Title: Decarbonising the UK residential sector: the dependence of national abatement on flexible and local views of the future

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Abstract

The UK has some of the worst performing residential buildings in the EU from an energy efficiency perspective. Natural gas remains a dominant feature of existing and new-build housing with strong historical, technical, and social barriers to change. Consequently, the residential sector is responsible for significant shares of national emissions and has a strong role to play under ambitious net zero targets.

To assess this role, this work combines long-term system-wide optimisation modelling with heat and electricity network models of representative residential locations. The scenario framework investigates key heating alternatives across futures with dwindling carbon budgets but lower restrictions on residential investment options. Comparing frameworks offers insights into “real life” applicability of technology solutions consistent with system-wide decarbonisation pathways to 2050.

Residential sector heat plays an increasing role in lowering emissions as targets tighten. Moving away from natural gas becomes unavoidable and long-term trajectories combine end-use electrification, at household or collective levels, with supply-side decarbonisation. This is preferable to alternative gases that continue to carry uncertain emission impacts, but requires significant local network reinforcement. This could be deferred where technically difficult using near-term hybrid approaches. Enabling this transition will rely on policies that support open and varied technology portfolios.

Key words

Energy system modelling;

Optimisation;

Residential heat;

Net zero;

Power system;

Network model;

1 Introduction

Enacted in 2008, the Climate Change Act is the primary piece of legislation for reducing emissions form all six Kyoto greenhouse gases (GHG) in the UK by 2050. Originally set to reach 80% reductions relative to 1990 levels, the act was ambitiously tightened in June 2019 and now commits the UK Government to achieving Net Zero (Great Britain, 2008). The independent Committee on Climate Change (CCC) was created by the act to advise Parliament in setting 5-year carbon budgets and in monitoring progress. It notes that while emissions in 2018 were 42% lower than in 1990, there is a widening policy gap to ensure the necessary reductions continue, now that low-hanging fruit such as decarbonisation of electricity generation has progressed rapidly (CCC, 2018). This context is only reinforced under the new net zero target.

Decarbonising heat is an important challenge for the future. In 2017, the 28 million UK dwellings (BEIS, 2018a) produced 14.3%[1] of UK GHG emissions through combustion of natural gas, and other fossil fuels, for space heat, hot water and cooking (CCC, 2018). Natural gas accounted for 76% of residential space heat (EUROSTAT, 2018), and for 67% of system wide heat (Figure 1a). Electricity, the second most widely used fuel, accounted for just 13%. While widely accepted domestically, this use of natural gas for residential heat makes the UK an outlier among European countries (average 43%), second only to the Netherlands (87%). Heating oil and solid fuels are still often used in off gas-grid rural dwellings (Figure 1b).

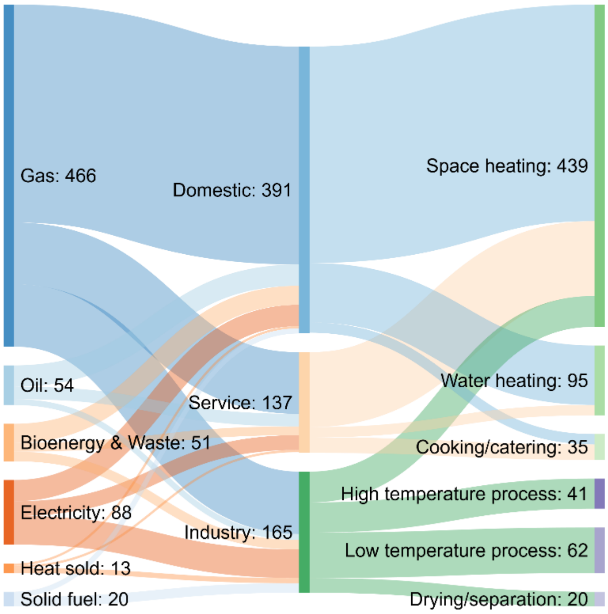

Figure 1a – 2017 UK heat consumption (TWh)(BEIS, 2018a)

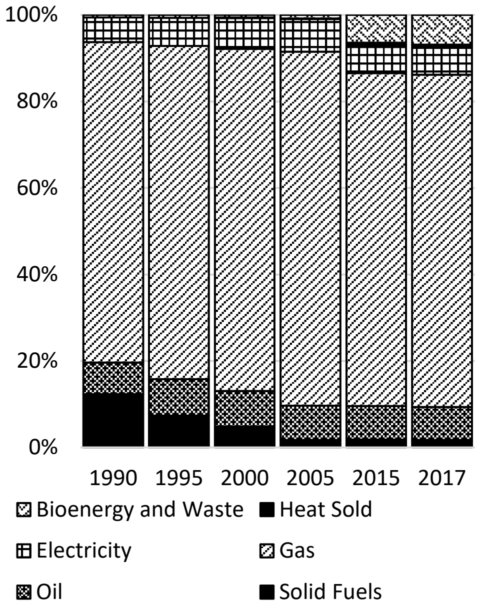

Figure 1b – Residential heat energy mix (BEIS, 2018a)

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[1] These refer to direct emissions only and do not include those due to e.g. electricity production.

After decades of increased household numbers and indoor temperature outstripping improved building regulations to leave demand for residential heat relatively constant (Eyre and Baruah, 2015), consumption has started to drop over the last 15 years (Figure 2). This is, in part, due to a combination of the 2004 policy prohibiting non-condensing boilers (Elwell et al., 2015) and of higher gas prices leading to boiler efficiency improvements[2]. It is also due to the incremental roll out of Supplier Obligation programmes from 1994 onwards with significant policy target increases in each phase from 2002. By placing the onus on energy suppliers to increase energy and, later, carbon efficiency in the residential sector, these policies have represented a key driving force for the roll-out of cost-effective energy conservation measure such as cavity wall or loft insulation (Rosenow, 2012).

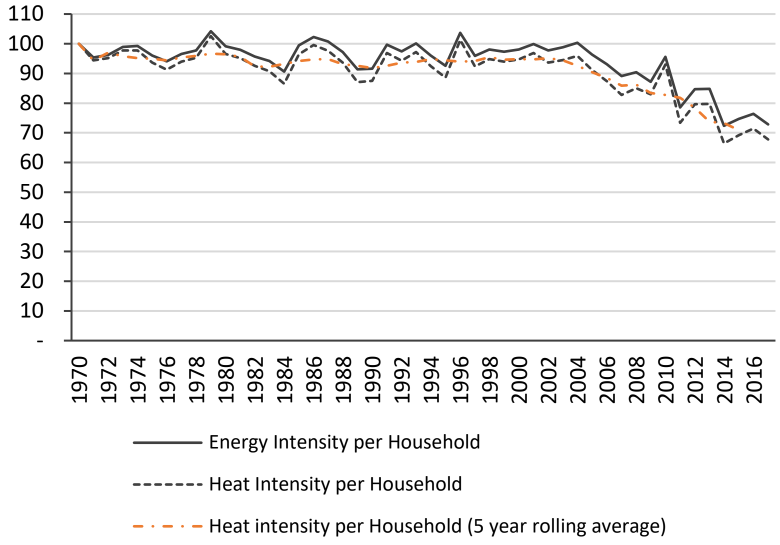

Figure 2 – Total energy and Heat consumption per household in the UK, 1970=100, (BEIS, 2018a)

Some European countries with even higher heating demands (e.g. Norway and Sweden), rely predominantly on electricity, renewables & waste, and derived heat (EUROSTAT, 2018), suggesting that decarbonising heat is not an impossible feat. The UK, however, has an unusually old housing stock. Pre-1940 buildings in particular tend to have poor thermal insulation, which contributes to the UK having some of the worst performing housing in energy efficiency terms in Europe (MacLean et al., 2016). Also, natural gas is not a cost-effective bridge to cleaner UK energy, as was once suggested (BEIS, 2015); rather, its continued use risks leading to investment in future stranded infrastructure (McGlade et al., 2018). This is controversial: natural gas is highly popular as it is well known, relatively cheap, responsive, reliable, quiet, and requires little space[3]. In fact, one of the strategies to reduce fuel poverty in the UK has been to connect “off-grid” properties to the gas networks and to fit natural gas boilers (Madhura, 2016). Hence advice from the CCC that no new dwellings use natural gas from the year 2025 (CCC, 2019a) has attracted scepticism from industrial stakeholders (Arntzen, 2019). While alternate (e.g. highly electrified) futures are also challenging, failing to address this “techno-

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[2] estimated at 1.25%±0.15

[3] The natural gas system footprint has reduced for many dwellings in recent years since the introduction of high-power combination boilers providing on-demand hot water, enabling the removal of hot water storage tanks.

institutional complex" risks long-term gas "lock in" (Unruh, 2002). This risk is, in part, magnified by restricting future systems to mirror existing ones.

As a result, there is much uncertainty over the extent to which heating might practically be decarbonised in the future. The first aim of this paper is to examine the system-wide implications that ambitious national decarbonisation targets have for the residential sector, using a national-scale energy system model. In contrast to other papers, this study examines the implications of technology deployment being limited by current expectations of the future as compared to deploying a more diverse portfolio of options.

Given the diversity of the housing stock, there is also uncertainty as to whether large-scale appraisals of decarbonisation potentials can, in fact, properly represent the cost and performance of low-carbon technologies in different dwellings. The second aim of this paper is therefore to critique the system-wide insights using two local-scale exemplar energy models, including their network-level implications at both national and local scales. Previous studies have not evaluated their insights in this way.

The paper is structured as follows. The policy drivers and previous modelling studies of decarbonising heating are examined in Section 2. The models and scenarios are described in Section 3, and the results are presented in Sections 4 and 5, respectively. Section 6 summarises the key conclusions and policy implications.

2 Background

2.1 UK decarbonisation policy for the residential sector

In 2017, annual UK CO_2 emissions had fallen by 227 $MtCO_2$/a (38%) since 1990. Power sector emissions have contributed for 60% of this drop. The residential sector has been more stagnant. Household numbers have close to doubled since the 1960s (EHS, 2017), but improved heating systems and household thermal efficiencies kept annual emissions between 80 and 90 $MtCO_2$/a for the best part of the 1990s and early 2000s. Policies implemented since 2004 have reduced emissions to 64 $MtCO_2$ in 2017, representing 6.3% of the annual CO_2 emissions savings since 1990 (BEIS, 2018b).

