Options and costs of using hydrogen for heating

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ABSTRACT

Converting the UK gas networks to deliver low-carbon hydrogen has moved from an academic concept to become the subject of major research programmes and demonstration projects. The Leeds H21 study proposed a "business-as-usual" approach in which the 85% of UK houses with gas connections continue to use boilers for heating and hobs for cooking, but with hydrogen instead of natural gas. We examine the implications of potential conversion programmes using a detailed spreadsheet model, and consider the wider ramifications of conversion for net zero using the UK TIMES energy system optimisation model. We find a role for hydrogen heating in the UK energy system, but the size of this role is unclear from an economic perspective as it depends on assumptions about economies of scale in a conversion programme. For many residences, hydrogen might best be a stopgap. We conclude that mandating the use of dual-fuel "HyReady" boilers would not provide a substantial economic benefit, but they could reduce the size of the peaks and troughs in the number of boilers required in future years. It will be important to consider political and equity issues when designing a conversion programme so that it is fair to gas users in terms of like-for-like technology replacements and socialising conversion costs.

1. INTRODUCTION

The focus of decarbonisation efforts is moving beyond electricity generation and "quick wins" to harder-to-decarbonise sectors such as heat. There are widespread expectations that electrification, using high-efficiency heat pumps, will have a prominent role (DECC, 2012). Yet the potential for using hydrogen instead of natural gas in countries with comprehensive natural gas systems is receiving increasing attention, particularly in the UK. Early academic studies suggested that gas network conversion could be technically-feasible and economically-optimal (Dodds and Demoullin, 2013; Dodds et al., 2015), and these were followed by industry-led studies that examined the engineering details in more detail (Sadler et al., 2018; Sadler et al., 2016). The UK has since invested around £30m in engineering development to further understand the issues (BEIS, 2018).

There are perhaps two principal benefits of decarbonising heat using hydrogen. First, households can continue using gas boilers for heating, which are popular due to their small size, low noise, high and responsive power output, and reliability. Figure 1 reflects the popularity of gas in the UK: while consumption has reduced by 20% since peaking in 2005, this has been achieved primarily by mandating the use of condensing boilers in all homes, and 85% (23 million) of households continue to use gas heating. Second, given the popularity of gas boilers, converting the gas networks to hydrogen might be the only politically palatable method of moving much of the population away from gas heating.

