of installations were at least partially driven by it[1].
- Although financial assistance persuades some people to use low-carbon heating, it is not crucial to all (Caiger –Smith & al. 2020). A few can be motivated directly by:
  - Environmental factors or because switching low carbon heating technologies would financially benefit them.
- Most consumers are not aware how to optimise financial incentives to finance low carbon heating technologies, for example, by combining bank loans and government subsidies. While some are aware of the various available schemes, they may struggle to determine the best way to use them. This can lead to financing options benefitting those with higher incomes, who are more likely to have the means to understand and employ the available schemes.

Element	Description
Financing of upfront costs	▪ Financing could be provided to cover the installation of new technologies or building efficiency upgrades. Policymakers would have to make decisions on who grants would be made available to (home-owners vs landlords), and the size of the grant (whether it would cover the full cost of installation or only partial costs). Decisions would also have to be taken on whether grants would be technology agnostic, or designed to incentivize specific technologies.

1) According to EST (2019), 2) This point is further developed in the 'Other' factor.

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

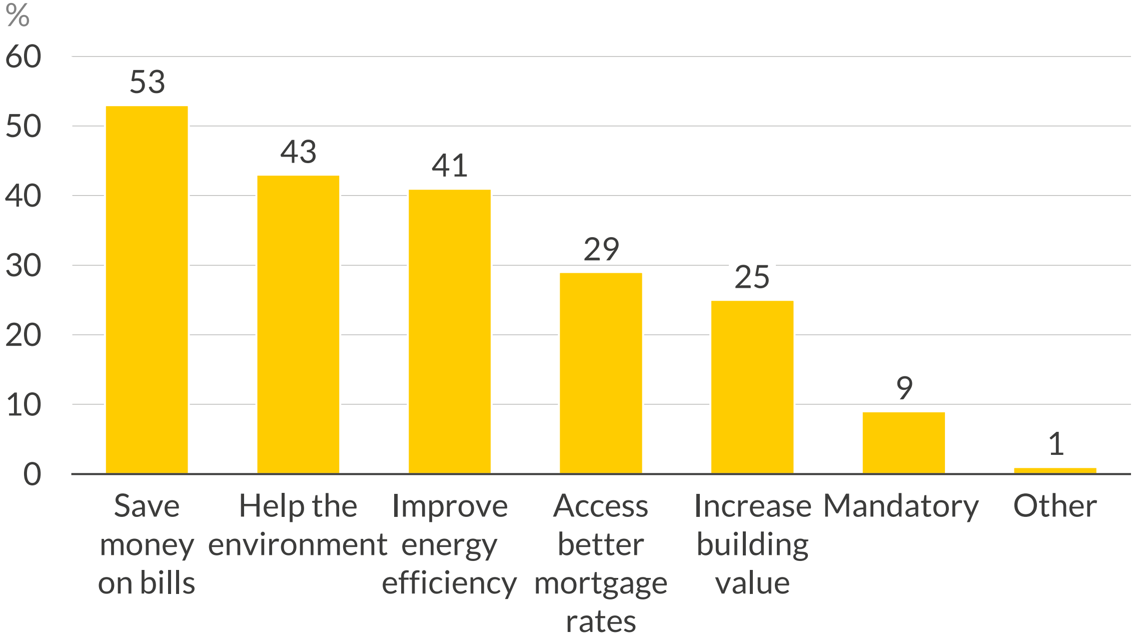
Studies have shown that existing financing options mostly benefit those who can already afford the upfront installation costs of low-carbon heating

AURORA

Dimensions	Consumer behaviour
Tenure	▪ If financing options are only available to owner-occupiers then private landlords may be further disincentivised to install technologies with high upfront costs, but lower ongoing costs for their tenants.
Socio-economic level	▪ If financing options only cover a portion of the upfront costs for low carbon technologies, this could disproportionately benefit consumers in higher-income households, who can afford to pay the remaining costs. This could allow higher-income households to benefit from technologies with lower ongoing costs, as the high upfront costs receiving financing assistance, whilst lower income households are unable to access these options and so face higher fuel costs. ▪ Some reviews of stakeholder feedback suggest that schemes like the RHI and FiT disproportionately benefited those who can already afford the upfront installation costs of low-carbon heating (Caiger-Smith et. Al, 2020).
EPC rating	▪ Buyers who purchase efficient homes (EPC A and B) have benefitted from Green mortgages. ▪ Inefficient homes could benefit from the government's Energy Company Obligation, which intends to assist in achieving the government's mandated goal of bringing fuel-inefficient dwellings up to EPC band C by 2030. ▪ Expansion of these schemes could incentivise efficiency improvements across the building stock.

Factor's impact on different heating technologies' uptake

Drivers behind homeowners taking out a green mortgage[1]



- Consumers that have accessed existing financing options have been motivated by the reduction of energy bills, as well as a desire to help the environment.
- The structure of future financing schemes will impact the level of bills reduction that may be achieved and may therefore impact its uptake.

1) IMLA, 2020

Sources: Aurora Energy Research, BEIS 2022, Citizens Advice 2021, Nesta 2022

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AURORA

Subsidies directly lower the upfront or running costs, but they do not always impact their target audience as intended

AURORA

4 **Subsidies:** Financial support, usually provided by the government, to lower the cost of low carbon heating technologies

£ **Impact mechanism:** Economical

Description

- Subsidies can be targeted at either upfront costs or ongoing running costs and can be an important factor in influencing a consumer's choice of heating technology.
- The scale of impact depends on various factors, such as the size of the subsidy, their target audience and their accessibility (such as knowledge of their existence, pre-requisite conditions and the hassle required to apply). There have been two main heating subsidies in the UK to date.

Element	Description
Subsidising of upfront costs	▪ Subsidies could be provided to cover the installation of new technologies or building efficiency upgrades. As with financing options, policymakers would have to make decisions on who grants would be made available to (home-owners vs landlords, and low vs high incomes households), and the size of the grant (whether it would cover the full cost of installation or only partial costs). Decisions would also have to be taken on whether subsidies would be technology agnostic, or designed to incentivize specific technologies, which would have a major impact on uptake rates.
Subsidising of ongoing costs	▪ Subsidy schemes could also be structured to relieve ongoing costs of low carbon heating. This option might particularly benefit households who were only able to install electric resistive heating (thereby facing higher ongoing costs), or private tenants whose landlords choose to install systems with higher ongoing costs. However, this form of financing may discourage energy efficiency, which policymakers would have to consider. A decision would also have to be made as to who might be eligible for subsidies of ongoing costs (for example, low vs high income households).

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

The structure of subsidy support will impact the decisions consumers make and the technologies that are selected

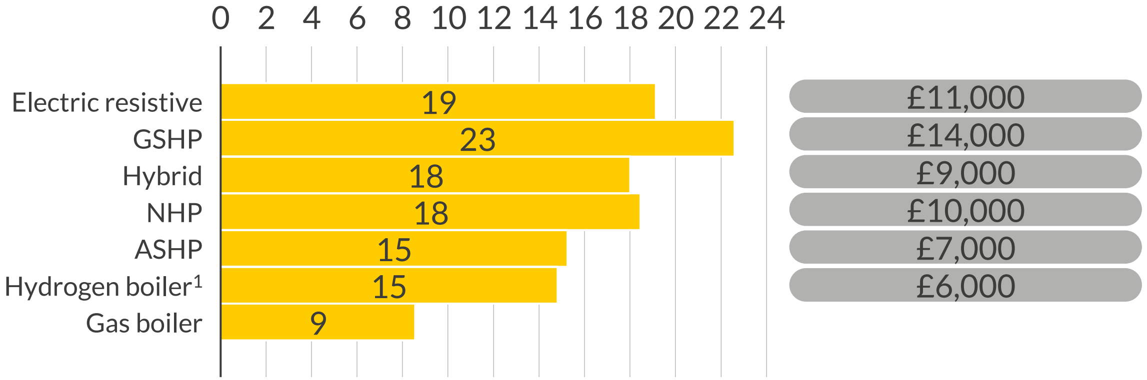
AURORA

Dimensions	Consumer behaviour
Tenure	▪ The structure of subsidy support could impact owner-occupiers vs rented properties differently. Policymakers will have to consider who is eligible for subsidy support. If private landlords are not eligible to benefit from subsidised upfront costs and efficiency improvements, this could result in them installing technologies with lower upfront costs that result in higher ongoing costs for tenants, or deciding against decarbonizing heating systems until forced to do so.
Socio-economic level	▪ The level at which subsidy support is set may impact which socio-economic groups it benefits. If costs are only partially subsidized, lower income groups may still be unable to afford to install high-cost technologies.
EPC rating	▪ Policymakers will have to consider whether subsidies should also be made available for efficiency improvements. This would reduce overall energy usage and would allow more efficient heat pump technologies to be installed in many homes.

Factor's impact on different heating technologies' uptake

Net present value of new heating technologies, when switching from a gas boiler[1]
£000's

NPV difference between technology and gas boiler



- Cost is the biggest barrier for consumers to switch to low carbon heating systems.
- The structure of subsidy support provided could impact the technology switch that is decided on. If subsidy support is technology agnostic, the lowest cost options to support would be air source heat pumps and hydrogen boilers, however, policymakers may wish to consider alternative factors.
- Subsidies that are targeted at upfront costs are more likely to increase the number of heat pumps installed, whereas subsidies targeted at reducing ongoing costs would benefit buildings with electric resistive heating.

1) NPV for an efficient, owner-occupied house

Sources: Aurora Energy Research, Nesta 2022

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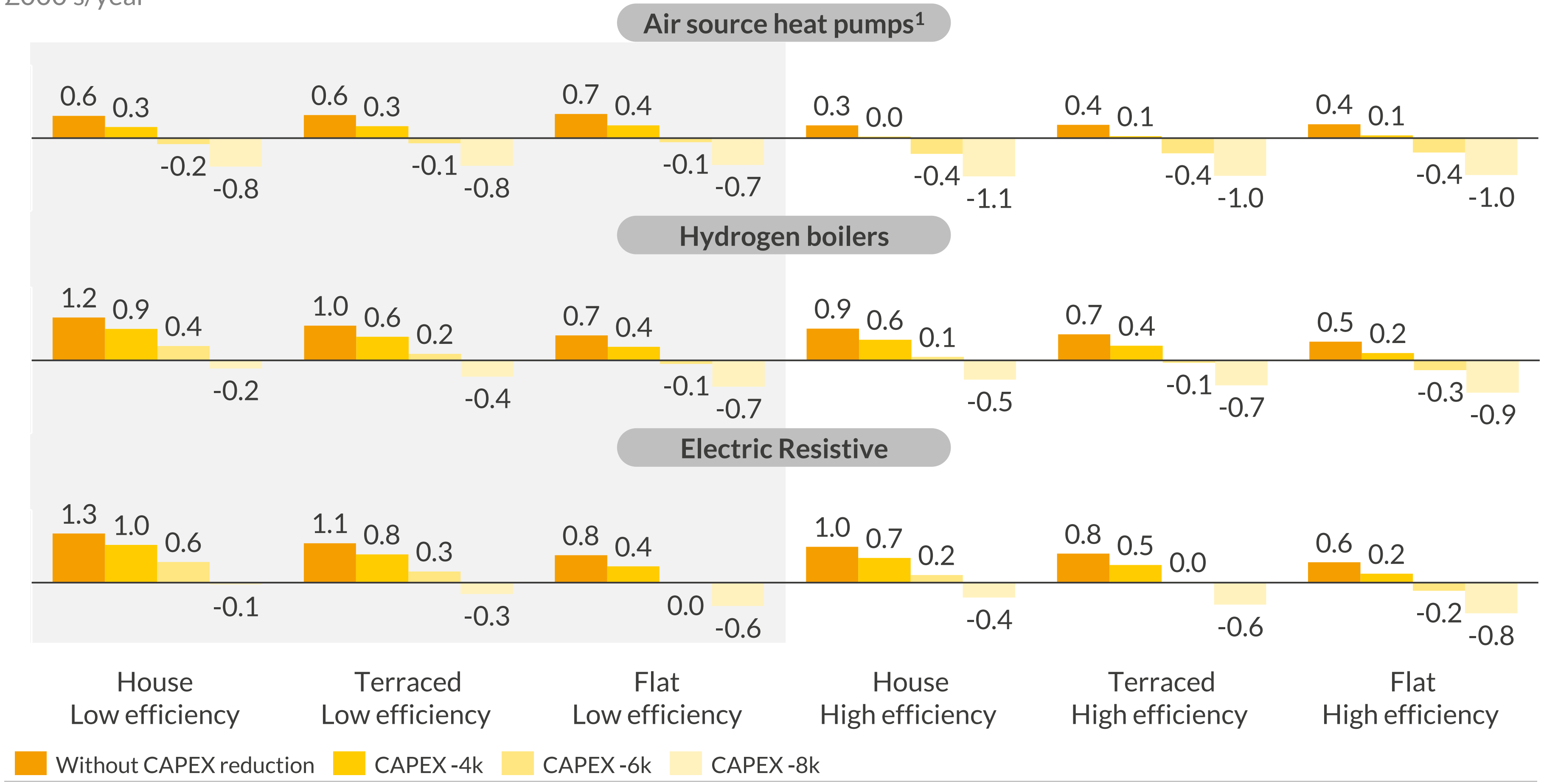
By 2030, CAPEX grants of c.£4-6k allow the annualised costs of air source heat pumps to reach cost parity with gas boilers

The necessary CAPEX reduction in order to close the cost gap to gas boilers is calculated by equating it to the NPV of the annual cost delta over new technologies assumed lifetime of 15 years and a 4.5% discount rate.

Annualised cost delta between a gas boiler and low carbon heating technology in 2030

£000's/year



1) High temperature air source heat pumps assumed for low efficiency buildings. 2) Boiler Upgrade Scheme.

Source: Aurora Energy Research

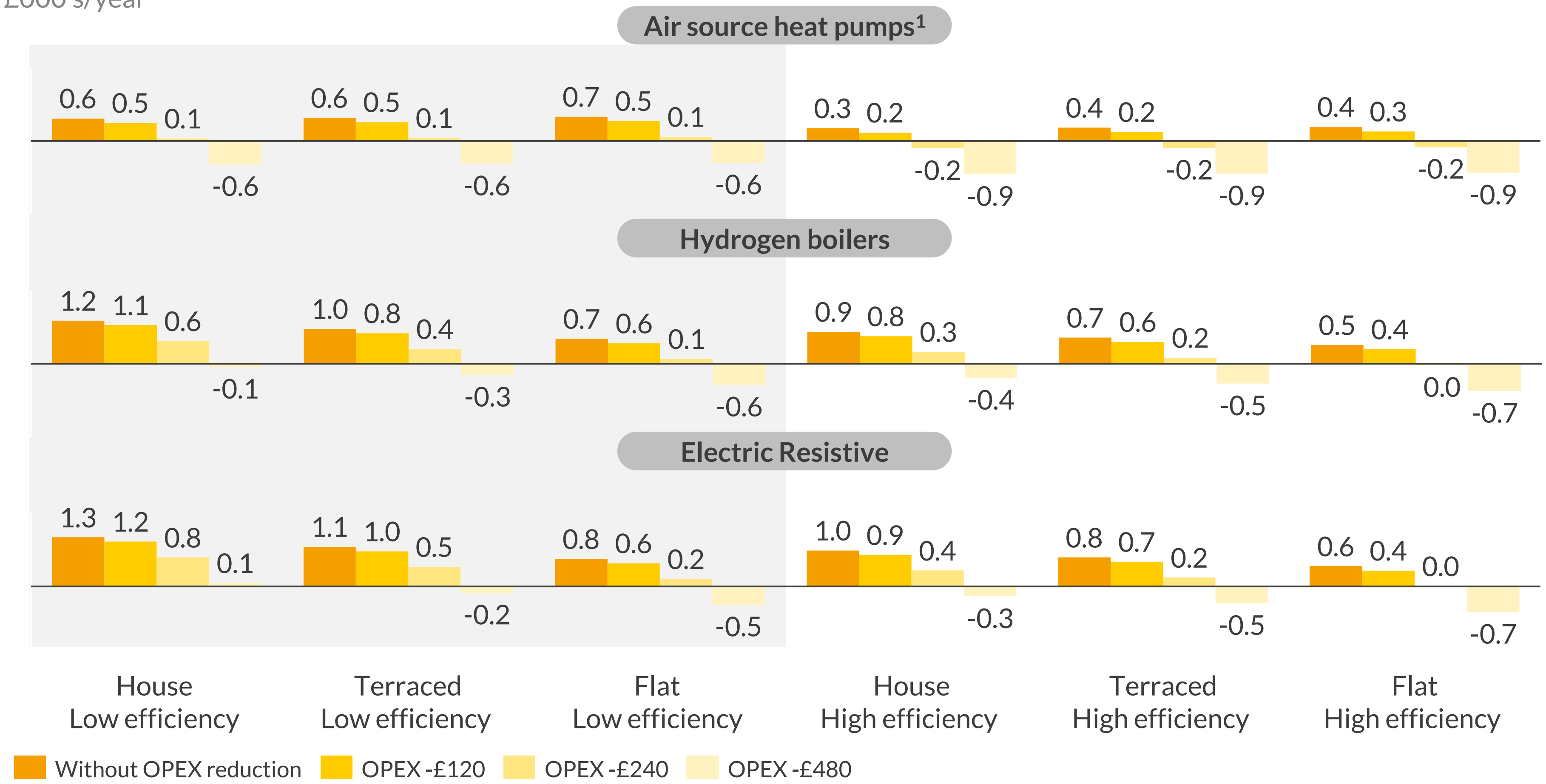
- For low efficiency homes, CAPEX grants of c.£6k are required to lower the upfront cost of heat pumps and allow these to achieve cost parity with gas boilers, while for high efficiency homes cost parity is achieved through grants of c.£4k.
- For hydrogen boilers and electric resistive systems, which have lower upfront cost compared to heat pumps, but higher running costs, higher levels of subsidy support are required to achieve cost parity with gas boilers (c.£8k for low efficiency homes and c.£6k for high efficiency homes). This support would be more appropriate as an OPEX grant to lower the high running costs.
- Currently the BUS[2] offers a £5-6k upfront grant, which is sufficient to achieve parity in lifetime costs in high efficiency homes by 2030 on an NPV basis. However, consumers may still be put off by the high upfront cost of heat pumps.

OPEX grants of c.£480/year are required to achieve cost parity of hydrogen boilers or electric resistive systems with gas boilers

The necessary OPEX reduction in order to close the cost gap to gas boilers is calculated by equating it to the NPV of the annual cost delta over new technologies assumed lifetime of 15 years and a 4.5% discount rate.

Annualised cost delta between a gas boiler and low carbon heating technology in 2030

£000's/year



1) High temperature air source heat pumps assumed for low efficiency buildings.

Source: Aurora Energy Research

- Subsidising the ongoing costs of a technology could also provide incentives for consumers to switch, particularly for technologies with higher running costs such as hydrogen boilers and electric resistive heating systems. Note for heat pumps, which have high upfront costs but relatively low running costs, CAPEX grants are a more suitable subsidy mechanism.
- Heating fuel subsidies would be likely to benefit lower income households.
- For hydrogen or electric resistive systems, annual subsidies of £480 are required in all but the highest efficiency flats in order to achieve cost parity with gas boilers (on an NPV basis).
- Heat pumps, which have higher efficiencies and consume less energy, have significantly lower running costs and require OPEX subsidies of c.£240/year to achieve parity with gas boilers.

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AURORA

Hassle Factors: These are encountered at all stages of the technology lifecycle and is an impediment to adoption of low carbon heating systems

AURORA

5 **Hassle Factors:** Inconveniences, typically non-economic, associated with installing a low carbon heating technology

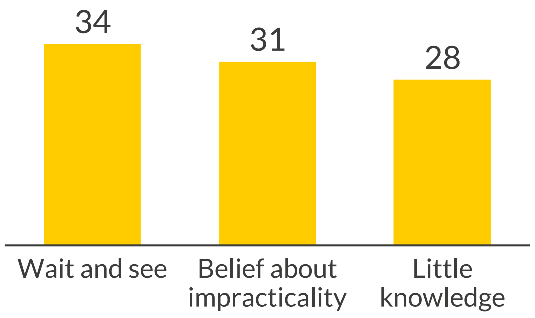
Impact mechanism: Behavioural

Description

- Hassle factors relate to various inconveniences when switching to a low carbon heating technology that are not directly captured by the economic considerations:
  1. There are significant perception and knowledge barriers that prevent consumers seeking out and choosing to install low carbon heating technologies.
  2. The consumer must select from a non-standardised and wide range of suppliers offering different qualities of service at different prices.
  3. Complex paperwork may be required to apply for subsidies. In some situations, planning permission may also be required, particularly for non-Residential buildings.
  4. Many households will only choose to upgrade when their existing heating system fails, meaning a rapid replacement is required, and consumers may not have time to learn about alternative low carbon choices or make other modifications required.

Element	Description
Perception barrier	▪ The process is perceived to be costly and complicated - more than 80% consumers believe that switching heating systems is expensive, inconvenient, and unreliable[1].
Knowledge barrier	▪ Lack of knowledge to make an informed decision on the optimal low carbon heating solution. ▪ This issue is more pronounced for renters, who tend to be less familiar with their own heat technology.
Dishonest practices	▪ Trouble identifying a reputable installer and finding reliable information about low carbon heat technologies. ▪ While TrustMark certifies government schemes, there is no mandatory accreditation framework, and fraudulent or dishonest behaviour further deters consumers.
Complex paperwork	▪ It is a significant barrier especially if there are time constraints, especially if the replacement is urgent. ▪ Households with children or adults working full time are less willing to adapt due to having less time.
Lack of transparency	▪ Installation costs can vary between suppliers can vary significantly, mainly driven by installation quality and service: - This leads consumers to develop a lack of trust and a feeling of confusion when it comes to selecting suppliers and installers.

Why owners are unlikely to install low carbon heating tech[2], %



1) Understanding Net Zero: A Consumer Perspective, Catapult Energy Systems 2) BEIS Public Attitudes Tracker: Heat and Energy in the Home Summer 2022

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

Hassle Factors: Tenants, low socio-economic households and owners of inefficient houses are the groups most affected by hassle factors

AURORA

Dimensions	Consumer behaviour
Tenure	▪ The knowledge barrier is more pronounced for renters, who tend to be less familiar with their own installed heat technology, although they will not typically be the decision maker.
Gas connection	▪ New heating technologies installation is an obstacle to consumers. Off-grid properties would be less impacted as household appliances would not need replacing. DECC (2013) reported that out of the households that were positive about ground source heat pumps, (53%) among those who were off the gas grid compared to 17% of the general population.
Socio-economic level	▪ Households with children or adults working full time are less able to spend time researching and understanding decarbonisation options. ▪ The knowledge barrier is lower for educated households. Awareness of minimum energy efficiency standards was higher among people educated to degree level (56% compared with 45% of those with other qualifications and 31% of people with no qualifications), according to BEIS 2022.
EPC rating	▪ Hassle factors are more pronounced for inefficient homes due to the additional efficiency measures that would be implemented.

1) Households with EPC D and lower are considered to be inefficient

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

Agenda

Levels of Service: Lack of customer support and maintenance erodes consumer confidence in low carbon heat systems

AURORA

6 **Levels of service:** The performance and ease of service of low carbon heating technologies over their lifetime

Impact mechanism: Economical

Behavioural

Description

- This factor relates to how the level of customer support during installation and maintenance of the heating technology influences a consumer's likelihood of choosing a low carbon heating technology:
  1. The lack of customer support, throughout the technology's lifetime, can lead to people having little confidence in adopting these technologies, and reluctant to invest. Citizen Advice reveals that out of all the customers who contacted them about problems relating to low carbon heating technologies, the biggest issue was to do with repairment problems.
  2. Lack of sufficient or standardised information on how to effectively run a low carbon heating system can also deter consumers from opting for these fewer familiar technologies.

Element	Description
Repairment	▪ During operation, consumers can struggle to find installers willing to make repairs or redeem a guarantee, particularly for newer technologies.
Customer training	▪ Consumers have different knowledge levels of the installed systems, and some cannot accurately identify the level of service they require. Many confirm that they would benefit from greater control to their systems. ▪ There is a general lack of training on operating some technologies efficiently, especially when considering newer technologies that might behave differently to conventional gas boilers.

Sources: Aurora Energy Research, BEIS 2022, Nesta 2022

Agenda

Other: Further economic and behavioural factors exist that present a barrier to the success of low carbon heating technologies

AURORA

7 **Other:** Consumer behaviour and psychology that are not captured by the other factors

Impact mechanism: Behavioural

Description

- The combined effect of all the factors considered so far can create a complicated experience for consumers, who might struggle to get reliable information, have difficulties evaluating finance options and identifying a reputable installer, encounter problems during installation or struggle to find a skilled repairperson.
- This section outlines some additional elements which can prevent consumers from opting for a low carbon heating technology.

Element	Description
Disconnection to climate change	▪ While 74% people thought climate change is a global emergency, only 49% identified gas boilers as contributing to climate change[1]. However, Consumers are more receptive about the idea of upgrading their home's energy efficiency in order to help the climate rather than switching to a low-carbon heating technology.
Perception difference	▪ Consumers have a positive perception of gas; it is easy to use, convenient and reliable. In contrast, heat pumps are perceived to be inconvenient. As a result, many homeowners wouldn't choose a heat pump even if they cost the same as a boiler.
Target Demographics	▪ Young homeowners are most likely to adopt low carbon heating technology, as they tend to be more engaged with issues around climate change. ▪ Homeowners who are retired, renting or unemployed are less likely to make any changes. - This provides opportunities to create effective campaigns targeted at different demographics to adopt low carbon heating technologies.
Timing of availability of options	▪ Some consumers may have a strong preference to convert to hydrogen, rather than to electrified heating, whether due to building suitability constraints or because of consumer preference. However, a decision on hydrogen conversion can only be taken by a household if a decision has been taken by policymakers to implement a hydrogen network that will connect in the household's local area. This decision would have to be announced in time for the consumer to factor it into their decision-making.

1) Understanding Net Zero: A Consumer Perspective, Catapult Energy Systems

Source: Aurora Energy Research, Energy Saving Trust, 2019, Catapult Energy Systems, Caiger –Smith & al. 2020

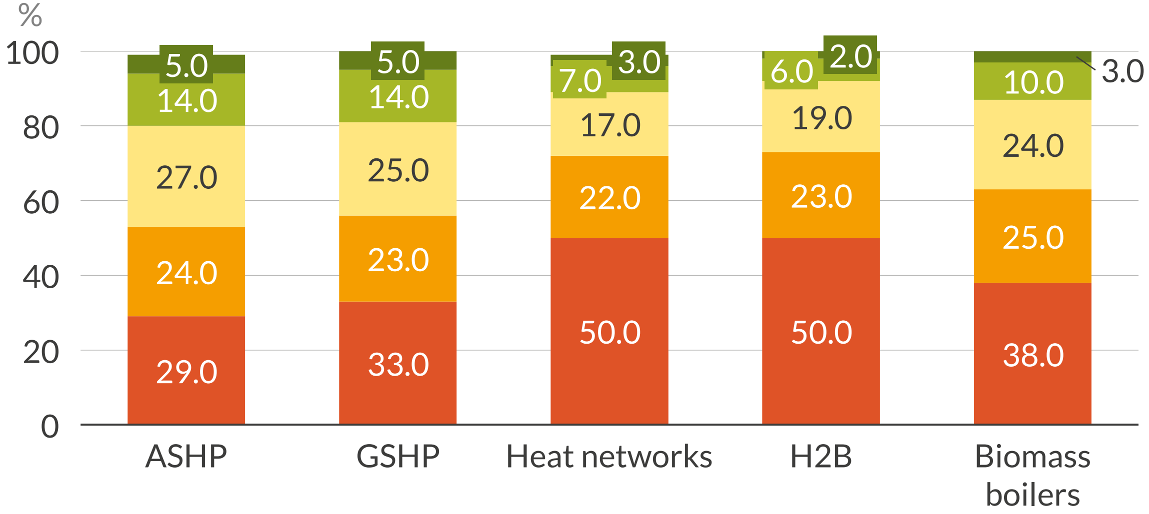
Other: Homeowners' demographics and technology knowledge play an important role in the decision making of heating and efficiency changes

AURORA

Dimensions	Consumer behaviour
Building type/ Tenure	▪ According to NESTA 2022, individuals renting a flat with one or two other people from the council or a housing association are less willing to make a heating technology or home efficiency change, although these occupants are not typically the decision maker. Social landlords and Public buildings are more likely to be able to take decarbonisation decisions in bulk, especially if policy decisions are taken to target this.
Socio-economic level	▪ Young homeowners are most likely to adopt low carbon heating technology, as they tend to be more engaged with issues around climate change. ▪ Homeowners who are retired, renting or unemployed are less likely to make any changes.
Gas connected	▪ Owners of gas connected buildings who wish to convert to using hydrogen will be heavily dependent on how the timings of any possible gas grid conversions will interact with the timings at which their heating system needs replacing.
EPC rating	▪ Individuals having already made efficiency changes in their own home are typically more willing to make further changes, which might make efficiency improvements of the worst performing buildings harder to target.

