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Technology pathways, efficiency gains and price implications of decarbonising residential heat in the UK

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ABSTRACT

The UK government's plans to decarbonise residential heating will mean major changes to the energy system whatever the specific technology pathway chosen, driving a range of impacts on users and suppliers. We use an energy system model (UK TIMES) to identify the potential energy system impacts of alternative pathways to low or zero carbon heating. We find that the speed of transitioning can affect the network investment requirements, the overall energy use and emissions generated, while the primary heating fuel shift will determine which sectors and networks require most investment. Crucially, we identify that retail price differences between heating fuels in the UK, particularly gas and electricity, could erode or eliminate bill savings from switching to more efficient heating systems.

1. Introduction

To tackle climate change and put the UK on course to meet emission reduction targets enshrined in law [1], significant system wide changes - such as those described in the UK Government's recently published Net Zero Strategy [2] - will be needed. Heating buildings is the source of nearly a quarter of UK emissions. Thus, meeting net zero targets will involve virtually all heat generation in buildings to be decarbonised [3]. As part of the UK Government strategies to reduce emissions from buildings over the coming decades, electrification of heat is proposed as a key action in reducing emissions from homes where the majority of emissions are associated with boilers currently running on methane gas. In the Heat and buildings strategy [3], the UK Government set out its plans to deliver at least 600,000 heat pump systems per year by 2028. The strategy also recognises the role that hydrogen might play in decarbonising heat, considering that up to 4 million homes could be served by hydrogen by 2035 [2]. The UK Government are due to decide by 2026 on whether to take this option forward.

Regardless of what mix of technology options is taken forward, significant changes to the energy system - including the upgrade of the energy networks and increasing renewable energy generation capacity - will be needed alongside the installation of new heating systems in residential properties. Understanding how these costs are distributed, where benefits might accrue and how the energy system might be impacted is a key aim of this paper.

These issues and concerns are set within a quickly changing policy environment where - for example - surging global gas prices have driven a significant increase to the energy price cap (+96% or +£1223 annual costs for the average household by October 2022, relative to October 2021 [4]; for GB energy consumers. Combined with the wider cost-of-living crisis, affordability is an emerging and growing concern and major public policy challenge. Although the significant increase in international gas prices has markedly narrowed the gap between the retail cost of electricity and gas, this price differential - where consumers currently pay significantly more per physical unit of energy for electricity [5] - remains an important factor for understanding how different decarbonisation options will affect the affordability of heating systems.

In this paper, we explore the type of challenges emerging around delivering a sustainable and equitable low carbon heat transition. We aim to provide insight on the potential impacts of the planned UK's low carbon heat transition in terms of network investments, changes in fuel use, fuel cost and emissions. Here, we use the UK TIMES whole energy system model [6] which covers the whole integrated energy system (all supply vectors, conversion and demand, across all sectors: agriculture, services, residential, industry, transport). We consider three different low carbon heat technology transition scenarios. These vary in terms of

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the technology and fuel options for residential heating going forward (heat pumps using electricity or hydrogen boilers) and the pace in which heat pumps are adopted in electrification scenarios. Additionally, we consider an energy efficiency only scenario (i.e., implementing retrofitting of domestic buildings to improve energy efficiency but with no heating technology changes), which allows us to assess and compare passive solutions as well.

The work developed in this paper aims to provide policy-relevant insight on the wider energy system impacts of the decarbonisation of residential heat, analysing the system-wide implications of the low carbon transition under different technology scenarios, enabling discussion of best practices to inform energy policy development. We make three new contributions. First, we conduct an analysis of the impact of the low carbon heat transitions in the UK, in terms of fuel changes, energy costs, CO2 emission reduction and gas and electricity network investments. Second, we analyse these outcomes in the context of different heating technologies and strategies, based on current UK policies and trends. Third, we provide insight into how the relative difference on electricity and gas retail prices translates and/or offsets potential costs savings from reduced physical energy use required to run residential heating systems. We then propose and discuss further research questions to extend and complement the analysis developed in this paper. To the best of our knowledge, such integrated analysis, considering these residential heat decarbonisation pathways has not been developed in the literature (see section 2 for lit review).

The rest of the paper is structured as follows. Section 2 presents a brief review of existing studies analysing the impacts of residential heat decarbonisation on the power network or the wider energy system. Section 3 describes the methodology used in this paper. Section 4 shows the different low carbon residential heat scenarios. Section 5 focuses on the results and discussion of the analysis and section 6 presents the conclusions of this study.

2. Literature review

In analysing the whole energy system impacts from decarbonizing residential heat, the available literature to date have focused on this area from different perspectives, with diversified modelling methodologies and diverse scenario pathways examined. Against this background and acknowledging the relatively broad scope of the literature relating to our research purpose, we aim to summarize the referential significance and gaps from the literature, while also helping inform and base our study on a full techno-economic perspective.

[7] examine the system-wide implications that national decarbonisation targets have for the UK residential sector, by analysing and contrasting the national-scale UKTM model results with two local-scale exemplar energy network models of representative residential locations. The two 'exemplar' models are of respectively high- and low-population density areas, where both short-run dispatch and long-run investment costs for different domestic heat technologies are investigated. They find that although air sourced HPs are placing a greater bulk and peak demand on local networks, they could replace gas boilers at a negative CO2 abatement cost in both high and low demand density areas. In addition, gas/electricity hybrid options could offset requirements for electricity network reinforcement in the short-term. The study also highlights that energy conservation measures in line with fabric-first building stock refurbishment are a cost-effective first step to reducing emissions in the residential sector. However, this study mainly focuses on the household sector, without considering other sectors and the wider energy system.

[8] conducts a comparative exercise of two opposing decarbonisation scenarios compliant with achieving the UK 2050 emissions reduction target, in terms of energy security and feasibility, and environmental and financial costs. The two energy supply scenarios consider one with nuclear power and renewables including wind, solar photovoltaic, tidal and river hydro, and another with natural gas/hydrogen combined with carbon capture storage (CCS). Using the EnergyPLAN energy system model, the study finds that, in contrast to findings of [9]; the nuclear and renewables scenario is preferable than the one focusing on hydrogen and CCS, in terms of energy production and consumption, carbon emissions and costs. However, this study focuses on the supply side of the energy system, without considering other factors from the demand side (e.g. changes in heat demand and/or energy vectors for heat).

[10] use UKTM modelling to investigate the scale of technology mix change for UK residential heat under different carbon reduction targets relative to the 1990 level. Both a conservative and a progressive scenario are compared, and they find that along a conservative pathway, natural gas heating in 2050 is nearly halved for an 85% emissions reduction target and disappears beyond a 95% reduction, while in the progressive pathway it disappears in a 90% reduction target. The study concludes that heat pumps, district heating and energy savings are the most cost-effective options to meet net zero. However, the comparison of the required large-scale technology change is only limited in year 2050 across different hypothetical reduction targets, while the time span before 2050 is not in focus nor potential impacts on energy networks.

[9] evaluate the implications of heating electrification on future electrical supply and demand balancing for the UK energy system using a top-down national model comprising hourly historic weather patterns, demand data and installed generator capacities. They find that compared to the renewables and nuclear scenarios, which the authors deem as not viable due to the frequency of unserviceable energy deficits, CHP (combined heat & power), district heating and heat pumps combined is a viable solution to enable highly decarbonized systems to deliver a reliable energy supply. They also highlight the significant role of heating demand management alongside heating electrification in achieving energy balance. However, given the findings that electric heating has a significant influence on electricity peak load, the study does not consider further needs on network reinforcements or expansion or other cost impacts for residential consumers.

[11] assess the performance of HP-TES (heat pump - thermal energy storage, in the form of hot water storage tank with a resistive back-up heater) relative to conventional heating systems for heat decarbonisation. The heating system is modelled through a heat demand model using linear programming optimization which requires the annual heat demand, temperature and occupancy profiles. The results show that while the equipment and operational cost of a HP system without TES are significantly higher than a conventional gas system, the integration of TES reduces the operational cost. This, combining further with the Renewable Heat Incentive (a UK government financial incentive to promote the use of renewable heat technology, which it is now closed for its successor scheme) make the HP-TES systems even cost competitive against conventional gas systems. However, the model framework is more of a complement to energy system models, and is limited in accounting for a wider range of energy system impacts.