The UK Government published a heat strategy framework in 2012 that broadly proposed longer term electrification (DECC, 2012a). In 2013, the subsequent heat strategy was more circumspect: electrification was one option among others (DECC, 2013). Converting the gas networks to deliver hydrogen was proposed (Dodds and Demoullin, 2013) and has been pursued by the gas industry through engineering feasibility reports, for example for the city of Leeds (Northern Gas, 2016), and through lobbying (Lowes et al., 2018). More recently, the CCC has suggested that future heat demand could be met using a mix of pure-electric and hybrid heat pumps. This could incorporate hydrogen or natural gas boilers for peak heat generation to avoid potentially expensive electricity system upgrades (CCC, 2019a), as demonstrated in a recent project in South Wales (Freedom Project, 2018).

Existing policies have encouraged the deployment of energy conservation measures, which have been claimed to have negative marginal abatement costs as reported by to the CCC e.g. (AEA Energy & Environment, 2008; Element Energy, 2013). On-the-ground, different schemes have however had varying levels of success.

The Green Deal (GD) and the Energy Company Obligation (ECO) were launched together in 2013. The GD introduced a market-led "pay as you save" model under which refurbishments carried out by accredited professionals to improve a residential property's energy performance were paid for using corresponding energy bill savings. To be eligible, measures needed to comply with the "Golden Rule" by which savings would exceed the cost of the loan provided by the Green Deal Finance Company. The scheme closed in 2015 having barely registered 20,000 installed "measures" (DECC, 2015). While official reviews stated that the scheme did not deliver "value for money" (NAO, 2016), others tagged it a "dramatic policy failure" (Rosenow and Eyre, 2016a). Concerns raised both before its inception (Eyre et al., 2012) and after the fact (Rosenow and Eyre, 2015, 2013) noted governments' un-substantiated optimism for the schemes' success. They highlighted that targets fell short of stated objectives for emissions reduction and fuel poverty alleviation; that the lack of consideration for end-users overlooked known, and significant, barriers to efficiency measure uptake; or that the combined golden rule and high interest on GD financing restricted this scheme to low-cost improvements.

This last change marked a significant departure from existing policy which relied on supplier obligations to place requirements on electricity and gas suppliers to reduce carbon emissions from domestic buildings. Maintaining an affordable cost of energy while passing the cost of these improvements on to the consumer implicitly supported the aforementioned low-cost measures (e.g. cavity wall and loft insulations). These schemes included the Carbon Emissions Reduction Target, the Community Energy Saving Programme, or the Energy Efficiency Commitment. While these arguably reaped some low-hanging fruits, they all achieved their targets (Ofgem, 2019). This structure was overturned with the introduction of ECO which focused on harder-to-treat homes requiring more expensive measures and was intended to complement the GD. Overall, it was strongly suggested that this new policy structure would lead to reduction in energy savings of around 80%, projections that have been largely correct (Rosenow and Eyre, 2016b).

The principal policy supporting low-carbon heat technologies has been the Renewable Heat Incentive (DECC, 2011a). Opened to domestic applicants in 2014, it has targeted off-grid locations, subsidising new renewable heating in 54,000 dwellings to date. It is paid for from taxation, and provides quarterly payments over the first seven years post-installation of eligible technologies[4]. It is set to run until 2020 costing £1.3-2.4bn/a.

Local initiatives also exist. For example, The London Plan[5] supports decentralised heating and cooling networks to help provide 25% of London's heat and power requirements through "localised decentralised energy systems" by 2025 (GLA, 2016). Progress in the rest of the UK could be deemed slow with district heating (DH) representing just 0.8% of domestic heat supply (BEIS, 2019). Notwithstanding, total heat network customer numbers have more than doubled between 2013 and

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[4] biomass boilers, air-source heat pumps, ground source heat pumps and flat/evacuated tube solar thermal panels

[5] By its official name, the Spatial Development Strategy for London.

2018, increasing from 211,000 to close to 500,000 served by an additional 15,000 networks over the same period (ADE, 2018). While many of these networks remain small (CMA, 2018), their rapid increase in number could represent a significant benefit as they increase in size and / or expand[6].

Looking forward, the Clean Growth Strategy pledges £3.5 billion for building upgrades and supports the roll-out of low-carbon heating systems (BEIS, 2017), but needs clearer implementation steps. Rosenow et al. (2018) deem some of its proposals “lacking in either detail or ambition” and suggest that current policy is at risk of failing to deliver even limited ambitions.

Yet there are growing opportunities. The closure of coal power stations and the increase in renewable generation have reduced UK electricity carbon intensity to around 280 gCO_2e/kWh (BEIS, 2018c). This suggests that air-source heat pumps (ASHP) can reach carbon footprints between 60 and 170 gCO_2e/kW_{th}[7] where natural gas boilers retain footprints of around 230 gCO_2e/kW_{th} delivered heat (POST, 2016).

2.2 Modelling residential heat decarbonisation

Uncertainty in the UK’s heat decarbonisation strategy is mirrored by the challenges of modelling its various options, involving an understanding of: (i) required levels of decarbonisation; (ii) diversity of housing stock; (iii) system-wide impact of heat electrification; (iv) spatial sensitivity of technology costs; (v) uncertainty about the cost, performance, and acceptability of low-carbon technologies; and, (vi) potential for changes in societal views of heating.

The combined objective of supplying clean, sustainable, and affordable energy can be achieved through a variety of different pathways. Decarbonising all residential heating may not be required if other sectors can take a greater share of the burden. Yet the recent move to net-zero emissions in the UK sets a gold standard that has so far not been considered and could require deeper cuts than currently envisaged. Regional and global tones set by the Paris Agreement (UNFCCC, 2015) and by reports of accelerating changes in climate (Lenton et al., 2019) only serve to reinforce this reality.

Energy system models such as UK MARKAL (Anandarajah et al., 2009), UK TIMES (Pye et al., 2017) and ESME (Fell et al., 2019) represent the whole UK energy system and are used to identify pathways that meet emissions and other targets. Existing studies have highlighted the benefits of air source and other HPs as effective strategies for decarbonising residential heat supply in the UK, supported by district heat (DH), and occasionally natural gas (CCC, 2019b; ETI, 2015; Qadrdan et al., 2015; Strbac et al., 2018a; Zhang et al., 2018). Although energy system models can represent a wide range of decarbonisation options, and interactions between heating and other parts of the energy system such as the electricity system, they have the disadvantage of aggregating the housing stock and having a low temporal resolution for the electricity system. Where clear least-cost technologies exist for “average” houses, for example ASHPs, then user-defined limits on their deployment

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[6] Note that the term “heat network” should also be treated with caution as it is used interchangeably to describe both communal heating, i.e. singe building systems, and district heating, which will cover multiple buildings (BEIS, 2018e).

[7] Values derived for an assumed electricity emission intensity of 250 gCO_2e/kWh.

will have an important influence on the decarbonisation pathway. In UK TIMES, ASHP and DH deployment are limited to reflect the assumption that some houses are unsuitable for these technologies.

Housing stock models attempt to represent the diversity of the housing stock using hundreds to thousands of categories, so they can resolve minor differences between types of dwellings (Dodds and Hawkes, 2014). They have the disadvantage that the wider system is not represented, so the level of decarbonisation is a model input, and that crucial interactions with the electricity system are not considered. Using UK MARKAL, Dodds (2014) concluded that introducing a more disaggregated representation of the housing stock into a UK energy system model would have minor system-level impacts, but produces more detailed insights *within* the residential sector.

Electrified heating could greatly increase peak demands, and hence the cost of electricity generation. Strbac et al. (2018b) examine residential sector decarbonisation in a high temporal resolution electricity system model and aggregate UK housing stock into a single “average” dwelling. They conclude that there could be an important role for hybrid heat pumps in the future. Stock models assume exogenous electricity prices and consequently do not account for such electricity system interactions, which are evidently important.

Large-scale electrification of heating could require substantial reinforcement for electricity transmission and distribution networks, incurring costs that are difficult to assess. Spatial models are being developed to account for these costs; for example, Energypath has been applied to the Greater Manchester area (ESC, 2017). In a detailed GIS model study of Bristol, (Jalil-Vega and Hawkes, 2018) assess the cost of heat networks against other low-carbon technologies. These models are useful for understanding how decarbonisation options are affected by spatial and stock variations, but the insights cannot necessarily be applied to the whole country.

Conducting a full review of the current evidence base, (BEIS, 2018d) underline that while the range of technologies available is well known, little consensus emerges in terms of economic strategy. Different studies make different assumptions that could have an important influence on the benefits of, for example, hybrid heat pumps. Not all dwellings are suitable for technologies such as ASHPs, and the imposition of deployment constraints can greatly affect model results where the technology has the lowest cost. The most appropriate sizing, cost, and performance of low-carbon technologies for different buildings are not well understood. The security of supply, emissions intensities, or wider system impacts of alternative solid fuels or gases is unclear. Moving away from fossil fuels and diversifying the technology mix is challenging but involves inherently lower levels of risk than relying on a single technology (Eyre and Baruah, 2015). Finally, the deep transformations required assume changes in end-user behaviour and public awareness, and both remain low. Li and Strachan (2019) underline this factors’ importance by showing that strong government policy for heat is necessary but insufficient to instigate fundamental changes if societal views do not evolve.

2.3 Aims of this study

Section 2.2 shows that no model offers a single holistic approach to understanding heat decarbonisation. While different frameworks can be applied to assess future heat pathways for the UK, many either focus just on the residential sector, are restricted to a single model year, or lack key parameters such as capital costs (Jalil-Vega and Hawkes, 2018). Recent studies have tended to combine two model types or to increase spatial or temporal detail. This paper takes a similar approach, based on two premises:

1. The recent move to tighter, net zero emission targets creates a need to better understand the uncertainty that surrounds levels of, and pathways for, residential heat decarbonisation.
2. Constraints on technology deployment characterised in energy system models may have little supporting evidence, yet can substantially affect the results.

This paper complements results from techno-economic, long-term, investment modelling with those provided by spatially and temporally explicit, local, energy system simulation models. The long-term model examines the implications of tighter ranges of decarbonisation targets for the residential sector. The technology constraints are systematically relaxed to understand their impacts. This acknowledges that technological change in long term optimisation models should not reproduce "status-quo" pathways under narratives that deep change is either technically complex, unpopular, unprecedented or otherwise unrealistic. The results are tested against insights from two detailed "exemplar" network models that examine heat provision in high- and low-density locations, at high temporal resolution. These models challenge whether proposed, optimal, decarbonisation pathways are feasible and practical. To the author's knowledge, this is the first time that energy system and detailed spatial models have been combined in this way to analyse residential heating pathways.

3 Methodology

The whole-system scenario analysis uses the established TIMES model of the UK. Results are then assessed through the lens of two local exemplar network models defined for low- and high-density[8] UK case studies.

3.1 The UK TIMES energy model

TIMES is a least cost optimisation, bottom-up, dynamic, partial equilibrium, techno-economic model generator typically used to represent local, regional or national energy systems (Loulou et al., 2004).