Factor's impact on different heating technologies' uptake

Knowledge about low-carbon heating systems[1]



- Knowledge and perception on low-carbon heating systems is an important barrier for the technologies' uptake.
- Consumers know the least about Heat Networks and H2 Boilers, which suggests these technologies may face the largest perception barrier.
- Heat pumps (air source and ground source) and biomass boilers have the lowest knowledge gap.

A lot | A little | Never heard of this | A fair amount | Hardly anything but I have heard of this

1) Data retrieved from 'BEIS Public Attitudes Tracker: Heat and Energy in the Home Summer 2022, UK'

Sources: Aurora Energy Research, Nesta 2022

Summary: Consumer choice

AURORA

1. Costs are one of the most significant factors for consumers to take into account when selecting a decarbonised heating technology. If choosing between electrified technologies, consumers must weigh between technologies with high upfront costs and low running costs, or technologies with low upfront costs but high fuel costs.

2. For rented properties, the landlord makes the decision on which low carbon technology to install. As landlords pay the upfront costs but not the ongoing costs, they may be incentivised to select technologies with low upfront costs. However social landlords and Public sector buildings may take a more holistic approach.

3. Financing and subsidy schemes could influence the deployment of different heating technologies, depending on whether policies are technology agnostic, or whether they focus on supporting upfront or ongoing costs.

4. Non-financial factors, such as hassle factors, must also be considered. Consumers may be put off by technologies like heat pumps which can have significant requirements for efficiency upgrades, and that behave materially differently to their existing system. Consumers may also be influenced by perceptions on the availability of services for newer technologies or lack of education on options available.

5. Switching to hydrogen incurs low upfront costs, however running costs could be high depending on the cost of hydrogen. In addition, hydrogen could be a lower hassle option, as hydrogen behaves in the same way as natural gas, such that there may be fewer perceived barriers to switching for consumers. However, consumers will not be able to make individual decisions on whether to install a hydrogen system even if they are already connected to the gas network, but will be dependent on policy or commercial decisions taken and the timings of these.

Source: Aurora Energy Research

Agenda

We explore a range of scenarios with varying degrees of hydrogen penetration and electrification via different technologies

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Scenario		Description
Electrification of Heating scenarios (no hydrogen)	Max Heat Pump (MHP)	Represents a scenario where the majority of consumers favour the adoption of a heat pump where technically feasible. No H2 network is deployed.
	High Heat Pump (HHP)	Represents a scenario where a high proportion of consumers favour the adoption of a heat pump where technically feasible. No H2 network is deployed.
	Balanced Mix (BM)	Represents a scenario where the adoption rates of different electrified heating technologies is balanced. No H2 network is deployed.
	High Electric Resistive (HER)	Represents a scenario where a high proportion of consumers favour the adoption of electric resistive heating where technically feasible. No H2 network is deployed.
	Max Electric Resistive (MER)	Represents a scenario where the majority of consumers favour electric resistive heating. No H2 network is deployed.
Hydrogen deployment scenarios (Balanced Mix)	H21 Phase 1 deployment (Low H2)	Represents a scenario where Phase 1 of the H21 study is enacted, allowing buildings in the North of England to switch to H2 heating where technically feasible. Other buildings decarbonise heating though a balanced mix of electrified heating technologies.
	H21 Phase 1-3 deployment (Mid H2)	Represents a scenario where Phases 1-3 of the H21 study are enacted, allowing buildings in the North of England, South Yorkshire & the Midlands, and Scotland[1] to switch to H2 heating where technically feasible. Other buildings decarbonise heating though a balanced mix of electrified heating technologies.
	H21 Phase 1-6 deployment (High H2)	Represents a scenario where Phases 1-6 of the H21 study is enacted, allowing buildings located all parts of the country to switch to H2 heating where technically feasible. Other buildings decarbonise heating though a balanced mix of electrified heating technologies.

- Scenarios are designed to reflect choices consumers may make and building archetypes are assigned a preferred low carbon technology in each scenario. **Scenarios do not represent the most economic or efficient decarbonisation paths, or consider the impact the pathway would have on the power sector**.
- In all scenarios, the pace of decarbonisation allows CB6 targets to be met.[2]
- Buildings are assigned heat technologies based on their characteristics and suitability criteria (see pages 97-98) and install the new system when the existing system needs replacing.
- A gas boiler[3] build limit is used to allow emissions targets to be met. No gas boiler ban is implemented, however the build limit means gas boilers are phased out by 2050.
- The gas, H2 and electricity price are consistent across scenarios. Heat network deployment is also constant.

1) Note that our modelling here focuses only on the decarbonisation of the English building stock 2) 47-62% reduction in carbon emissions by 2035, relative to 2019 levels. 3) Other high emitting systems such as coal and oil systems also face build limits.

Sources: Aurora Energy Research, NIC, H21

Deployment rates of heat pumps and electric resistive heaters reflects differing levels of willingness of consumers to adopt each technology

AURORA

- In our electrification of heating scenarios, no hydrogen network deployment takes place and so decarbonisation of heating takes place entirely through electrification
- Each building archetype has a favoured electrified heating system in each scenario, allowing us to test the impact of the choices that consumers may make
- In all scenarios, space constrained buildings can only convert to electric resistive heating
- The deployment of heat networks takes place in urban areas, heat network deployment is otherwise evenly distributed across other building archetypes

	Socially rented						Privately rented						Owner Occupied						Share of electric heating systems[2] (%)	
	Detached/ Semi-Detached Houses		Terraces		Flats		Detached/ Semi-Detached Houses		Terraces		Flats		Detached/ Semi-Detached Houses		Terraces		Flats			
	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Heat pumps	Electric resistive
Max Heat Pump	HP	HP	HP	HP	HP	HP	HP	HP	HP	ER	ER	ER	HP	HP	HP	HP	HP	ER	75	25
High Heat Pump	HP	HP	HP	HP	HP	ER	HP	ER	ER	ER	ER	ER	HP	HP	HP	ER	HP	ER	58	42
Balanced Mix	HP	HP	HP	ER	HP	ER	ER	ER	ER	ER	ER	ER	HP	HP/ ER[1]	HP	ER	ER	ER	48	52
High Electric Resistive	HP	HP	HP	ER	ER	ER	ER	ER	ER	ER	ER	ER	HP	HP/ ER[1]	HP	ER	ER	ER	32	68
Max Electric Resistive	HP	ER	HP	ER	ER	ER	ER	ER	ER	ER	ER	ER	HP	ER	HP	ER	ER	ER	17	83

Abbreviations

Eff.	Efficient	Ineff.	Inefficient	HP	Heat Pump	ER	Electric Resistive

1) The number of inefficient owner-occupied detached/semi-detached houses installing heat pumps and electric resistive heaters varies in these scenarios. 2) The share of deployed electric heating systems, not including electric heat networks, that are either heat pumps or electric resistive systems.

Sources: Aurora Energy Research, NIC

Heat pumps and electric resistive heaters will also be deployed in Public and Commercial buildings

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- Each building archetype has a favoured electrified heating system in each scenario, with archetype dimensions reflecting the differing properties of Public and Commercial buildings
- In all scenarios, space constrained buildings can only convert to electric resistive heating
- The deployment of heat networks takes place in urban areas, heat network deployment is focused on larger buildings (representing large commercial spaces such as shopping centres, or large public buildings such as hospitals) which could effectively install a network

	Public				Commercial				Share of electric heating systems[2] (%)	
	Large		Small		Large		Small			
	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Eff.	Ineff.	Heat pumps	Electric resistive
Max Heat Pump	HP	HP	HP	HP	HP	HP	HP	HP	100	0
High Heat Pump	HP	HP/ER[1]	HP	HP	HP	HP/ER[1]	HP	HP	86	14
Balanced Mix	HP	HP/ER[1]	HP	HP/ER[1]	HP	HP/ER[1]	HP	HP/ER[1]	49	51
High Electric Resistive	HP/ER[1]	ER	HP	ER	HP	ER	HP/ER[1]	ER	32	68
Max Electric Resistive	HP/ER[1]	ER	HP/ER[1]	ER	HP/ER[1]	ER	HP/ER[1]	ER	6	94

Abbreviations

Eff.	Efficient	Ineff.	Inefficient	HP	Heat Pump	ER	Electric Resistive

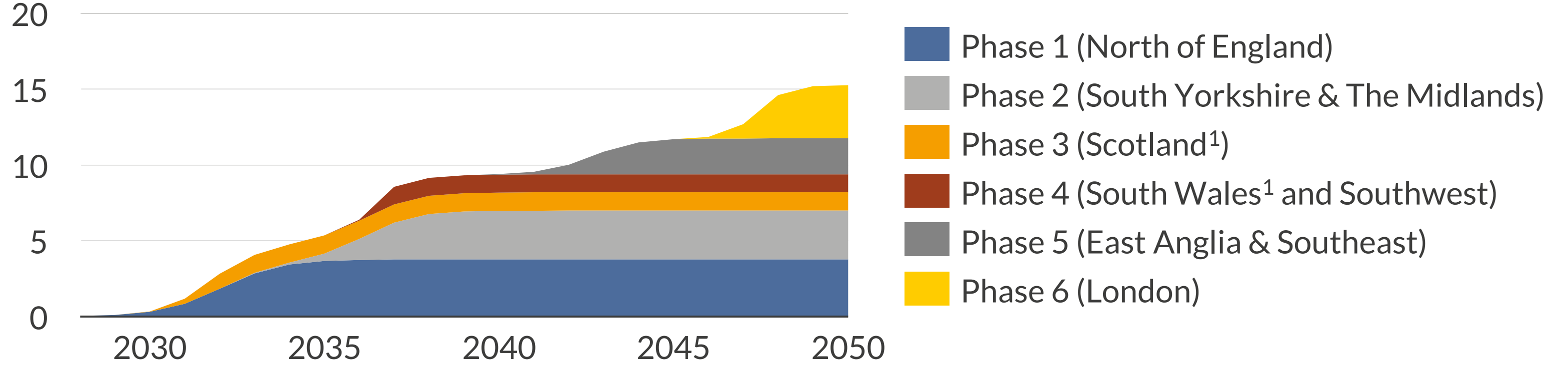
1) The number of inefficient owner-occupied detached/semi-detached houses installing heat pumps and electric resistive heaters varies in these scenarios. 2) The share of deployed electric heating systems, not including electric heat networks, that are either heat pumps or electric resistive systems.

Sources: Aurora Energy Research, NIC

We assume hydrogen deployment will take place on a region-by-region basis, aligned with the deployment timeline in the H21 study

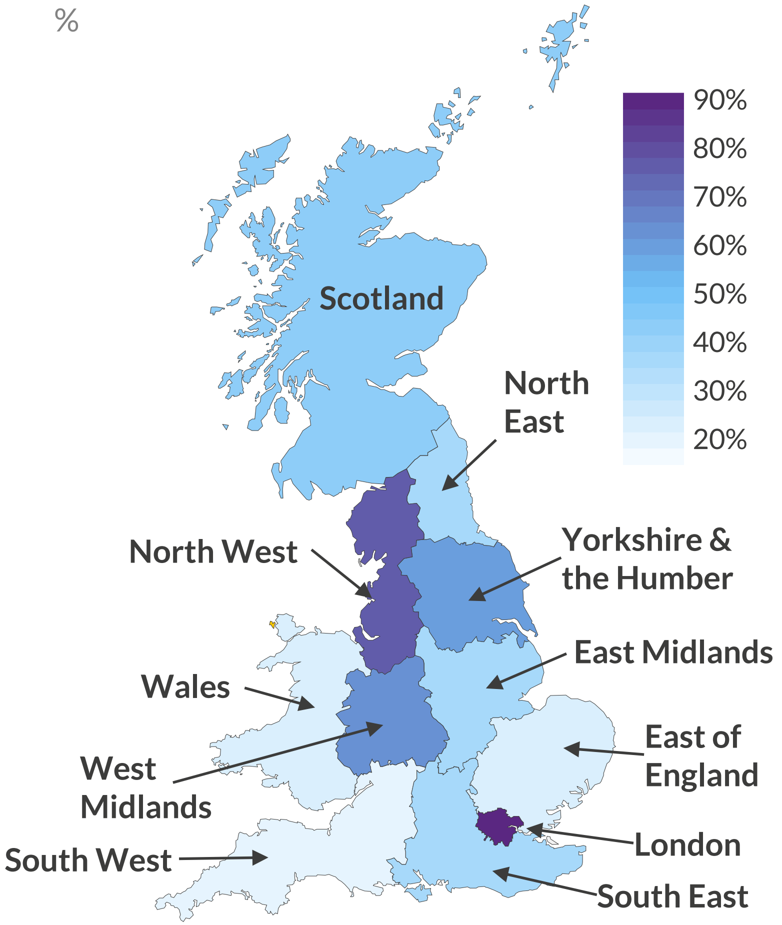
Timeline of homes converted to hydrogen under H21 phases 1 – 6

Million homes



Map showing share of homes in each region[2] converted to hydrogen after H21 Phases 1-6

%



- **We assume hydrogen distribution network deployment will take place at the rate modelled in the H21 study. However, the uptake assumed of hydrogen heating in each of our scenarios diverges from H21, in order to allow CB6[3] targets to be met. In addition, while Phase 1 of H21 is planned to begin in 2028, we delay this by 2 years, in light of delays in the UK's town heating trial, such that no hydrogen is available for heating until 2030.**
- The H21 study is an industry initiative that models the development of six major H2 clusters in the UK, focused around industrial hubs. We use the timings of deployment of the H2 network laid out in the H21 study to inform our assumptions on when consumers in each region will be able to switch to a H2-based heating system.
- We assume homes due for H2 conversion have H2-ready boilers installed in advance; these can be easily switched to H2 as the H2 network is rolled out.
- We model three H2 deployment scenarios: Phase 1, Phases 1-3, and Phases 1-6.
- Only buildings connected to the existing gas grid are assumed to be able to convert to a H2 system. Other buildings decarbonise heating though a balanced mix of electrified heating technologies, and heat network deployment occurs at the same level as for the electrification scenarios.

1) Scotland & Wales not modelled as part of this project. 2) Note regions within Aurora's model do not directly correspond to H21 regions; South Yorkshire & the Humber sees H2 network deployment in both Phase 1 & 2 of H21. 3) 47-62% reduction by 2035 vs 2019 levels.

Sources: H21 North of England Report, Aurora Energy Research

Agenda

AURORA

To understand the range of costs and heat demand for each pathway, we consider key underlying assumptions

AURORA

Input	Assumption	Source
New buildings	• New builds make-up c.12% of the total building stock by 2050 • A proportional share of new buildings is assumed across the building stock archetypes • New buildings are assumed to be high energy efficiency only, in line with government targets	National Grid Future Energy Scenarios (2022)
Retirement rates	• An even age distribution is assumed for existing heat technologies on the system, resulting in a constant retirement rate of heating technologies, so that the same proportion of heating systems within a building type require replacement in any given year	Aurora
Heat networks	• 8.1% of the building stock are assume to be on heat networks by 2050 (from Element Energy's "Barriers" district heating scenario) • All new heat networks are assumed to be low carbon • Existing non-electric heat networks (serving ~60k buildings) decarbonise, via electrification, by 2050	Aurora; Element Energy[1] (2015)
Fuel split	• All buildings connected to the mains gas network have a gas boiler • Share of gas connected buildings varies by subregion according to BEIS LSOA data • Non-gas heating technologies are distributed among the portion of the building stock that is not connected to the gas grid, according to current fuel shares observed in for each building type in each subregion • We assume the same subregional fuel share split for non-residential buildings not connected to gas as for residential buildings	ONS Energy Efficiency of Housing, England and Wales, Local authority districts (2022); BEIS[2] (2022)
Heat demand	• Base assumptions for annual heating demand are taken from the EHS (residential) and VOA (non-residential) data sets • Space constrained buildings have 25% lower heat demand compared to their analogous non-space constrained buildings • Low efficiency buildings (EPC Level D or below) have c.37% higher annual heating demand than high efficiency buildings	Aurora; English Housing Survey – Energy (2022); VOA[3] (2022)
Non-residential buildings	• Commercial and public buildings are represented as a single 'non-residential' building stock, due to lack of extensive data on their individual components • Non-residential stock is split into 2 parts, representing 'small' and 'large' buildings, based on a threshold of 1000m^2 total floor area	Aurora; BEES[4] (2016); VOA[3] (2022)
Efficiency upgrades	• Heat pump installations in inefficient buildings are assumed to be accompanied by energy efficiency upgrades at an average cost of c.£7k/10k/13k per household for flats/terraces/houses	Aurora; English Housing Survey – Energy (2022)
Technology costs	• Residential heating technologies use cost assumptions from Element Energy • Non-residential heat technologies are sized according to non-residential heat demand, and use cost data from EE report where available otherwise costs are scaled based on heat demand	Element Energy[5] (2021); VOA[3] (2022)

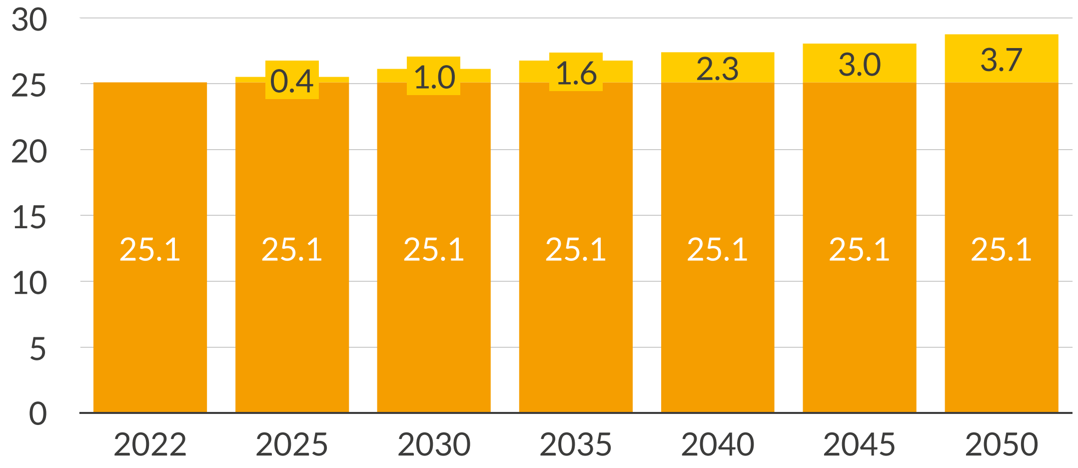
1) "Research on district heating and local approaches to heat decarbonisation", study by Element Energy for the CCC. 2) "Domesitc properties not on the gas grid by Lower Layer Super Output Area, Great Britain, 2015-2020", Department for Business, Energy & Industrial Strategy. 3) "Non-domestic rating: stock of properties including business floorspace, 2022", Valuation Office Agency. 4) "Building Energy Efficiency Survey, 2014-15", Department for Business, Energy & Industrial Strategy. 5) "Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget", report for the Climate Change Committee.

Sources: Aurora Energy Research

Our heat model considers the heating technologies installed in the roughly 25m buildings in England

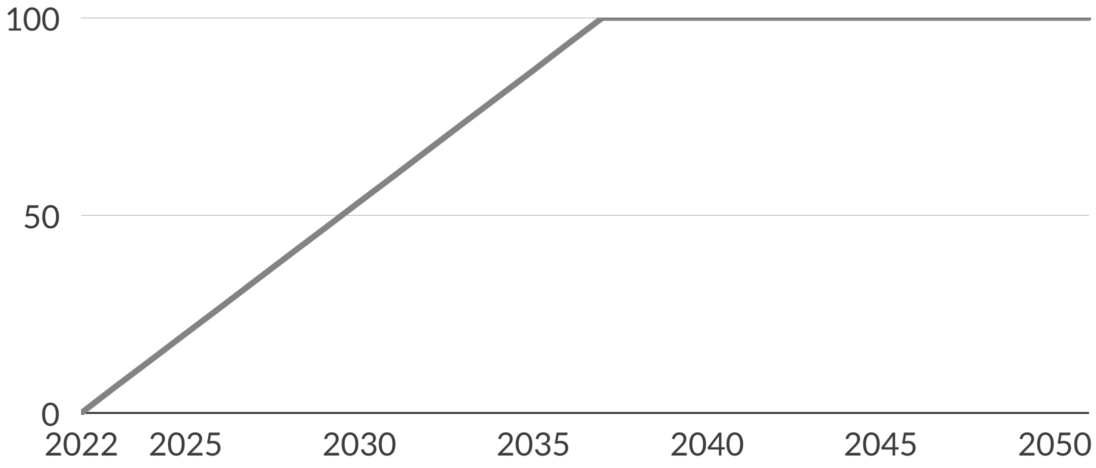
AURORA

Total buildings in England
Millions of buildings



- We model the decarbonisation of the existing c.25 million buildings in England and consider the impact of heating new-builds through low carbon technologies.
- We assume the building demolition rate to be negligible.
- By 2050 we assume an additional 3.7 million buildings have been constructed in England.
- We assume that all new builds from 2022 onwards are energy efficient, aligned with government targets.

Retirement profile of existing heat technologies (excluding heat networks)
% of original



- We assume a linear retirement rate of existing heating technologies, such that the number of units that are replaced each year is constant.
- We assume that most technologies (other than heat networks) have a 15-year lifetime, such that by 2037 all existing units will require replacing.
- Consumers have a choice as to whether to replace the existing system on a like-for-like basis or whether to install a low carbon system, which means that higher carbon technologies remain on the system over the forecast horizon. However, this choice is constrained by the input assumption that all scenarios meet emissions targets in 2035 and 2050.

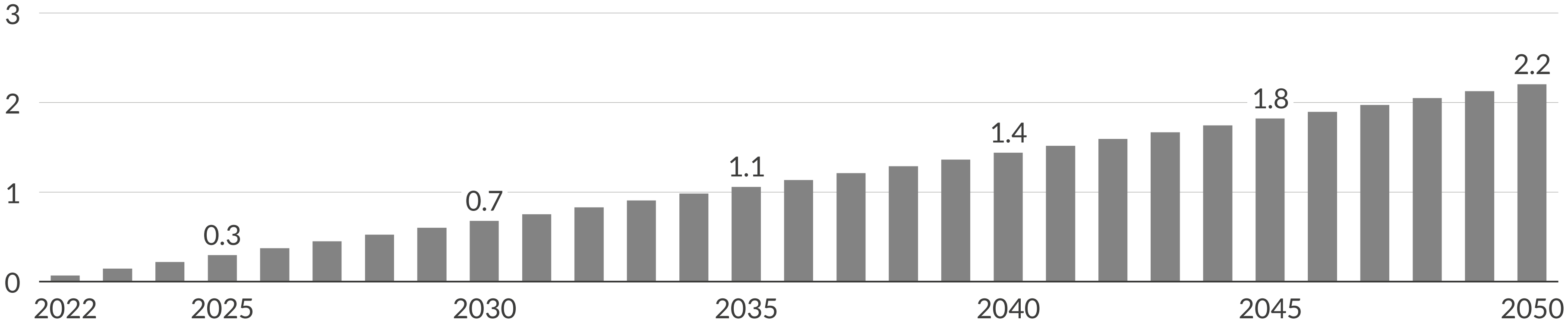
Existing | Cumulative new build since 2022

Sources: English Housing Survey, Welsh Housing Conditions Survey, Scottish House Condition Survey, NGESO FES2020, ONS

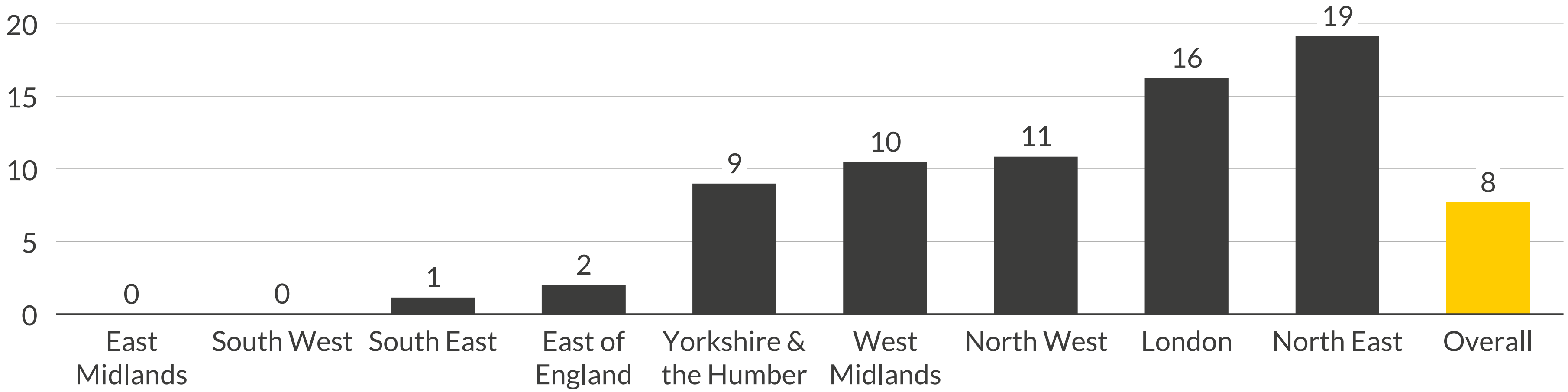
We assume c.8% of English buildings will be connected to a heat network by 2050

AURORA

Timeline of buildings connected to heat networks
Millions of buildings



Proportion of homes connected to heat networks in 2050, by region
%



Sources: CCC, BEIS, ONS

Assumptions:

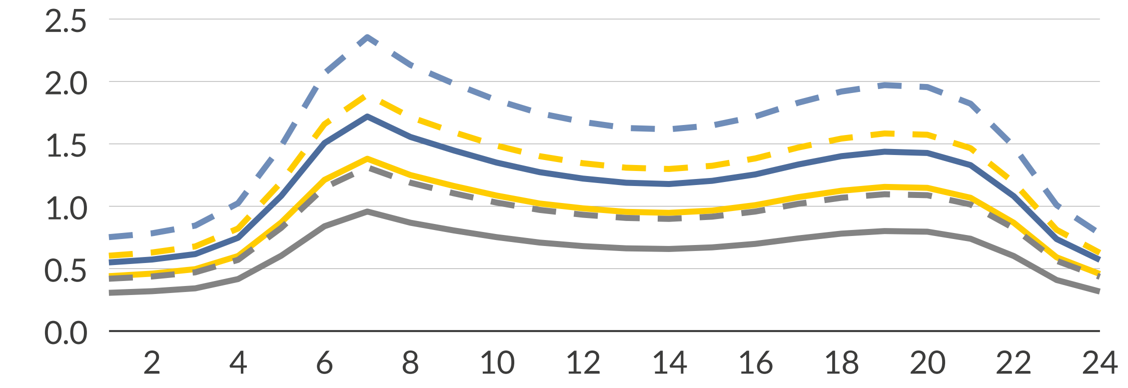
- In line with the CCC "barriers" scenario, we assume c.8% of homes will have their heating demand met through heat networks by 2050, and assume the deployment of heat network in Public/Commercial buildings will follow the same trajectory.
- Current heat networks are apportioned to regions based on historic data from BEIS.
- Future heat networks are apportioned to regions in proportion to the urban population of each region. After the urban rating is accounted for, we assume a similar deployment of heat networks across building archetypes.