[12] compare the three main heating technologies ASHP (air source HP), hybrid heat pump systems HP-Bs (ASHP and gas boilers) and DHN (district heating networks) in terms of electricity system impacts as well as economic costs in the UK. The model is formulated as a linear programming problem minimizing whole system costs - investment and operation costs, under a mixed series of energy demand profiles and technology operating constraints. Their result suggests the significant cost advantage of the hybrid HP-B over the other two heating technologies, while DHN may play an important role in urban areas under the optimized heat decarbonisation strategy. Other than that, this study does not include any hydrogen technologies in their analysis or look at the impact on the power network or the rest of the energy system.

[13] incorporate heterogeneous households' preferences into the modelling process of the UKTM model. The modelling scenario is set as the UK Government legally binding GHG emissions reduction of 80% on 1990 level by 2050 and the fifth UK carbon budget. It compares and contrasts the same scenario with and without the different types of households' preference constraints, and assesses the implications of

these constraints for the residential sector and energy system in terms of heat provision, system costs, emissions, and carbon prices. The authors find that heat pumps and electric heaters are deployed much less, due to households' preferences, than in the pure cost-optimal result; extensive district heating using low-carbon fuels and conservation measures should thus be deployed to provide flexibility for decarbonisation. Note that the study is outdated in terms of policy scenario considered (the emissions reduction target) and does not include more details on transmission and distribution network.

[14] analyses the impacts of two different decarbonisation scenarios of the power and heat sectors in the UK. The two scenarios represent different shares of technology mix in heat supply constrained with the same power generation capacity, both of which are compared with a reference case in 2010. They find that the electrification of heat supply will have a significant impact on the low-pressure gas distribution networks, while only slightly impact the high-pressure networks. The authors also highlight the role of gas supply in meeting winter energy demand peaks due to gas-fired power generation compensating for variability of wind. However, the study does not consider the role of hydrogen in heat and power decarbonisation.

[15] analyses the potential of reducing and restructuring energy service demands to achieve Ireland's decarbonisation targets. The authors develop an Irish Low Energy Demand (ILED) mitigation narrative, using the TIMES-Ireland Model (TIM). ILED represents a scenario where energy service demands are decoupled from economic growth. This scenario takes a less technology and supply side focused approach to analyse alternative changes on based shifting travel options (e.g. active travel), increasing end-use efficiency, densifying urban settlement (to reduce heat demand), and changing social infrastructure. Compared to a scenario where energy demands follow 'Business-*as*-usual' growth, ILED enables the achievement of steep decarbonisation targets with a less rapid energy system transformation, lower capital and marginal abatement costs, and with lower reliance on the deployment of novel technologies. However, authors recognise that such an scenario would require significant behaviour change that would need large-scale investment to enable and motivate these system wide changes.

[16]; presents the design of a low-carbon multi-vector district heating system in Northern Italy. The system is based on a low-temperature and small-size wood biomass district thermal plant, designed to be integrated with groundwater heat pumps (GWHP) and solar photovoltaic (PV) systems. The authors design the system based on seasonal heating an cooling demands for the selected district case study. The authors conclude that the integration of a small size wood biomass CHP and GWHPs coupled with roof-integrated PV systems in a district heating system may be successful. The choice of proper temperature levels and optimal operative parameters ensures a synergist operation with a low request for grid electricity. The authors also recognise limitations on the study, such as not considering economic parameters, energy markets or policy frameworks which may affect the feasibility of such low-carbon heating systems.

[17] present a different lens to energy decarbonisation modelling, with a focus on the UK residential heating sector. The authors argue the importance of representing societal factors in energy modelling, and analyse the social mechanisms that have the potential to impede or foster rapid energy transitions, for example, resistance to change and the diffusion of environmental values. The study provides suggestions on incorporating social mechanisms of change into a UK-focused probabilistic energy system model, with a focus on people's attitudes towards residential heating technologies. The authors conclude that efficient policy-making for decarbonisation needs whole-system approaches, support the more constrained segments of society, and account for interconnected socio-political factors. Certainly, this study provides an interesting methodology development, by adding non-monetary factors in an energy system model, which could have important policy implications. However, the analysis on energy system-wide impacts is limited.

The literature investigating residential heat decarbonisation so far has diversified points of focus in terms of sectors impacted, technology pathways, and scenario settings [18]. While several studies tend to focus discussion from the perspective of households, such as implications of households' preferences, energy demand and building stock categories, many of them do not cover the rest of the energy system, especially on network implications. Also, the technology mix considered in some of these studies tends to be constrained with options of electrification and renewables generation, so the pathway of hydrogen adoption tends to be overlooked unless it is the main subject of the study. Moreover, few studies look into different speeds of heat decarbonisation across the transition time span, and there is little detail regarding network reinforcement/expansion needs in response of different technology adoption paces. With these elements presenting important policy concerns, this paper aims to cover the gap and contribute to the understanding of the wider technology, energy use and emissions implications of residential heat decarbonisation in the UK; in addition to also providing insight on the potential implications of future energy prices and the importance of the price differential between gas, electricity and hydrogen in terms of cost to residential consumers.

3. Methodology

3.1. Modelling framework

The Integrated MARKAL-EFOM System (TIMES) is a bottom-up energy system-wide model. The TIMES model generator is developed by the Energy Technology Systems Analysis Programme (ETSAP), which is part of the International Energy Agency [19]. TIMES has been used widely to analyse different policy questions including decarbonisation scenarios, as in Refs. [20,21], or the energy system impacts of specific technologies and policies, as in Refs. [22–24].

UKTM is the UK version of the TIMES model [6] and is a single-region energy system model of the UK, used for medium to long-term analysis of energy systems. UKTM considers all the processes that transform, transport, distribute and convert energy to supply energy services (see Fig. 1). The inputs (exogenous variables and parameters) of the model are service demand curves, supply curves (e.g., primary energy resources such as wind power or availability of imports), and techno-economic parameters for each technology/process (e.g., technology efficiencies and availability factors, investment cost per capacity unit, O&M cost per unit of production, etc). The outputs (endogenous variables) include energy and commodity flows, marginal costs, technology installed capacities and emissions, etc.

The sectors considered in UKTM include industry (organised by subsectors: cement, pulp and paper, food and drinks, petrochemicals, etc.), agriculture and land use, transport, residential, services and the power sector. The power system (electricity sector) representation in TIMES includes a very large number of electricity generation technologies and models the transmission and distribution networks. The representation of these networks is limited due to the single region aspect of UKTM. However, it is useful to assess if current network capacity would be enough to accommodate the expected generation and demand.

The time horizon in UKTM runs until 2050, with time periods of 5 years, taking 2010 as the base year. To reduce complexity in the optimization model, TIMES considers only some representative time-slices that work as an average of the elements of that time period. UKTM considers 16 time slices categorised into four time divisions within a year representing seasons (spring, summer, fall and winter), and four daily divisions for each season (night, day, evening peak and late evening).