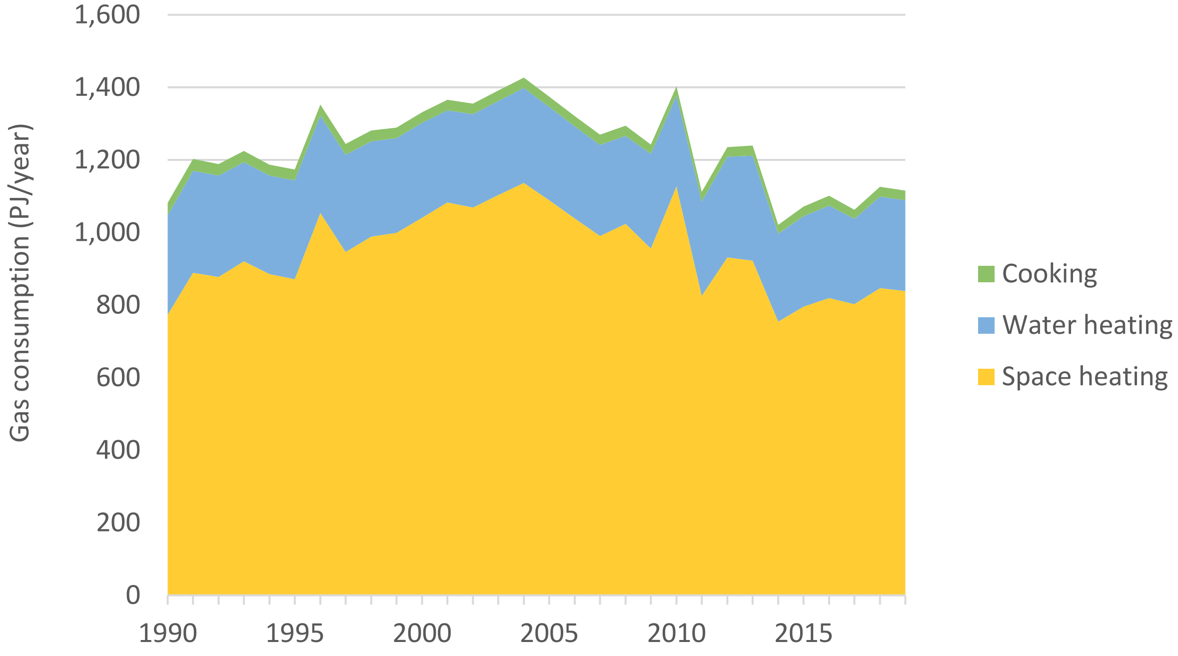

Figure 1. Gas consumption for residential heating in the UK since 1990 (BEIS, 2021).

The UK and many other countries previously underwent a gas networks conversion programme from town gas to natural gas. Town gas was produced from coal gasification in local plants and contained 50% hydrogen, as well as carbon dioxide, carbon monoxide, methane, and various contaminants. It was widely used in the UK for lighting from 1820 and cooking from 1870. Starting in 1967, following the discovery of North Sea gas, the UK converted all gas networks and appliances in all homes over a 10-year period to use natural gas. Gas central heating was progressive retrofitted to UK homes and 95% of UK homes now have centralised heating (https://www.ons.gov.uk/peoplepopulationandcommunity/personalandhouseholdfinances/expenditure/datasets/percentageofhouseholdswithdurablegoodsuktablea45). Since the 1990s, the Iron Mains Replacement Programme (IMRP) has been replacing all iron mains gas pipes on the distribution networks within 30 m of buildings with polyethylene pipes, which are suitable for carrying hydrogen with low leakage. This programme is planned to conclude in the early 2030s, when a conversion programme to hydrogen could commence. Such a programme would take 10–20 years and require appliances in all homes to be adapted or replaced with hydrogen equivalents, as hydrogen has quite different combustion properties to natural gas.

1.1 Scenarios for gas network conversion

The gas industry vision for gas network conversion, as espoused in H21 and other reports (e.g. Cadent and Progressive Energy, 2018; KPMG, 2016), is similar to the natural gas conversion programme. Teams of gas fitters would progressively convert all residences, with boilers and other gas appliances replaced "for free" (i.e. with costs socialised across gas users or through general taxation). Everyone that currently uses natural gas would switch to using hydrogen boilers in the future. The strengths of this approach are that heating is fully decarbonised, residents have a similar quality of service to what they have had in the past, and there are potentially economies of scale for purchasing and fitting new devices. The weaknesses are that hydrogen might not be the best or cheapest option for some households, there would be little or no consumer choice (with some people possibly receiving worse replacement appliances), there would be fairness and equity issues, and there would be methane leakage from the natural gas system and residual GHG emissions from steam methane reformers if "blue" hydrogen were produced from natural gas as is proposed in the H21 studies.

In an alternative vision, only parts or none of the gas networks would be converted, with the remainder being decommissioned. Consumers would choose whether to continue using gas or to switch to another fuel. The strengths of this approach are that consumers would be able to choose the best option for themselves in a fair playing field, sidelining incumbent gas companies might create opportunities for other technologies to spur innovation, and there would be fewer fossil fuels in the energy system. The weaknesses are that switching off a gas supply without an affordable alternative would be politically very difficult, and decommissioning the network is not necessarily cheap.

1.2 Research questions and paper structure

As the gas networks are highly-regulated independent monopolies in the UK, government direction would be required for a conversion programme to take place. We examine some of the policy decisions in this study:

1. Would all of the UK gas networks be converted, as proposed, or only those parts where hydrogen is a competitive decarbonisation option?
2. Would customers be expected to use hydrogen boilers, which the Leeds H21 study envisaged would be fitted to each house, or would it be better for them to instead use a different hydrogen-powered device (e.g. hybrid heat pump or fuel cell micro-CHP), or a non-hydrogen option?
3. What are the decarbonisation costs of network conversion? Can costs be reduced by introducing dual-fuel "HyReady" boilers and cookers in the period prior to conversion? Moreover, while the Leeds H21 study calculated a carbon cost as a function of the cost of conversion and future fuel costs, it did not account for residual boiler asset values (in the

conversion from town gas to natural gas, the greatest paper cost was losses on the gas works that became stranded assets).