Developed in 2014 by UCL Energy Institute as a successor to UK MARKAL (Kannan et al., 2007), the UK TIMES (UKTM) model has been applied in a number of UK energy scenario studies (Fais et al., 2016a, 2016b; Fuso Nerini et al., 2017; Pye et al., 2017; Zeyringer et al., 2018). Recent versions have been co-developed by HM Government's Department for Business, Energy and Industrial Strategy (BEIS, previously DECC) and by the CCC to underpin the fifth UK Carbon Budget (CCC, 2012).

UKTM is a detailed model of all energy chains in the UK. These rely on a network of technologies that consume, transform and produce energy carriers to serve end-use energy service demands. These include existing and potential future energy

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[8] In terms of occupancy and energy demand per unit land area

infrastructure. The model considers fuel mining, primary and secondary fuel production (electricity and heat), exogenous trade, and final consumption in the residential, industrial, service, transport and agricultural sectors. By representing all sectors, UKTM provides a holistic approach to tracking sectoral and economy wide GHG and other emissions[9] under national climate targets, trading off mitigation efforts between sectors.

Structurally, UKTM is a single spatial node model with a temporal resolution of 16 time-slices (one typical day for each season, split into daytime, evening peak, late evening and night, chosen according to electricity consumption in 2010). All sectors are calibrated to a 2010 base year and are modelled using five-year time-steps to 2050 (DECC, 2011b, 2011c). Technologies are represented using a rich set of techno-economic data including (but not limited to) CAPEX and OPEX costs, efficiency, capacity factor, expected and economic lifetimes, hurdle rates etc. All annual system costs[10] are discounted to the base year using a social discount rate of 3.5% (HM Treasury, 2018). They are summed to form the total discounted energy system cost that the optimisation approach then minimises.

Further details are found in (Daly and Fais, 2014).

3.2 The Residential Sector in UKTM

To represent space heating and hot water demands, the existing residential stock is disaggregated into houses and flats, each with solid or cavity walls. The number of dwellings is assumed to decrease at a constant demolition rate of 19.1 k.hh/a[11], based on recent trends (MHCLG, 2014). New-build is aggregated into a single category that grows in line with national projections (BEIS, 2016a). This topology is based on the National Household Model and Table 1 shows corresponding assumptions for stock numbers, energy conservation potentials and heating technologies operating in 2010 (BEIS, 2016b).

Table 1 – Existing stock heat provision and energy conservation assumptions, base year. Shares of conservation potentials are viewed across house type; heat provision technology shares are for one house type and across technology options.

		Unit	House		Flat		
			Cavity wall	Solid wall	Cavity wall	Solid wall	Total
Conservation technology potential	Number of dwellings	'000	15,462	5,819	3,701	1,853	26,835
	Cavity wall insulation - easy	%	76	-	24	-	100
	Cavity wall insulation - hard	%	75	-	25	-	100
	Solid wall insulation	%	-	77	-	23	100
	Loft insulation	%	63	37	-	-	100
Heat provision technology in the base year	Biomass boiler	%	-	○	-	-	n.a.
	Coal boiler	%	0.8	1.2	○	0.2	n.a.
	Coal heater	%	○	0.7	○	○	n.a.
	Electric boiler	%	-	-	○	-	n.a.
	Electric heater	%	0.7	1.0	7.5	5.2	n.a.
	Electric night storage heater	%	3.7	3.6	23.5	10.9	n.a.

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[9] CH_4, CO_2, HFCs, N_2O, NO_x, NH_3, PM_{10}, $PM_{2.5}$, SO2, VOC

[10] Investment costs are annualised over the economic lifetime using technology specific hurdle rates, all other costs are incurred “in year”.

[11] hh/a are households per annum

Electric standard boiler	%	0.1	0.2	0.4	0.7	n.a.
Gas back boiler	%	9.4	6.4	3.2	1.9	n.a.
Gas condensing boiler	%	9.0	5.9	4.5	4.3	n.a.
Gas heater	%	1.7	2.1	1.0	1.2	n.a.
Gas combi-boiler	%	23.9	31.7	24.8	36.0	n.a.
Gas condensing combi-boiler	%	13.2	15.0	12.9	15.8	n.a.
Gas standard boiler	%	31.3	22.7	13.6	19.6	n.a.
Heat pump	%	○	-	-	-	n.a.
Heater	%	○	0.3	0.2	0.2	n.a.
LPG boiler	%	0.9	0.8	-	○	n.a.
LPG heater	%	○	0.2	○	0.3	n.a.
Oil boiler	%	4.2	7.5	-	0.2	n.a.
Oil condensing boiler	%	0.4	0.5	-	-	n.a.
Oil heater	%	-	-	-	-	n.a.
District Heating	%	0.2	○	8.0	3.3	n.a.
Total	%	100	100	100	100	n.a.

"○" the technology is used but total numbers are negligible; "-" the technology is not used i.e. the value is zero.

Source: National Household Model (NHM)[12] (CSE, 2014; HM Government, 2017; McKenna et al., 2016) inputs provided by central government Department for Energy and Climate Change (DECC now BEIS)

This paper focuses on fuel consumption and corresponding emissions for the provision of residential space heat and hot water[13]. Each housing category has its own demand for both. Noting the relative energy inefficiency of the aging housing stock, new-build heating demand is lower than for equivalent existing dwellings (Li et al., 2018).

A simplified diagram of the heating technologies that can be installed after 2010 is presented in Figure 3. Energy efficiency measures – loft, solid and cavity wall insulation[14] – can be installed in houses that do not yet have it. This provides end-use energy savings, reducing upstream system needs. The remaining demand is supplied by combining heat delivery and heat production options. The first includes standalone heaters, radiators or underfloor heating. The second is split between onsite or communal heat production. Household technology choices range from status quo gas or oil systems, through to efficient boilers, ASHP, GSHP, hybrid systems, or micro CHPs. Similar large-scale options exist on a district level. In both cases the model structure allows for multiple "technology-fuel" combinations.

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[12] The NHM is based on the English Housing Survey and Scottish House Condition Survey. The authors note that baseline data presented here for 2010 differs from that presented in national statistics of Energy Consumption in the UK who, while relying on the same survey input data, follow a different scaling methodology. This discrepancy is in the order of 10% and relates to numbers of non-condensing boilers, and decreases rapidly over the two first model periods with a phase out of older systems no new non-condensing systems installed. Comparisons beyond 2020, which are the focus of this paper, are not affected by this difference.

[13] Note that UKTM also accounts for energy demands for cooking and recreational/other uses.

[14] Conservation potential for each household type is calculated based on the number of eligible households for each refurbishment measure and the average amount of energy that each measure is able to save.

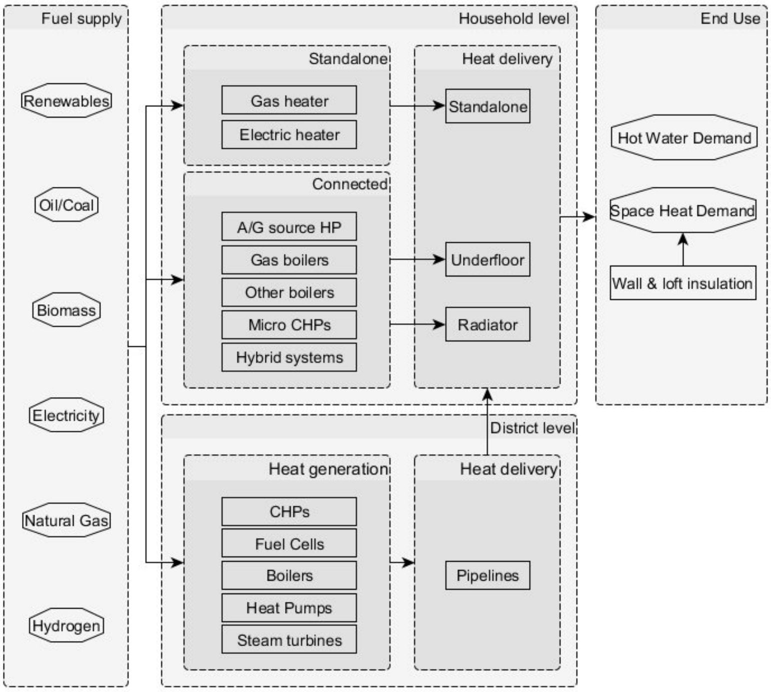

Figure 3 – Simplified UKTM residential sector heat, loosely based on (Li et al., 2018)

There has been concern in the literature that electrification of heating will lead to high electricity demand peaks, since peak gas demands are much higher than peak electricity demands from both seasonal and time-of-day perspectives (e.g (Sansom, 2014)). In UKTM, space heating and hot water demand load curves are modelled as a function of the time of day in each season based on gas boiler measurements from (Summerfield et al., 2015). Where heat is electrified, electricity consumption will be added to the total load in each time-slice. Although there are peak heating demands in the morning and the evening, the peak electricity demand still occurs in the evening after electrification since other electricity demands, elsewhere in the system, peak in the evening. To ensure that there is sufficient electricity generation to meet peak day demand in each season, rather than just the average day that is represented in UKTM, an electricity generation reserve capacity factor is applied based on the 2010 system. Although peak heat demands during a very cold period in winter might exceed this factor, the peak loads would likely be dampened through heat pumps having a flatter load than gas boilers, and substantial heat storage. Further research at a higher temporal resolution, using heat demands for several years, would be required to understand whether peak electricity demands are during in a very cold period in the future might be underestimated.

3.3 Local exemplar models

Heat provision depends on a number of spatial and temporal factors, including thermal losses in transport, network requirements, short-term behavioural impacts and building thermal envelopes. UKTM is a single-region model with aggregated representations of energy demand, supply and mobility. As such, rigorous local impacts investigation of its national-scale technology scenario results has value.

Figure 4 – Low-density network layout, showing 292 properties including semi-detached, detached and terraced housing. The secondary 500 kVA transformer is in the centre and supplies four colour coded electricity feeders/properties. Dashed lines indicate low pressure gas pipework.

Within the UK context, 2 'exemplar' models of respectively high- and low-density areas are used to investigate the full details of both short-run dispatch and long-run investment costs for different domestic heat technologies. These exemplars incorporate high-resolution per-household demand derived from a stochastic behavioural model (Flett and Kelly, 2016) coupled with building thermal models described in (Allison et al., 2018), alongside representation of extant last-mile electricity and gas networks down to a street and household level.