Peak heating demand is derived from hourly heat demand profiles; these are differentiated across building types

AURORA

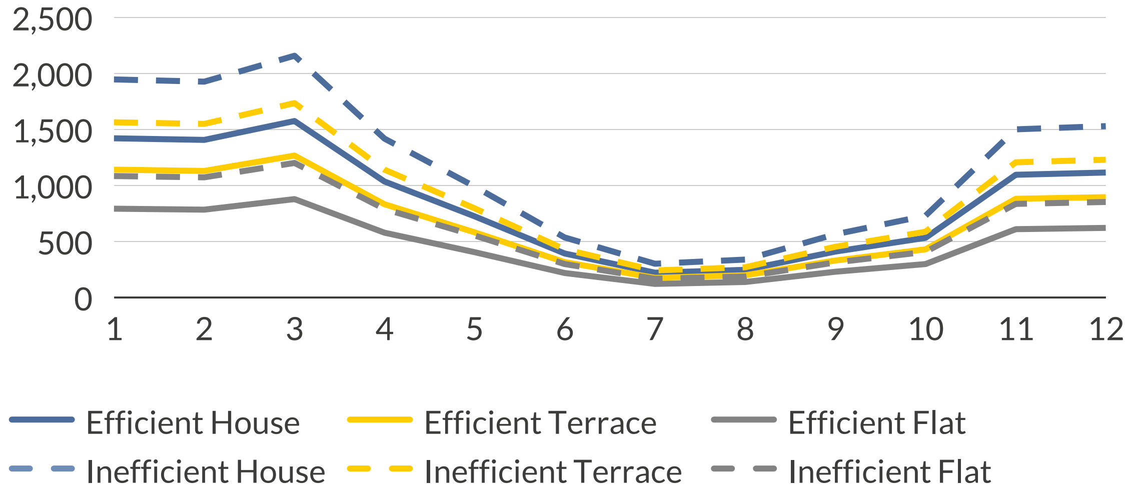
Average hourly home heat demand

kWh_{th}



Average monthly home heat demand

MWh_{th}



- Demand for heating varies on an hourly level, with higher demand in the morning and evening, as well as seasonally, with demand in winter far exceeding that in summer.
- Peak demand for heating occurs during the winter, and hourly heat demand profiles are used to determine the contribution towards total peak heating demand that is made up of different heating technologies in each segment of the building stock.
- The hourly heat demand profiles used in this study are taken from a combination of:
  - Normalised hourly pattern from simulated data (Ruhnau et al, 2019), and
  - Base annual heat demand from the English Housing Survey.
- Each efficient building has the following base heat demand assumptions for both space heating and hot water:
  - House: 10.1 MWh/year
  - Terrace: 8.2 MWh/year
  - Flat: 5.7 MWh/year
- Inefficient buildings have c.37% higher base heat demand than efficient buildings, while demand in Public/Commercial buildings is scaled up in proportion to their floor area (hourly heat demand profiles are assumed to be similar).

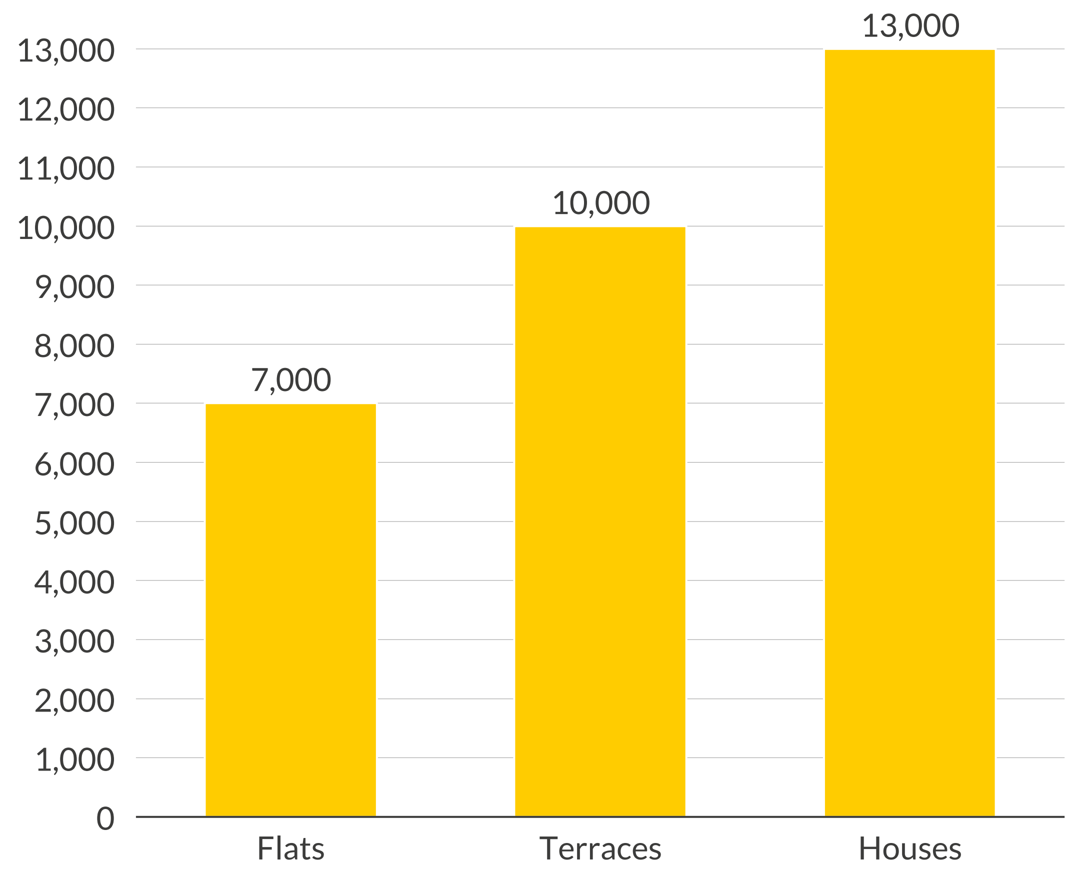
Sources: BEIS, English Housing Survey, National Energy Efficiency Data Framework, Ruhnau, O., Hirth, L., and Praktiknjo, A. (2019). Time series of heat demand and heat pump efficiency for energy system modeling. Scientific Data, 6, 189

Low efficiency buildings installing heat pumps must first undertake an energy efficiency upgrade procedure

AURORA

- The Microgeneration Certification Scheme (MCS)[1] guidance recommends that homes with a peak heat loss rate exceeding 100 W/m^2 may face challenges with the efficient operation of heat pumps.
- Specifically, without any mitigating measures (such as improved insulation), a home will require a backup heating source or encounter insufficient heating when running a standard heat pump at 45˚C to heat a home to the average temperature of 19˚C for an extreme cold day with regional external temperatures varying from -2˚C to -6˚C.
- To account for these challenges in our modelling, we have assumed that inefficient homes, with a peak heat loss rate of greater than 100 W/m^2 (represented by having an EPC Level D or below), cannot install a heat pump without also installing a standard energy efficiency upgrade package.
- We assume the cost of the standard energy efficiency package to differ by building type, and costs are aligned with English Housing Survey data and Element Energy's standard high package from their work for the 6th Carbon Budget (c.£12.5k):
  - £7k (flats)
  - £10k (terraces)
  - £13k (semi-detached/detached houses)
- Installation of the standard energy efficiency upgrade package lowers the building's annual heating demand in line with its efficient counterpart.

Cost of standard energy efficiency upgrade packages
£ (real 2021)

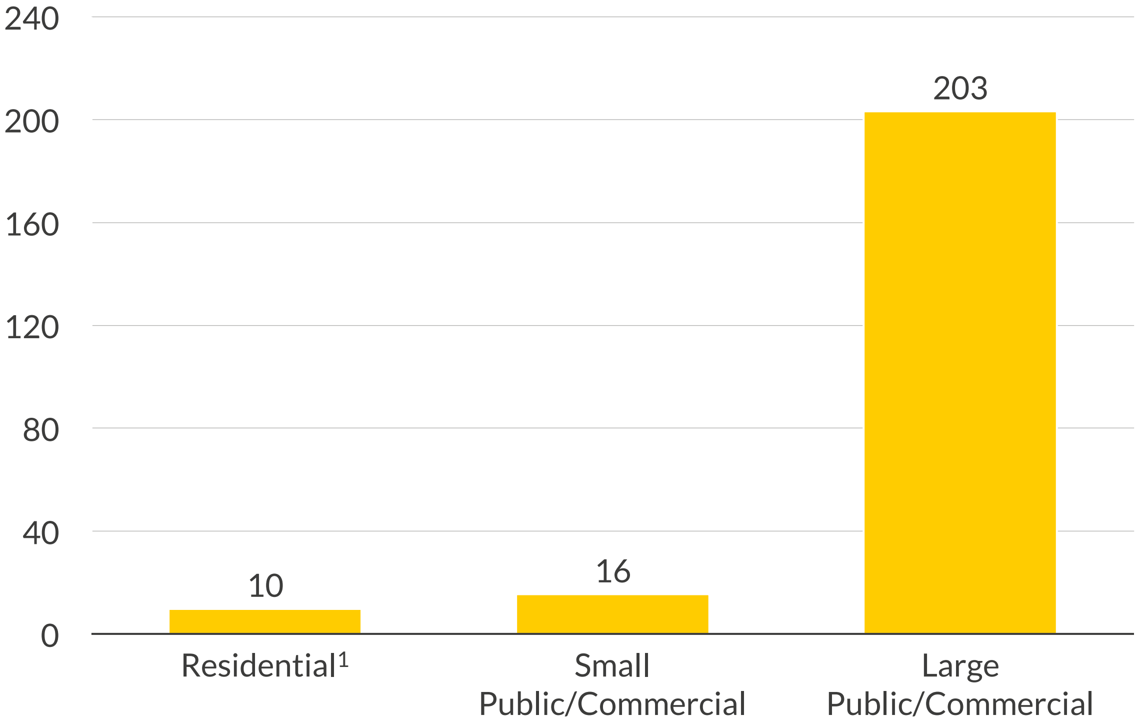


1) The UK standards organisation which certifies low-carbon products and installations, such as air source heat pumps

Sources: MCS, BEIS, CCC, Element Energy

Average annual heat demand for Public/Commercial and Residential buildings are used to determined the required capacity of a heating technology

Average annual heat demand
MWh/ year



- Average annual heat demand for large and small Public/Commercial buildings are assumed to be c.20x and 1.6x that of Residential buildings respectively, based on average building sizes
- These average heat demand ratios are used to scale up the capacity of the heating technology required for Public/Commercial buildings

Heat technology capacity requirements
kW

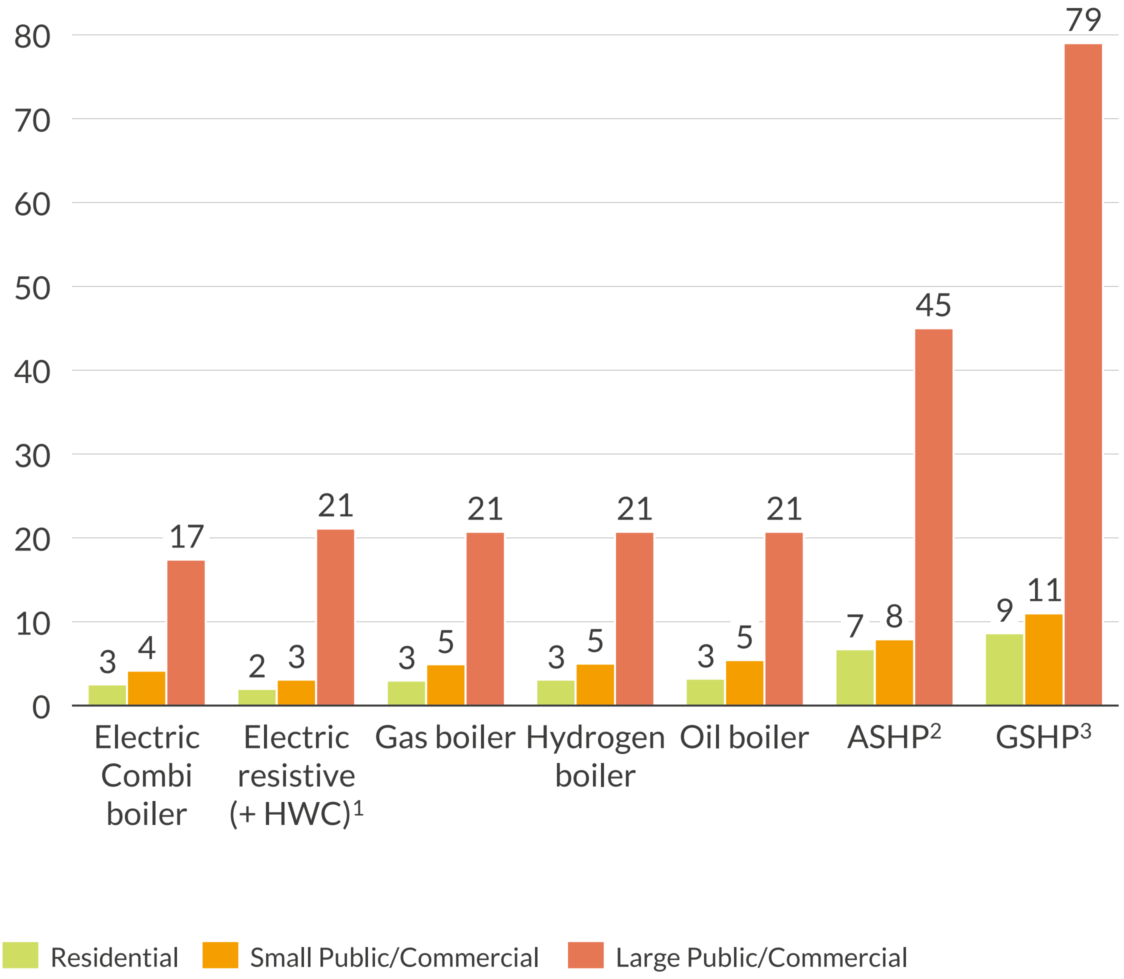
	Building sector		
Technology	Residential	Small Public/ Commercial	Large Public/ Commercial
Gas boiler	24	40	500
Oil boiler	24	40	500
Hydrogen boiler	24	40	500
Electric Combi boiler	24	40	500
Ground source heat pump	5	8	100
Air source heat pump	5	8	100
Electric resistive (+ hot water cylinder)	5	8	100

1) Reflects average of heat demand for flats, terraces and houses

Source: Aurora Energy Research

CAPEX costs of heating technologies for Public/Commercial buildings are scaled up in line with their variation in annual heat demand

CAPEX of heating technologies
£000's (real 2021)



- Heating technologies for Public/Commercial buildings require a larger capacity to meet the higher heating demand of these buildings, and their costs are scaled accordingly, where cost data is not directly available. Cost assumptions are benchmarked against existing products on the market where data is available.
- As well as CAPEX costs, OPEX and transition costs are also scaled up in line with the ratio of annual average heating demand.

1) Hot water cylinder provides water heating. 2) Air source heat pump. 3) Ground source heat pump.

Source: Aurora Energy Research

Agenda

Higher penetration of heat pumps results in reduced electricity demand and peak demand, reduced total costs and reduced emissions

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Power Demand

- Increasing levels of electric resistive heating deployment leads to higher overall power demand for heating and therefore would require a larger power system overall.
- By 2050 the Max Electric Resistive scenario has 270% higher total power demand compared to the Max Heat Pump scenario. Decarbonisation through electrification relies on the decarbonisation of the power sector, meaning a significantly higher deployment of renewables and low carbon capacity would be required.

Peak Demand

- Increasing levels of electric resistive heating also increases peak demand, and therefore the amount of peaking capacity that would be required on the system.
- By 2050 the Max Electric Resistive scenario has 410% higher peak power demand compared to the Max Heat Pump scenario, substantially increasing the amount of flexible capacity required and increasing system operability challenges.

Emissions

- Higher power demand in scenarios with higher electric resistive deployment results in higher emissions, although CB6 targets[1] are meet in all scenarios.
- We assume power sector emissions intensities are consistent across scenarios, however the higher levels of demand and peak demand in scenarios with higher levels of electric resistive heating would mean that substantially higher levels of renewable and low carbon flexible capacities would be required in order for this to be achieved.

System Costs

- Higher electric resistive penetration leads to higher costs for the heating sector overall, due to the lower efficiencies of electric resistive heating compared to heat pumps.
- Electricity costs (including transmission and distribution costs) are assumed to be consistent across all scenarios, however the larger power sector required for high levels of electric resistive deployment would be expected to increase costs for these scenarios further. Note, however, that total power system costs are not included in results.
- Regional variations in power demand and peak power demand are also likely to lead to higher levels of transmission network charges, and could lead to higher levels of distribution charges, particularly regions with high peak demand, such as London and the South East.

Costs to consumers

- Upfront costs to consumers are significantly reduced with higher electric resistive deployment due to the cheaper technology cost and reduced efficiency requirements for homes. However, this is more than offset by the high running costs of electric resistive heaters.

1) 47-62% reduction by 2035 vs 2019 levels

Source: Aurora Energy Research

By 2050, hydrogen deployment results in higher costs, higher emissions, and higher overall power demand, but lower peak demand

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Power Demand

- Increasing levels of H2 deployment reduces the direct electricity demand for heating. However, H2 is assumed to be produced through a combination of blue H2 and electrolytic H2, the proportions of which are consistent across scenarios. Therefore, higher H2 deployment would see higher demand for electrolysis and would require a larger power sector overall.
- Additional deployment of renewables and low carbon capacity would be required to produce additional low carbon electrolytic hydrogen for use in the heating sector.

Peak Demand

- Increasing H2 deployment reduces the level of peak electricity demand, reducing the flexible capacity required. Reduced peak demand also helps system operability.

Emissions

- More rapid emissions reductions can be achieved through the deployment of H2 in heating, which allows all buildings connected to the gas network to be converted to decarbonised heating in bulk. However, for 2035 emissions reductions targets to be met, the decarbonisation of buildings in regions outside the North of England, where H2 is deployed post-2035, is also required through electrification, which then reduces the number of buildings that can later be converted to H2.
- By 2050, emissions are higher in scenarios with high H2 deployment, driven by residual emissions from blue H2 and from power sector emissions. The carbon intensity of H2 is assumed to be consistent across all scenarios. However, where higher volumes of H2 are deployed, increased renewable deployment would be needed.

System Costs

- The high fuel cost for H2 means the total system costs for heating are higher with higher H2 deployment.
- H2 and power costs are assumed to be consistent across scenarios. However, H2 distribution costs may vary substantially on a regional level, as the different pace of rollout of the H2 distribution network results in proportionally different numbers of buildings being connected, compared to the size of the network that needs to be maintained (note that hydrogen network costs are not modelled). Higher H2 deployment reduces peak electricity demand, especially in regions with early H2 deployment, which could reduce electricity distribution costs.
- Therefore regions with later H2 rollout could face both higher H2 and higher electricity distribution costs compared to regions with earlier deployment.
- London and the South East see lower levels of H2 roll out in all scenarios as the network is deployed here later. This leads to higher power and peak power demand in these regions, potentially leading to higher power transmission and distribution costs, and also higher H2 distribution costs as the number of households H2 is being supplied to is reduced.

Costs to consumers

- Consumers face higher costs as a result of hydrogen deployment, driven by the high fuel cost for hydrogen production, potentially high distribution costs, and increased costs through the requirements for a larger power sector.
- Additional expenditure may also be required as the full cost of the hydrogen network is not considered here.

Source: Aurora Energy Research

Agenda

Electrification scenarios

The assumed uptake of electrified heating means 44% of buildings have a gas or other form of non-decarbonised heating system by 2035

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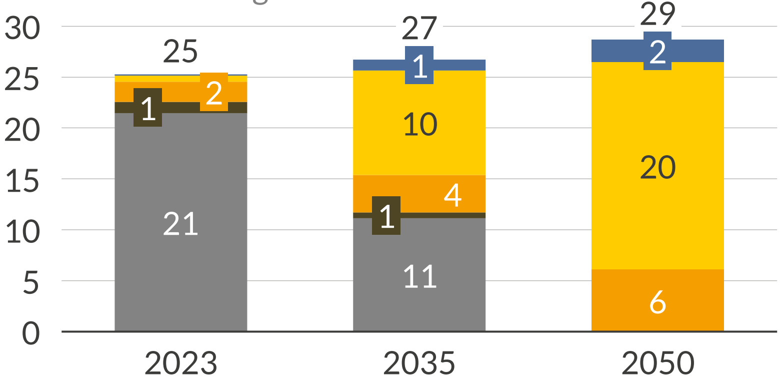
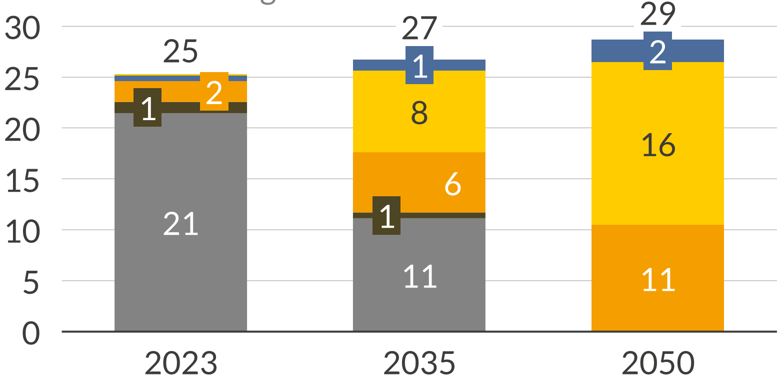
Max Heat Pump

Technology installed
Millions of buildings



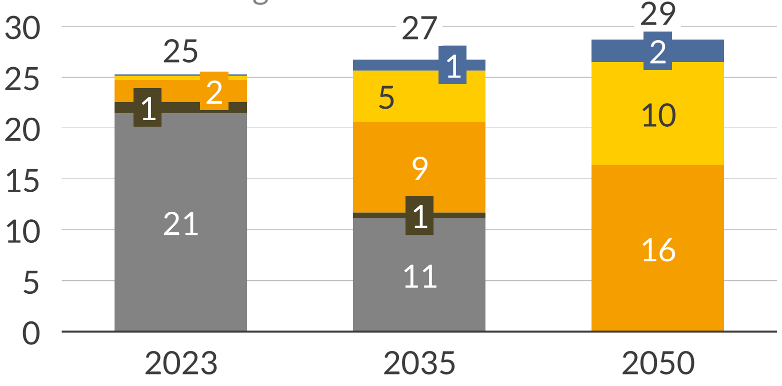
High Heat Pump

Technology installed
Millions of buildings



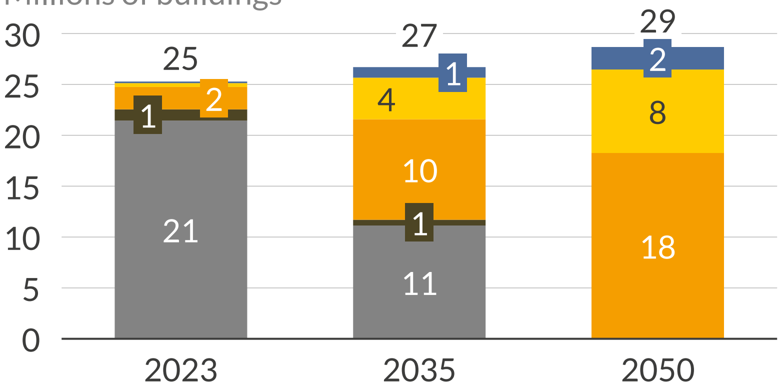
Balanced Mix

Technology installed
Millions of buildings



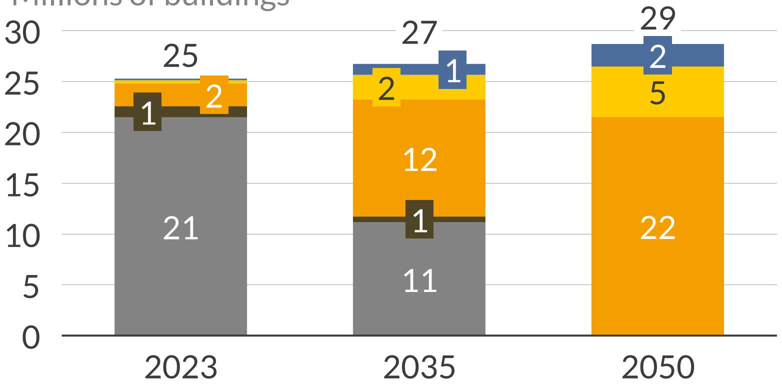
High Electric Resistive

Technology installed
Millions of buildings



Max Electric Resistive

Technology installed
Millions of buildings



Heat networks | Heat pumps | Electric resistive | Oil boilers | Gas boilers

- In 2023, 89% of all buildings have fossil boilers. By 2035, this falls to 44% in all electrification scenarios in order to meet CB6 targets[1].
- By 2050 we assume all buildings have installed a decarbonised heating technology.
- We assume all building archetypes decarbonise at the same pace.
- The deployment of electric heating takes place on a continuous basis. We do not model the impact of any decommissioning of gas distribution networks, which might take place when penetration of gas as a heat source for individual buildings reaches a certain threshold.