Moreover, UKTM is a partial equilibrium model-generator assuming perfectly competitive markets and full foresight. The model uses linear-programming to find a least-cost energy system (calculated as sum of investment, fixed and variable operation and maintenance (O&M), and import and export costs/revenues for all the modelled processes), able to meet specified energy service demands, according to a number of user

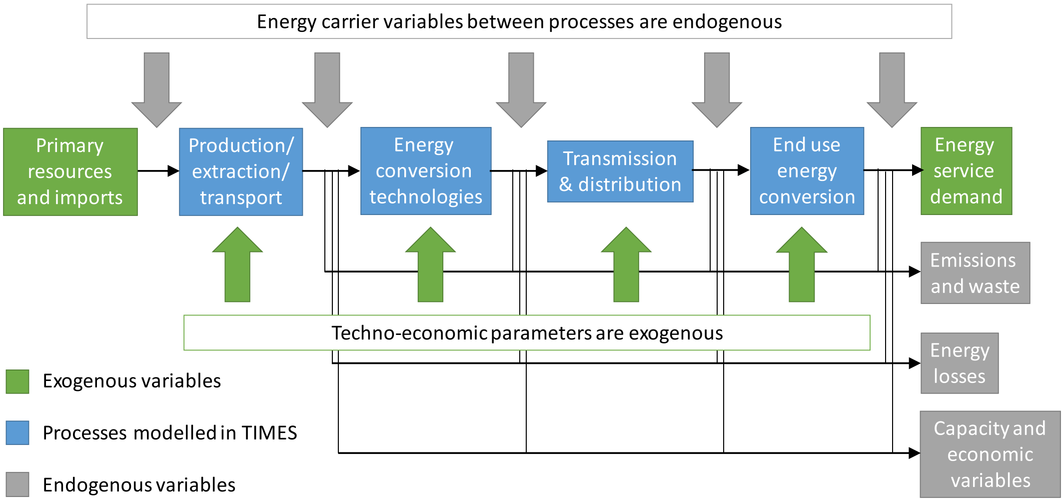

Fig. 1. Modelling of the energy system in TIMES [25].

constraints. To avoid 'penny-switching' (i.e., dramatic technology changes in a short period of time, triggered by a small cost saving), technology adoption constraints are set in the model trying to replicate realistic technology adoption scenarios.

The TIMES objective function minimises Net Present Value (NPV) [26], as in the equation:

$$\min\ (NPV) = \min\left(\sum_{r=1}^{R}\sum_{y\in YEARS}\left(1+d_{r,y}\right)^{REFyear} * ANNCOST(r,y)\right)$$

Where:

- ***NPV*** is the net present value of the total cost for all regions (the TIMES objective function);
- ***ANNCOST(r,y)*** is the total annual cost in region ***r*** and year ***y***. This includes capital costs (investment and decommissioning), operation and maintenance cost, and a salvage value of all investments still active at the end of the horizon;
- $\boldsymbol{d_{r,y}}$ is the general discount rate;
- ***REFyear*** is the reference year for discounting;
- ***YEARS*** is the set of years for which there are costs, including all years in the horizon, plus past years (before the initial period) if costs have been defined for past investments, plus a number of years after end of life where some investment and decommissioning costs are still being incurred, as well as the Salvage Value; and
- ***R*** is the set of regions in the area of study. The UKTM version we are using is a single region model so $R = 1$.

A more detailed description of the UKTM model and its database can be found in Refs. [25,27] and official TIMES documentation can be found in Refs. [26,28].

3.2. *Residential heat demand projections*

Table 1 shows the expected residential heat and domestic hot water demand, and the expected number of households up to 2050, based on Office for National Statistics projections [29]. The table shows that there is an assumed growth of 35% in number of households by 2050, relative to the year 2010. The domestic hot water demand increases steadily with the number of households. However, the residential heat demand reduces slightly from 2010 levels and stays at a stable level up to 2050. The assumption that residential heat does not follow the increase of domestic hot water demand is based on new houses and flats being more energy efficient (EPC rating B or A) than existing housing stock, and thus the increased number of households do not represent a significant increase in total heat demand.

3.3. *Technology parameters required for this study*

Technology parameters are other important inputs for TIMES, as they describe the cost and performance characteristics of technologies. Based on these parameters, the model can decide on the most cost-effective way to meet the energy demands.

Table 2 summarises the main heat technology parameters used in UKTM. The technical efficiency is expected to remain stable, whereas heat pump upfront costs and operation and maintenance costs are expected to decrease in the future. In particular, these costs are reduced more from the first commercial options in 2010–2030 costs, and it is expected to continue to decrease in the future. These projections roughly align with the forecasts provided by the International Energy Agency [30].

Table 3 shows the considered capital investment, operation and maintenance costs per capacity unit for electricity and hydrogen network reinforcements (new capacity). These parameters are used to compute the total cost of all new network capacity implemented in the energy system as a result of the increasing hydrogen and electricity demand of low carbon heating technologies. These costs parameters roughly align with different network reports including the analysis developed by Kiani Rad and Moravej [41], IEA ETSAP [40] and the Electricity Networks Strategy Group [39].

4. Heat decarbonisation scenarios description

We analyse four different heat decarbonisation scenarios. These scenarios consist of two electrification scenarios, focusing on heat pump rollout, one hydrogen focused scenario and one energy efficiency scenario, which only involves retrofitting buildings but does not consider any other technology changes or changes in how residential heating services are delivered. All scenarios are analysed and compared to a base case that continues with the status quo, without changing incumbent heating technologies. In other words, in the base case, residential heat is mainly produced using gas (i.e., natural gas, methane) boilers, as is currently the case in the UK. The impact of the transition to low carbon residential heat is analysed in terms of network investments, energy use and cost changes, and emission reductions. Note that, to avoid over constraining the model and to allow to analyse the effects of these residential heat decarbonisation pathways, the scenarios are implemented in isolation and no other sectoral or whole energy system decarbonisation targets have been implemented.

The heat decarbonisation scenarios are:

Table 1
Residential heat and domestic hot water demand projections.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
RESIDENTIAL HEAT (PJ)	1043.1	929.2	951.5	934.6	937.1	938.3	938.7	942.8	944.9
DOMESTIC HOT WATER (PJ)	212.2	245.0	261.2	267.1	278.5	289.2	299.3	311.3	322.4
HOUSEHOLDS (MILLIONS)	26.32	27.48	28.81	30.04	31.23	32.33	33.39	34.47	35.54

Table 2
Heat technology parameters used in this study.

	HEATING TECHNOLOGY	2010	2030	2050
LIFETIME (YEARS)	Gas boiler	15		
	Hydrogen boiler	15		
	Air source heat pump	20		
	Ground source heat pump	20		
TECHNICAL EFFICIENCY	Gas boiler		0.84	
	Hydrogen boiler		0.84	
	Air source heat pump		2.51	
	Ground source heat pump		2.84	
TECHNOLOGY COST[a] (CAPEX) (M£/GW)	Gas boiler		89.88	
	Hydrogen boiler		97.76	
	Air source heat pump	1327.35	1061.82	929.05
	Ground source heat pump	1819.94	1456.02	1274.05
FIXED OPERATION & MAINTENANCE COST[a] (OPEX) (M£/GW)	Gas boiler		3.54	
	Hydrogen boiler		3.54	
	Air source heat pump		13.94	
	Ground source heat pump		7.73	

[a] 2010 prices.

Table 3
Transmission and distribution network reinforcement cost parameters used in this study.

	TECHNICAL LIFETIME (YEARS)	INVESTMENT COSTS[a] (M£/GW)	FIXED OPERATION & MAINTENANCE COST[a] (M£/GW)
ELECTRICITY TRANSMISSION	40	628.26	6.34
ELECTRICITY DISTRIBUTION	25	328.13	12.61
HYDROGEN TRANSMISSION	80	84.83	1.58
HYDROGEN DISTRIBUTION	80	499.45	11.76

[a] 2010 prices.

- Slower electrification - Almost 20% of households using heat pumps for heating by 2035 (40% low carbon) and over 65% using heat pumps by 2050% (99% low carbon)
- Quicker electrification - Over 55% households using heat pumps for heating by 2035 (90% low carbon) and around 65% using heat pumps by 2050% (99% low carbon)
- Hydrogen - Around 20% of households using hydrogen heating by 2035 (around 45% low carbon) and over 60% by 2050 (99% low carbon)
- Energy efficiency only - Around 65% of households on energy performance certificate (EPC) rating of C or above by 2035, and 90% by 2050

These scenarios are linked to recent UK government policies on residential heat and energy efficiency. The two electrification scenarios are based on policy targets set in the Net Zero Strategy [2], high electrification scenario, and the Heat in Buildings strategy [3], stating that 600,000 heat pump systems are to be installed per annum from 2028 to 1.9 million per year by 2035, this will translate to around 13 million homes with low carbon heating by 2035, of which 11 million will be using heat pumps and 2 million will be on heat networks.[1] The difference between the considered electrification scenarios is the pace at which electrification is adopted until 2050. The quicker electrification scenario roughly follows the UK Government target, whereas the slower electrification scenario is assumed to have a slower uptake, not meeting the 2035 target, but ramping up adoption after this and reaching a similar total heat pump uptake by 2050.