Based on specific locations, the two low- and high- density exemplar models are compared to the house/flat categorisation in UKTM. The low-density model represents 292 households located across 5 streets in north Darlington, a large town in the north of England. The housing stock is a mixture of 1 detached, 260 semi-detached, and 31 terraced houses. The network layout, typical of low-density suburban areas of the UK and including 1930's housing stock, is shown in Figure 4. This combination of street layout, housing density and network topology is useful as a representative case for a large section of the UK population and housing. The high-density model represents two tower blocks containing 208 flats in the north of Glasgow, currently supplied by gas condensing boilers but with significant DH opportunity.

The models simulate high-resolution demand data corresponding to each domestic property with occupancy and behaviour inferred from UK census data. They were developed with a spatial representation of all extant infrastructure using data from relevant electricity and gas network operators (ENA, 2015), overlaid with hypothetical heat networks. Losses and reinforcement costs are included per metre of network infrastructure to determine additional CAPEX and OPEX requirements (e.g. for electrical feeder reinforcement and transformer replacement if large numbers of heat pumps (HP) are installed). Each heat decarbonisation technology option is then simulated at a 15-minute resolution using climate-driven energy demand data for 2010. Further information is available in (Hawker, 2018).

3.4 A scenario-based approach

Decarbonising the residential sector calls for large scale, important and yet uncertain infrastructural changes in the UK. These may involve upgrades to existing, and roll-out of new, national network infrastructure for heat, electricity, or gas. These may also involve transformational shifts in household energy efficiency and domestic heating systems.

The level and type of change respond to future UK energy system targets and account for a-priori assumptions, or expectations, of technical feasibility, for example, for significant DH system roll-out. This work does not make assertions about ease or likelihood of changing such expectations in practice. Instead, it develops scenarios that assess how shifts in assumptions for residential heat provision in UKTM might affect medium to long-term sectoral and system-wide change. From a technical perspective, it then considers these shifts in context: it uses results from explicit exemplar model runs to comment on implications and practicability, in real-world terms, of UKTM model runs.

3.4.1 UKTM Scenarios

These scenarios combine two dimensions. The first dimension looks at residential constraints representing e.g. technical, behavioural, economic or acceptance barriers to technology deployment. These constraints are grouped together and their levels are dropped in line with reduced target values for 2050. This drop represents potential policy interventions to facilitate the introduction and roll-out of new technology. The second dimension reflects current socio-political discussions by examining incrementally tighter 2050 GHG emission targets. The scenario matrix and corresponding constraint levels are presented in Table 2.

Table 2 - Scenario Matrix, green to red showing increasing levels of constraint, reference case is 80_C1. Full constraint level descriptions are provided in Table 3.

			GHG emission reduction (% of 1990) [a]				
			80	85	90	95	*100 [b]*
Combined technology constraint level (% of baseline case levels)	100 %	C1	80_C1	85_C1	90_C1	95_C1	*100_C1*
	83.3 %	C2	80_C2	85_C2	90_C2	95_C2	*100_C2*
	66.6 %	C3	80_C3	85_C3	90_C3	95_C3	*100_C3*
	50 %	C4	80_C4	85_C4	90_C4	95_C4	*100_C4*

a) GHG emission reductions listed here refer to total system emission levels, including the residential sector.

b) 100% reduction in emissions cover an indicative set of runs that do not solve without backstop – i.e. technologies that provide emission cuts to the system at a very high cost – due to conservative assumptions about availability of sustainable biomass, CCS options, and structure of the industrial and transport sectors

The nature and levels of constraints that change under dimensions C1-4 are detailed in Table 3. They include annual capacity growth-rate limits and upper bounds on shares of heat provided annually by specific technology groups. These constraints apply either to the full household topology or to individual categories. For each constraint, level C1 is the status-quo level and levels C2-4 represent pathways where the C1 level is lowered. Starting in 2025, the constraint is dropped linearly to a 2050 target value. Target values for level C4 represent the midway point between status-quo and total constraint removal[15]. Target values for levels C2 and C3 are then 1/3rd and 2/3rd of the way between status-quo and C4.

GHG emission[16] targets rely on a system-wide constraint that includes carbon dioxide, methane, nitrous oxide and hydrofluorocarbons. It covers all sectors, accounts for trade and negative emissions[17]. Allowable emissions follow the five legislated carbon budgets to 2032 and are linearly interpolated thereafter to 2050 target values defined as % reductions in emissions compared to 1990 levels. The range of targets used in this study reflect the particular situation in which the UK now finds itself at the time of writing. The reference case recognises that the current policy landscape is geared towards reaching 80% emissions reduction to 2050. The maximum ambition case reflects the tighter, net zero, amendment to UK climate legislation, but for which a substantial policy gap exists. Intermediate targets are defined in 5% increments between 80% and 100% reduction by 2050 to explore this transition.

Combining these dimensions highlights how low-emission futures and trade-offs with other marginal sectors may shift the value of alternate heating systems that emerge from more ambitious technology constraints.

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[15] For growth rate constraints C4 cases represent a doubling of the maximum annual growth.

[16] Accounted for in CO_2e according to global warming potential

[17] Including fossil and biomass with carbon capture and storage, as well as conservative levels of reforestation.

Table 3 – Nature and level of constraints applied to the residential sector under C1-4 scenarios

			Across full housing stock				Existing																New build			
							House								Flat											
							Cavity wall				Solid wall				Cavity wall				Solid wall				Aggregate			
	Heat Delivered		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
Central heating	Minimum from wet heating systems	% of annual heat demand					94	78	63	47	94	78	62	47	67	56	45	34	82	69	55	41	87	72	58	43
HP penetration	Maximum from heat pumps	% of annual heat demand					82	85	88	91	79	82	86	89	13	27	42	56	10	25	40	55	68	74	79	84
Gas grid penetration	Maximum from natural gas	% of annual heat demand					93	94	95	97	89	90	92	94	63	69	75	81	83	86	88	91	90	91	93	95
DH penetration	Maximum from district heating	% of annual heat demand	34	56	78	100																				
	Annual Growth																									
HP, Micro CHP and solar water heater capacity growth	Maximum rate for the technology group	% additional capacity to previous year	20	27	33	40																				
NSH, DH, underfloor heating, biomass boilers capacity growth	Maximum rate for the technology group	% additional capacity to previous year	10	13	17	20																				

3.4.2 Local Exemplar Scenarios

Scenarios for the two local energy models cover specific technology sets. This reflects the likelihood that technology preference within a specific area is likely to be similar, sharing costs of implementation, demographics and support mechanisms (e.g. via a local authority) for homogenous local housing stocks. The scenarios cover:

- natural gas condensing boilers (base case);
- gas condensing boilers fuelled by biomethane[18] utilising the existing gas distribution network;
- gas condensing boilers converted to hydrogen utilising the existing gas distribution network, including costs of household conversion;
- HP[19], including air-to-air low temperature, air-to-air/water high temperature, ground-to-air/water, gas[20], and gas/electricity hybrid; and,
- a DH network[21] supplied by an appropriately sized OCGT and hot water storage, with interface units in each property, with separate scenarios for methane, biomethane and hydrogen,

These systems also supply hot water and include domestic-scale hot water tanks to buffer between service demands. This excludes air-to-air low temperature HPs where extant gas condensing boilers are maintained in parallel. Households are assumed to have undergone minimum efficiency improvements (cavity wall insulation, loft insulation and modern cladding where applicable) – for comparison we include a non-improved scenario utilising natural gas condensing boilers. While electrical network upgrade costs within the local system[22] are included, deeper reinforcements are not considered as they depend on technology selection in other residential areas and on changes in industrial and commercial consumption.

Technology parameters are assigned a ‘low’, ‘central’ and ‘high’ value for the purposes of conducting sensitivity analysis against costs. Affected parameters relate mainly to: (a) capital costs, evaluating the spread in cost reduction forecast for each technology according to current-day estimates; (b) grid-side fuel costs (electricity and gas); and, (c) the emissions intensity (EI) of transmission-level electricity. Non-cost parameters are mapped to each scenario in terms of cost impact (e.g. condensing boiler efficiency values are allocated in reverse, with high efficiency mapping to the ‘low’ cost scenario). in (DECC, 2012b). For hydrogen scenarios, the low/central/high cost scenarios each relate to the costs and emissions associated with, respectively, Steam Methane Reformation (SMR) with CCS, Alkaline Hydrolysis from zero-

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[18] Costs and emissions intensity ranges for hydrogen and biomethane are taken from (Speirs et al., 2018)

[19] Coefficients of performance (COPs) are treated as time-variant with ambient temperature within the ranges specified in (DECC, 2012b), using a local annual temperature profile from 2010.

[20] A relatively lesser-used technology which uses a gas engine and compressor to achieve greater efficiency in heating and cooling than traditional boiler technology

[21] The network mapping follows extant Low Voltage electricity network topology.

[22] In this context, the local system is understood as including the LV transformer and the downstream infrastructure.

emissions renewables, and bioenergy with CCS (assuming zero associated emissions).

For each technology scenario, the delivered cost of energy (DCOE) (disaggregated by fuel supply, technology CAPEX/OPEX and network reinforcement) and the resulting emissions intensity (EI) of the delivered energy are calculated[23]. This supports a validation of the carbon abatement potentials of key technology pathways demonstrated in the UKTM analysis, and helps to assess potential barriers to uptake mirrored by constraints in the higher-level model.

The scenarios modelled use 2030 as a target year for simulation, with an electricity grid emissions intensity of 41/85/94gCO_2/kWh for the low/central/high scenarios, with the first 2 cases relating to the 2035 and 2030 projections in the latest BEIS assessment of future grid carbon intensity (i.e. the low case reflecting a more aggressive reduction pathway than currently expected), and the third case reflecting the CCC's most recent assessment of the most cost-effective pathway. This is intended to reflect the potential reduction that may be unlocked by the use of electrification where policy decisions are enacted which simultaneously aim to reduce the intensity of supply-side electricity while moving end-use demands away from the gas grid, in keeping with the system-wide transition that may be selected within the UKTM model.

4 Modelling results

4.1 Long term residential heat pathways

4.1.1 Comparing emission targets under status-quo futures

UKTM results show different residential technology portfolios across the scenario matrix. Looking at conservative[24] systems, Figure 5 shows annual aggregate heat provision by technology group under baseline emission targets (80_C1, left) and 2050 results across tighter targets (right).

Suggesting a fabric-first approach, conservation measures are adopted early and exhausted by 2035, saving around 10% of final demand[25]. At this point, 84% of existing houses and efficient new-build rely on natural gas boilers. Later, smaller carbon budgets increase pressure on the residential sector, reducing this share to 63% in favour of lower carbon technologies including HP (17%), DH (9%) and other standalone systems (11%).