We first use a spreadsheet model to examine the implications and costs of gas network conversion programmes. We then use the UK TIMES energy system model to explore conversion within the context of decarbonising the wider energy system.

The paper is organised as follows. Section 2 discusses the spreadsheet model and the underlying assumptions, and Section 3 presents the scenario analyses from this model. Section 4 explores gas network conversion in the context of the wider energy system using the UK TIMES model. Some wider issues are explored in Section 5 and we conclude in Section 6.

2. MODELLING GAS NETWORK CONVERSION PROGRAMMES

Our spreadsheet model calculates the deployment and retirement for natural gas, HyReady dual-fuel and hydrogen boilers, both on the open market and as part of a national gas networks conversion programme, for the 23 million homes with gas boilers (CCC, 2016).

We assume boilers have a lifetime of 15 years, which means around 1.5 million replacements each year at present; for comparison, 1.67 million gas boilers were sold in the UK in 2019 for the residential and non-residential sectors (Installer, 2020). We assume for simplicity that other appliances also have a 15-year lifetime and are replaced at the same time as a boiler. In scenarios in which HyReady appliances are mandated, we assume that only HyReady versions of boilers, heaters and hobs will deployed from a given date. In line with the Leeds H21 study, we assume that it will not be practicable to produce a HyReady version of a gas oven, so all natural gas ovens will need to be replaced during the conversion programme.

The fraction of appliances in each home and the average time required to convert each appliance in a conversion programme, as assumed by the Leeds H21 study, are shown in Table 1. In the spreadsheet model, the proportion of HyReady appliances depends on the scenario. In line with that study, we assume that 60% of *gas-connected* homes have a gas heater and 56% have a gas hob. In contrast to Leeds H21, since a survey recorded 60% of UK homes having electric heating and since a quarter of those are likely to be the off-gas homes, we assume that 60% of *gas-connected* homes have a gas oven.

	Appliances per house	**Time required per house (hours)**
HyReady boiler	50%	2
Natural gas boiler	50%	8
HyReady heater	32%	2
Traditional heater	28%	5
HyReady hob/freestanding	40%	1
Traditional hob	16%	13.5
Traditional grill/oven	48%	4
Pipework adjustment and meter replacement		1

Table 1. Assumed numbers of gas appliances in the Leeds H21 study and average time estimated to change each appliance.

	Leeds H21	**NGN North of England**	**CCC**	**This study**	
				Open market*	Conversion
Non-boiler appliances per house	1.6	1.0	N/A	Leeds H21	
Appliance costs					
Natural gas boiler	£1,040	£500	£1,500	*£2,319*	£800
HyReady boiler	£850			*£2,469*	£100
Natural gas heater	£450			*£1,719*	£250
HyReady heater	£300			*£1,719*	£100
Natural gas hob	£750			*£400*	£150
HyReady hob/freestanding system	£300			*£400*	£100
Natural gas grill/oven	£450	£250		*£400*	£250
Total appliance replacement costs		*£750*	*£1,500*		*£736*
Other in-house work					
In-house pipework and meter	£100	£0	£0		£100
Domestic/small service labour costs					
Management cost uplift	21%				20%
Basic technician cost (£/hour)	£46.30				£35.00
Initial survey and administration costs	£140	£191			£126
HyReady boiler changeover	£112				£63
Natural gas boiler replacement	£449	£191			£336
HyReady heater replacement	£112				£84
Traditional heater replacement	£280				£210
HyReady hob or freestanding replacement	£56				£84
Traditional hob replacement	£757				£126
HyReady grill/oven replacement					
Traditional grill/oven replacement	£224	£191			£168
Pipework adjustment and meter replacement	£56				£42
In-house labour total		*£572*	*£1,500*		*£588*
Total cost per house with Leeds H21 appliance assumptions	**£2,665**	**£1,323**	**£3,000**		**£1,424**