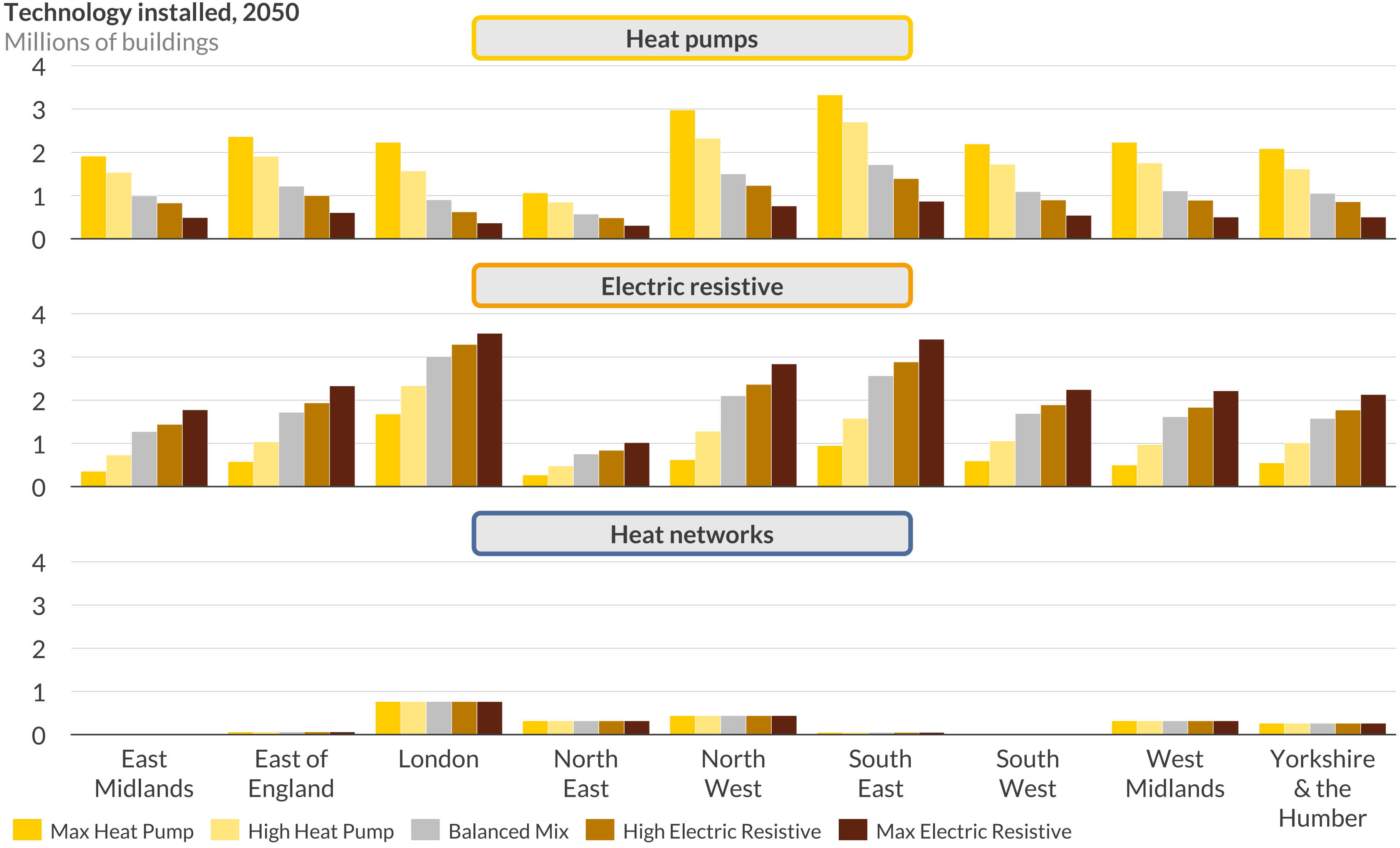
1) 47-62% reduction by 2035 vs 2019 levels

Sources: Aurora Energy Research, NIC

Electrification scenarios

The distribution of electrified heating technologies by region is determined by the regional building stock characteristics (1/2)

Technology installed, 2050
Millions of buildings



Heat pumps

- The highest number of heat pumps are seen in the South East and North West, driven by the high number of buildings in these regions.

Electric resistive

- The highest level of electric resistive heating is seen in London, which has a high number of space constrained buildings which cannot install heat pumps in any scenario. High levels of electric resistive heating are also seen in the North West and South East, driven by the high number of buildings in these regions.

Heat networks

- The highest level of heat network deployment is seen in London. Deployment takes place where buildings have a high urban rating, resulting in limited deployment in the South West, South East, East Midlands and East of England.

Sources: Aurora Energy Research

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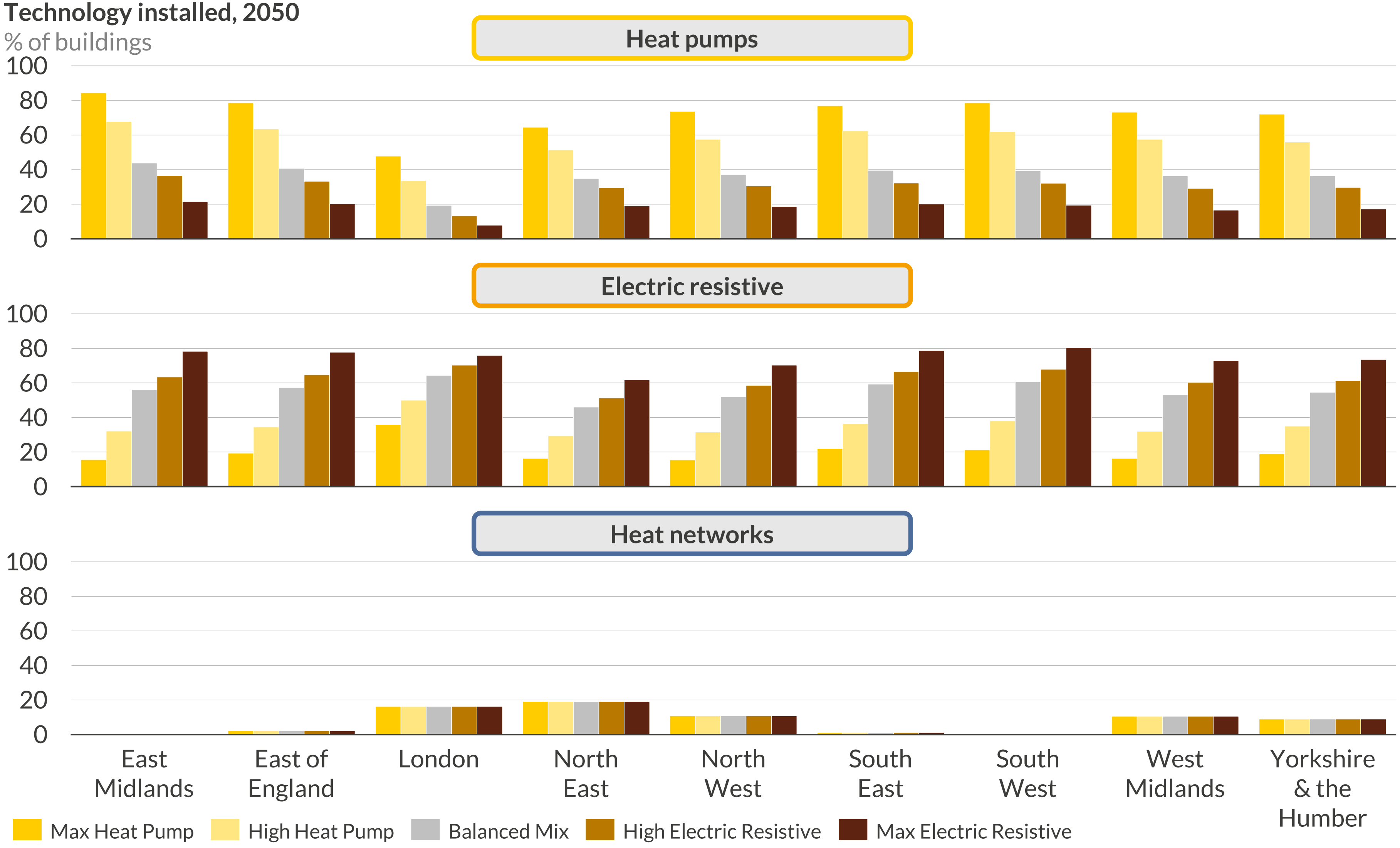
The distribution of electrified heating technologies by region is determined by the regional building stock characteristics (2/2)

Technology installed, 2050
% of buildings



Sources: Aurora Energy Research

Heat pumps

- The East Midlands, East of England and South West have the highest share of heat pumps. This results from a higher proportion of detached/ semi-detached houses, and higher owner-occupancy, plus lower urban ratings and so reduced heat network roll out.

Electric resistive

- In Max Heat Pump, London has the highest share of electric resistive heating, installed in space constrained buildings. In High/Max Electric Resistive, regions with low urban ratings have higher elective resistive deployment, as fewer heat networks are installed.

Heat networks

- London and the North East see higher shares of heat networks. In the North East, buildings are concentrated in the Newcastle area, meaning a high proportion have a high urban rating.

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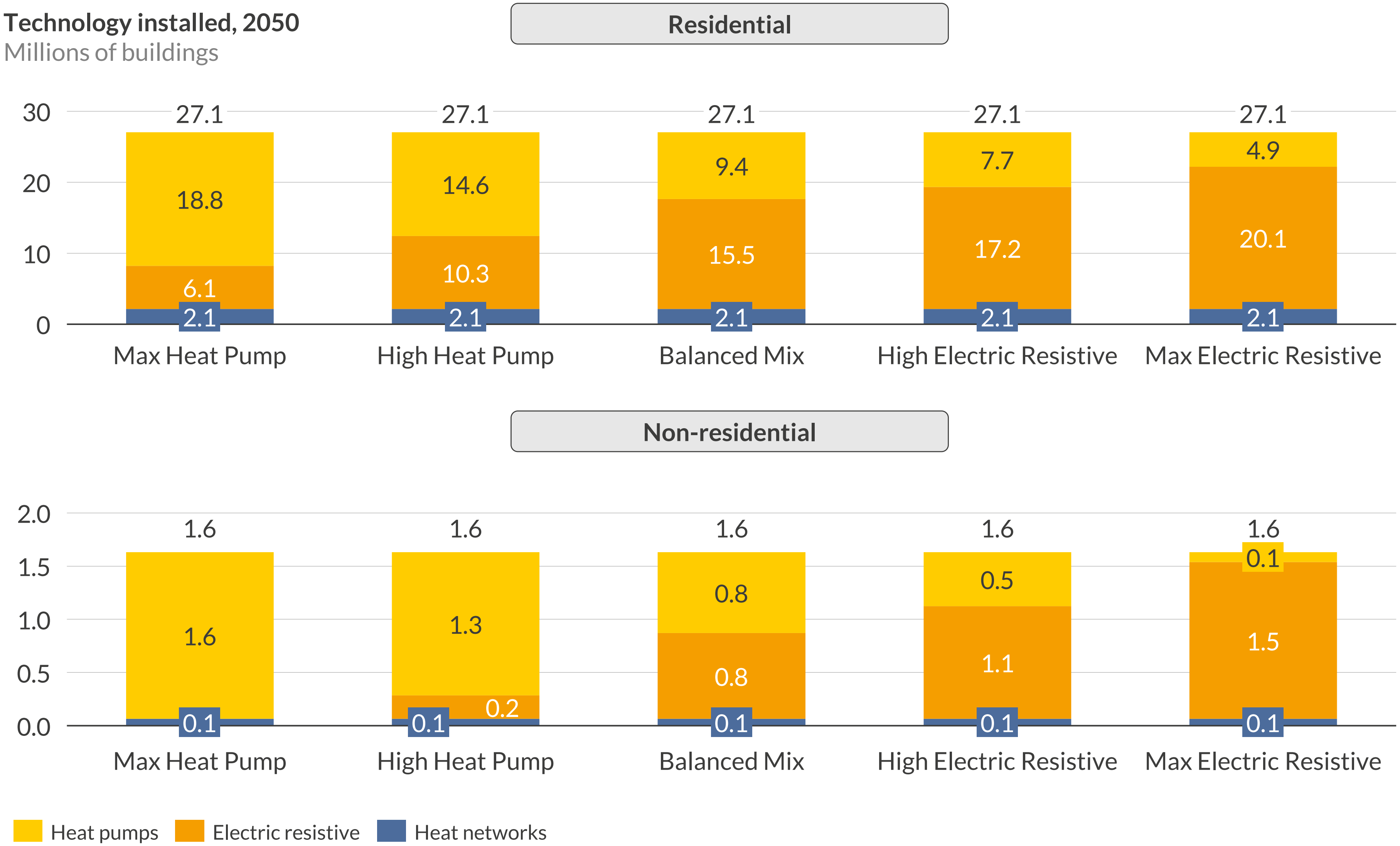
Non-residential buildings are also able to decarbonise via electrification

Technology installed, 2050
Millions of buildings



1) Except in Max electric resistive

Sources: Aurora Energy Research,

Heat pumps

- Non-residential buildings see a higher proportion of heat pumps in every scenario except Max electric resistive compared to residential buildings. This is because fewer non-residential buildings are space constrained, so face fewer technical barriers to heat pump installation.

Electric resistive heating

- Non-residential buildings see a lower share of electric resistive heaters, as there are fewer space constrained non-residential buildings. It may also be easier for public/commercial building owners to choose to install heat pumps despite high upfront costs.

Heat networks

- Heat networks are also deployed in non-residential buildings. We assume these to be used in larger buildings, such as shopping centres or hospitals.

The uptake of decarbonised heating means 35% of buildings have gas or other form of non-decarbonised heating system by 2035 in the H2 scenarios

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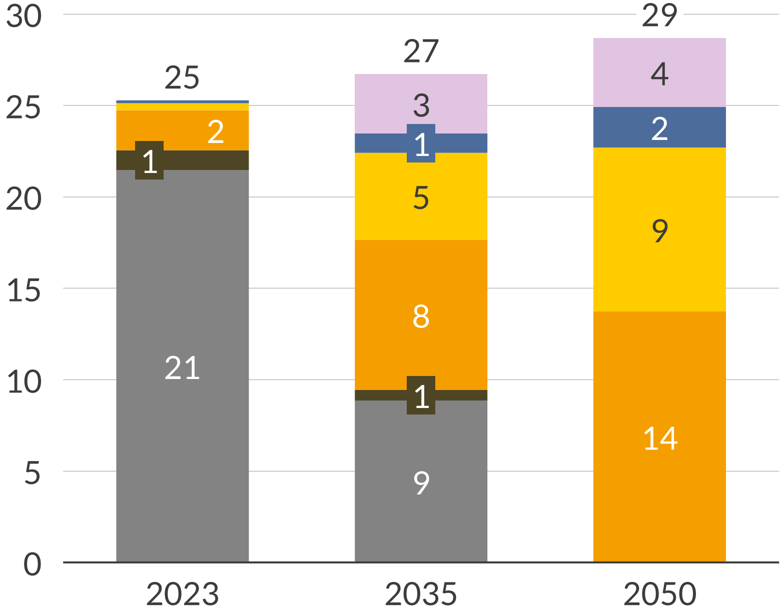
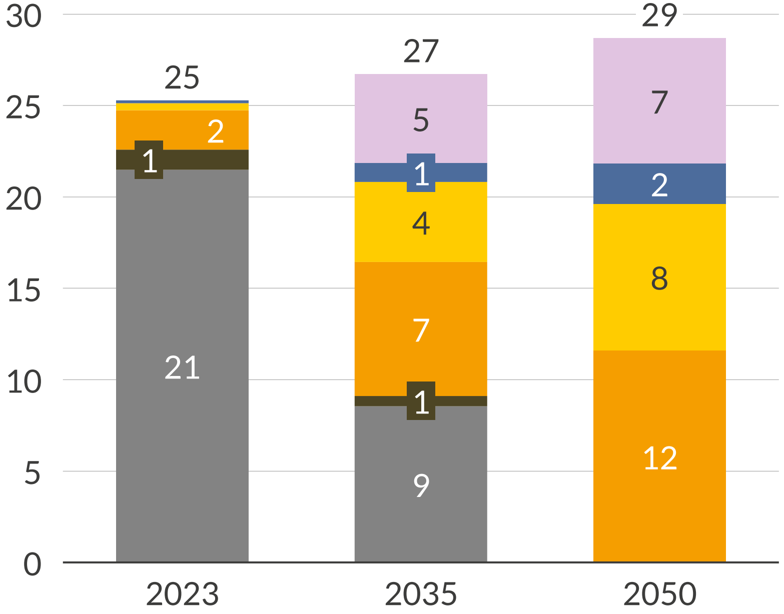
Low H2 (H21 Phase 1)

Buildings with each technology installed
Millions of buildings



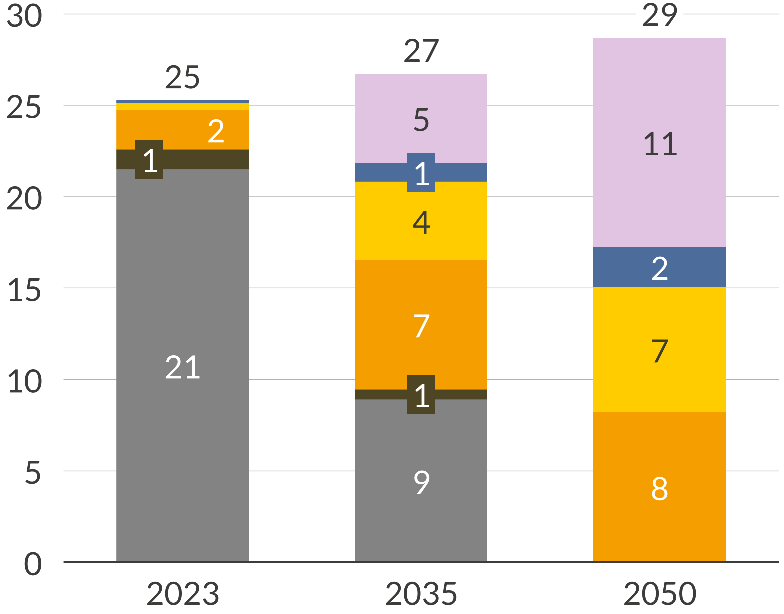
Mid H2 (H21 Phases 1-3)

Buildings with each technology installed
Millions of buildings



High H2 (H21 Phases 1-6)

Buildings with each technology installed
Millions of buildings



- By 2050, 40% of English buildings (11.4 million) in the H21 Phase 1-6 (Max H2) scenario are connected to the hydrogen network. This compares to c.13.5 million English buildings in the H21 study.
- H21 deployment ambitions, on a buildings connected to the H2 network basis, are not met as the pace of deployment of the hydrogen distribution network means that hydrogen is not available in many buildings until after 2035. In order to meet 2035 targets for the decarbonisation of heating set out by CB6[1], electrification of heating is therefore also required. We assume that once electrification has taken place, buildings would not convert back to a gas/hydrogen-based system.
- The mass conversion to hydrogen of buildings in the North of England under H21 Phase 1 results in more buildings having converted to low carbon heating by 2035 in the hydrogen scenarios, compared to the electrification scenarios.

Hydrogen boilers | Heat networks | Heat pumps | Electric resistive | Oil boilers | Gas boilers

1) 47-62% reduction by 2035 vs 2019 levels

Sources: Aurora Energy Research, H21

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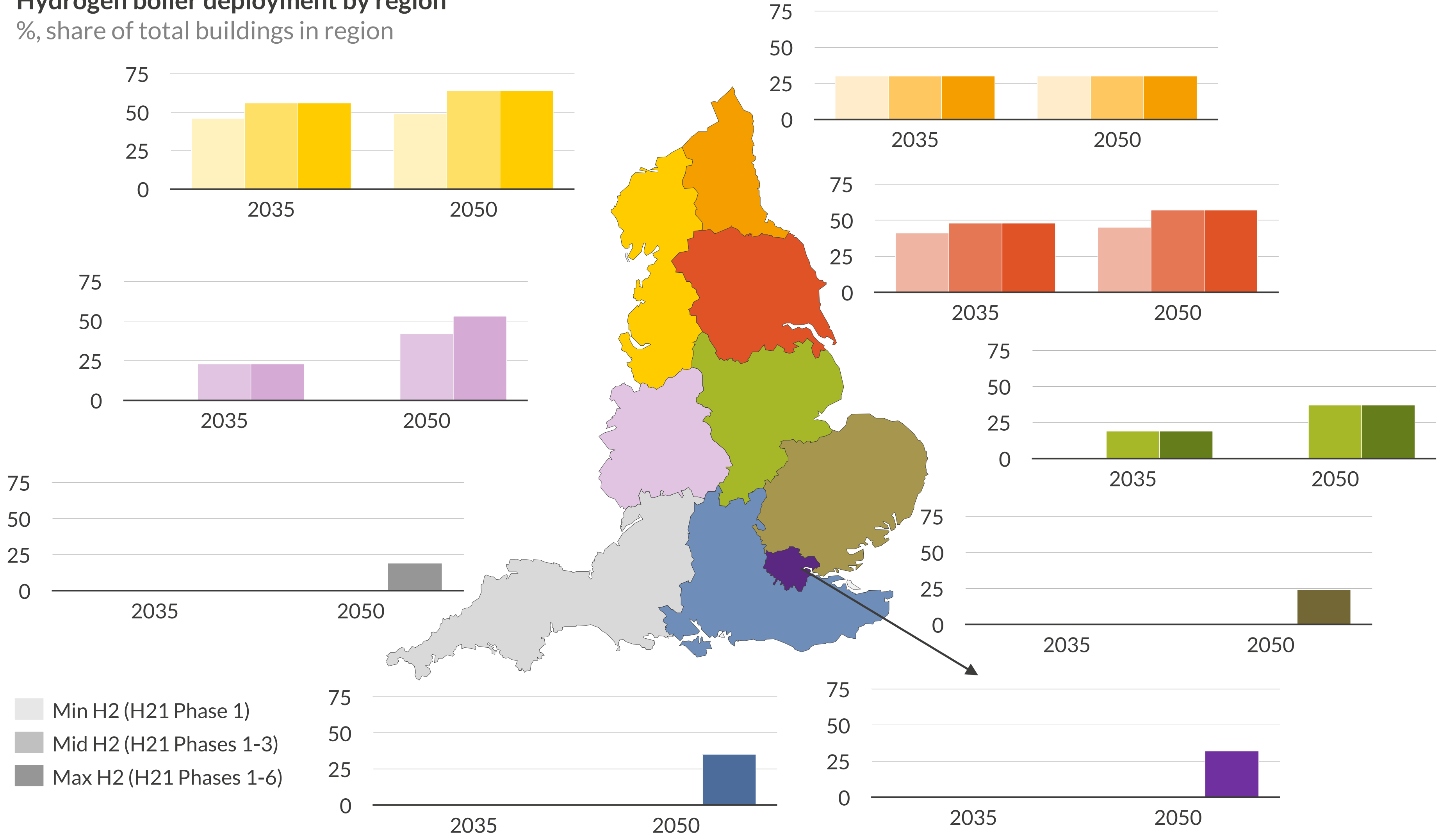
Regional variations in hydrogen uptake are driven by the pace of deployment of the hydrogen distribution network

Hydrogen boiler deployment by region
%, share of total buildings in region

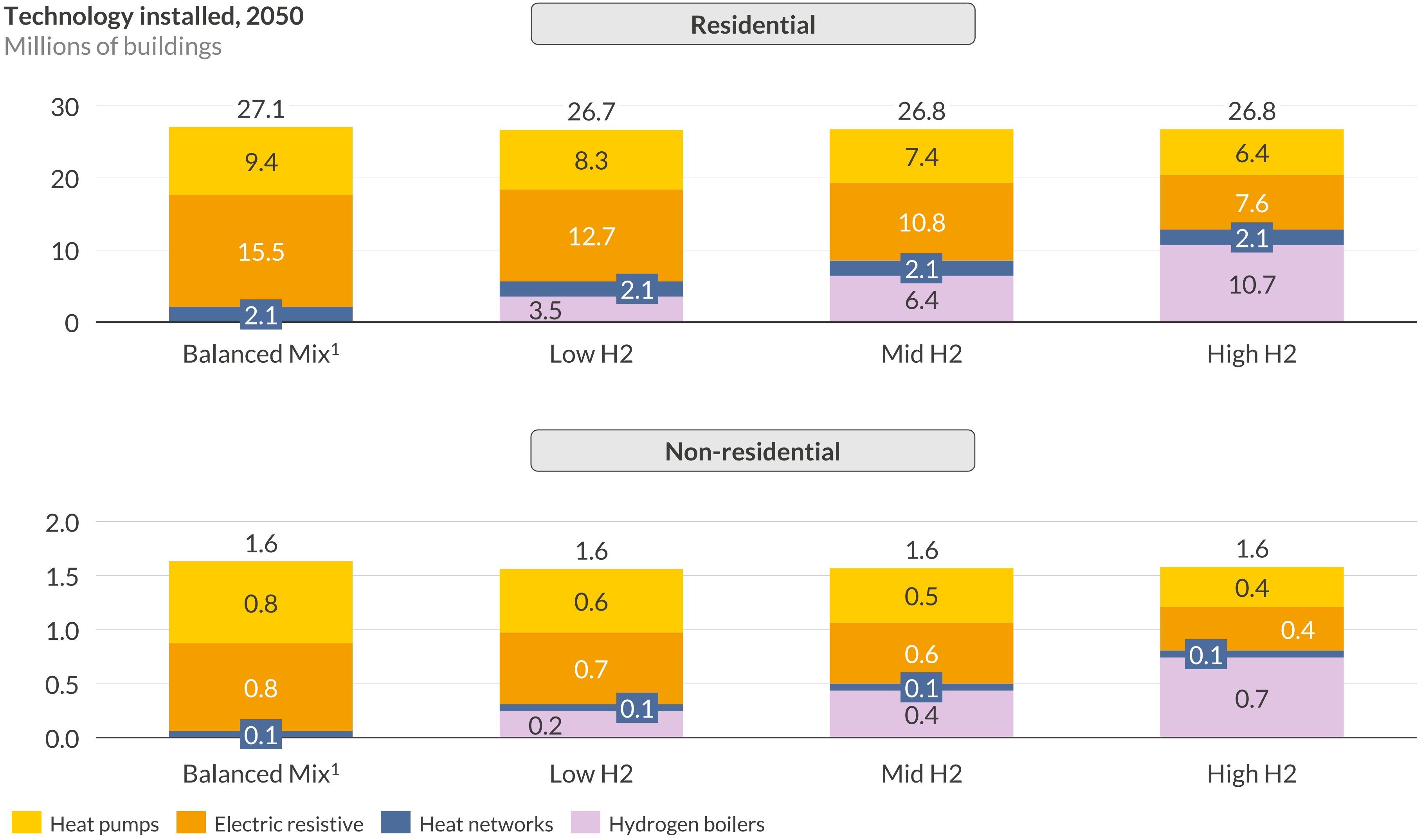


- Hydrogen uptake varies significantly on a regional basis, driven by the pace of roll out of the hydrogen network in each region, and is a result of scenario design based on the H21 study, rather than a modelled outcome. The number of gas grid connected buildings also impacts the total number of buildings that have the option to decarbonise using hydrogen.
- Regions in the South, in particular the South West and East Anglia, see lower levels of hydrogen uptake (as a proportion of the total number of buildings) compared to the Northwest and Yorkshire & the Humber, as hydrogen is not available in these regions until the 2040s, when many buildings have already decarbonized via other mechanisms.

Sources: Aurora Energy Research, H21

Non-residential buildings see a higher deployment of hydrogen compared to residential buildings

Technology installed, 2050
Millions of buildings



- A higher proportion of non-residential buildings convert to hydrogen compared to residential buildings in all scenarios, despite the fact that fewer non-residential buildings are connected to the gas network. This is because the larger average sizes and lower efficiencies of some non-residential buildings means hydrogen is a more attractive choice compared to electrification.