This trend away from natural gas is reinforced under stricter emission targets and it is almost entirely absent for ambitions exceeding 90% GHG reduction. Showing a preference for centralised low-carbon electricity and heat over clean gas options, electric ASHP and DH systems play an increasingly important role in completing the mix. Increasing climate targets by 5% (85_C1) shows a 21 percent point increase in

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[23] Note that the DCOE includes the cost of carbon assumed by DECC/BEIS fuel price estimates used as supply-side cost inputs to the model.

[24] This is not meant in the political sense, but should instead be understood to mean traditional, or conventional. The term is used here to describe scenarios that sit at the opposite end of the spectrum to “liberal” futures.

[25] Energy conservation potentials are based on conservative assumptions of numbers of implementable measures, presented in table 1, and on typical savings per measure per house type for each individual measure.

HP penetration. When deployment rate constraints see HP systems plateau, DH picks up the slack, providing over three times more heat under 95_C1 than under baseline ambitions.

Notwithstanding a small role in scenarios with targets tighter than 90%, contributions from hybrid systems remain limited by their emissions. They are used as a transition technology and phased out by 2050 without representing more than 1% of total annual heat.

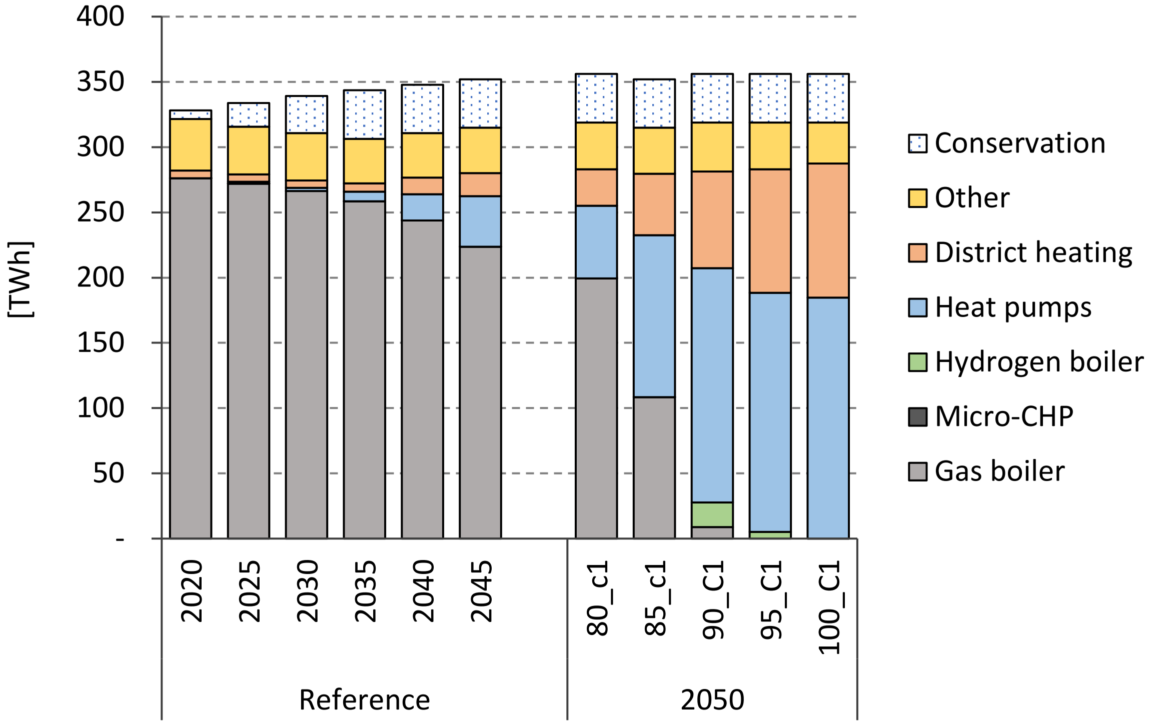

Figure 5 – Residential heat provision (aggregated) – 80_C1 scenario to 2045 (left) and compared cases in 2050 (right).

The baseline development of DH networks, while not insignificant, remains modest until the late 2030s (Figure 6). A relatively rapid expansion both in solid wall insulated flats and new-build households follows. Early DH systems rely on natural gas and municipal solid waste based thermal cycles. In later years, however, centralised ASHPs capitalise on low-carbon electricity and, depending on emission targets, grow to represent between 77% and 83% of output from DH by 2050. This is contingent on including significant amounts of thermal storage that charge during night time periods and release heat during either day or peak time-slices, allowing HPs to be run more continuously, and reducing capital costs per unit-energy delivered.

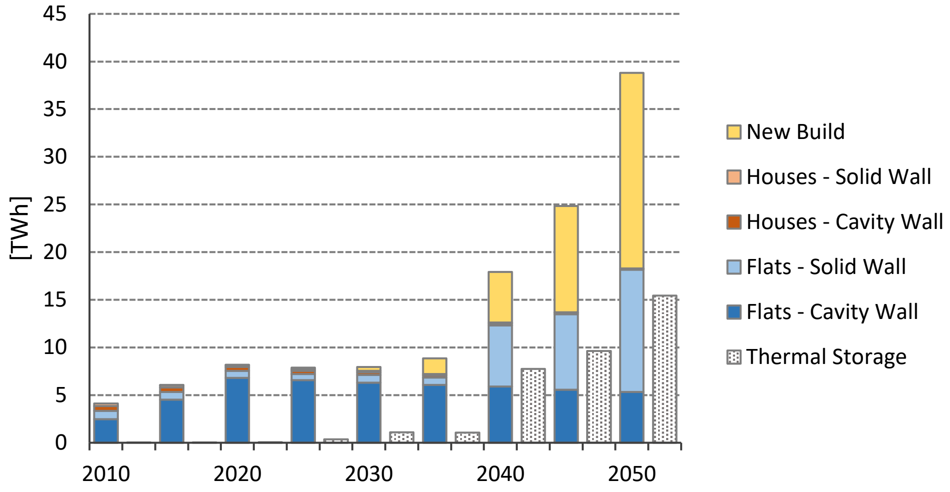

Figure 6 – District heat, per household type, baseline.

4.1.2 The impact of more liberal investment constraints

Topology-level baseline results highlight the relative weight of each household type in the overall pathway (Figure 7). As houses built today are expected to still be standing, new-build represents just 22% of total heat demand in 2050. The order of magnitude difference between demands in existing flats and existing houses reflects both lower heat demands per dwelling and significantly lower numbers of flats relative to houses. Notwithstanding, both decrease over time as a combination of demolition rate assumptions and conservation measures[26].

Existing cavity-wall houses continue to rely heavily on natural gas boilers under baseline conditions. Though similar for the first half of the modelling period, solid wall houses shift from 2035 onward to include high penetrations of HP systems. Considering known issues with using HP systems in less efficient homes (Staffell et al., 2012), we note the full roll out of conservation measures in this sector[27] which lead total demand to reduce at a faster pace than the one induced by simple demolition rates. Representing smaller areas with typically denser heat requirements, flats rely on a different suite of options. Increasing amounts of DH represent 69% and 27% of all heat delivered in solid and cavity wall flats respectively by 2050. This is supplemented by contributions from more modular options including night heat storage (NHST) and standalone heating systems.

New-build households bring the diverging tendencies of houses and flats together. While initially reliant on incumbent natural gas with efficient modern boilers, new-build shifts from 2045 onward to include DH and modular standalone systems. Demand in this category grows near linearly in accordance with national building rates.

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[26] New-build households are assumed to be energy efficient and are therefore not candidates for energy conservation methods.

[27] As per Table 1, 77% and 37% of solid wall houses are assumed to be eligible for solid wall and loft insulation.

Though still used as late as 2030, the high emissions of oil boiler systems mean they are later rapidly phased out across the archetype definition.

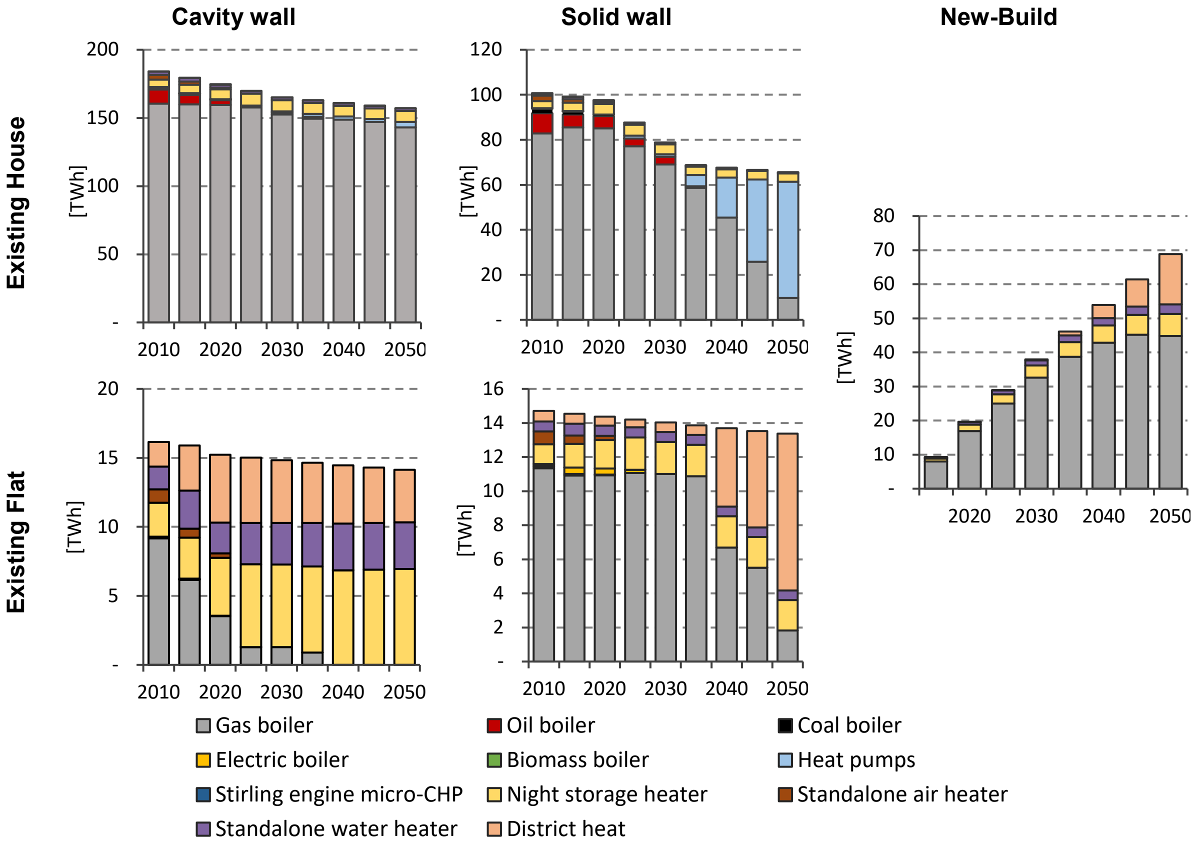

Figure 7 – Disaggregated heat provision in households – 80_C1 Reference scenario

Result for less conservative futures (Figure 8) suggest that higher technology diversity at the outset changes key investment decisions. For given climate targets, freer investment conditions see even dominant technologies concede output shares to modular and standalone options. HP penetration rates correlate positively to levels of climate ambition, exceeding 50% under targets beyond 90%. Yet moving from C1 to C4 under GHG90 and GHG95 cases sees HP heat provision drop by 3 and 6 percent points respectively. Similar dynamics for DH technologies lead to significant shifts in installed capacity. While C1 cases with strong climate ambitions can see a threefold increase (GHG80 to GHG95), freer investment conditions for a given GHG target can lead to drops in installed capacity of between 27% (GHG90) and 60% (GHG95).