*Table 2. Cost estimates for replacing gas appliances during a conversion programme (GBP in the year 2016). * Open market figures for this study include capital and labour costs, and are for appliances procured and fitted piecemeal outside of the conversion programme. Costs are based on UK Government assumptions in the National Household Model. HyReady devices are assumed to be fitted only through the open market in this study.*

The cost assumptions for appliance conversion and replacement are summarised in Table 2. While the Leeds H21 study assumed a total conversion cost of £2665/house, they assumed this would reduce by 40% in the longer term. The H21 North of England study reflects this assumption with much lower capital and labour costs (£1323/house). It asserts that conversion programme costs will be much lower than open market costs due to economies of scale in both buying replacement appliances and having teams of gas fitters working house-to-house. In contrast, the Climate Change Committee assumes a cost of £3000/house. In this study, we assume that HyReady appliances will have higher capital costs than gas boilers, but that conversion capital and labour costs will both be substantially lower than for the open market. Using these assumptions, the cost of converting HyReady appliances is around half the cost of replacing natural gas with hydrogen appliances. The total Leeds H21-equivalent cost is higher than for the NGN North of England study but substantially lower than for the Leeds H21 and Climate Change Committee studies.

3. IMPLICATIONS AND COSTS OF CONVERTING THE GAS NETWORKS

The UK Government roadmap for hydrogen heating aims to first convert a small number of houses, then a small village, and then a town to hydrogen, in the late-2020s, before commencing a conversion programme in the 2030s. As a base case, therefore, we examine a conversion programme starting in 2030 and concluding in 2049, converting 5% of the network each year. Conversion would need to take place street-by-street, as the same pipes cannot carry both natural gas and hydrogen. Since boilers in each street have a range of lifetimes, many natural gas boilers would be replaced that would not have reached the end of their lives. At the outset of the programme, there would be a sharp increase in the number of boilers that would need to be replaced in the first year, to more than 2.5 million, with more than half of these continuing to be natural gas boilers (Figure 2). This would create both supply chain and labour issues as this peak would be repeated in the future.

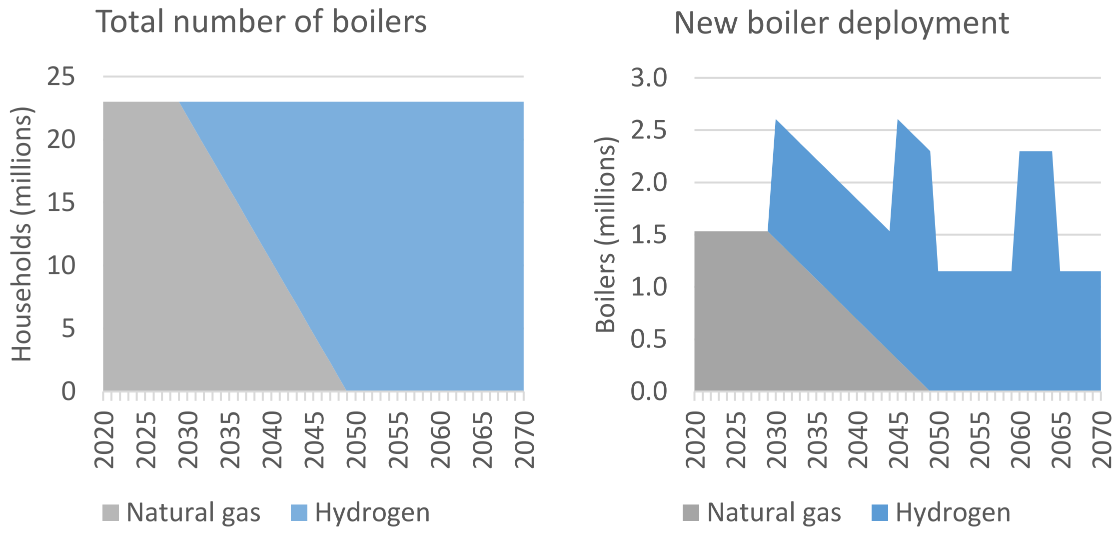

Figure 2. Boiler types and the rate of boiler deployments over time during a 20-year transition to hydrogen from natural gas from 2020–2039.

Mandating the use of HyReady boilers for all replacements from 2025 would reduce this peak to around 2.2 million boilers/year (Figure 3) as a substantial number of boilers could be converted rather than replaced (Figure 4). By 2040, no natural gas boilers would continue to be used in the UK.