1) Balanced Mix scenario has no hydrogen for heating

Sources: Aurora Energy Research, NGESO, EE

Agenda

AURORA

All scenarios

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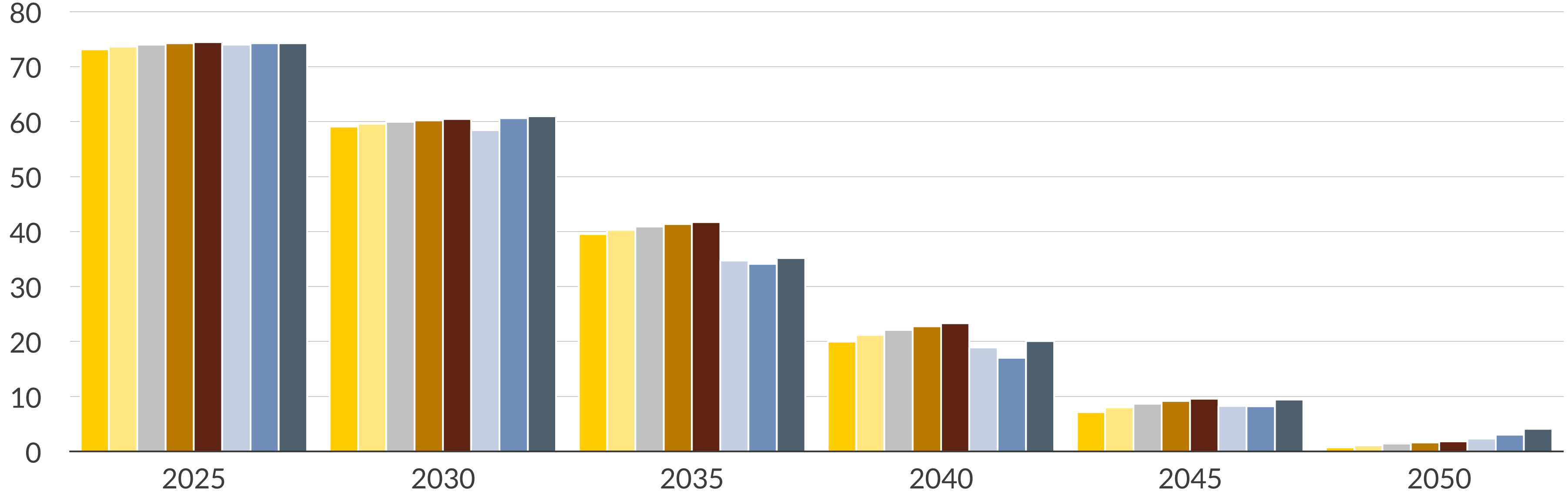
H2 scenarios see faster emissions reductions due to accelerated retirement/replacement of gas, but have higher long term emissions

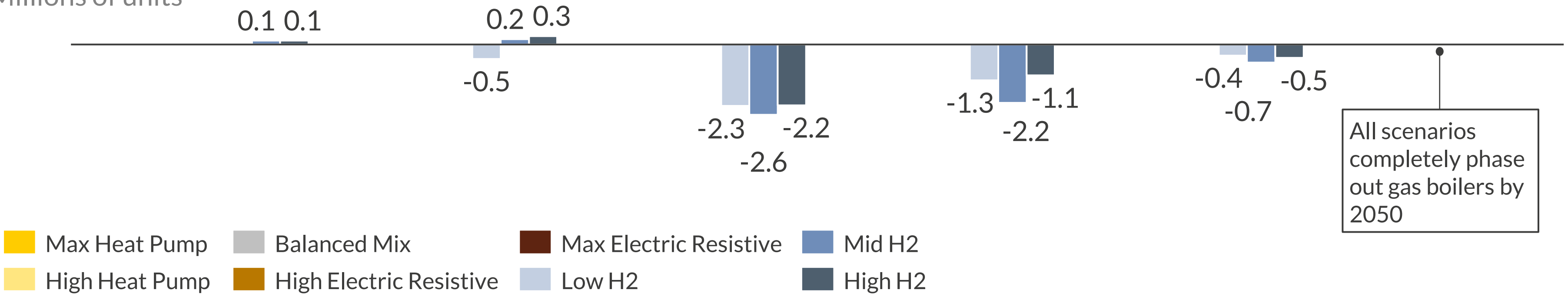
Carbon emissions from heat sector[1]

$MtCO_2e$/year



Delta in number of gas boilers, relative to the number deployed in the Balanced Mix scenario

Millions of units



- The assumed roll out of H2 for heat means a higher level of emissions reduction is achieved by 2035, as the conversion of gas-connected buildings to H2 in the North of England takes place by this date, while regions without H2 proceed with electrification at a similar rate as in the Balanced Mix scenario.
- However, by 2050, scenarios with H2 for heating see higher emissions resulting from emissions from production of blue and electrolytic H2[2].
- Higher deployment of heat pumps reduces emissions, due to their reduced electricity consumption compared to electric resistive heaters.
- In all scenarios, the carbon intensity of power and H2 (where deployed) is assumed to be the same. In reality, higher roll out of electric resistive heat would require a larger power sector with more peaking assets, likely increasing emissions further.

1) Includes contribution of emissions from electricity used in heating (see appendix for power sector carbon emissions trajectory. 2) Assuming a 90% carbon capture rate for blue hydrogen production. Emissions from production of electrolytic hydrogen calculated based on carbon intensity of the power sector, however trajectory does not account for the different size of power sector required in some scenarios).

Source: Aurora Energy Research

All scenarios

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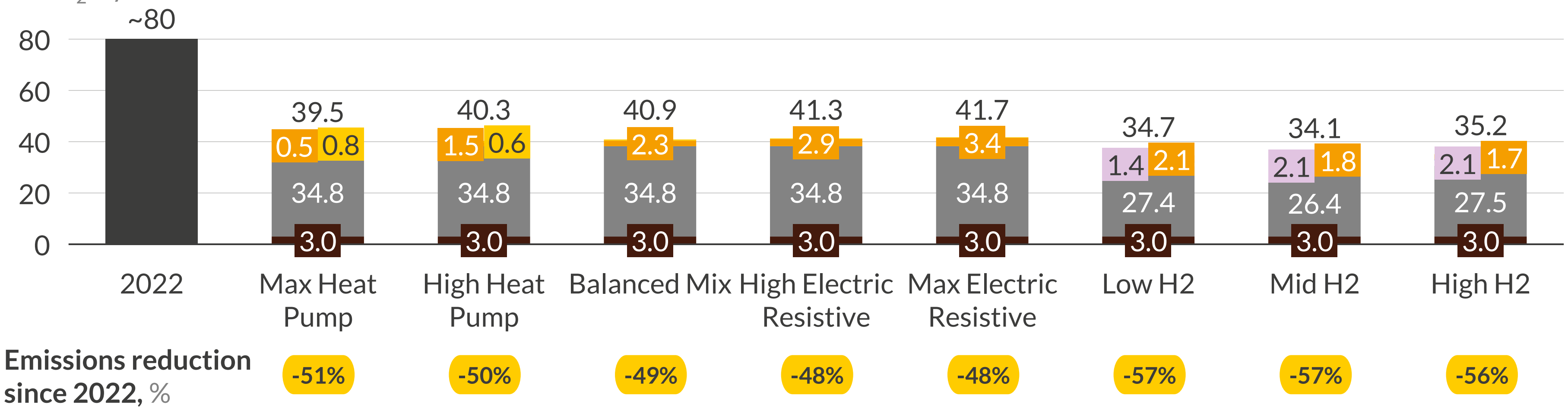
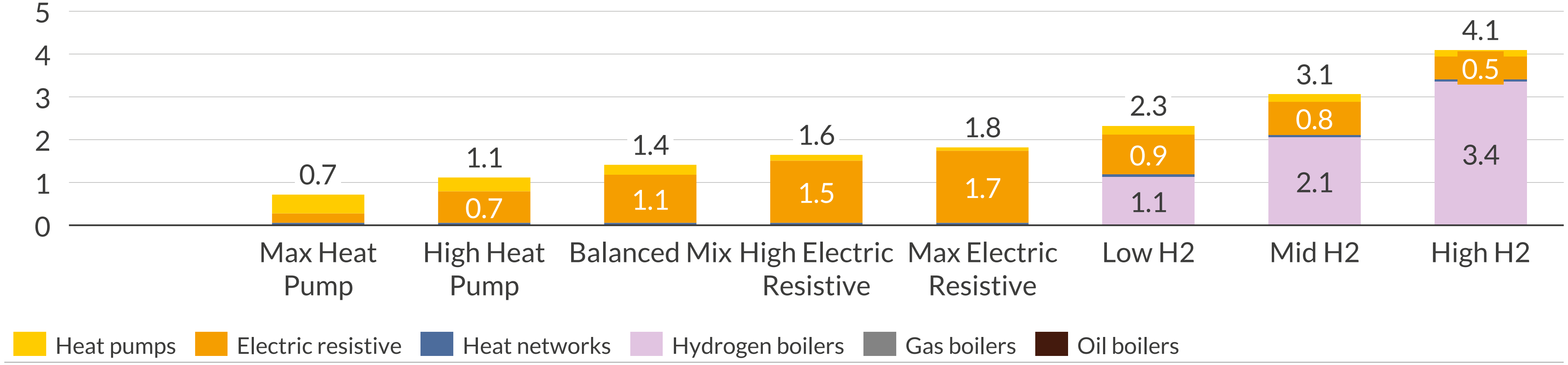
By 2050, hydrogen deployment in the heating sector leads to higher emissions, driven by residual emissions from blue H2 production





1) Includes contribution of emissions from electricity used in heating (see appendix for power sector carbon emissions trajectory. Power sector emissions trajectory does not account for the different size of power sector required in some scenarios). 2) Hydrogen for heating is assumed to come from a combination of blue and green hydrogen (see Appendix for modelled shares).

Source: Aurora Energy Research

- Most heat sector emissions are derived from gas boilers. By 2035, all scenarios achieve at least a 48% emissions reduction versus 2022, due to phasing out of gas boilers to meet CB6. By 2050, all fossil boilers have been retired and remaining emissions result from power sector emissions (for power production for heat) and residual emissions from blue H2 production[2].
- Heat pumps are 4-5 times more efficient compared to electric resistive heaters and so emissions resulting from heat pump utilisation are significantly lower than from electric resistive heaters in all scenarios, even where heat pump deployment significantly outpaces electric resistive heater deployment.
- Residual emissions from blue H2 production results in higher carbon emissions in scenarios where H2 is deployed in 2050, compared to electrification scenarios.

All scenarios

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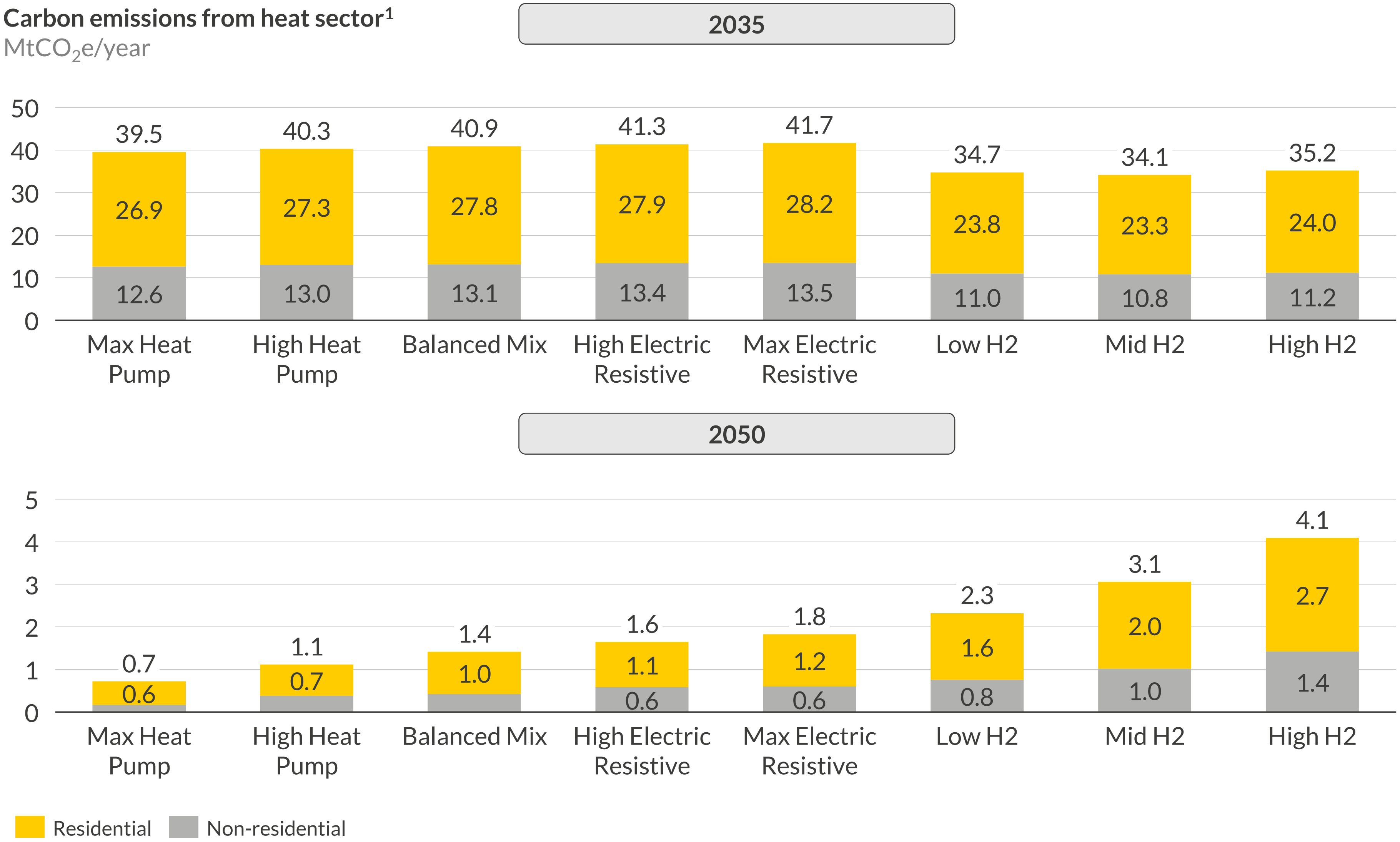
Emissions are proportionally higher from non-residential buildings owing to their larger size

Carbon emissions from heat sector[1]
$MtCO_2e$/year



- Non-residential buildings make up 8% of the building stock, but typically result in c.33% of buildings emissions in all scenarios
- Higher non-residential emissions result from larger building sizes and a larger proportion of buildings with very low energy efficiencies (Band F and Band G)

1) Includes contribution of emissions from electricity used in heating (see appendix for power sector carbon emissions trajectory. Power sector emissions trajectory does not account for the different size of power sector required in some scenarios)
Source: Aurora Energy Research

Agenda

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Total costs are dominated by fuel costs, and are lowest in the Max Heat Pump scenario

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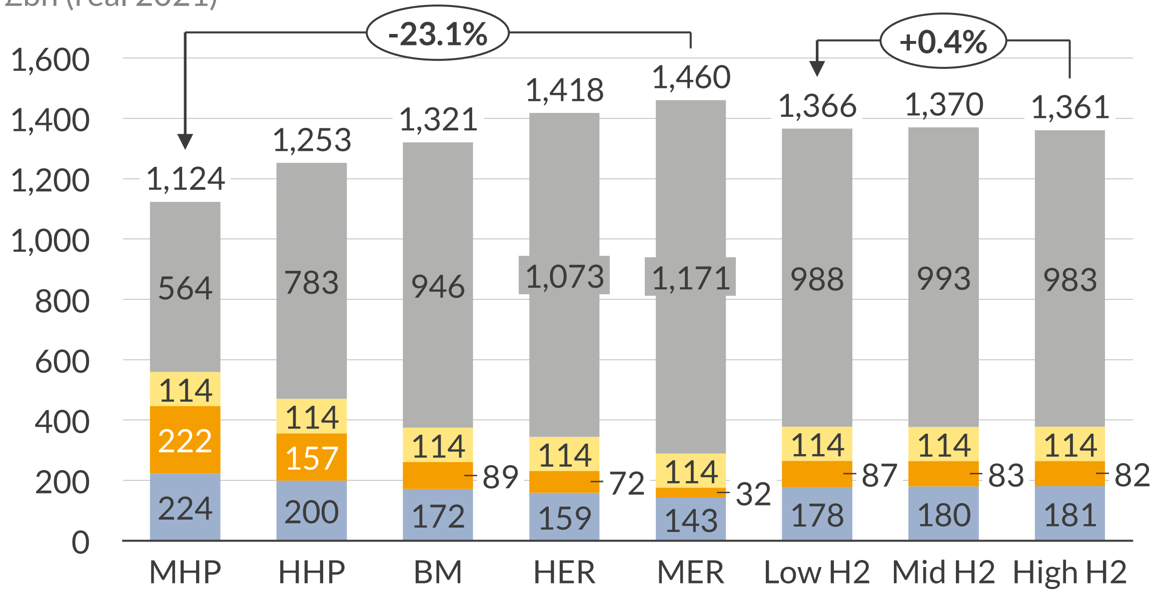
Total heat system costs, 2023-2050
£bn (real 2021)



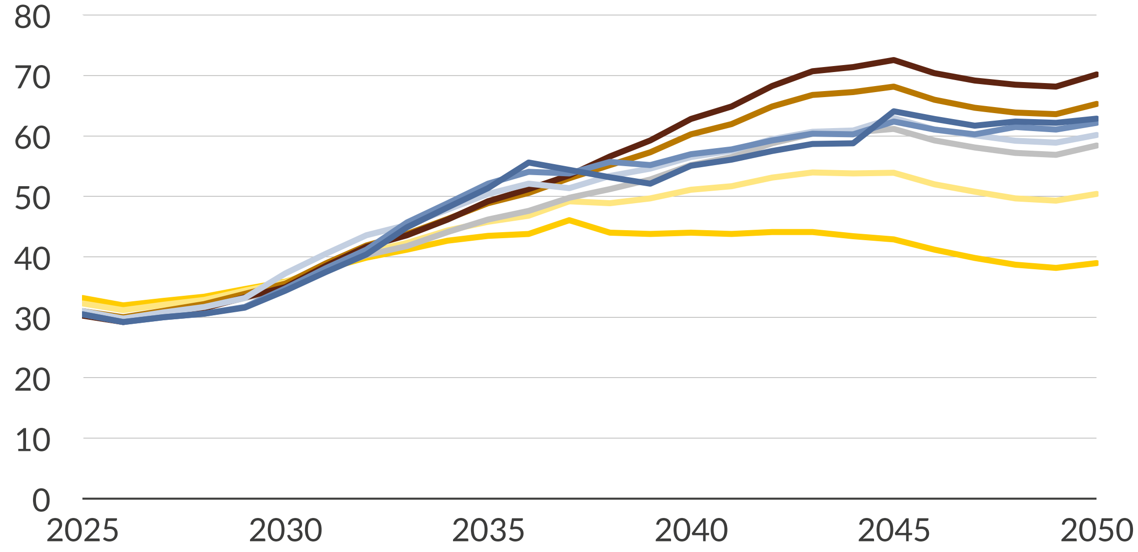
Fuel cost share of total costs, %

MHP	HHP	BM	HER	MER	Low H2	Mid H2	High H2
50%	62%	72%	76%	80%	72%	72%	72%

- Total heating costs are lowest in the Max Heat Pump scenario, and are 23% lower than the Max Electric Resistive scenario
- Total costs are similar across the 3 hydrogen scenarios as lower transition costs in the Max H2 scenario are offset by higher CAPEX costs (see deep dives into cost components on the following slides)

Fuel costs | OPEX | Transition cost | CAPEX

Total annual heat system costs
£bn/year (real 2021)



- Total annual heating costs remain similar between scenarios before 2035, at £30-40bn/year, as all scenarios follow a similar decarbonisation trajectory of gas boilers
- After 2035, total costs begin to diverge, with the Max Heat Pump scenario plateauing and then falling to £40bn/year by 2050, while the Max Electric Resistive scenario costs increase to £70bn/year, with the other scenarios falling between the two

Max Heat Pump | Balanced Mix | Max Electric Resistive | Mid H2
High Heat Pump | High Electric Resistive | Low H2 | High H2

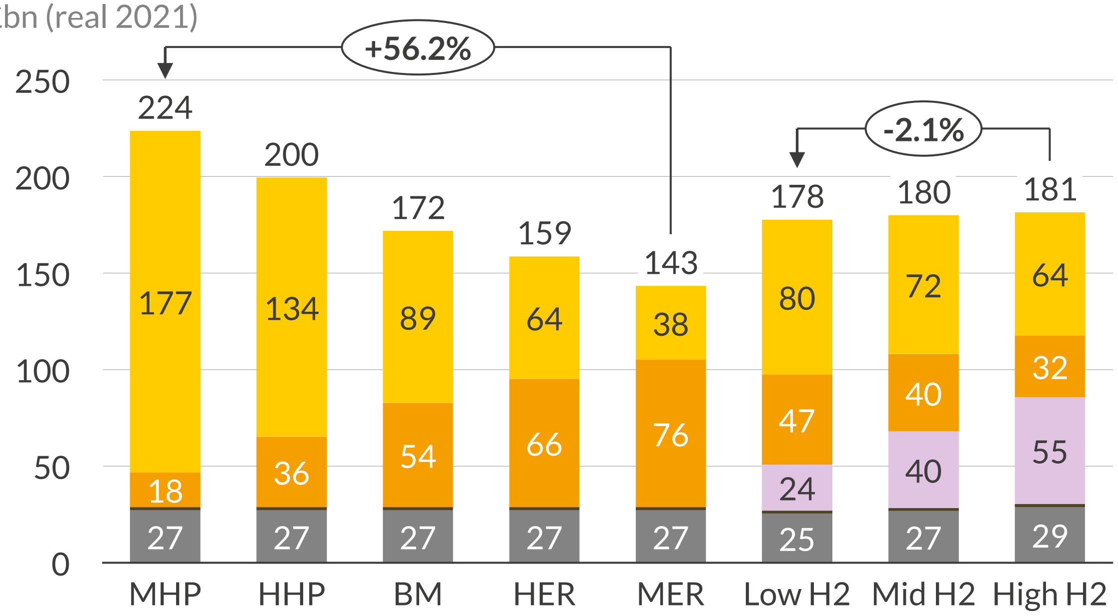
All scenarios

Total CAPEX costs are highest for the Max Heat Pump scenario and lowest for the Max Electric Resistive scenario

AURORA

Total CAPEX costs, 2023-2050

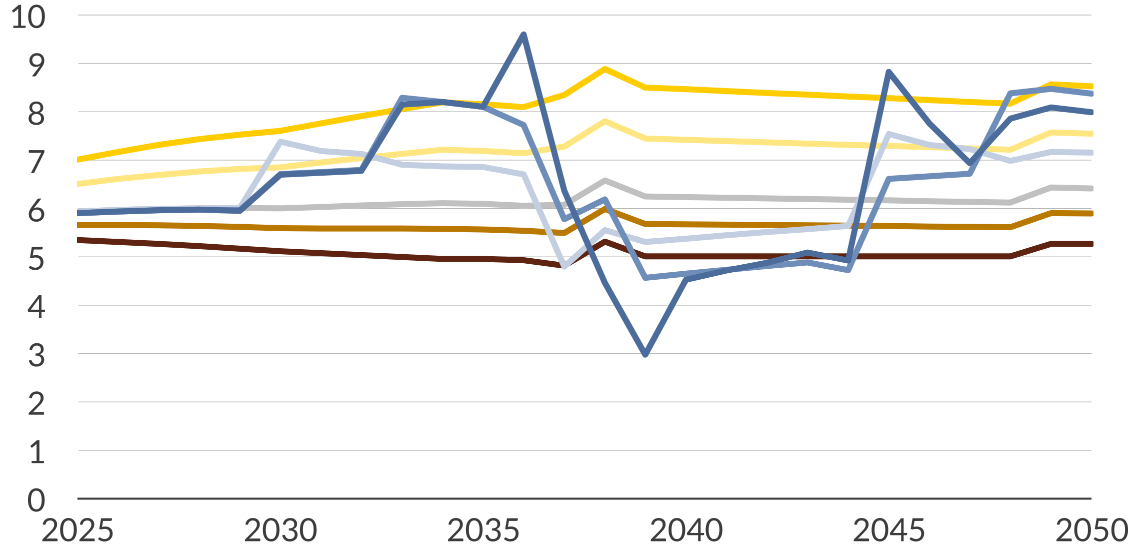
£bn (real 2021)



- Total CAPEX costs are 56% higher in the Max Heat Pump scenario vs the Max Electric Resistive scenario, as heat pump CAPEX is 2-3x higher than electric resistive heating systems. However, heat pump CAPEX is projected to fall as investments are made in the supply chain, while similar cost declines are not expected for electric resistive systems.
- Total CAPEX costs remain consistent between the hydrogen scenarios, at ~£180bn between 2023-50, as hydrogen boilers replace a mix of both heat pumps (higher CAPEX) and electric resistive heating systems (lower CAPEX).

Total annual CAPEX costs

£bn/year (real 2021)



- Annual CAPEX cost is a function of new heat technology deployments as well as replacements, and varies between £3-10bn/year per scenario.
- The uneven trajectory for hydrogen scenarios mirrors the nature of the modelled hydrogen network deployment that results in significant ramping up of hydrogen boiler deployments in certain years.
- 2038 sees an uptick in total CAPEX as heating systems that were installed in the first year of the forecast (2023) come to the end of their 15-year lifetime and need replacing.

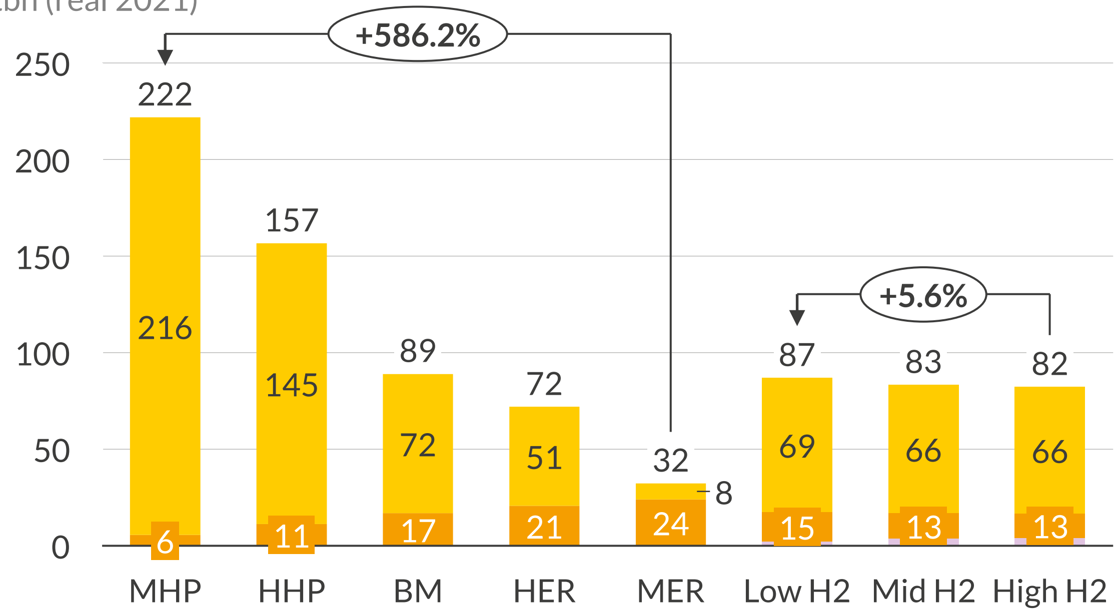
Source: Aurora Energy Research

All scenarios

Total transition costs are dominated by heat pumps, which require costly energy efficiency upgrades in inefficient buildings

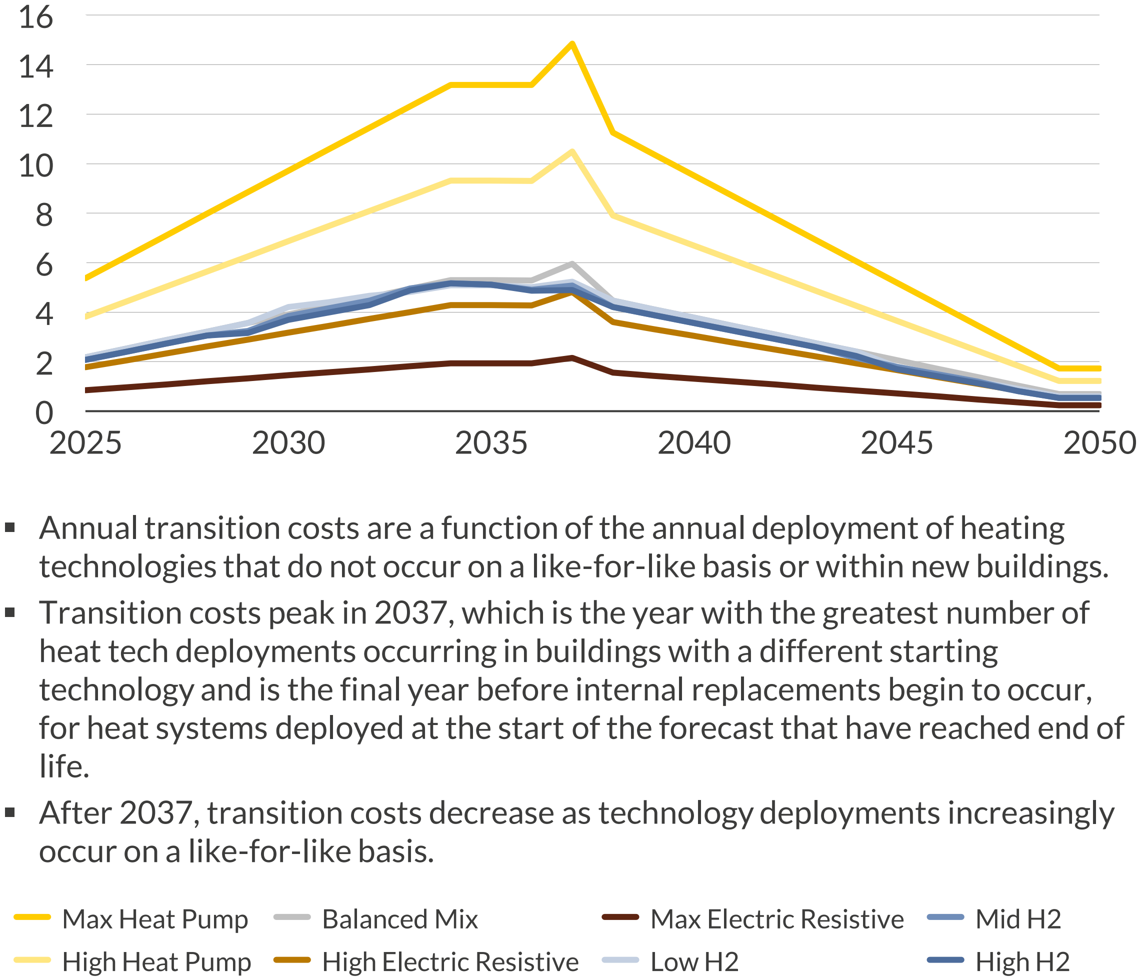
AURORA

Total transition costs, 2023-2050
£bn (real 2021)



- Transition costs are driven by heat pump deployments in inefficient buildings, since these are accompanied by energy efficiency upgrade packages, therefore are 7x higher in the Max Heat Pump scenario compared to the Max Electric Resistive scenario, however they remain comparable with total CAPEX costs and significantly less than lifetime fuel costs.
- Total transition costs vary less between the 3 hydrogen scenarios since the variation in the number of heat pumps in these scenarios is lower.