Conversely, all standalone heating systems (air, water and NSTH), little used across conservative pathways (~11% effective heat in 2050), respond positively to even moderately more liberal futures and can provide up to 29% of final heat (90_C4).

Finally, though hydrogen[28] boilers have been described as a "drop-in replacement" option, their contribution to the system relies on high climate ambitions and conservative assumptions about future investment.

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[28] Hydrogen is produced either through electrolysis or SMR with CCS at 95% capture rate

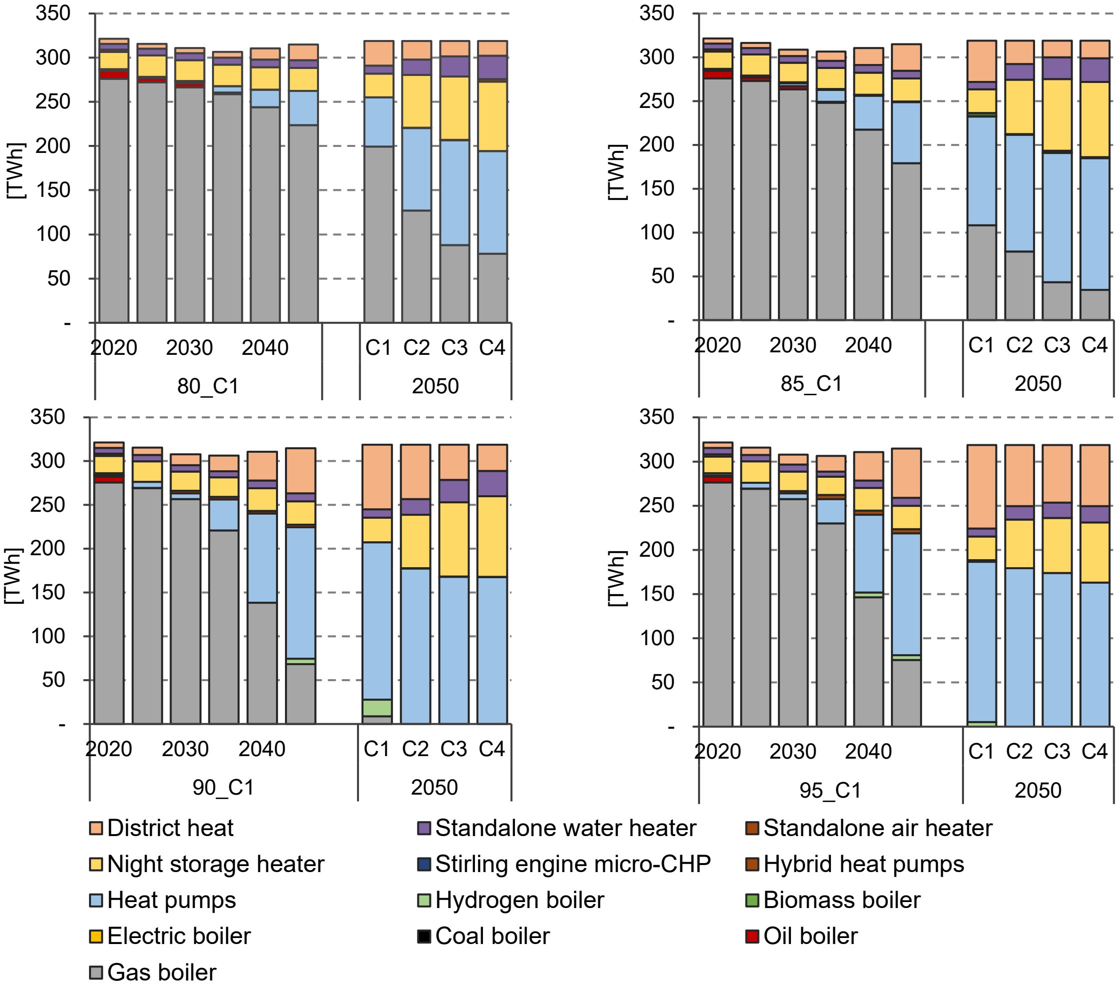

Figure 8 – Residential heat provision showing alternative technical constraint cases under increasingly tighter GHG constraint level. Clockwise from top-left showing GHG targets of 80%, 85%, 95% and 90%.

4.1.3 Sectoral emissions in context

Net UK GHG emissions were 456 $MtCO_2e$ in 2017 (BEIS, 2018b). Under the previous 80% target, these should reduce to 150 $MtCO_2e/a$ by 2050[29] (Figure 9a). Second only to the transport sector, residential emissions account for one third of this total with 52 $MtCO_2e/a$ in 2050 from gas boilers (89%), oil boilers (4%), gas cooking (5%) and small CHP and solid fuel systems (2%). These levels represent a reduction of 31% compared to modelled emissions for 2020 (Figure 9b).

As targets are tightened, emissions from hard-to-decarbonise sectors contract slower than residential sector emissions. Figure 9b suggests that the sector sits at the margin for system decarbonisation. Moving to a GHG85 target leads to residential emission cuts of 41% in 2050, while transport sector emissions contract only by 11.5%. Another increase to GHG90 cuts residential emissions by 77%. These reductions reflect sectoral changes as early as 2035, with strong shifts in

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[29] Negative emissions are provided by bioenergy with carbon capture and storage for power under conservative biomass availability assumptions.

2040 and 2045. Beyond a 95% target there is no space in the system for emissions from residential sector heat[30]. Importantly, we note that reaching net-zero by 2050 implies that the timing of emission cuts seen under GHG95 has to be brought forward by five years (Figure 9b, black bars in 2035, 2040 and 2045).

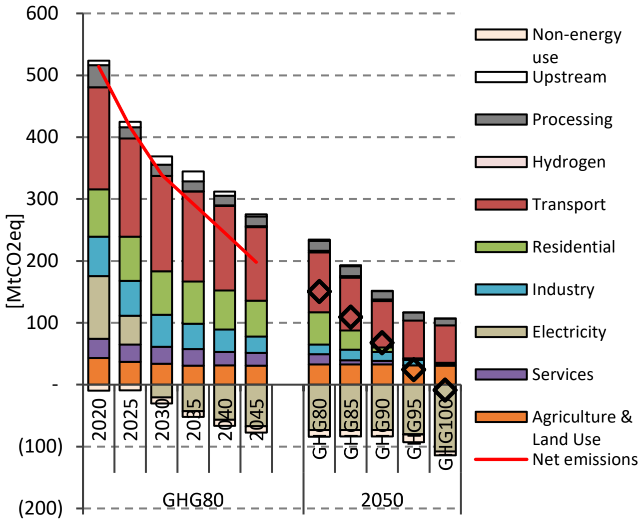

Figure 9a – System wide GHG emissions under C1 constraint levels: comparing GHG80 to 2045 with tighter 2050 targets

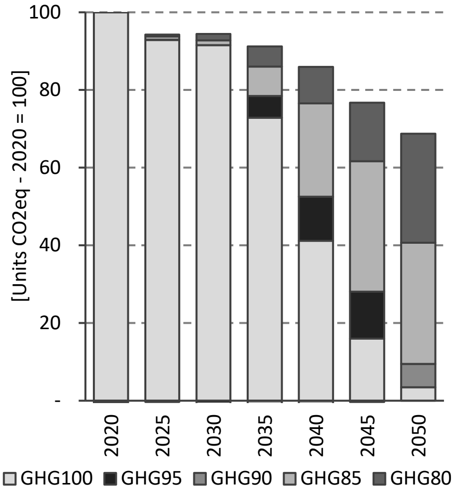

Figure 9b – Emissions allowance for the residential sector under tighter emission pathways – normalised to 2020

Residential sector emissions in 2050 are affected by less conservative views of future heating system design. For each 2050 GHG target, the dotted and dashed lines in Figure 10 show that more liberal variants of each emissions constraint undercut corresponding C1 cases. This suggests that any freed-up emissions are allocated to hard-to-decarbonise sectors. This is particularly noticeable under GHG80 and GHG85 targets: moving from C1 to C4 variants in these futures can free up between 16 and 28 $MtCO_2e/a$ in 2050 (Figure 10). These dynamics remain true under deeper decarbonisation futures with trends for C2-4 lines following visibly more concave trajectories than their C1 counterparts. Absolute savings are smaller as allowable sectoral emissions in these futures are already nil by 2050 under the C1 variants.

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[30] Note that emissions presented in Figure 9 include GHG emissions from other residential sources such as e.g. HFCs from refrigeration.

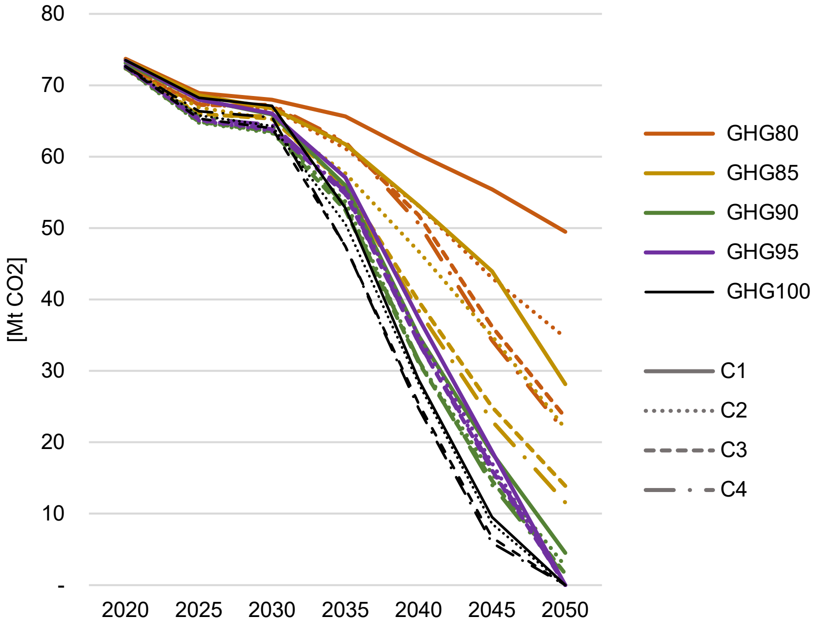

Figure 10 – Residential sector CO_2 emissions across scenario families

4.2 Local exemplar results

Considering the case where network capacity is set as a hard constraint, Figure 11 shows a one-year dispatch for optimum[31] air-to-air HP capacity in the low-density model, representing a hybrid heat pump/natural gas scenario. Heat pumps are preferred to condensing gas boilers up to the local network limit, net of non-heat electrical demand. Condensing gas boilers then "in-fill" morning and evening space heat demand peaks, resulting in relatively low utilisation outside of the winter season and a correspondingly low annual load factor.