This would reduce the number of lost boiler years due to early retirement from 154 million to 13 million (Table 3) compared with the scenario with no HyReady boilers, and the undiscounted cost of the appliance conversion programme from £51bn to £28bn (GBP in 2020). Yet the total 25-year capital cost over the period 2025-2049 is £13bn higher in the HyReady scenario due to more boilers being purchased on the open market and because there is still as substantive cost to converting HyReady appliances. If the £26bn difference in the accounting cost for the early retirement of gas boilers is taken into account, the non-HyReady scenario becomes £13bn higher than the HyReady scenario over that period.

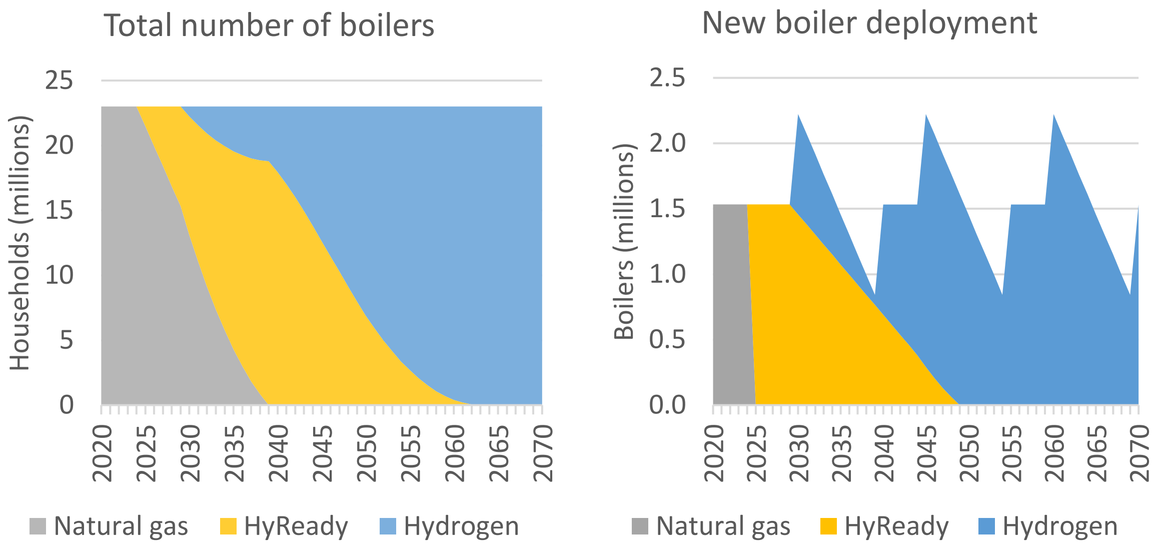

Figure 3. Boiler types and the rate of boiler deployments over time during a 20-year transition to hydrogen from natural gas from 2020–2039, where HyReady boilers are fitted from 2025 due to a ban on new boilers burning only natural gas.

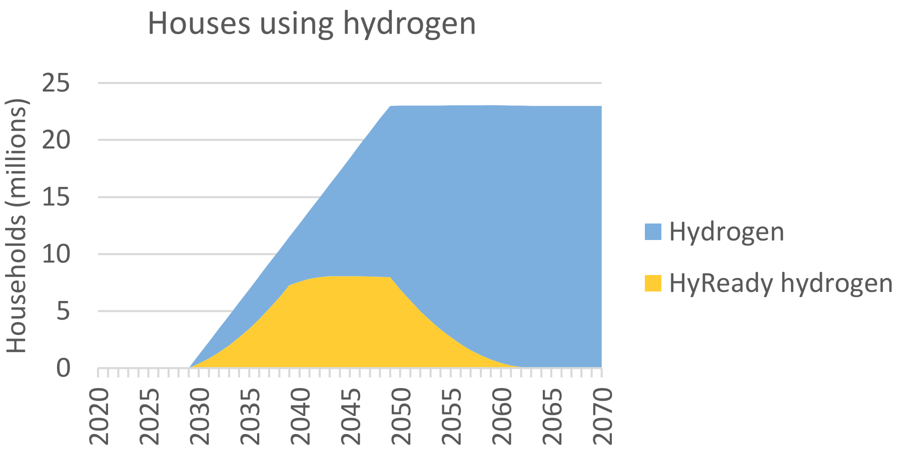

Figure 4. Number of houses using hydrogen during a 20-year conversion programme to hydrogen from natural gas from 2020–2039, where HyReady boilers are mandated from 2025.