Total annual transition costs
£bn/year (real 2021)



- Annual transition costs are a function of the annual deployment of heating technologies that do not occur on a like-for-like basis or within new buildings.
- Transition costs peak in 2037, which is the year with the greatest number of heat tech deployments occurring in buildings with a different starting technology and is the final year before internal replacements begin to occur, for heat systems deployed at the start of the forecast that have reached end of life.
- After 2037, transition costs decrease as technology deployments increasingly occur on a like-for-like basis.

1) Note that some consumers might choose to install 'hydrogen-ready' gas boilers, ahead of the hydrogen network being deployed in their area. This would have a smoothing effect on the annual CAPEX trajectory in the hydrogen scenarios.

Source: Aurora Energy Research

Fuel costs are dominated by electric resistive heating systems, which have a relatively low efficiency and a high retail fuel price

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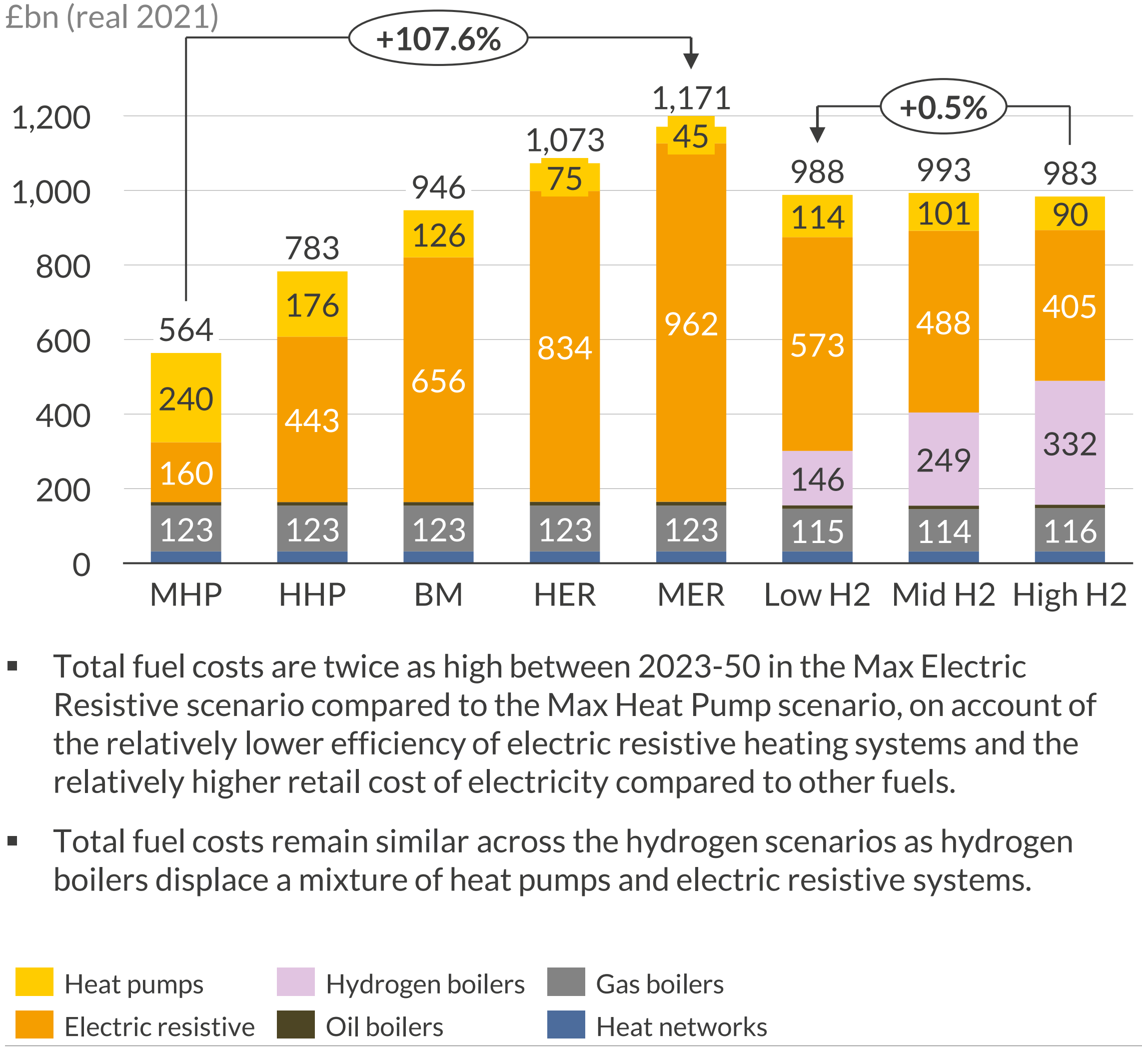
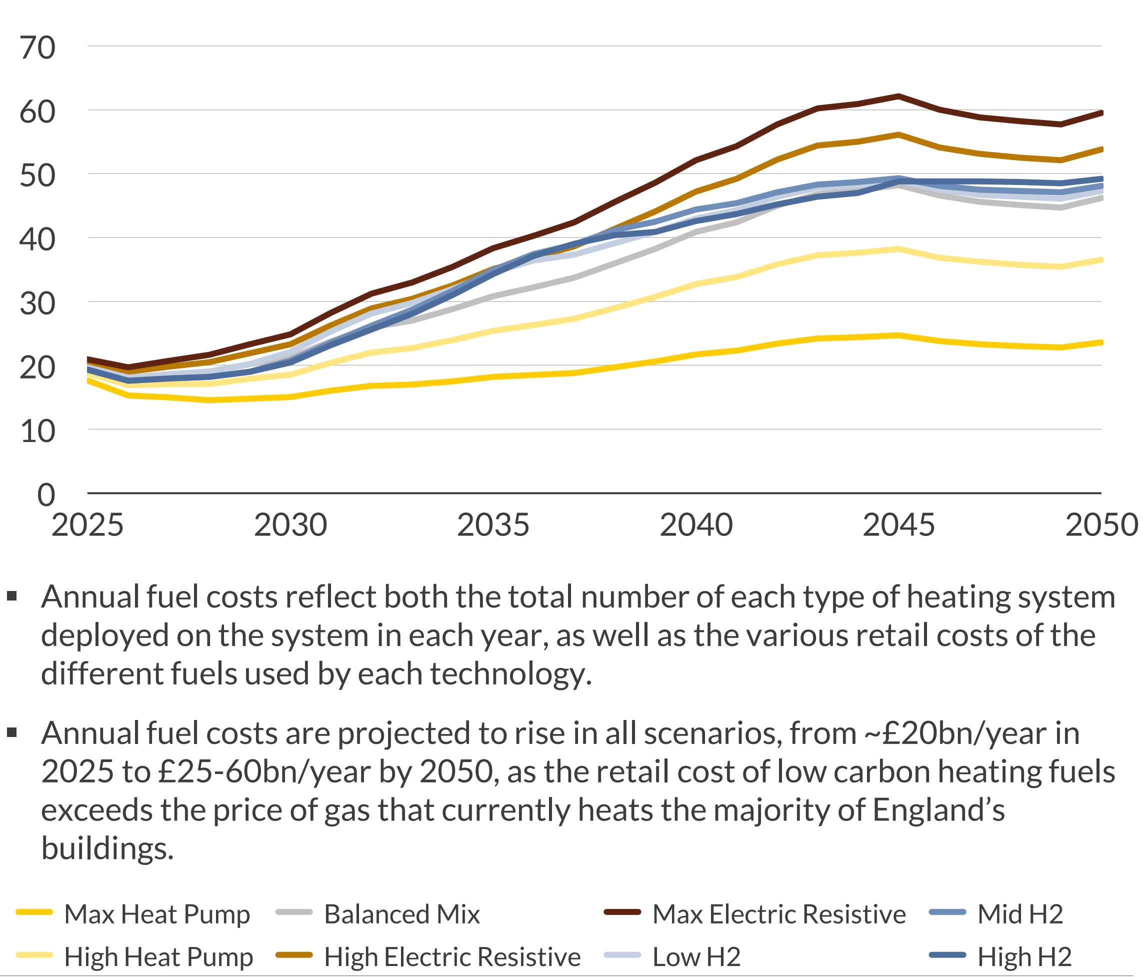
Total fuel costs, 2023-2050
£bn (real 2021)



Total annual fuel costs
£bn/year (real 2021)



- Total fuel costs are twice as high between 2023-50 in the Max Electric Resistive scenario compared to the Max Heat Pump scenario, on account of the relatively lower efficiency of electric resistive heating systems and the relatively higher retail cost of electricity compared to other fuels.
- Total fuel costs remain similar across the hydrogen scenarios as hydrogen boilers displace a mixture of heat pumps and electric resistive systems.

- Annual fuel costs reflect both the total number of each type of heating system deployed on the system in each year, as well as the various retail costs of the different fuels used by each technology.
- Annual fuel costs are projected to rise in all scenarios, from ~£20bn/year in 2025 to £25-60bn/year by 2050, as the retail cost of low carbon heating fuels exceeds the price of gas that currently heats the majority of England's buildings.

1) Note that some consumers might choose to install 'hydrogen-ready' gas boilers, ahead of the hydrogen network being deployed in their area. This would have a smoothing effect on the annual CAPEX trajectory in the hydrogen scenarios.

Source: Aurora Energy Research

All scenarios

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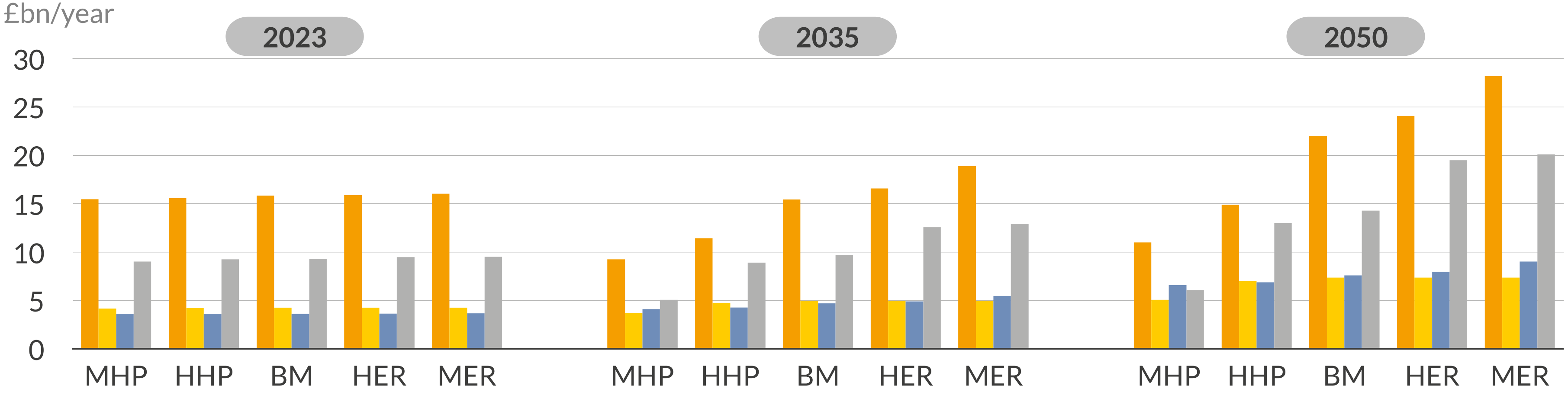
Owner-occupied buildings see the most variability in fuel costs across scenarios, as well as the highest share of total fuel costs

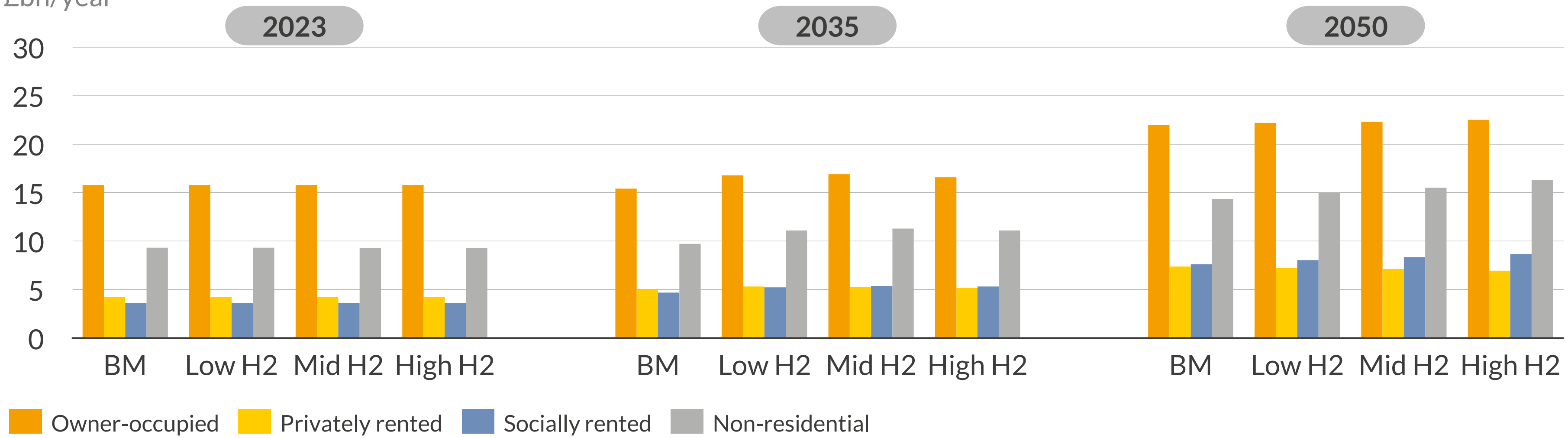
Annual fuel costs for heating by tenure, electrification scenarios

£bn/year



Annual fuel costs for heating by tenure, hydrogen scenarios

£bn/year



- Owner occupied buildings see the greatest variability in annual running costs in the electrification scenarios as more electric resistive heating is installed.
- Lower income socio-economic groups are more likely to live in privately or socially rented buildings, compared to higher income deciles. There are higher proportions of rented flats and terraces compared to detached/semi-detached houses. This means lower socio-economic groups are more likely to have electric resistive heating installed (whether by their decision or their landlord's decision) in all scenarios, resulting in higher fuel costs.

Source: Aurora Energy Research

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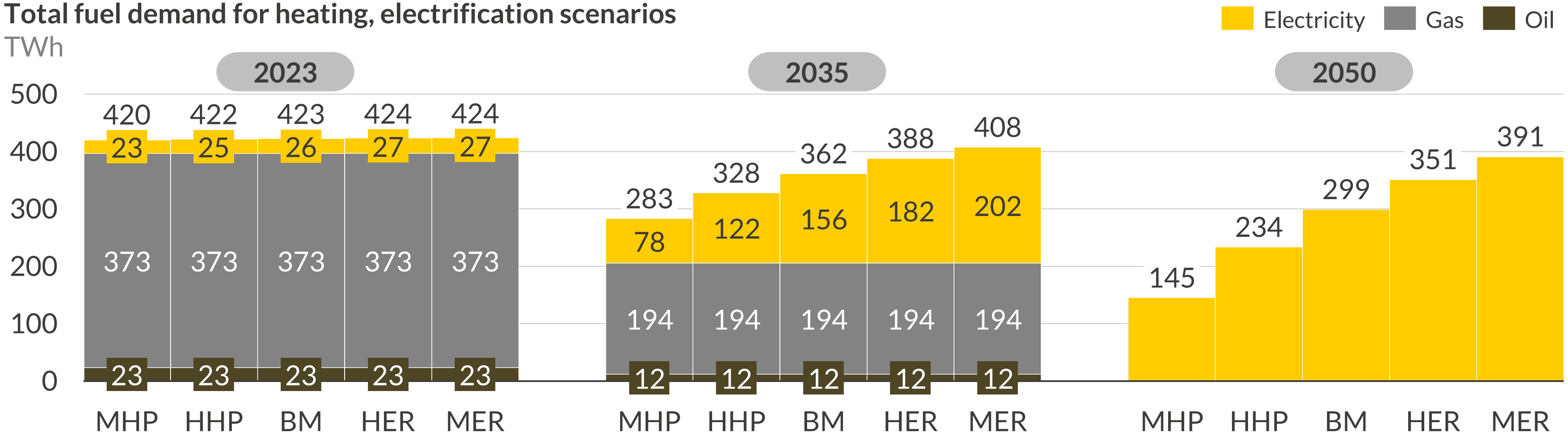
Max Electric Resistive has 270% higher demand for heating compared to Max Heat Pump, requiring a significantly bigger power sector

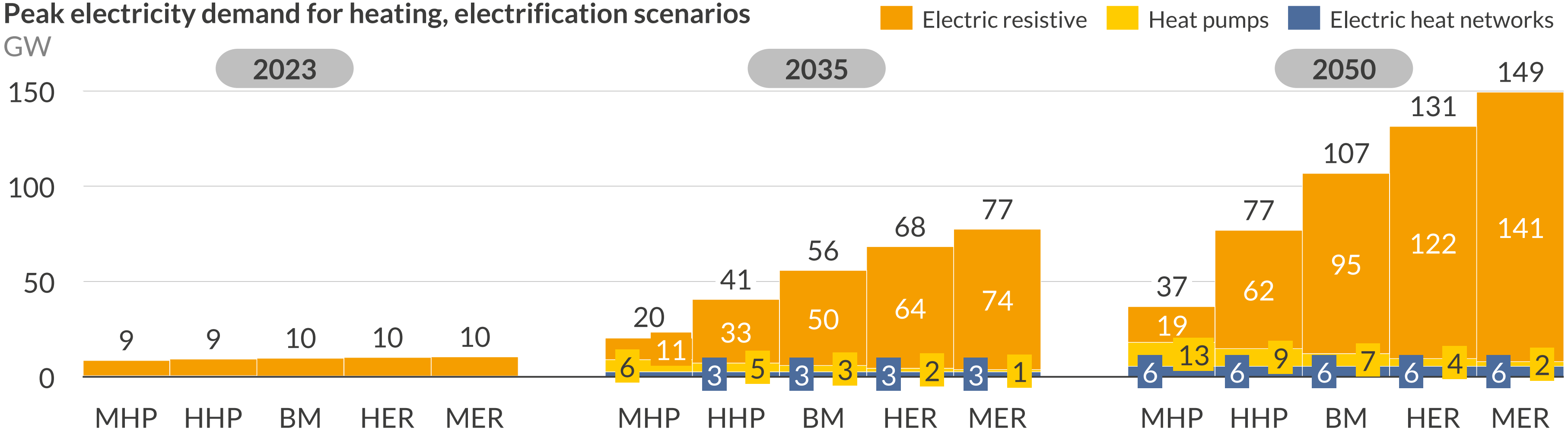
Total fuel demand for heating, electrification scenarios

TWh



Peak electricity demand for heating, electrification scenarios

GW

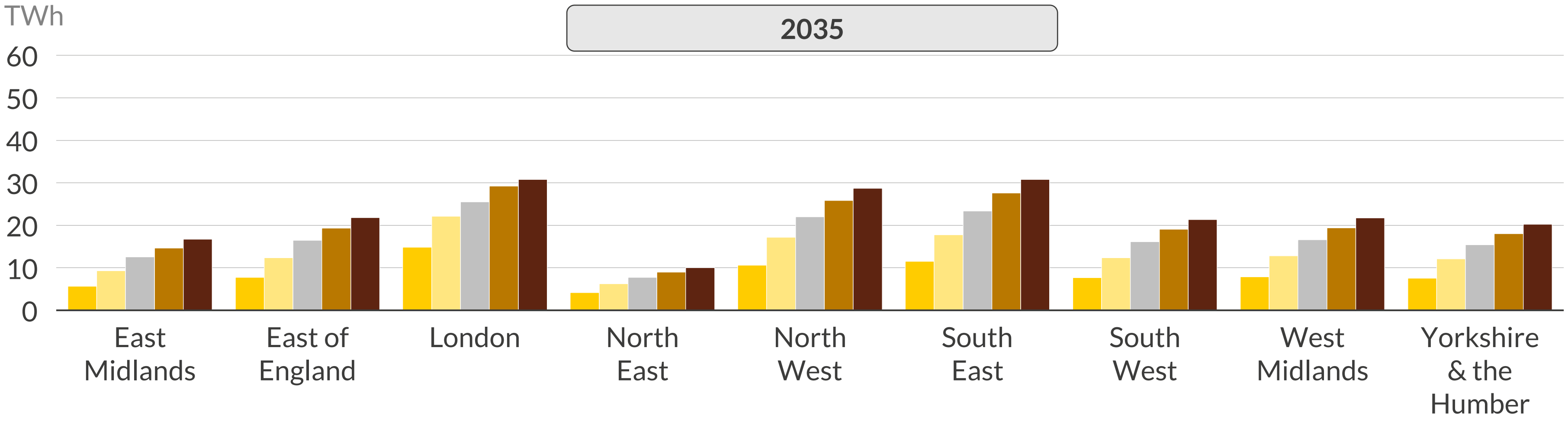


- In all our electrification scenarios, electricity demand for heat increases over the forecast horizon, but total energy demand for heat falls
- Consumer choices have a major impact on the overall size of the power sector required
- The MER scenario has 270% higher total power demand for heat compared to MHP, and 410% higher peak demand due to the inefficiency of electric resistive heating
- The power sector in the MER scenario would have to be significantly larger, with a high level of peaking capacity
- This would be expected to result in a higher power sector carbon intensity, making emissions targets harder to meet
- High peak demand could also present significant challenges in terms of network operability, which would have to be addressed

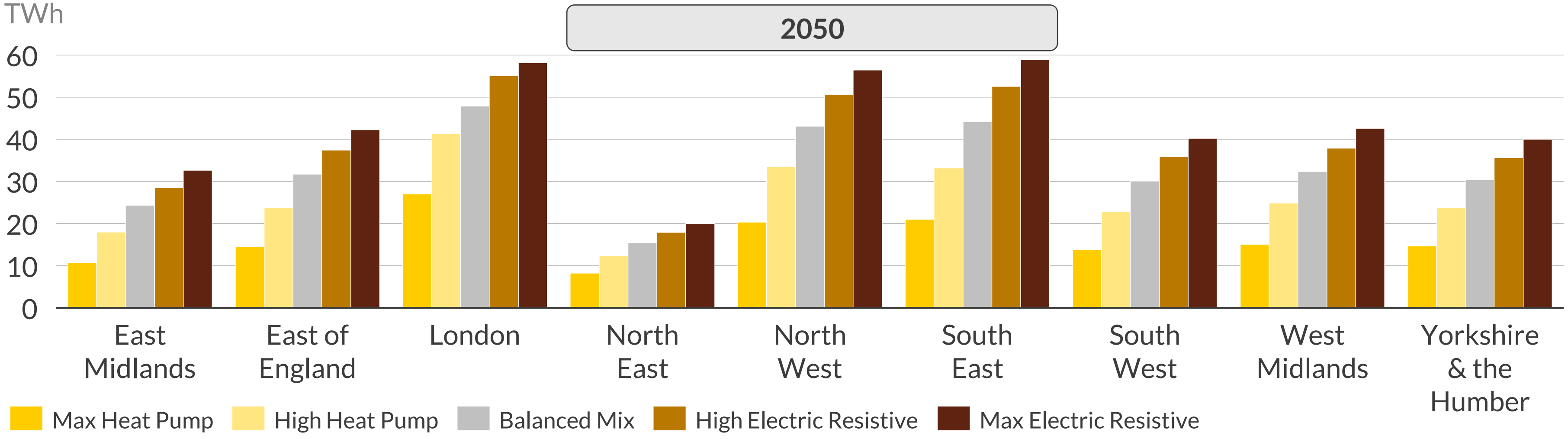
Sources: Aurora Energy Research, NGESO, EE

Total Electricity Demand: Total power demand for heat varies by region, with highest demand in London and the South East

Total electricity demand for heating, electrification scenarios



Total electricity demand for heating, electrification scenarios



- In all scenarios the highest total electricity demand for heating comes from London and the South East, as well as from the North West. Higher electric resistive heating penetration leads to higher overall electricity demand, as electric resistive heating has a much lower overall energy efficiency.
- High levels of electricity demand, especially in the South East and London, would require substantially higher capacities to be located in these regions, or would result in higher requirements for transmission network build out, which could further increase costs to consumers.