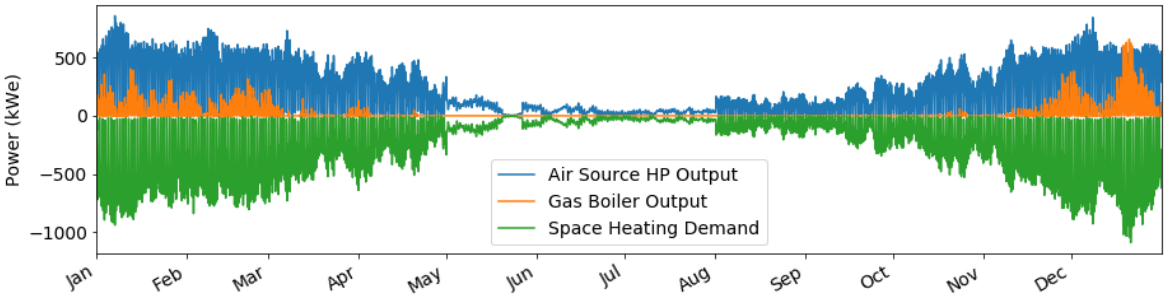

Figure 11 - Example dispatch of condensing boiler to infill across modelled year with air-to-air HPs, low-density houses

The resulting delivered cost of energy (DCOE) and emissions intensity (EI) for the different residential heat technologies modelled are shown in Figure 12. The maximum level of HP capacity is defined by the capacity of the local electrical network with remaining demand infilled by gas condensing boilers. Gas heat pumps are included as an illustrative case where condensing gas boilers are replaced

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[31] Minimum energy emission intensity

completely. All heat pump cases other than the explicit air-to-air case are air-to-water and supply hot water in addition to space heating (subject to the same network capacity constraint).

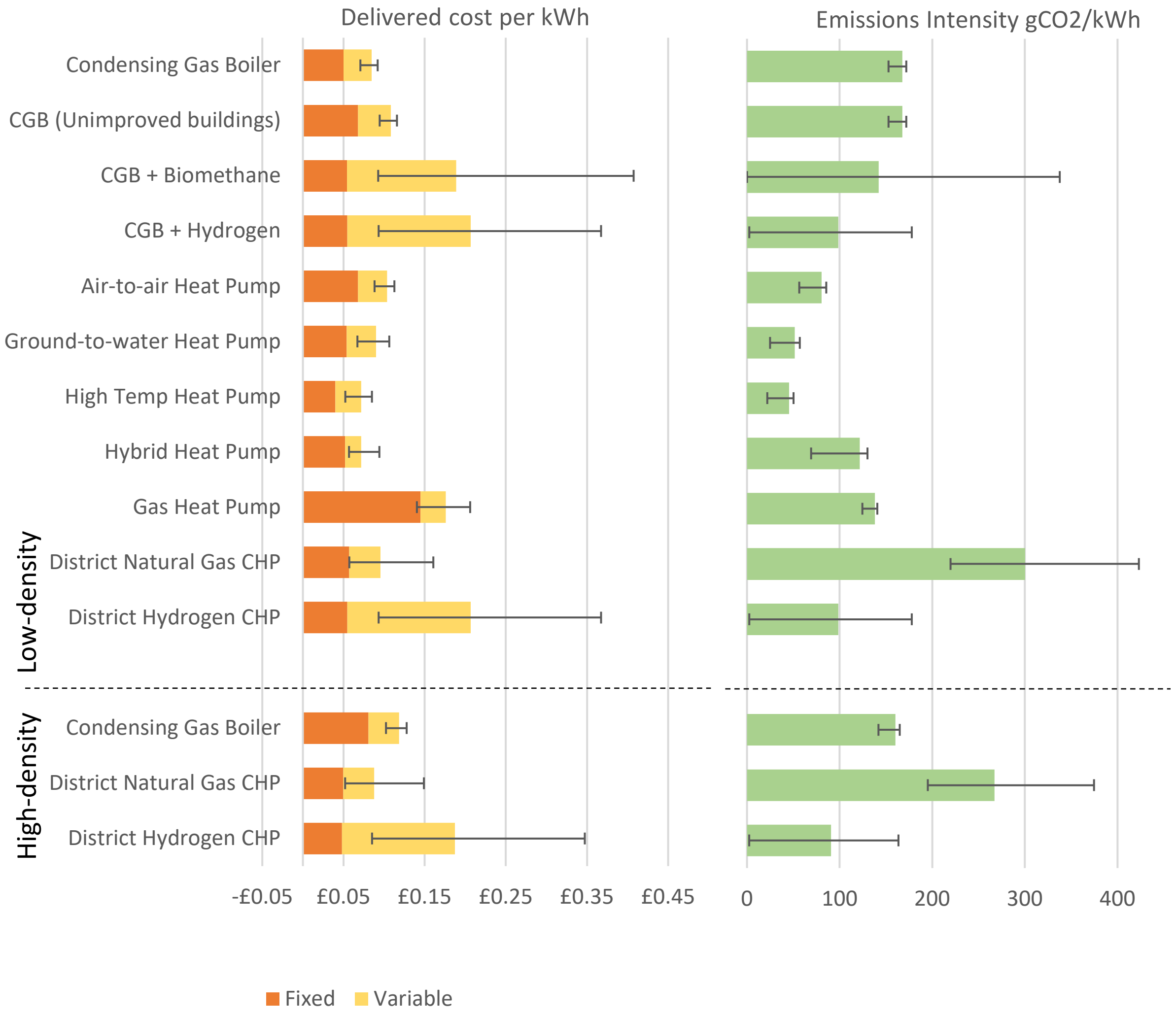

Figure 12 - DCOE (left) and Emissions Intensity (right) for different heat technology scenarios, low-density and high-density housing models. The total cost for the central scenario is shown, subdivided into fixed and variable costs, with the total cost/emissions ranges across the three sets of scenario assumptions.

Base-case (condensing gas boiler) results show higher DCOE for high-density over low-density models: while high-density dwellings have lower demands (lower occupancy and smaller housing size) they have similar fixed system costs. Within the low-density exemplar model, the use of air-to-air source HPs marginally increases the DCOE against the use of condensing boilers. In this scenario the HPs are unable to supply the full demand and gas in-filling is required which results in an increase in fixed costs. The relative difference in DCOE of heat pumps is not purely driven by technology costs, but also (for the cases where the HP technology may supply hot water in addition to space heat) the reduced cost of infilling technology which may have a lower capacity for heat pumps with greater COP.

Results for the district heating CHP cases clearly show expected cost reductions for higher- over lower-density district heating networks with reduced capital costs and lower losses. In both lower- and higher-density cases however, lower efficiency due to transport losses and – potentially – reduced conversion efficiency lead to increased emissions intensities of natural gas CHP compared to base case values, highlighting its inadequacy as a viable decarbonisation option without parallel decarbonisation of the gas supply. However, use of district heating with alternative gases outweighs these transport losses, pointing to the value of short-term installation of heat networks as ‘unlocking’ future decarbonisation potential under future gas grid decarbonisation scenarios. This further points to the potential for micro-CHP technologies which combine the potential to utilise different future gas blends/compositions, while reducing these transportation and storage losses. The extent of these losses are highly variant between DH and CHP systems, and are driven by a number of economic factors including store and gas turbine sizing, so the values here are indicative rather than likely to be universal.

To assess the range of abatement costs for different alternative gases (biomethane and hydrogen), the condensing gas boiler scenarios were re-run with their respective projected costs and emission intensities (BEIS, 2016a) for the low-density case, as shown for the Condensing Gas Boiler cases. The high range of costs and emissions in the alternative gas cases relates to the wide variety of supply-side technologies. Similarly, the wide range for the district heating systems encompasses the wide range of costs and losses that might be assumed for a local network. For comparison purposes, a single scenario was run with non-improved building stock to demonstrate the relative value of demand reduction and thermal buffering gains against technology options.

As the above cases are constrained by local network capacity (on the assumption that within the short-term timescales evaluated, a national-scale upgrading of LV network has not been achieved) the impacts of electrification of vehicles – and specifically their charging within residential networks – will have a compounding effect on any constraint on heat pump deployment. While analysis of such additional electrical demand is outside the scope of this work, the volume of headroom available for heat pump deployment is likely to be further constrained in the medium term. This can be managed to an extent through load-shifting, but the reduced diversity of space heating loads (due to the duration of heat service demands, which are likely to be highly coincident for similar building stock undergoing a similar ambient temperature profile), with relatively little capability to ‘pre-load’ building thermal capacity with the extent of energy efficiency improvements that are likely to be normal in the near-term for the UK. This in turn indicates a role for thermal storage and building efficiency improvements as deferring technologies for distribution network upgrades.

5 Discussion

Current trends in residential heating have shown few signs of moving to low-carbon alternatives despite being the focus of dedicated policies. Encouragingly, baseline results do not make such changes seem unattainable. They require sectoral emissions to drop year-on-year by just 0.93 $MtCO_2e/a$[32] to 52 $MtCO_2e/a$ in 2050. Providing context, the 2003 condensing boiler policy induced decarbonisation rates of 1.75 $MtCO_2e/a$. Tightening emission targets could, however, imply drops of 3 $MtCO_2e/a$ or more as the sector, being at the margin for system decarbonisation, contributes disproportionately to deeper emission cuts. Specifically, it provides over

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[32] Calculated from 2030 onward.

half the savings needed to move from an 80% to 90% target. This ambition may be easier with increased technology flexibility. For given GHG ambitions, more liberal assumptions about future heat delivery allow a mix of household and district-level technologies to push natural gas boilers further out of the solution. This supports faster decarbonisation and reaffirms the sector's "marginal" position: freed-up emissions are allocated to other, hard-to-decarbonise sectors (transport and industry).