The hydrogen scenario considered roughly follows the one set up in the UK Government Net Zero Strategy [2] where up to 4 million houses will use hydrogen for heating by 2035. Lastly, our energy efficiency only scenario implements the energy efficiency target from Heat in buildings strategy [3] stating: ‘as many homes as possible to achieve an Energy Performance Certificate[2] (EPC) band C by 2035 where practical, cost effective and affordable’. TIMES residential heat demand is described in units of energy and does not recognise EPC ratings. Therefore, we translate this policy target using the state of current building stock from the Heat in Buildings strategy [3], and the average energy use per EPC band from (Department for Business, Energy & Industrial Strategy, 2017)[38].

Our assumed energy efficiency pathway for this scenario is shown in Fig. 2. Due to the state of the building stock in the UK,[3] it has been recognised that it is not feasible and/or practical to retrofit most existing buildings to an EPC A standard. Therefore, our assumption is that most buildings are more likely to reach EPC C by 2050. In terms of the average energy use values for the different EPC bands, this energy efficiency improvement would represent an energy saving of 12.4% by 2050, relative to 2020 levels.

Note that we only try to replicate the energy savings shown in Fig. 2 in our energy efficiency scenario, whereas the other proposed scenarios do not impose the implementation of energy efficiency technologies. However, these other scenarios do have the possibility to implement energy efficiency where cost-effective.

Moreover, while implementing these scenarios, the objective was to constraint the TIMES model the least possible, allowing technologies to be implemented as in the base case (e.g. district heating and other technology investments are allowed in all scenarios) and just

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[1] For reference, according to the Office of National Statistics, the Number of UK households was 27.8 million in 2019.

[2] For more information regarding Energy Performance Certificates, please see https://energyguide.org.uk/energy-performance-certificates-epc-explained/.

[3] According to the BRE Trust report [31] ‘The UK has the oldest housing stock in Europe, and most likely in the world. This is largely due to the legacy of dwellings built during the industrial revolution, which still form the backbone of our urban areas today. While still widely valued, these homes present challenges in making them healthy, safe and suitable for the future.’

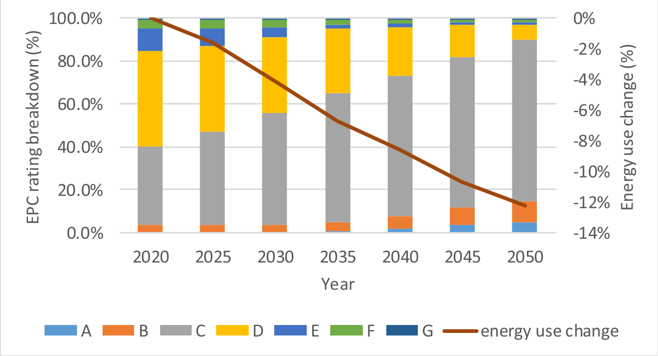

Fig. 2. Considered energy performance certificate (EPC) evolution of the UK housing stock and related energy use changes, relative to 2020 levels, for the energy efficiency scenario.

implementing a small number of constraints where necessary to develop the scenarios. For example, in both electrification scenarios, the constraint imposed was on gas use (limiting its use increasingly until 2050) and this makes the model to implement alternative technologies to gas boilers, such as heat pumps, DH, etc. In this case, hydrogen is not used significantly because is less cost-effective than electrification options. For the hydrogen-focused scenario, in addition to the gas use constraint, we also implemented a constraint setting a minimum level of hydrogen use. These constraints together resulted in the technology mix shown in Fig. 3, which also roughly align with the policy targets described above. For the energy efficiency scenario, the objective was to analyse the effect of the UK Gov. Energy efficiency target in isolation, so we removed the gas use and hydrogen constraints and implemented a minimum level of energy efficiency technologies, to simulate the pathway shown in Fig. 2. Therefore, this scenario was allowed to implement technologies and use fuels as in the base case, but with greater household energy efficiency.

5. Results and discussion

5.1. Residential heat technology changes

Fig. 3 shows the technology changes for the residential heat decarbonisation scenarios and of the base scenario. The technologies considered are biofuel, electric, oil, coal, gas and hydrogen boilers; in addition to hybrid and conventional heat pumps (HP), electric night storage heaters, district heating and standalone electric heaters.

The base scenario (Fig. 3a) follows the current technology mix, maintaining a high penetration of gas boilers (over 85%), and it is used as the benchmark to compare against the four decarbonisation scenarios. The slower electrification scenario (Fig. 3b) presents a slow start of heat pump adoption, with just over 6% of households using this technology by 2030. Then, picking up by 2040, where heat pump use (34.4%) surpasses gas boilers (33.8%), reaching almost 65% heat pump penetration by 2050. The second most important heating method in this scenario is district heating, with almost 20% of households using the technology by 2050. The quicker electrification scenario (Fig. 3c) also focuses on heat pump rollout, but in this case, the adoption of the technology is faster; heat pump use surpasses gas boiler use (around 35% vs 30%) by 2030 and continues with a rapid increase in heat pump adoption until 2050, where a similar technology mix is ultimately achieved for both electrification scenarios. The implications of the speed of heat electrification adoption are reflected in higher electricity demand emerging at an earlier stage, which, in turn, affects the network reinforcement needs and the timing of investments and overall emissions. Essentially, an earlier electrification would produce lower cumulative emissions in the residential sector than in a slower electrification scenario. These implications are discussed in detail in sections 5.2 to 5.4.

The Hydrogen scenario (Fig. 3d) focusses on the use of hydrogen boilers, replacing gas boilers, and complemented by heat pumps and district heating, but at a lower degree than in the electrification scenarios. The adoption of hydrogen starts slowly, with just over 5% penetration by 2030, but it ramps up significantly reaching over 43% penetration by 2040. By 2050, more than half (56.6%) of all households will be using hydrogen boilers, almost a third will be using heat pumps or hybrid heat pump systems (also using a hydrogen boiler for peak heat demand) and the rest using district heating or other electricity-based systems (e.g., storage heaters). The energy efficiency only scenario (Fig. 3e) focuses only on energy efficiency measures for the housing stock (e.g., wall and loft insulation, window double-glazing, etc.) and does not consider a change in heating technologies. Therefore, the technology mix is very similar to the base case, where most of the heat is produced with gas boilers.

Fig. 4 shows the energy savings on residential heat due to energy efficiency measures implemented in all scenarios. The energy efficiency only scenario implements the higher level of energy efficiency measures, translating to the biggest energy savings. However, other scenarios also consider energy efficiency, complementing their technology changes. The base scenario (i.e., without any changes to the heating technology), includes energy efficiency measures but at a lower degree than the other scenarios. This shows that some energy efficiency interventions can be cost effective, even if the incumbent technologies (i.e., gas boilers) are to be maintained. However, this is more applicable to the scenarios where costlier heating system changes are considered (i.e., heat pumps or hydrogen boilers).

5.2. Energy use changes

Fig. 5 shows the residential energy use changes (considering all energy demands, not only heat) for the base and the residential heat decarbonisation scenarios. The energy use mix in the base scenario (Fig. 5a) is composed more of gas than electricity. This reflects the fact that most of the residential energy demand in the UK relates to heating (due to typical cold and wet weather), which is currently supplied by gas. Thus, energy use demand in the base scenario remains fairly flat until 2050. There is a small reduction from 2025, which is attributed to improvements in energy efficiency (see Fig. 4).