	No HyReady	With HyReady
Total boiler years lost (millions)	154	13
Conversion programme cost (£bn)	51	28
Total undiscounted capital costs 2025-2049 (£bn)	175	188
Early gas boiler retirement costs (£bn)	28	2
Total cost (£bn)	203	190

Table 3. Comparison of scenarios without and with a requirement to fit only HyReady boilers from 2025.

Scenario			Undiscounted capital costs (£bn)				Peak boiler installations (mn/year)
HyReady mandated	Conv starts	Time to convert (years)	Conversion cost	Capital costs 2025–2049	Early retirement	Total	
None	2030		51	175	28	203	2.6
2025	2030	20	28	188	2	190	2.2
2025	2030	15	30	188	3	191	2.5
2030	2030	20	34	181	8	189	2.6
2025	2035	10	25	188	0	188	1.9
2025	2040	10	23	191	0	191	1.5

Table 4. Total appliance costs as a function of the conversion strategy.

4. GAS NETWORK CONVERSION IN THE CONTEXT OF WIDER ENERGY SYSTEM DECARBONISATION

We use the UK TIMES model to examine gas network conversion within the wider move to a net zero energy system. This bottom-up, least-cost optimisation model identifies pathways and technologies to decarbonise the UK economy. It represents energy service demands across all sectors of the economy, both now and in the future, and also all greenhouse gas emissions from energy and non-energy sources. Sixteen annual timeslices are used to represent seasonal and intraday variations in energy demand and supply. UK TIMES was used by the UK Government in 2017 to identify decarbonisation pathways for the Clean Growth Strategy.

4.1 Representation of hydrogen energy systems in UK TIMES

UK TIMES has a detailed representation of hydrogen technologies across a range of sectors. These include hydrogen road and rail transport options, use across industry for heat and as a feedstock for ammonia production and a reductant for iron smelting, and for decarbonising gas streams and providing flexible electricity generation. Hydrogen can be produced from a range of feedstocks including electricity, natural gas, coal, biomass and waste. Electrolysers can be used to convert excess renewable electricity to hydrogen in order to support the deployment of renewable electricity generation.

In the version of the model used by the UK Government, hydrogen could only be used for heating if a new hydrogen distribution network were constructed. We have created a range of new gas network conversion options in UK TIMES that examine the implications of optional or compulsory conversion, and restrictions on heating technology choices. We have added HyReady boilers and appliances that can be deployed prior to the conversion, and cheaper hydrogen appliances that can be fitted during a conversion programme. The costs assumptions are shown in Table 2 and are the same as for the spreadsheet model.

Accounting for early retirement of natural gas boilers is challenging in an energy system optimisation model as it will always replace the oldest boilers with hydrogen boilers, as this is the lowest-cost approach, rather than a range of boilers of different ages. Rather than trying to force the model to retire capacity early, which would require rewriting the model equations, we instead apply a tax to natural gas boiler capacity during conversion years equal to 25% of the total annualised capital cost, based on the spreadsheet model findings in Section 3 (156 million boiler years lost is roughly 25% of all natural gas boiler years during the conversion period).

4.2 Results

A UK TIMES version of the "gas industry" scenario, with full conversion of the gas network to hydrogen, is shown in Figure 5. This scenario departs slightly from the gas industry vision as householders are able to use any appliance that has a hydrogen input (e.g. boilers; hybrid heat pumps; micro-CHP). The cost-optimal technology is hydrogen boilers in most homes, but hybrid heat pumps are used in high-demand homes. Hydrogen is produced primarily through steam-methane reforming with carbon capture and storage ("blue" hydrogen), with emissions offset through negative emission technologies. This scenario suggests that the "gas industry" scenario would be compatible with achieving net zero emissions in the UK by 2050.