Sources: Aurora Energy Research, NGESO, EE

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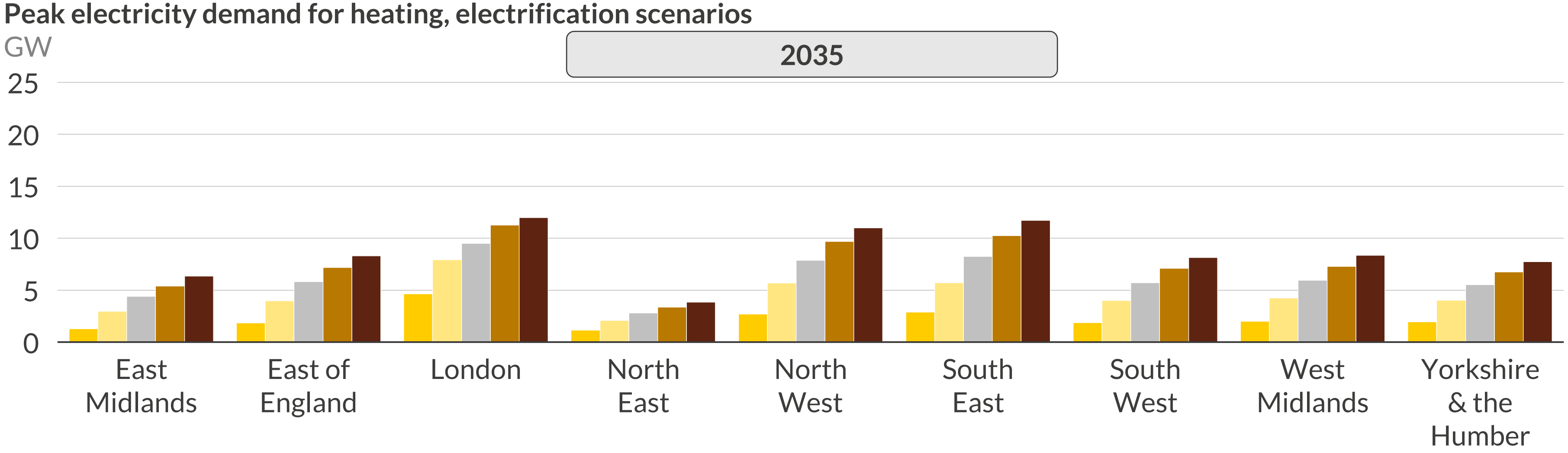
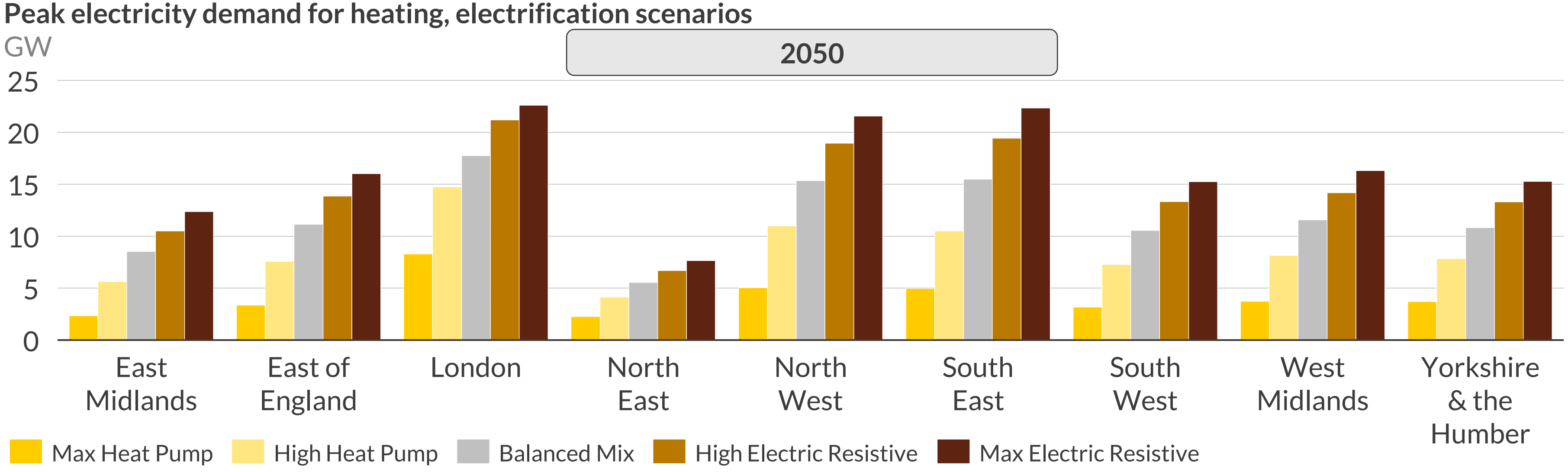
Peak Electricity Demand for heat: Total heat demand varies by region, with highest peak demand in London and the South East





- In all scenarios the highest level of peak electricity demand for heating is seen in London and the South East, followed by the North West
- The increase in peak demand in these regions could result in higher distribution costs, which currently differ at the DNO level
- High levels of peak demand in some regions, especially in the HER/MER scenarios could increase network operability challenges significantly

Sources: Aurora Energy Research, NGESO, EE

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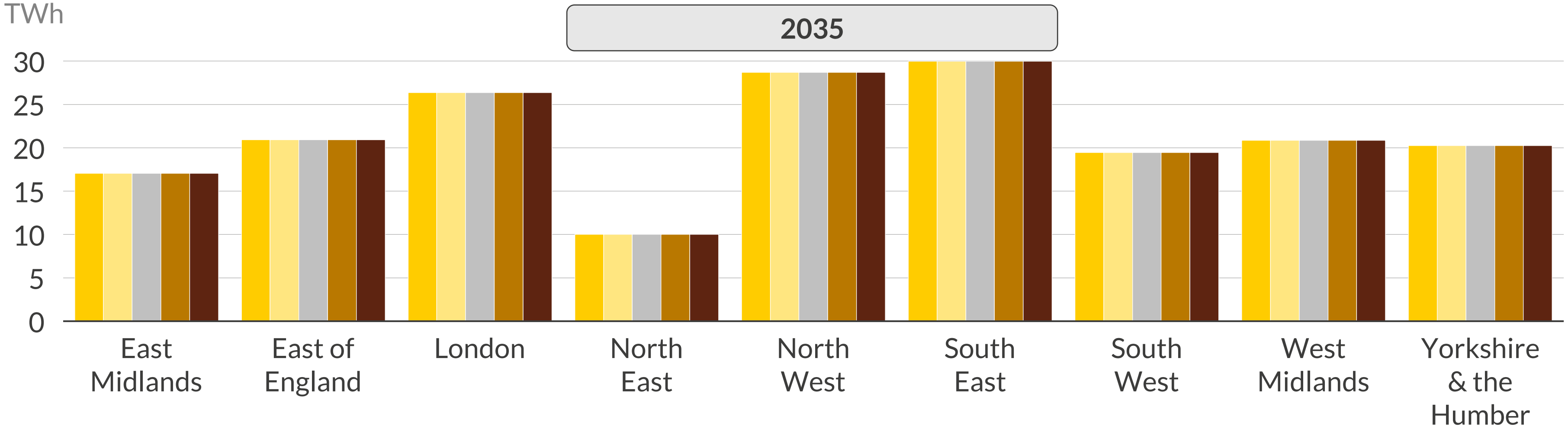
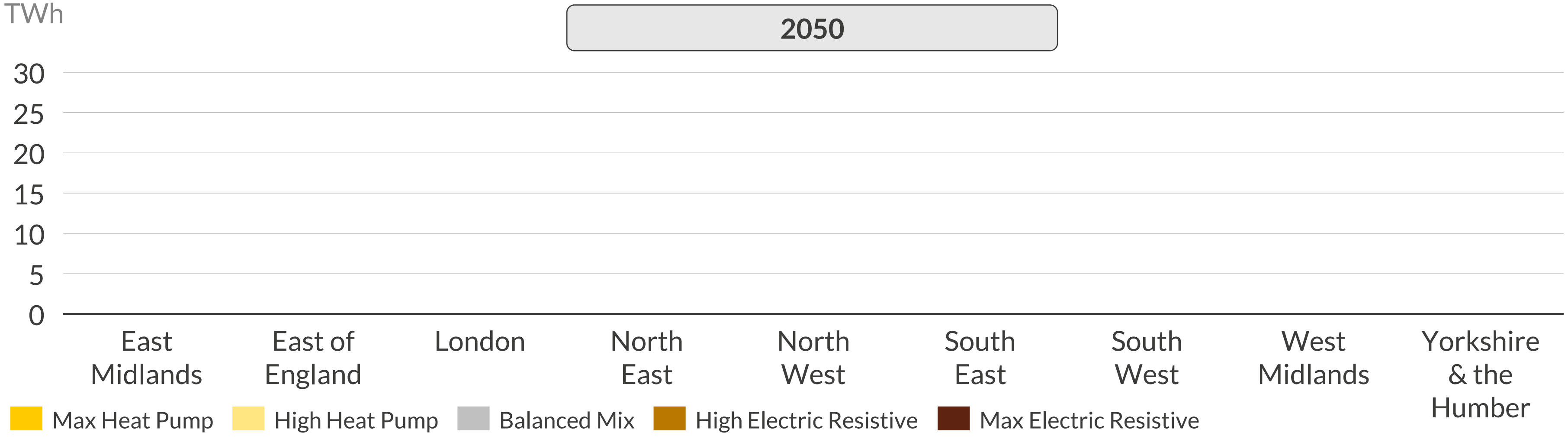
Total Gas Demand: Total gas demand for heat is consistent across scenarios, falling to zero by 2050 as gas boilers phase out entirely

Total gas demand for heating, electrification scenarios
TWh



Total gas demand for heating, electrification scenarios
TWh



- Gas demand for heat is driven by the level of gas boilers on the system, which is consistent across the electrification scenarios (an input assumption, in order to meet CB6)
- The South East and North West of England see the highest number of gas connected buildings and have the highest gas demand for heating, while the North East sees the lowest demand
- By 2050, we assume gas for heating has been completely phased out in all regions, in order to achieve emissions targets

Sources: Aurora Energy Research, NGESO, EE

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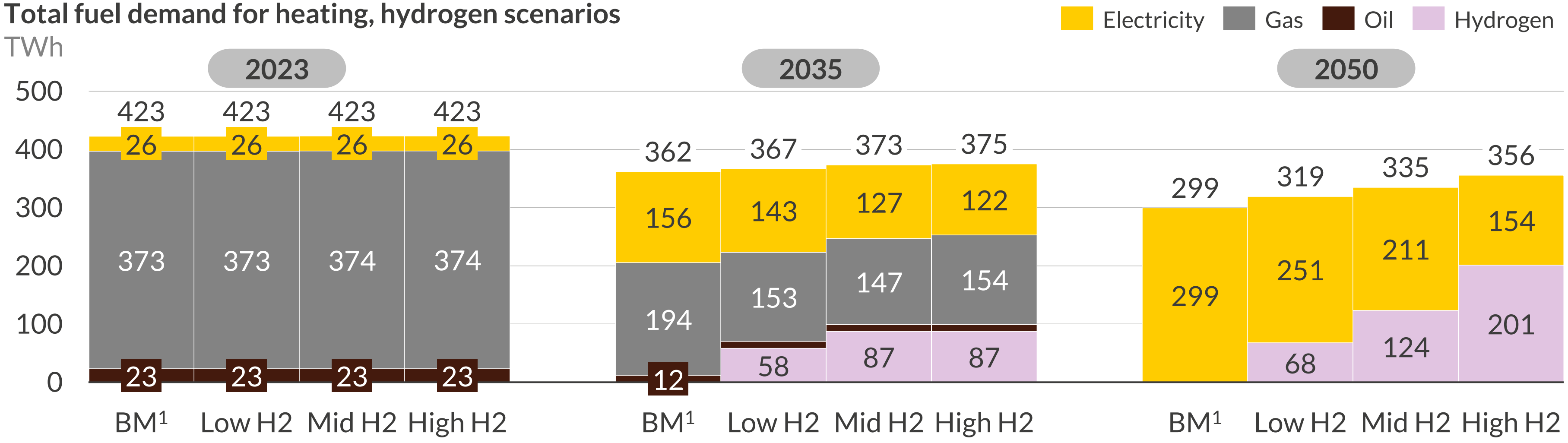
In all our hydrogen scenarios, hydrogen demand for heat increases in the decades ahead, but total energy demand for heat falls

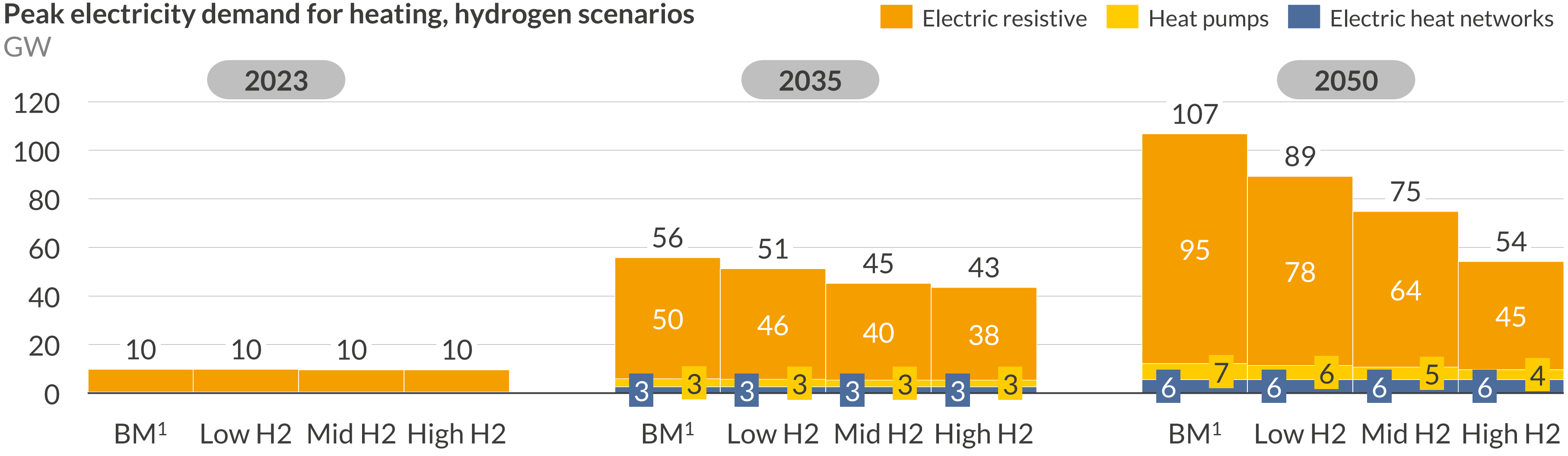
Total fuel demand for heating, hydrogen scenarios

TWh



Peak electricity demand for heating, hydrogen scenarios

GW



1) Balanced Mix scenario has no hydrogen for heating

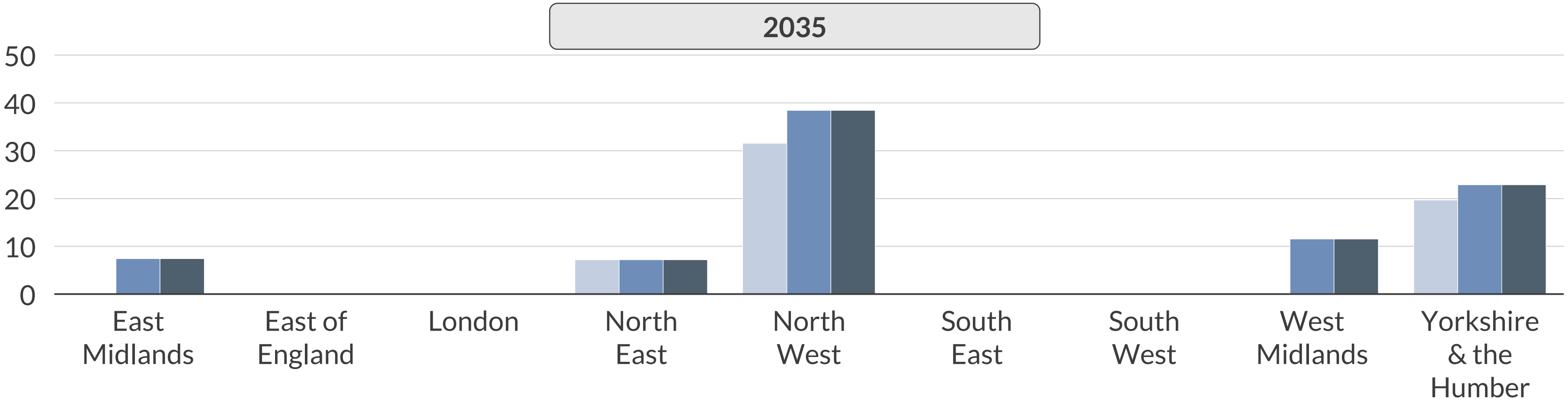
Sources: Aurora Energy Research, NGESO, EE

- In all hydrogen scenarios, total energy demand for heating falls across the forecast horizon, but electricity demand and hydrogen demand for heating increase.
- Deploying hydrogen in the heating sector reduces the amount of power that is needed for direct heating provision. However, as additional volumes of electricity would be required for electrolytic hydrogen production, the overall size of the power sector would not be expected to decrease.

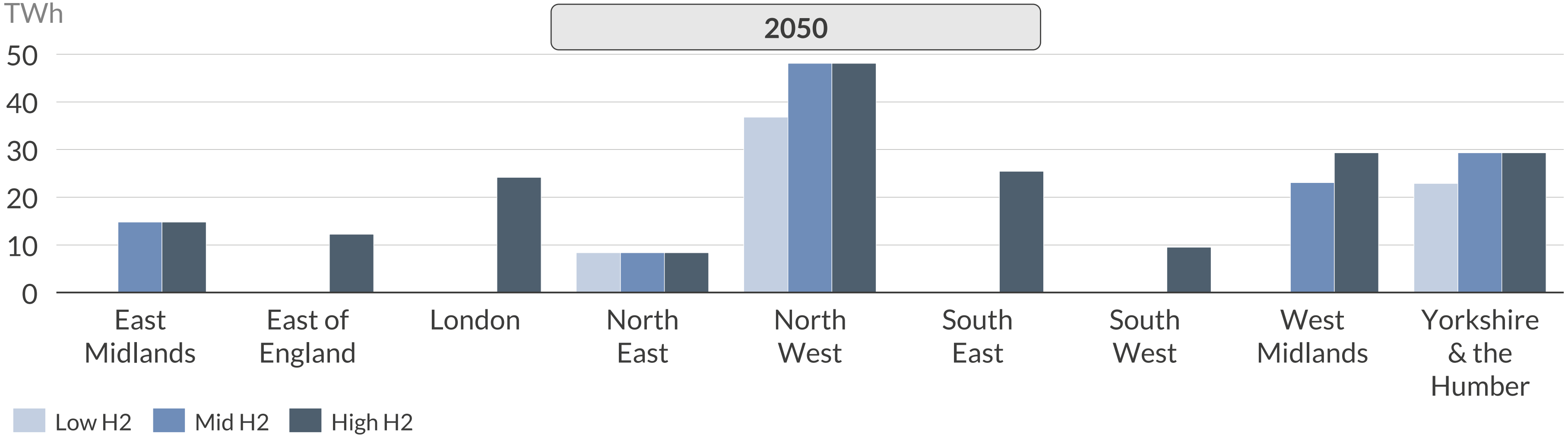
Hydrogen scenarios

Total H2 Demand: Regions with early deployment of hydrogen continue to see the highest level of demand for hydrogen in heating

Total hydrogen demand for heating, hydrogen scenarios
TWh



Total hydrogen demand for heating, hydrogen scenarios
TWh



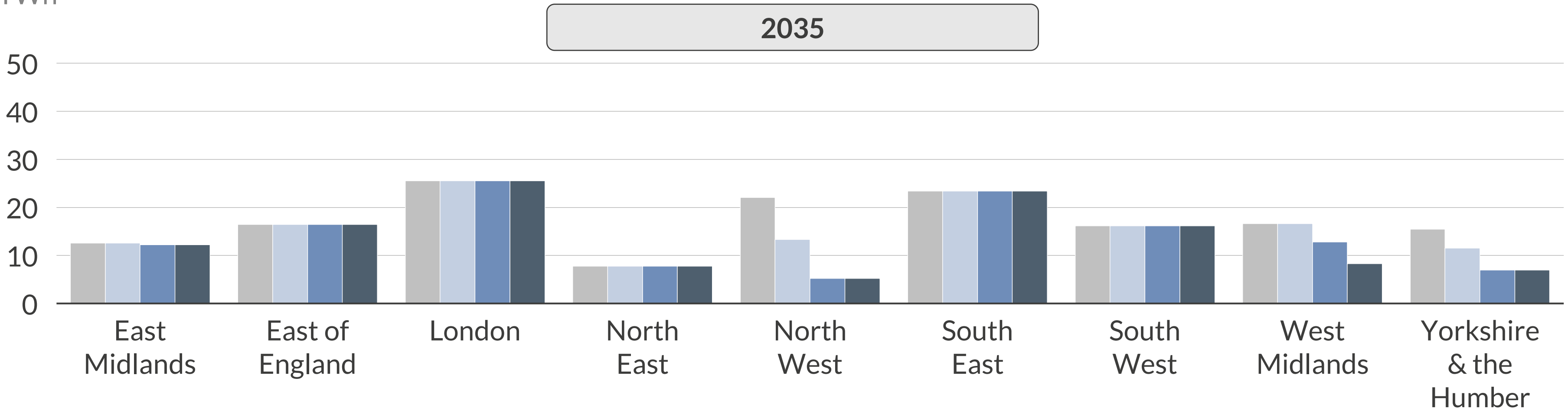
- The North West, North East and Yorkshire and the Humber see the earliest deployment of H2 distribution networks under the H21 plan, which means a higher portion of buildings have yet to decarbonise by other means at the time H2 is rolled out. As the deployment of a H2 network means gas is no longer available, these regions see high levels of conversion to H2, resulting in high H2 demand across the forecast horizon.
- In regions such as London and the South East, where the distribution networks are not assumed to convert to H2 until the 2040s, many buildings have already decarbonised through electrification by the time the H2 network is deployed, meaning H2 demand in these regions remains low. As the H2 distribution network will have to be maintained despite lower uptake of H2, this could result in higher H2 distribution costs on a £/MWh basis.

Sources: Aurora Energy Research, NGESO, EE

Total Electricity Demand: Early deployment of hydrogen reduces the regional demand for power for heating

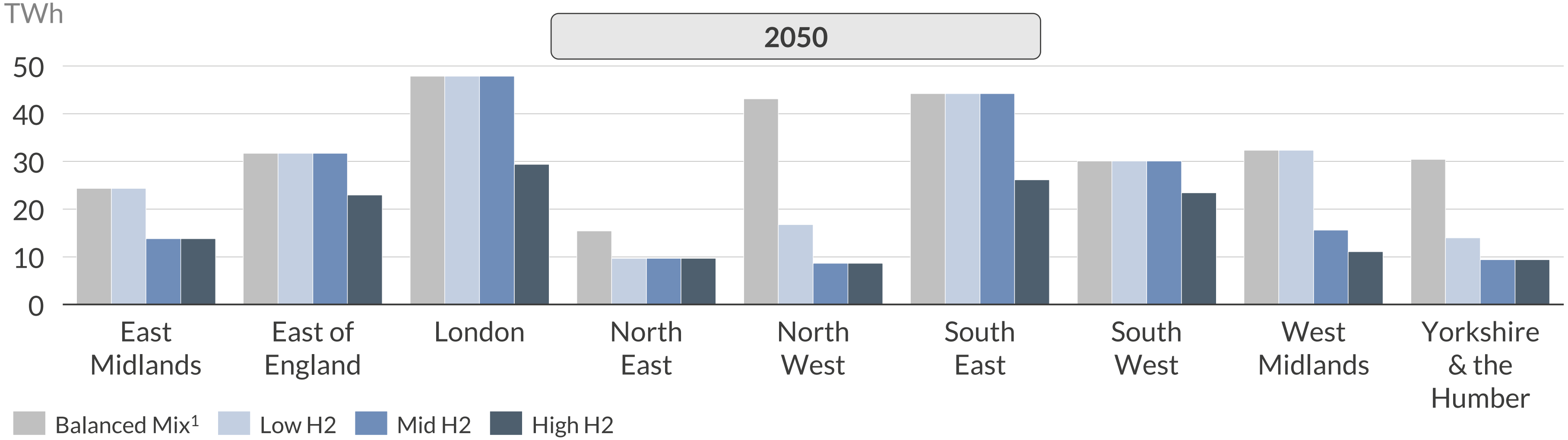
Total electricity demand for heating, hydrogen scenarios

TWh



Total electricity demand for heating, hydrogen scenarios

TWh



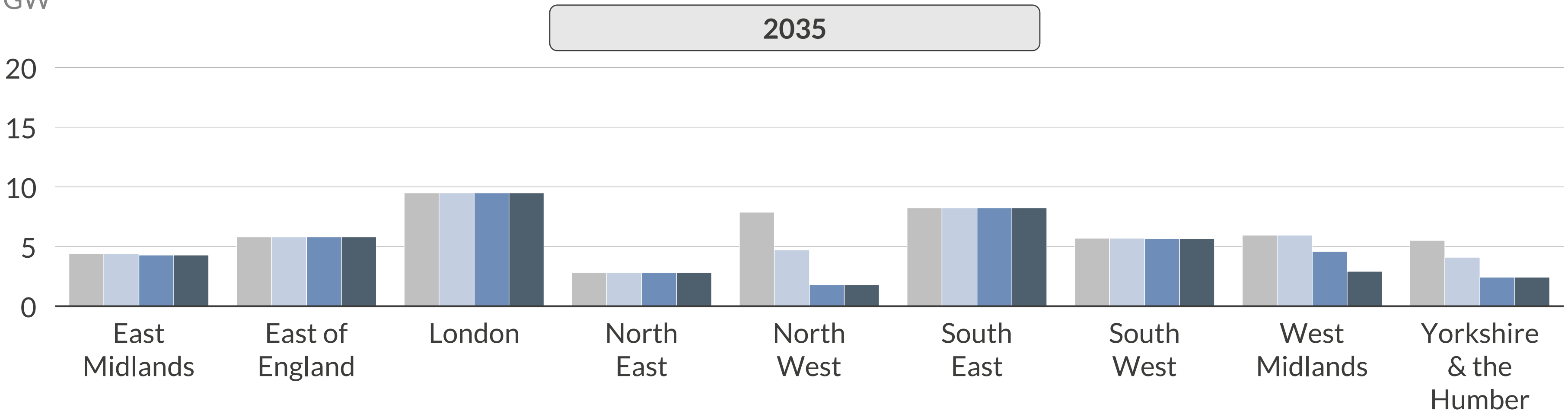
1) Balanced Mix scenario has no hydrogen for heating

Sources: Aurora Energy Research, NGESO, EE

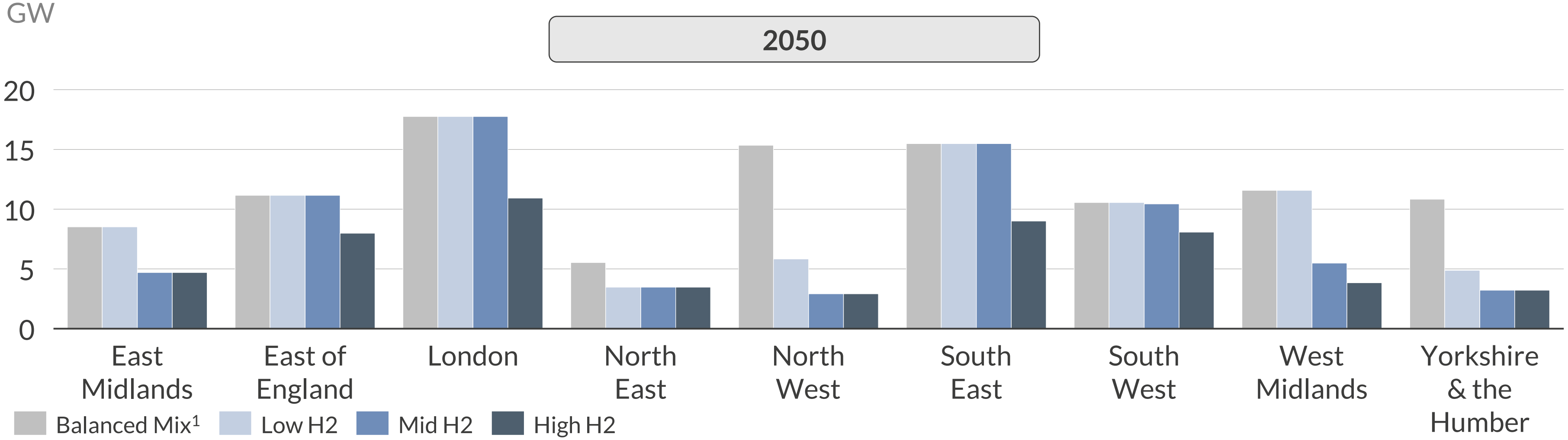
- The early deployment of hydrogen reduces total direct power demand for heating in the North of England
- However, in London and the South East, power demand is higher in all scenarios in 2050, as hydrogen is introduced later, meaning some buildings have already chosen to decarbonise via electrification

Peak Electricity Demand: Peak demand is higher in London and the South East, where H2 deploys later in the forecast horizon

Peak electricity demand for heating, hydrogen scenarios
GW



Peak electricity demand for heating, hydrogen scenarios
GW



1) Balanced Mix scenario has no hydrogen for heating

Sources: Aurora Energy Research, NGESO, EE

- Peak electricity demand is highest in London and the South East in all scenarios, including the electrification scenarios, driven by the higher number of buildings in these regions and the higher number of space constrained buildings which can only install electric resistive heating.
- London and the South East also see hydrogen deployment in H21 Phase 5 and Phase 6, meaning hydrogen is not available for heating until the 2040s. This means more buildings in these regions decarbonise through electrification, leading to higher peak electricity demand in these areas.
- This could increase network operability challenges in these areas and lead to higher power distribution costs.