Both the slower and quicker electrification scenarios reach a similar level of energy use reductions of almost 40%, relative to the base case by 2050. This is achieved due to the higher efficiency of heat pumps (shown by the coefficient of performance (COP) parameter, see Table 2, which means that heat pumps create greater heating output per unit of input electricity), relative to gas boilers. However, these scenarios differ in the speed in which they reach this saving level, which reflect the speed of the heat pump rollout (see Fig. 3). For instance, the slower electrification scenario presents a more linear energy reduction, whereas the quicker electrification has a fast decline in energy use up to 2035 and plateaus from there.

In the hydrogen scenario (Fig. 5d), the gas use is mostly replaced by hydrogen and electricity, but to a smaller degree. The overall energy use reduction in 2050 is 8.5%, this is considerably less than in the electrification scenarios. The lower share of heat pumps in this scenario causes the smaller energy savings. It is important to note that the use of hydrogen boilers, does not contribute to energy savings as they have a similar efficiency to gas boilers. For the energy efficiency only scenario (Fig. 5e), the energy savings are even lower than in previous scenarios (4.3% in 2050). The main reason behind this modest energy saving is the lack of heat pump deployment, which drives higher energy efficiency levels. Note that the base scenario also implements some energy efficiency for the building stock (see Fig. 4) and thus, the actual energy saving by year 2050 is smaller than the pathway modelled in Fig. 2, which compares against 2020 levels. The results of this scenario show that retrofitting buildings and energy efficiency measures can contribute to reducing energy use. However, these measures alone are unlikely to

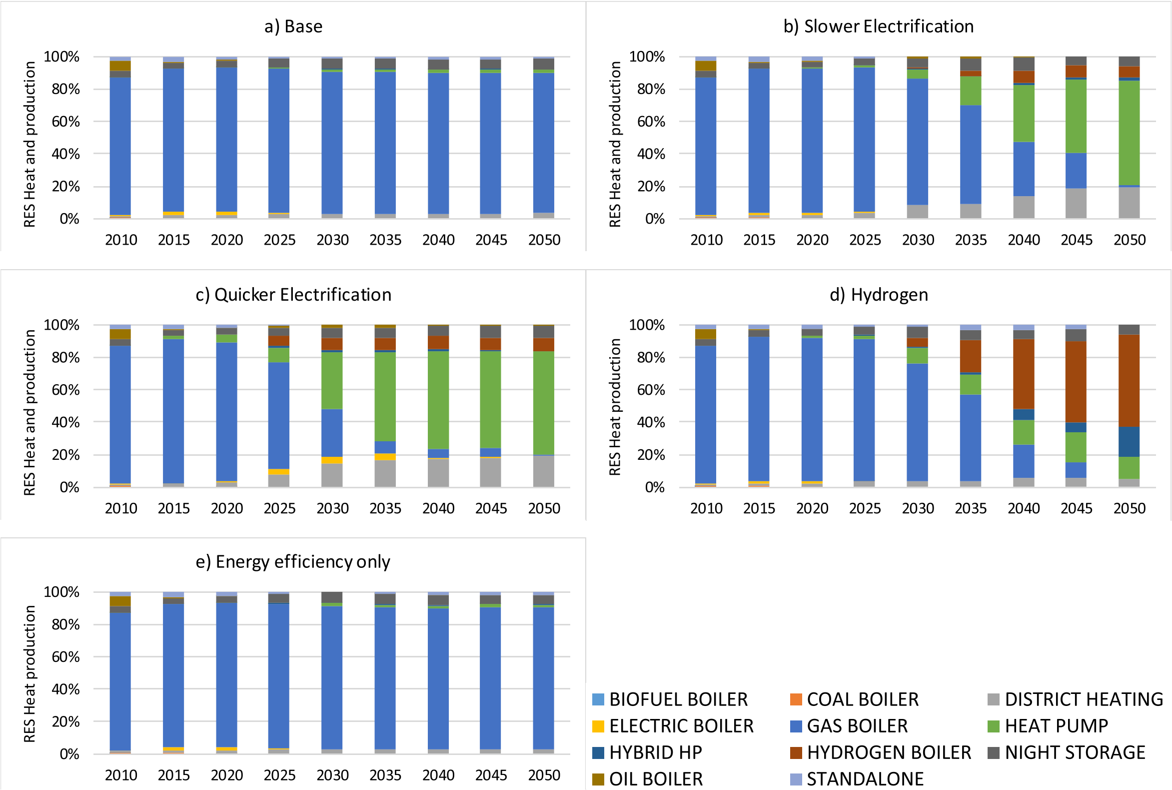

Fig. 3. Residential heat technology change pathways for all scenarios.

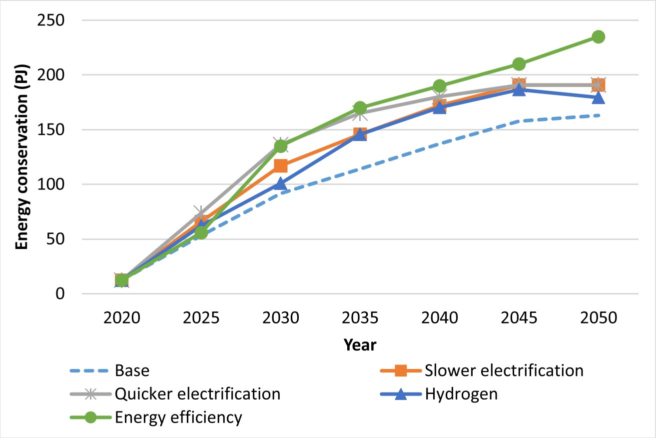

Fig. 4. Residential heat energy savings due to energy efficiency measures, for all scenarios.

reach the levels of decarbonisation required to reach net zero targets.

5.3. Network investments

Figs. 6 and 7 show the extra network investments required, relative to the base case, to accommodate the increased electricity and hydrogen demand, respectively, for the considered scenarios. For the electricity network (see Fig. 6), as expected, the electrification scenarios have the higher investment needs, with more than £21b investment in total, whereas the hydrogen scenario only requires £7.9b extra investments on the power network. The energy efficiency scenario shows a small saving in potential investments, caused by the slightly lower energy demand requirements relative to the base case. Note that the electrification scenarios present a very different investment pattern, with the quicker electrification front-loading most of the investment in years 2030–2035, while the slower electrification has a more evenly spread investment up to 2050. The level and timeframe of the network investments are also important, particularly in the context of challenging labour supply conditions which could result in disruptive near-term wider economy impacts [32]. For the hydrogen/gas network investments (Fig. 7), the hydrogen scenario shows the largest investments, reaching a total of almost £20b. All other scenarios have considerably smaller investment requirements to accommodate hydrogen.

5.4. Emission reductions

Fig. 8 shows the total sectoral emissions for all scenarios. The sectors are agriculture (AGR), electricity (power sector, ELC), hydrogen production (HYG), industry (IND), residential (RES), services (SER), and transport (TRA). Note that in this study we analyse scenarios only affecting residential heat, to analyse the drivers and outcomes of our scenarios in isolation, and other low-carbon transitions (e.g. decarbonising the power sector) are not implemented.

In the electrification scenario, as expected, residential emissions decrease between 27% and 45% relative to the base scenario. However, the additional electricity required for heat pumps leads to higher electricity production, and consequently, increased emissions in the power sector between 12% and 25%. Other sectors do not show significant changes. Note that the quicker electrification scenario, with the faster uptake of heat pumps has a lower cumulative residential emissions impact (−45%) and overall (−3.9%), compared to the slower electrification scenario (−27% residential and −2.6% overall). This finding reflects that the speed of the rollout and uptake of low carbon systems are crucial to tackling climate change.