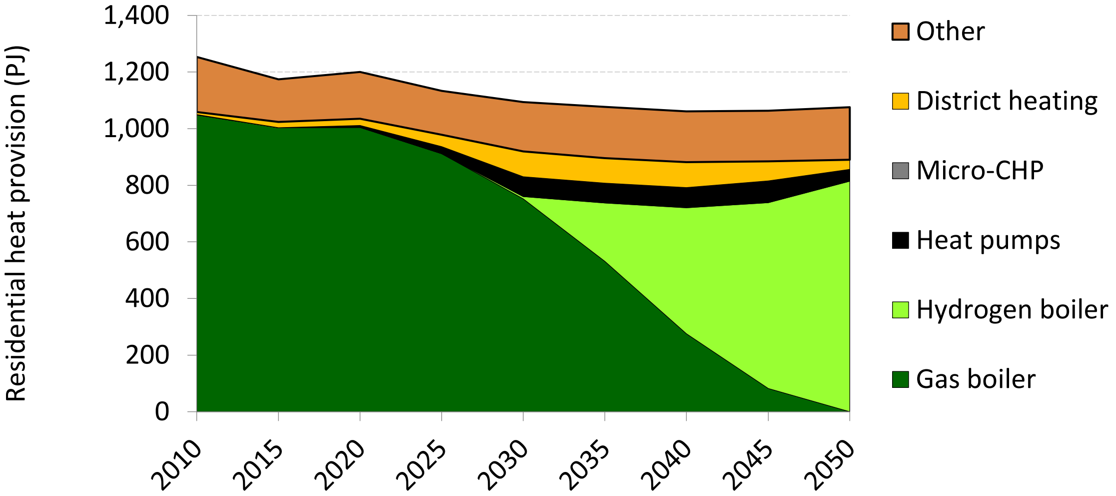

Figure 5. "Gas Industry" scenario with mandatory conversion and gas boiler replacement.

The scenario in which gas network conversion and hydrogen appliance uptake are optional is shown in Figure 6. Hydrogen use in 2050 is only around half that of the "gas industry" scenario. Hydrogen is a temporary option in solid-wall houses, alongside heat pumps which are more cost-effective in the long run. Most cavity-wall houses use hydrogen, and some flats where a gas connection is available. Advanced night-storage heaters are most appropriate in highly energy efficient new houses. Reducing hydrogen use reduces the discounted energy system cost by £22bn (0.5%) compared to the "gas industry" scenario.

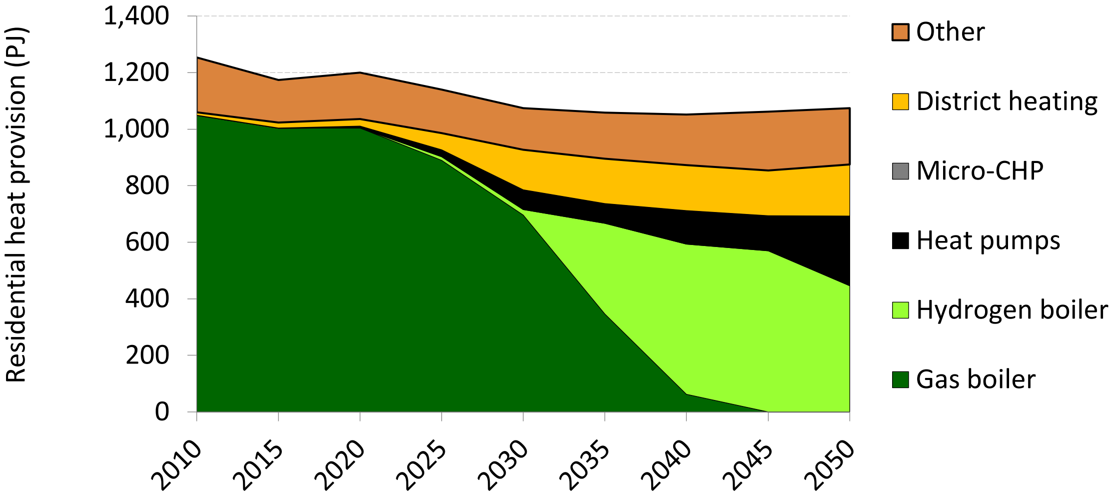

Figure 6. Least-cost scenario in which gas network conversion is optional.