Hydrogen scenarios

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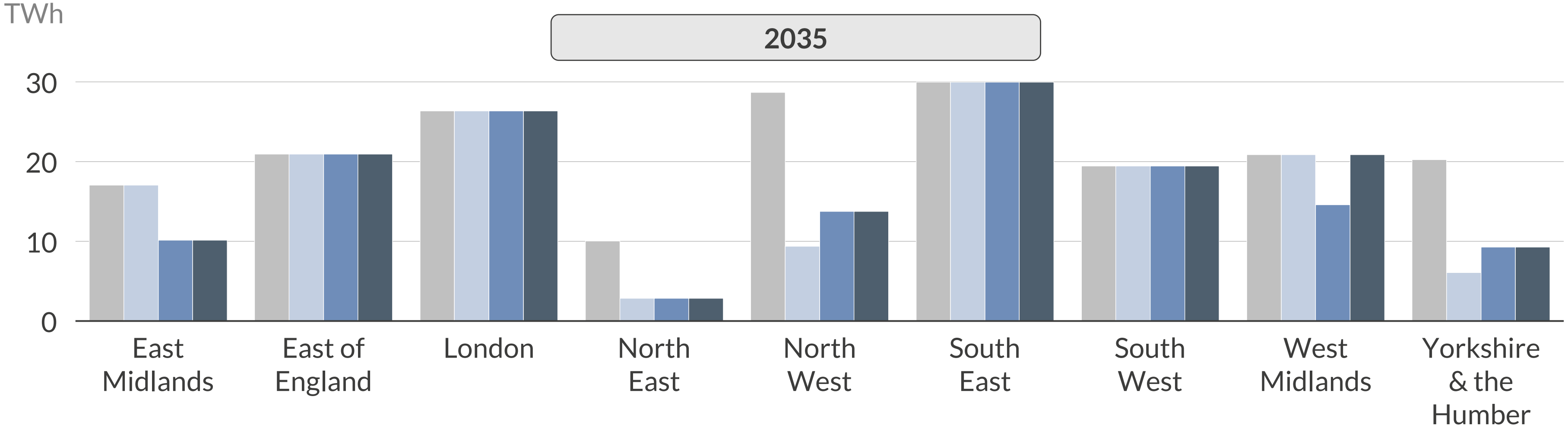
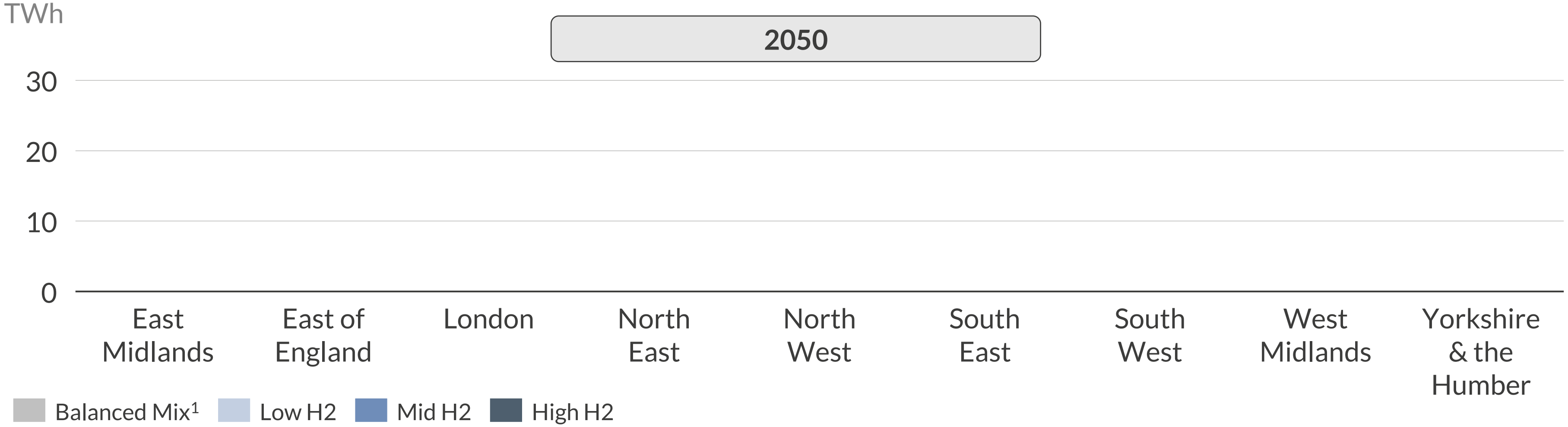
Total Gas Demand: Gas demand can be rapidly reduced in regions which see early deployment of hydrogen

Total gas demand for heating, hydrogen scenarios
TWh



Total gas demand for heating, hydrogen scenarios
TWh



1) Balanced Mix scenario has no hydrogen for heating

Sources: Aurora Energy Research, NGESO, EE

- By 2035, gas demand in the North of England (including the North East, North West and Yorkshire and the Humber), can be significantly reduced, as these regions see early deployment of hydrogen.
- However, the phase out of gas at the distribution level in these regions must be considered in conjunction with gas demand from other sectors, as thermal power plants that are connected to gas transmission networks are likely to be required for security of supply purposes post-2035.
- By 2050, we assume gas for heating has been completely phased out in all regions. Note there is still some gas demand for blue hydrogen used in heating in hydrogen scenarios.

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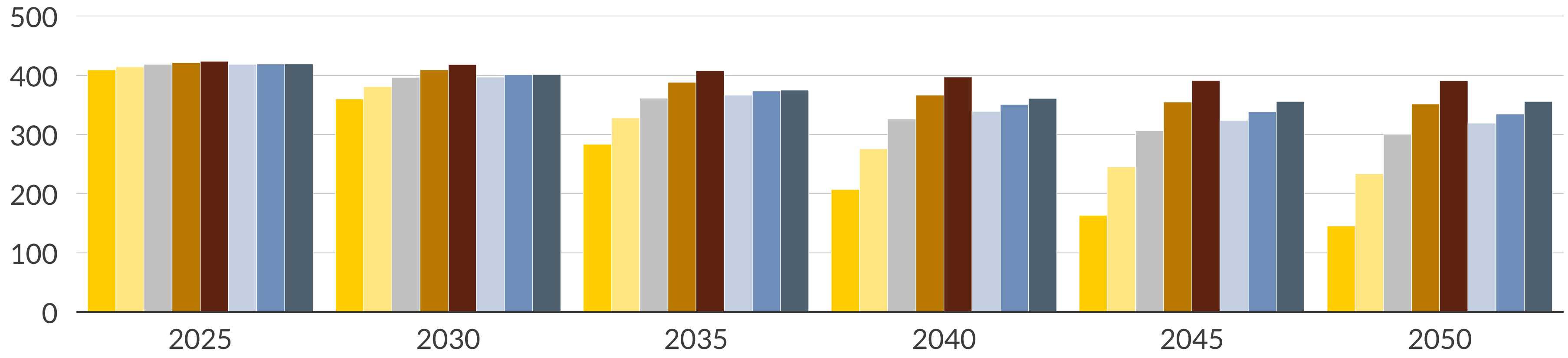
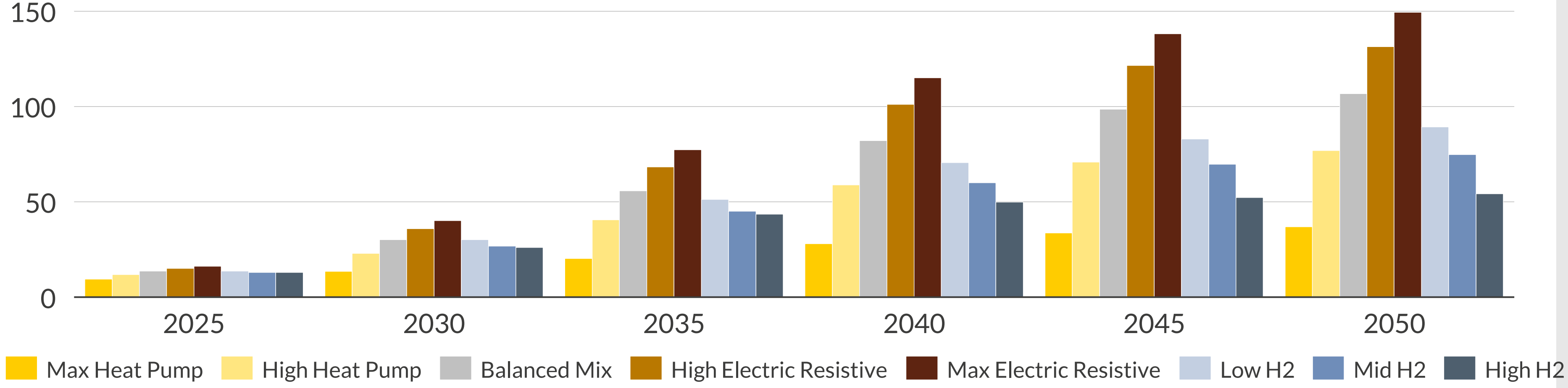
Total Fuel & Peak Demand: Max Heat Pump scenario sees the greatest reduction in fuel demand and the slowest growth in peak demand

Total fuel demand for heating, all scenarios
TWh



Peak electricity demand for heating, all scenarios
GW



- Total fuel demand for heating, and peak electricity demand for heat, are relatively consistent across all scenarios at the start of the forecast, driven by similar levels of gas boiler and electric resistive deployment.
- From 2030, scenarios begin to diverge considerably, with higher deployment of electric resistive heating driving significantly higher fuel demand for heating (although total demand still falls overall), as well as driving significant increases in peak electricity demand.
- The hydrogen scenarios see less variation in total fuel demand, since the buildings that are not converted to hydrogen decarbonise via a mix of heat pumps and electric resistive.
- The hydrogen scenarios see greater discrepancy in peak electricity demand by 2050, driven by differing deployment of electric resistive heating.

Sources: Aurora Energy Research, NGESO, EE

Summary: Low carbon heating decarbonisation pathways

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1 Higher penetration of heat pumps results in reduced electricity demand and peak demand, reduced total costs and reduced emissions, whilst higher penetrations of electric resistive heating will require a significantly larger power sector in order to meet demand and peak demand, which will increase costs to consumers and will likely make decarbonisation of the power sector harder to achieve.

2 Deploying hydrogen in heating could be an effective decarbonisation tool in areas where it is introduced early enough (before 2035), as it allows for the mass conversion of buildings to low carbon heating (presuming the corresponding rollout of 'hydrogen-ready' boilers). However, in areas where hydrogen is not introduced until later in the forecast, partial or even complete electrification of heating has already taken place in order to meet decarbonisation targets, reducing the need for hydrogen.

3 Hydrogen in heating would lead to higher emissions, due to the residual emissions resulting from blue hydrogen production, and higher system costs, owing to the high fuel costs for hydrogen. The total size of the power sector would also be larger if hydrogen is deployed, owing to the additional need for electrolysis, but peak demand would be lower.

Source: Aurora Energy Research

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Building efficiencies are categorised into EPC bands reflecting groups of properties with similar efficiency characteristics

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EPC ratings reflect the energy efficiency and energy consumption of a building, and are awarded based on professional surveys. Not every building has an EPC rating; in this report, data displayed on EPC ratings is based on extensive sample surveys.

What are EPC ratings ?

- Energy Performance Certificates (EPCs) ratings assess the energy efficiency of a building. They are used by homeowners and renters to estimate how much their energy bills will be. EPCs are also used as a tool to help homeowners improve a home's energy efficiency and marginal cost of heating.
- The EPC rating is determined by estimating :
  - The amount of energy used / m^2
  - The level of carbon dioxide emissions
- EPC ratings are valid for 10 years. It must be renewed if the building is rented to a new tenant or if the building is for sale.
- Since 1st April 2020, landlords owning properties that have an EPC rating below E cannot let or continue to let unless they have a valid exemption in place. In addition, the government aims to upgrade as many homes as possible to EPC rating C by 2035, as outlined in their Clean Growth Strategy.

What does the EPC rating report ?

- The property's current rating and potential rating.
- The key recommendations to make the building more efficient.
- A description of the dwelling's features, elements including:
  - Windows
  - Wall, roof and floor insulation
  - Main heating, secondary heating, hot water
  - Lighting
  - Fireplaces
  - Air tightness
  - The building measurement
  - The year the building was built.
- The property's space and water heating demand.

Not energy efficient, higher CO_2 emissions, higher running costs | **Very energy efficient, lower CO_2 emissions, lower running costs**

G [1-20]	**F** [21-38]	**E** [39-54]	**D** [55-68]	**C** [69-80]	**B** [81-91]	**A** [92+]

Scale: 0-100

Sources: Aurora Energy Research, EDF Energy, BEIS , Evergreen energy

Gas prices are expected to remain high until 2027 to then become the cheapest fuel, whilst electricity prices remain high

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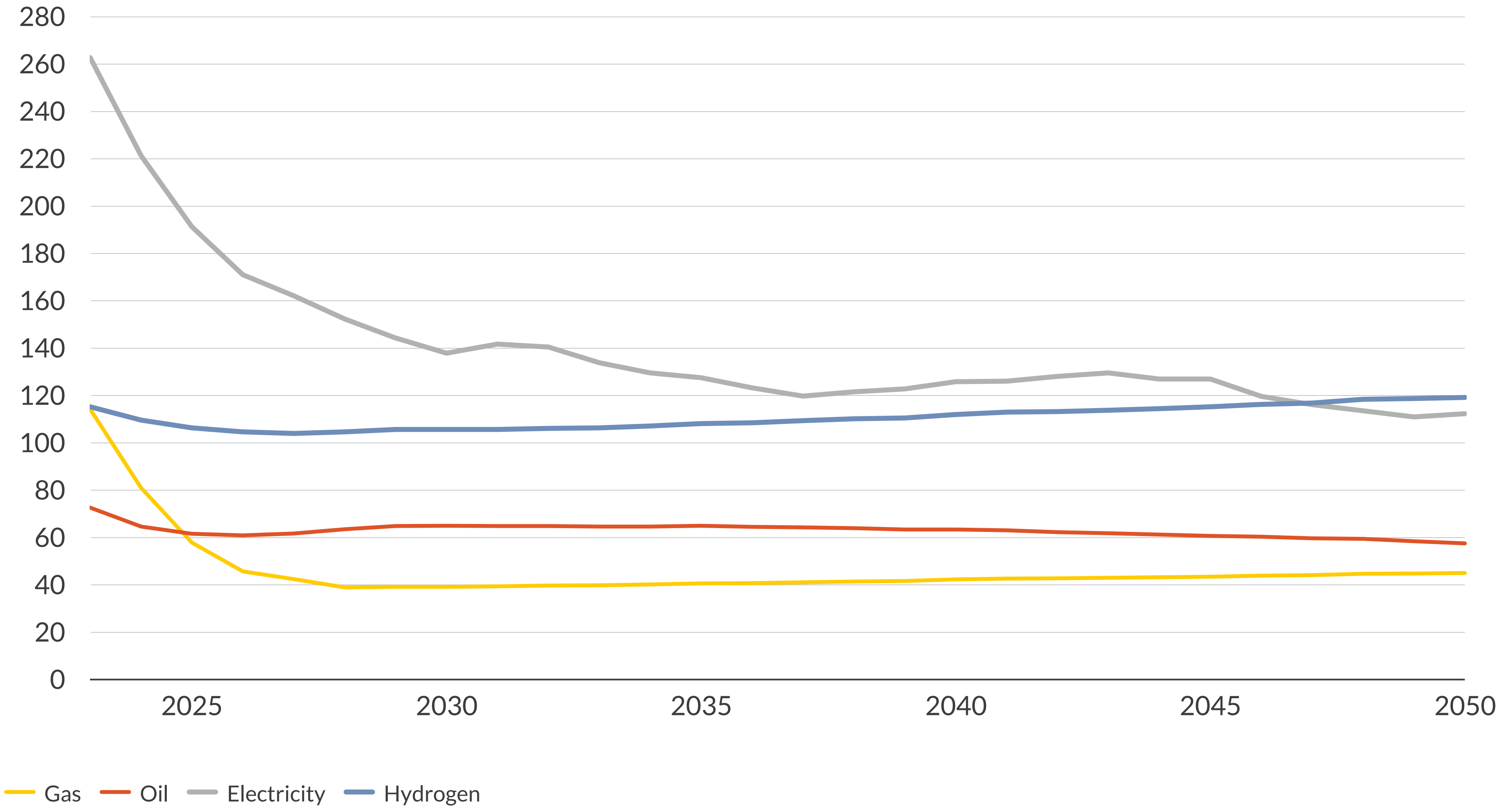
Aurora's retail fuel price forecasts for GB

£/MWh



1) Levelised cost of hydrogen production

Source: Aurora Energy Research

- Prices are taken from NIC Project A Base Case, and converted to retail price forecasts based on existing taxes and levies, and recoupment of future subsidy costs.
- The hydrogen retail cost is based on the LCOH[1] of blue hydrogen, produced by steam reformation of natural gas with carbon capture. This capture process is only ~90% efficient and the remaining 10% emissions are expected to be liable for carbon taxation, resulting in increasing cost to consumers through the forecast.
- Electricity remains the highest cost fuel until the 2040s on account of higher taxes and levies that are applied to consumer bills than for other fuels.

Power sector emissions fall rapidly to reach 7 $MtCO_2$ by 2035

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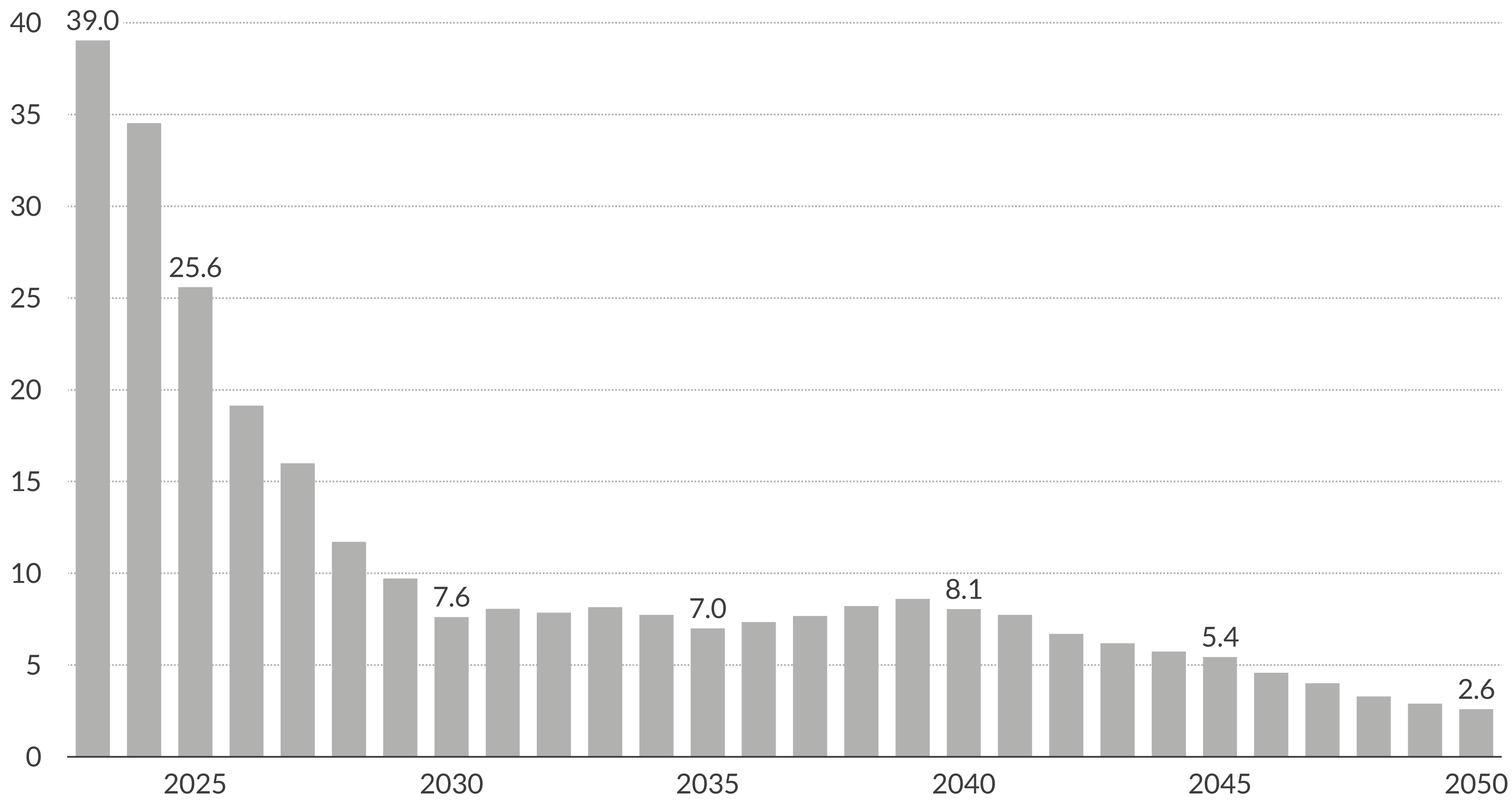
Emissions[1]
$MtCO_2e$



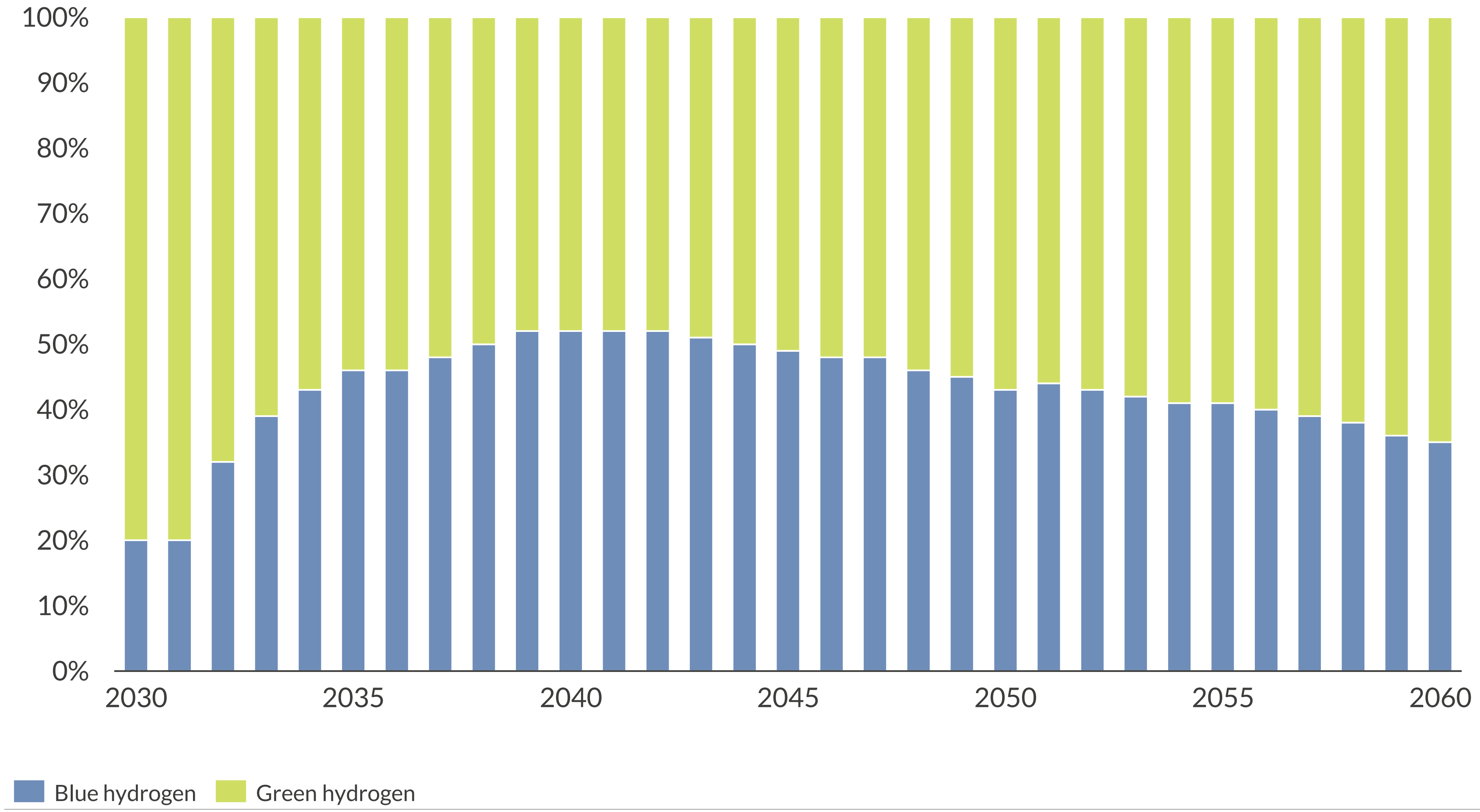
- Power sector emissions are assumed to be consistent across scenarios and no modelling has been undertaken on the different sized power systems required to serve the different resulting sizes of heat sector for the modelled scenarios

1) Emissions are taken from NIC Project A Base Case

Source: Aurora Energy Research

The mix of blue and green hydrogen is informed from NIC project A, with a predominant share of green hydrogen in all years

Share of hydrogen production by source
%



- Hydrogen production by source is a modelled output from the Base Case scenario from NIC project A
- All hydrogen production by 2030 is low carbon, produced either by steam methane reformation using carbon capture and storage (blue hydrogen) or by electrolysis of water using grid electricity (green)
- Blue hydrogen production capacity ramps up from 20% of total production in 2030, peaking at 50% of total production in 2040, falling back to 30% of the mix by 2060

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