In the hydrogen scenario, the residential emissions are also reduced (−28% relative to base case) but these are offset by increased emissions on the electricity and hydrogen production sectors (note that since there are no emission constraints in this simulation, the hydrogen used is

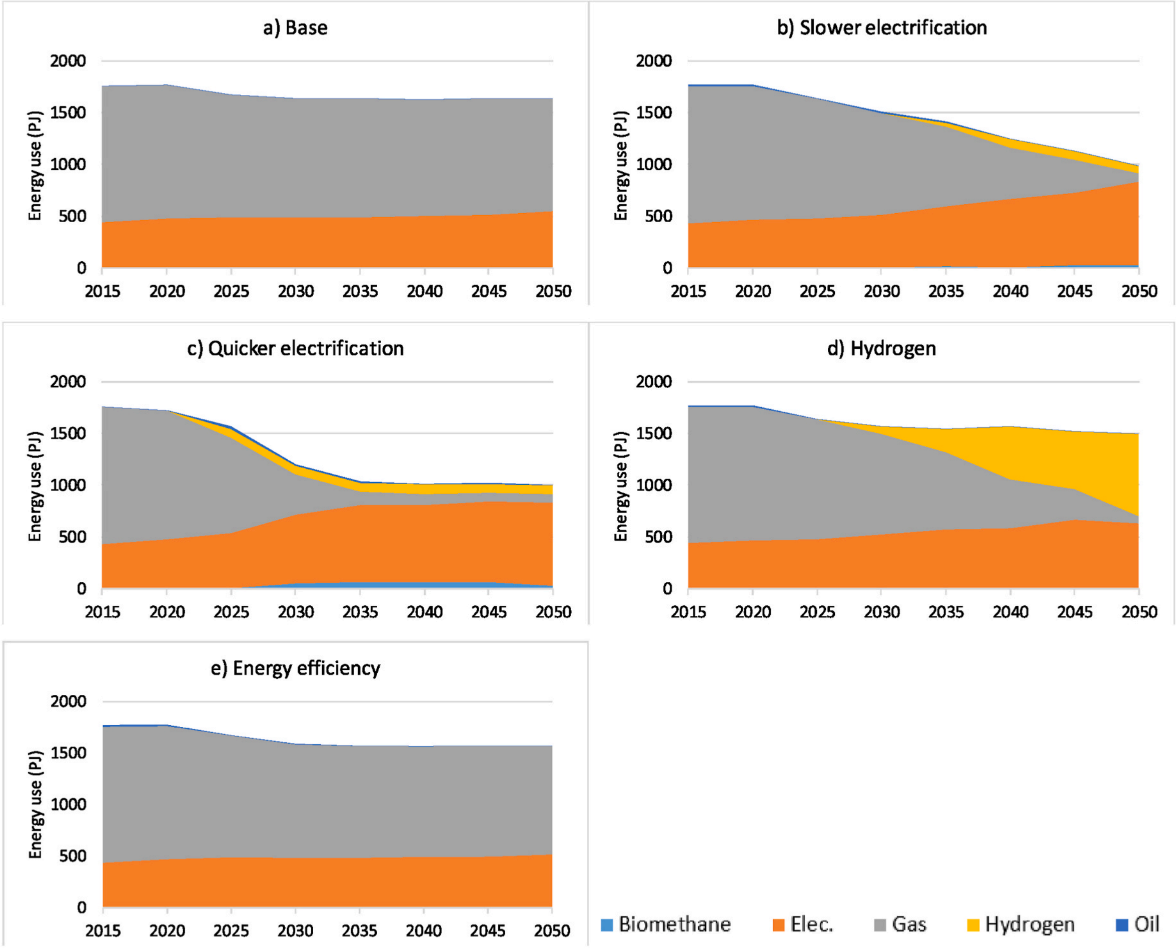

Fig. 5. Residential energy use pathways for all scenarios.

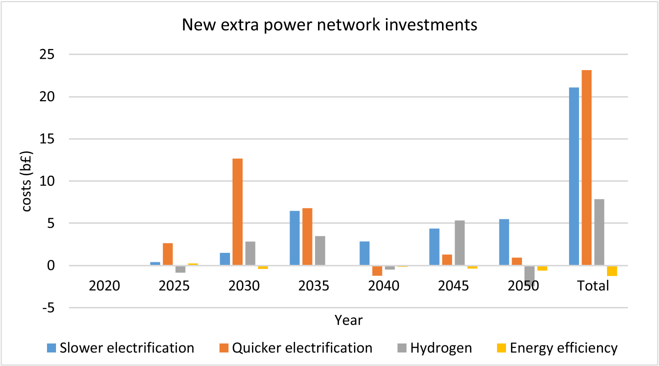

Fig. 6. Extra power network investments, relative to base case.

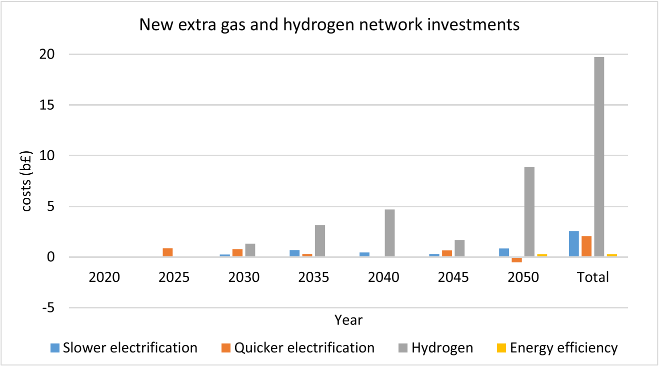

Fig. 7. Extra gas/hydrogen network investments, relative to base case.

mostly ‘grey’ hydrogen, i.e., produced from methane reforming without carbon capture and storage). Therefore, the overall emissions are 0.2% higher, relative to the base case. The energy efficiency scenario shows a smaller residential emission reduction (approx. −1%), but without the increased emissions in other sectors. Therefore, this scenario shows a small overall emissions reduction of −0.1%. The shift in sectoral emissions observed shows that it is important to take a whole-system approach and to consider renewable and ‘clean’ energy production policies in addition to residential heat policies, to avoid eroding and/or completely offsetting any potential climate benefits produced by low carbon heating systems.

5.5. *Discussion on results and long-term energy cost impacts*

From the results above, it is evident that a heating electrification scenario will require considerable power network reinforcements to accommodate the new heat pump loads, whereas a hydrogen scenario would involve important gas/hydrogen network investment to meet increasing hydrogen demand. This raises new questions regarding how investments are made, how they are spread and how they are paid for. Ultimately, the investment in network reinforcement will increase the activity in the power, construction, and gas sectors, among others. In practise if the investment is concentrated in a shorter time period (e.g., 3 years), it is likely to create negative wider economy impacts as the

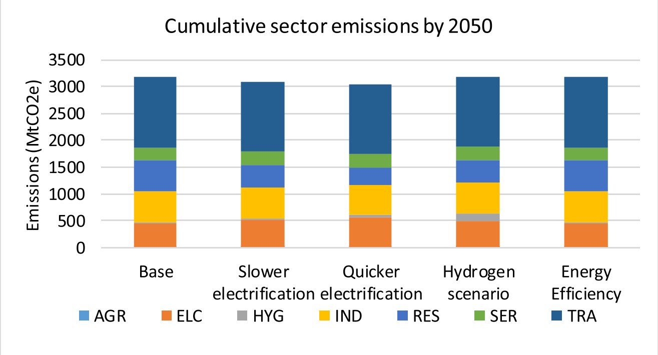

Fig. 8. Cumulative CO2eq emissions per sector for all scenarios.

sectors involved need to draw in additional (but scarce) labour and capital resources [33].[4] The construction and labour capacity constraints in these sectors are likely to be lessened if the spending and upgrade activity are spread over a longer timeframe.

A second key insight from our results is in terms of the impact to the consumer. The results on energy use changes, in Section 5.2 (see Fig. 5) show that consumers can reach important savings in energy use due to the higher energy efficiency of heat pumps, which requires almost 40% less energy by 2050 in the electrification scenarios considered. However, how these energy savings translate to cost savings will depend on the price differences between electricity, gas, and hydrogen, in the near, medium and long term.

Moreover, in the UK, it is expected that the funding of the necessary network upgrade and extra generation capacity for both electricity and hydrogen will be recovered through electricity bills, over the life of the asset. This potential increase in energy prices will affect all consumers. Therefore, it is important to consider how consumers may be impacted through both energy bills and the costs of other goods and services (as companies are likely to pass on their increased energy costs through their own prices). In this context, the impact on low-income households will be of significant interest to policy makers aiming to address regressive policies, considering that these vulnerable groups are less likely to have the required capital to invest in low carbon solutions and/or may not benefit from the potential energy savings due to the increased heat pump efficiency.