This exclusion of natural gas aligns with McGlade et al. (2018), who highlight its shrinking role in a decarbonised energy system. While baseline results suggest gas boilers may still deliver 63% of effective heat in 2050 but do not reflect increased levels of national climate ambition and a likely shift in technology diversity. Considering just marginal changes in both, cases 85_C1 or 80_C2 already see gas boiler penetration drop by 37% and 40% respectively. In line with Speirs et al. (2018), exemplar model results show that greening the gas grid suffers from significant uncertainties in both cost and emission levels attached to different production routes for alternative gases. Further, they show that some may lead to higher impacts than natural gas.

Replacement options are a function of climate ambition, portfolio diversity and household topology / local context. Yet key technology families emerge.

ASHP are present across scenarios. Their inclusion progresses with tighter climate targets and provides between 17% and 57% of final heat in 2050 under C1 cases. These HPs are mostly electric, placing a greater demand (bulk and peak) on local networks. Most of these networks would have been sized without accounting for additional heat-related load. Looking in detail at specific locations, exemplar model results assess the nature of this additional demand and the potential ability of local networks to cope. They show that selected, high-temperature, HPs could replace gas boilers at a negative abatement cost in both high and low demand density areas. These technologies' high COP support low DCOE and EI values in line with Marginal Abatement Curve findings. While these results include the cost of potential grid reinforcement, we note that EI values depend heavily on grid electricity emissions intensity: negative abatement costs are only achieved if electricity decarbonisation continues. Exemplar model results assume an intensity of 41-94 gCO_2e/kWh in 2030, compared to a 2018 UK grid electricity of 283 gCO_2e/kWh; ambitious policy support for renewable generators must be sustained to achieve the sectoral emissions reduction under electrification.

Other HP technologies are not as clearly supported by both system optimisation and exemplar modelling results. Gas-powered options use gas efficiently and lower variable costs but remain a relatively unknown technology that implies significant increases in fixed costs. They provide only marginal system benefits and have a high abatement cost. Hybrid HPs' value is less clear cut. For the exemplar models, they maximise the use of local electricity networks, have the potential to reduce capital costs vs. standard ASHPs constrained by network conditions combined with gas boiler infilling, and can result in lower EI than other options. This suggests hybrid options could offset requirements for network reinforcement in the short-term, but there will be competition for access to this headroom if, under aggressive GHG targets, there is significant parallel electrification of vehicles. This transitional role is not captured in the longer-term scenarios. This is, in part, due to modelling framework design: the support they provide during peak times may not be fully captured by UKTM's time-slice definition that assumes a three-hour peak. It also highlights that their emissions-to-cost ratio will rule them out of any longer-term solution under tighter, near net-zero targets. However, hybrid HPs allow investment in household-level technologies to advance ahead of parallel investment in networks and supply, dealing with the challenges presented by fuel lock-in.

DH systems also feature widely in our results and provide increasing shares of final heat as climate targets tighten. Conversely to HPs, this is – at least in part – a modelling artefact. Moving from C1 to C4 cases systematically leads to drops in DH penetration. How much it drops is a function of GHG target stringency: GHG80 and GHG90 targets show drops of 40% and 60% respectively; the same drop for GHG95 is only 27% with DH still providing around 1/5th of C4 2050 heat demand. This suggests that substantial investment in DH can take place without risk of stranding assets when the objective is to reach deep decarbonisation. From a technology perspective, this relies on the use of centralised electric ASHP combined with short term storage that dampens network requirement impacts. Other options may not be adequate: exemplar models highlight that local heat provision is not necessarily more environmentally-friendly as DH supplied using natural gas records medium range DCOE with relatively high and uncertain EI levels. This further underlines the need to align end-use technology incentives with supply-side decarbonisation, whether the energy carrier is gas or electricity.

Finally, technology suitability is location specific. Optimisation results pair HP systems with existing houses, where demand density is inherently lower; DH systems are rolled-out in existing flats and new-build where high demand density reduces unit and distance-based costs. Most existing buildings will still be standing in 2050 (CCC, 2016). Adjusting future heating solutions to the nature of the current UK housing stock is therefore important. While baseline results suggest that gas boilers could cost efficiently supply new-build heat, higher levels of technology freedom (80_C4) or tighter climate ambitions (90% and above) see installations peaking as early as 2035. In line with recommendations by the CCC (2019a), this essentially solves a problem before it occurs, offering potential emissions savings of 4.4 to 10.8 $MtCO_2e/a$ by 2050. Exemplar results reinforce the location-specific nature of these insights and show that heat technology DCOEs and EIs can vary considerably in relation to energy use density, nature of the housing stock, demographics, network capacity, as well as specific geophysical or space-related characteristics. In fact, these dependencies call into question the necessity for system optimisation models to reduce technology implementation to restricted categories with limited or indicative cost representations – ignoring e.g. last-mile network reinforcement; or existing technologies interactions.

6 Conclusion and Policy Implications

This study applies complementary modelling frameworks to analyse UK residential heating systems. First, the UKTM system optimisation model investigates scenarios that cross tighter carbon budgets with heating technology constraints that depart from status-quo views of the future. These highlight how the benefits provided by flexible technology portfolios shift under ambitious decarbonisation targets. Second, direct costs of energy and emission intensities for ranges of heat technologies are taken from exemplar model frameworks that combine thermal building models with a representation of extant last mile networks. These simulations focus on high- and low-density housing scenarios, grounding whole system level outputs more firmly into reality. We identify four key insights from comparing these two perspectives.

First, energy conservation measures in line with fabric-first building stock refurbishment are a cost-effective first step to reducing emissions in the residential sector. The UK has an older housing stock with lower energy efficiency than most European countries. Accordingly, UKTM considers improvements to home insulation to be a cost-effective abatement strategy and rolls them out rapidly. These changes are deployed ahead of any in-depth technological change - this is particularly important in practice. While residential heating is treated here as an exogenous variable, efficiency improvements may reduce consumers' space heating costs and be expected to lead to a rebound effect (Greening et al., 2000). While this affects the improvements' carbon efficiency and reduces potential sector contributions towards decarbonisation, it has external benefits for comfort and health. This underscores the need for policy which quantitatively combines the economic and social benefits of improved heating alongside the potential emissions benefits, and targets efficiency measures and technology replacement where multiple benefits may be derived.

Second, the results suggest that electrical systems could provide significant shares of future residential heat supply. This is reinforced as levels of climate ambition and investment freedom increase with outputs from UKTM suggesting high penetration levels of ASHPs, at district and household level, and modular NHST and standalone systems. In parallel, exemplar models suggest that, while their abatement value is sensitive to grid-electricity emission intensity, these options would be technically feasible. Together, this supports a three-pillared approach to decarbonisation focusing on electrification of end-demands for heat, efficiency improvements, and reduction of grid-electricity emission intensity. While exemplar models account for local network reinforcement costs, they do not consider likely build rate constraints. This suggests a short/medium term benefit to identifying areas currently able to shift from gas to electrical heating, with a priority on low-headroom areas for reinforcement. Shifting away from natural gas is unavoidable in the long term to meet climate targets. While alternative clean gases make good use of existing infrastructure, significant uncertainty remains as to their emission intensities. Further, contexts of limited sustainable biomass availability and continued high cost of electrolysis also question levels of sustainable supply in sufficient quantities at a competitive cost. Yet, hybrid solutions may still provide a transitional solution: while they are not picked by the whole system optimisation framework, exemplar results show that they maximise extant network use pending reinforcement. This strategy also requires mechanisms that transfer benefits of deferring network upgrades to end-consumers, as opposed to network operators being solely reactive to local demand levels and consumer technology selection.

Third, allowing for diverse portfolios of locally relevant technologies can support faster residential heat decarbonisation as well as less stringent emission allowances for other, hard-to-decarbonise sectors. Additionally, diverse local realities lead to different costs and benefits of alternative technologies, independently of upstream decarbonisation. This emphasizes the importance of aligning local opportunities with the reality of local residential heat demand. This approach would support decarbonisation, avoid wider system lock-in, and reduce the negative impact of centralised infrastructure overhaul agendas. It does however hinge on aligning national policy instruments with local actors who are better able to identify opportunities, creating a ‘leading edge’ to overcome the current inertia in the decarbonisation of residential heating. Their involvement would make gradual transition away from extant systems possible with national supply and transmission systems responding thereafter. Promoting local diversity supports deep decarbonisation while reducing uncertainty in technology options, avoiding the need for system actors to pick favourites until cost and technical parameters are more clearly known.

Fourth, our results echo recommendations from the CCC that no new homes should be connected to the gas grid after 2025. This is particularly true if new, more ambitious, emission targets are to be achieved. This highlights that avoiding gas for heating in new housing is an opportunity to solve a problem before it occurs. The built environment has a long life expectancy: many buildings in existence today will still be standing in 2050. New housing therefore presents a threat and an opportunity: mirroring current building and heating tradition risks locking the system into high emission and comparatively low energy efficiency futures, but new developments need not follow conservative, status-quo practices. Here we show that the UK’s increased national climate ambition will inevitably lead to replacing natural gas boilers in new-build with what results suggest should be a combination of district heating and modular, standalone electric, heating systems. Insights highlight the need to minimise fuel use and emission levels in new-build very much in line with e.g. the current London Plan, which suggests that energy use in new homes should “be lean, be clean, be green”. Local action through planning permission regulation can make a clear difference, in parallel with other developments in housing policy. Yet new-build is an area where the introduction of clear and ambitious standards at a national scale could make the strongest contribution.

Together, these insights underline the importance of supporting a diversified portfolio of technologies. Moving away from natural gas is now inevitable, even under moderate GHG targets. Designing and building a system that can replace it hinges on early and strong investments in key technologies with support for a portfolio of additional modular options. Current results point to advanced electric systems linked to home improvements as a logical choice. Notwithstanding, shifts in standard expectations may bring new contender technologies to the fore. This means that picking clear winners carries inherent risk that can be mitigated by designing an open and supportive environment for technology uptake.

Acknowledgements

This work is supported by the UK Energy Research Centre Phase 3 (UKERC), funded by the UK Research and Innovation Energy Programme under grant number EP/L024756/1. The authors would also like to thank the reviewers for their helpful and constructive comments that have helped to improve the final quality of this publication.

With thanks to Graeme Flett, John Allison, Andrew Cowie and Nick Kelly of the Energy Systems Research Unit (ESRU) at the University of Strathclyde for their assistance and advice in simulating local demand data.

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