We developed a sensitivity analysis of price projections for gas and electricity prices, to analyse how different price trends may affect overall cost savings for consumers under the different residential heat decarbonisation scenarios. We have developed three price scenarios: low (L), central (C), high (H) for both gas and electricity (see Fig. 9). The L, C and H scenarios follow the same path up to 2020, based on historical average prices from Ref. [35], and deviate from this point onwards. In the case of electricity prices, the high scenario (ELC-H) follows the historical upwards trend up to 2025 and then stabilises at 0.34£/kWh (which is the current, as of October 2022, retail price for electricity under the new ‘price freeze’ from the UK Government; [4]. The electricity central price scenario (ELC-C) also continues with the price increase trajectory but at a slower pace and settles from 2025 at 0.24 £/kWh, and the electricity low scenario (ELC-L) assumes a decrease in price up to 2025 and plateaus at 0.15£/kWh. In the case of gas prices, the gas high scenario (GAS-H) follows a rapid increase up to 2030, settling at 0.15£/kWh, which is the same long-term price level of ELC-L. The gas central scenario (GAS-C) also takes a price increase path but settling at 0.103£/kWh (this the current, as of October 2022, retail price for gas under the new ‘price freeze’ from the UK Government). Lastly, the gas low price scenario (GAS-L) follows the historical price trend keeping the price around 0.04£/kWh. The rationale behind these scenarios is to provide a range of potential cost implications to consumers. We have also attempted to represent the potential future trends in UK energy prices. For instance, the ELC-H and GAS-C have long-term prices that resemble the recent increased price freeze in the UK [36]. GAS-H could be considered to include a ‘carbon tax’, which could then be used to subsidise renewable electricity or hydrogen investments. GAS-L could be seen as the status-quo (up to 2020) and ELC-L would be a scenario where the lower costs of solar and off-shore wind production translate into lower retail prices for consumers.

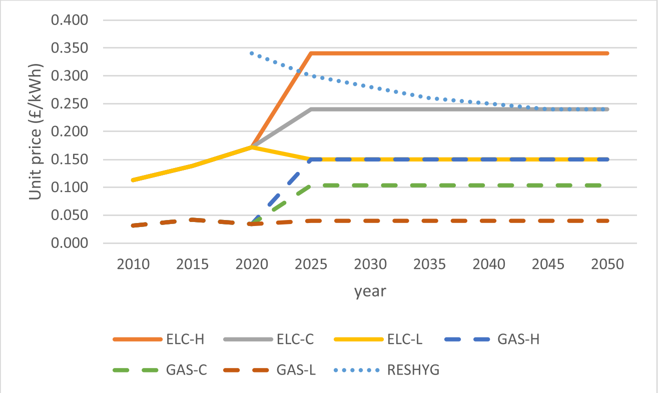

Fig. 9. Price scenarios for sensitivity analysis of consumer costs.

In the case of hydrogen, where the operation of the industry is at early stages, residential retail prices for hydrogen are not available. The only available data is on hydrogen production costs, but it is not clear what share of the tariff this would be and what other costs will be included (e.g. network investments and operation costs, taxes, levies, etc.). We have therefore assumed a hydrogen price scenario (REHYG in Fig. 9), that is comparable with the ELC-H and ELC-C scenarios, assuming that long-term hydrogen production will be done via electrolysis, using renewable electricity (green hydrogen). In addition to this, we expect that the cost of green hydrogen production will decrease over time as the technology matures [37].

Fig. 10 shows the change in cumulative energy costs for residential consumers, relative to the base case. The fuel costs are calculated as the product of energy use from Fig. 5 (i.e. technology capacities and energy use are taken from our results and are fixed for this sensitivity analysis) and the energy price scenarios from Fig. 9. These results show that the price of gas, the incumbent heating fuel, has a key role in translating the energy use savings into energy cost savings.

For the electrification scenarios (Fig. 10a and Fig. 10b), where the gas prices are high, energy cost savings are observed across all electricity prices scenarios, reaching 23% in the quicker electrification scenario (ELC-L and GAS-H). Conversely, when gas prices are low, energy costs increase independently of the electricity price scenario. The GAS-L prices can be around 4 to 8 times lower than the electricity price scenarios, thus the efficiency gains from using heat pumps are not sufficient to offset the difference in prices. This is an important consideration for policy making, to ensure that alternative low carbon heating technologies are competitive and attractive for consumers.

The hydrogen scenario (Fig. 10c) does not present energy cost savings. This is caused by the higher hydrogen price assumed relative to gas prices. Since gas and hydrogen boilers have similar efficiencies, the cost of hydrogen is the main deciding factor on potentially realising any costs savings. Therefore, if policy makers decide to take the hydrogen option for residential use forward, this needs to be done in a way where prices are comparable to gas, to incentivise consumer adoption. Lastly, the energy efficiency scenario (Fig. 10d) only reduces demand by retrofitting buildings and does not change the fuel mix from the base case;

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[4] [34] also find similar challenges when considering how the retrofitting activity of residential properties is spread over a 15-year period. The full report can be found at: https://doi.org/10.17868/76997.

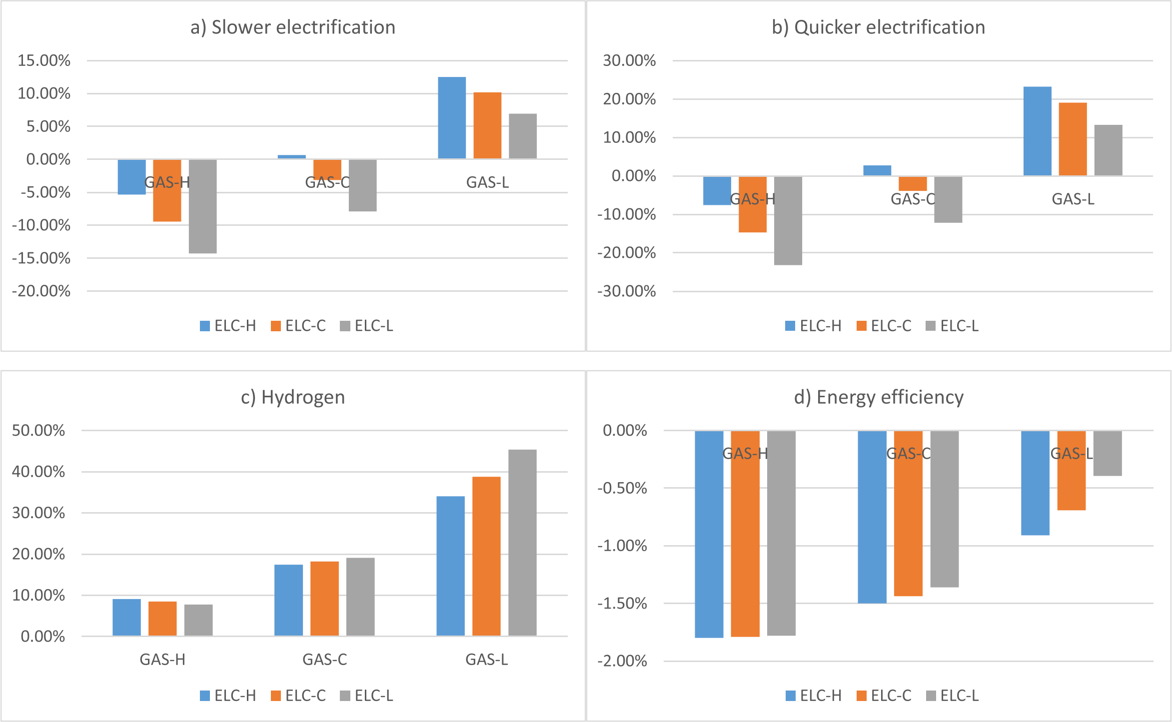

Fig. 10. Energy cost savings, relative to base case, under different price scenarios.

therefore, it has cost savings across the different price scenarios, albeit these are small (less than 2%).

5.6. Study limitations and future work

TIMES is a technology rich and powerful tool, with its main objective of analysing whole energy system long-term decarbonisation transitions. However, the size and complexity of the model brings sacrifices in detail in some areas, such as storage and flexibility requirements (which are normally more 'real-time' modelling issues) or energy networks representation, where other models with higher time and geographic resolution can capture better. Similarly, the model employs a relatively coarse-grained time-slice representation, and even though some weather variability is considered implicitly in the seasonal time slices used in the model, we do appreciate that the temporal coarseness creates an 'averaging' effect that is likely to undervalue peak demands due to extreme weather events, and thus, capacity and network requirements.

Certainly, the limited network representation and temporal resolution in TIMES could underestimate the scale of network reinforcement needs and flexibility provision. However, we believe it is a useful tool to develop initial analysis and provide insights on the order of magnitude for network expansion, required to accommodate new energy demands. These results could be validated with more detailed network and/or power system models, and we believe there is scope for soft-linking a whole-energy system model like TIMES with a more detail power system model to analyse these issues.

Another important consideration in this study is the focus on the residential sector. TIMES is commonly used to analyse whole system decarbonisation scenarios. However, we decided to limit the scope of our analysis to low-carbon transition for residential heat specifically, without considering other decarbonisation actions in other sectors. We took this approach to be able to see the drivers behind energy use and technology changes within the residential sector in isolation, as we believed that setting whole system net zero targets would over constraint the model and may not have allowed to analyse the scenarios proposed (e.g. energy efficiency would probably have been maxed out in all scenarios and other upstream changes may have directed and constrained technology changes at residential level). However, we understand that in practice, the decarbonisation of residential heat will be just one of many other transitions happening simultaneously. We will explore these whole energy system interactions and impacts in future work.

Also, as future work, we plan to use other models in combination with TIMES to expand the results obtained here. For instance, economy-wide (or economic system) frameworks, such as Computable General Equilibrium (CGE) models, can be used to provide insight on how network costs could be paid for and what impacts they have in the wider economy [33]. The CGE model can complement TIMES analysis, providing insight in terms of overall economic growth (GDP changes), job creation and wealth distribution across different consumer groups associated with investment, energy price and other factors emerging from TIMES. Employing such an integrated approach could also help us to understand winners and losers in the wider economy and potential pressure on skills and jobs to support the transition to low carbon heat.

6. Conclusions

This study provides insight on the wider effects of the transition to low carbon residential heat, analysing the implications of different technology scenarios, spanning potential electrification, hydrogen and energy efficiency pathways. We have analysed the impacts of these scenarios in terms of network investment needs to accommodate the increasing electricity and/or hydrogen demand, changes in fuel use and fuel costs for the final consumer and changes in CO_2 emissions. Our analysis provides valuable insight on the implications on network investments and energy use changes and costs of different types of low carbon heating options. Moreover, this study brings other important points of discussion on the transition to low carbon heat, including the timing of network investments and the economic impacts to consumers (direct and indirect). Therefore, we see this analysis as necessary first step for further research on the full implications of decarbonising residential heat in the energy system and the wider economy.

The results show that the electrification of heat can lead to improved energy use efficiency. However, higher electricity retail prices, relative to gas, are likely to offset cost reductions due to energy savings from heat electrification. Our analysis highlights key issues, such as the importance of the retail price differential between gas and electricity and how that may interact with other factors (including potential efficiency gains in shifting to electric systems) to impact the wider economy. Under an electrification scenario, we anticipate almost 40% energy savings for heating at point of consumption by 2050, largely due to the higher efficiency of heat pumps compared to gas central heating systems. However, we find that there is a turning point, where the retail price of electricity is sufficiently high relative to that of gas that efficiency-driven monetary savings in delivering heat/hot water services can be significantly offset or completely eliminated. Such net impacts on bills must also be set in the context of the upfront and/or financing costs of purchasing and installing a new heating system. These results therefore suggest that the impact on households, particularly those on low-income, could be significant, considering that these vulnerable groups are less likely to have the required capital to invest in low carbon solutions and/or may not benefit from the potential energy savings due to the increased heat pump efficiency.

Moreover, uncertainties remain around the role of hydrogen. Hydrogen remains at the centre of heating and industrial policies in the UK [2]. However, the extent of its potential future use for residential heating is not clear and the scenarios projecting the use of hydrogen tend to also consider other technologies, including heat pumps. Therefore, uncertainties remain around the level and location of hydrogen use, which will have implications on business models, investments, and potential costs differentials for those with access to hydrogen (requiring the development of specific networks) and those who do not. Key questions also remain around how hydrogen production supply chains will emerge, what sectors they will service and more generally, to what extent this will evolve as a new sector in the UK economy.

Considering the impact on CO_2 emissions (a central focus of heat decarbonisation policy), all scenarios presented a similar reduction in emissions for the residential sector. However, we observe a shift of sectoral emissions as the electricity and hydrogen production sectors increased their emissions (extra generation to meet heat pump or hydrogen boiler demand), effectively reducing the potential climate benefits of the transition to low carbon heating. These results show the importance of a whole system approach to tackle climate change, where there is no emission transfer to other sectors or 'outsourced' to other countries.

Credit author statement

Christian Calvillo: Conceptualization, Methodology, Software, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Antonios Katris:** Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing, Visualization. **Oluwafisayo Alabi:** Conceptualization, Methodology, Investigation, Data Curation. **Jamie Stewart:** Conceptualization, Investigation, Writing - Review & Editing, Project administration. **Long Zhou:** Conceptualization, Investigation, Data Curation, Writing - Original Draft. **Karen Turner:** Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2023.101113.

Appendix

Table A
Alternative heat technology parameters used in this study.

	HEATING TECHNOLOGY**	2010	2030	2050
LIFETIME (YEARS)	CHP - combined cycle (gas, biomethane, hydrogen)	15		
	CHP – fuel cell (hydrogen)	17		
	DH – gas boiler (gas, biomethane)	30		
	DH – Immersion electric	25		
	DH – biomass boiler	15		
	DH – water source heat pump (river, sewage or industrial)	20		
	Hybrid air s. Heat pump/gas boiler	20		
TECHNICAL EFFICIENCY	CHP - combined cycle (gas, biomethane, hydrogen)		0.81	
	CHP – fuel cell (hydrogen)		0.83	
	DH – gas boiler (gas, biomethane)		0.84	
	DH – Immersion electric		0.9	
	DH – biomass boiler		0.74	
	DH – water source heat pump (river, sewage or industrial)	3.33–3.49		
	Hybrid air s. Heat pump/gas boiler	2.51HP/0.84gas		
TECHNOLOGY COST* (CAPEX) (M£/GW)	CHP - combined cycle (gas, biomethane, hydrogen)	500.0–550.6		
	CHP – fuel cell (hydrogen)	6456	4661	4302
	DH – gas boiler (gas, biomethane)		0.4	
	DH – Immersion electric		4.7	
	DH – biomass boiler		10.3	
	DH – water source heat pump (river, sewage or industrial)	328–561	312–533	262–451
	Hybrid air s. Heat pump/gas boiler	533.15	432.01	381.44

(*continued on next page*)

Table A (*continued*)

	HEATING TECHNOLOGY**	2010	2030	2050
FIXED OPERATION & MAINTENANCE COST* (OPEX) (M£/GW)	CHP - combined cycle (gas, biomethane, hydrogen)	22.22–24.44		
	CHP – fuel cell (hydrogen)		531.65	
	DH – gas boiler (gas, biomethane)		0.63	
	DH – Immersion electric		0.95	
	DH – biomass boiler		17.03	
	DH – water source heat pump (river, sewage or industrial)	1.89–3.47		
	Hybrid air s. Heat pump/gas boiler		4.10	

* 2010 prices.

** Combined heat and power (CHP) here used for district heating (DH).

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