Both of these scenarios assume that substantial economies of scale can be achieved in the conversion programme, as suggested by (Sadler et al., 2018). Figure 7 tests the importance of this assumption by altering the optional conversion scenario so that there are no cost savings for fitting hydrogen appliances during the conversion programme. In the absence of these cost savings, hydrogen boilers have a relatively small role in 2050, supplying around 25% of residences, while heat pumps have a much greater role and become more cost-effective from 2050. Hydrogen has a greater role prior to 2050 and for many homes is an intermediate step towards decarbonisation.

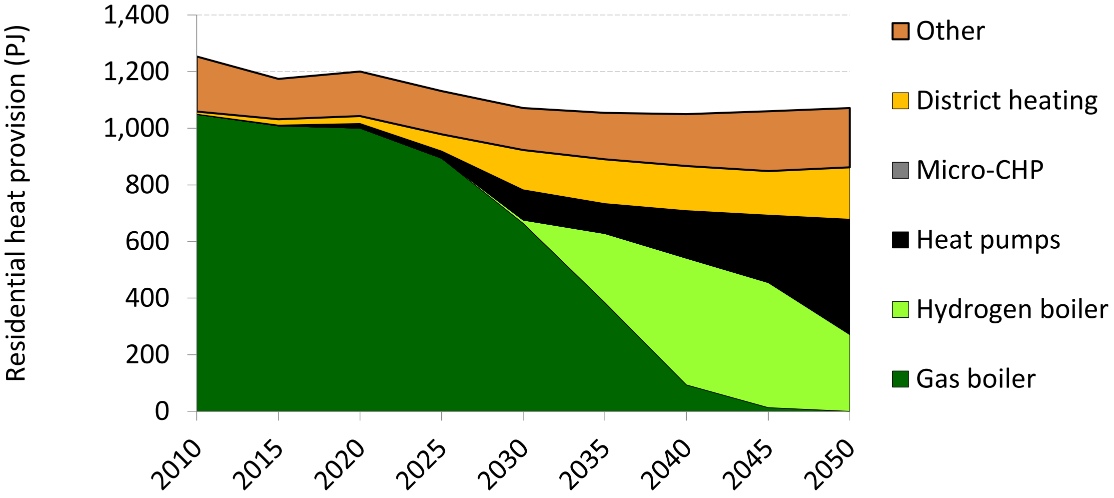

Figure 7. Least-cost scenario with an optional gas network conversion in which economies of scale during conversion are assumed to be not realised.

5. DISCUSSION

The conversion programme proposed by Sadler et al. (2016) has the potential to achieve net zero and would provide the population with a similar quality of heat service to that which they have at present. If other heat technologies could not provide a similar quality of service then such a programme might be the most appropriate option. But there are a number of issues that require reflection and action.

First, it is not clear how consumer choice would be reflected in the programme. Consumers might wish to use particular gas appliances, or might wish to move away from gas altogether, but would not have that option. A conversion programme would ideally ensure that such consumers would not be at a financial disadvantage by ceasing to use gas, so a focus on business models would be important. A poor choice of business model could lock-in more expensive heating systems for householders than would be necessary.

Second, it would be unfair to replace high-quality natural gas appliances with lower-quality hydrogen appliances if the same appliances were used across the UK to achieve economies of scale. Yet if there were like-for-like replacements, and the cost of the conversion programme was socialised, then this would lead to households with poorer appliances subsidising those with more expensive appliances, which would be unfair. Careful thought needs to be put into what extent the costs should be socialised across gas users or the whole population.

Third, hybrid heat pumps can contribute to electricity system balancing but do not have a role in the proposed conversion programme. There is a need to consider how such technologies could be included and how their value to householders and to the wider system could be realised through gas and electricity pricing structures.

Fourth, gas network conversion needs to be sustainable and deliverable by the gas industry. The peaks and troughs in the number of boilers that Section 3 shows could be needed in the future would not be sustainable for manufacturing or gas fitters, so careful thought should be put into how a programme might be scheduled to avoid these.

Finally, the politics of conversion has received little attention but is important. On one hand, conversion might be the only politically-viable approach to move much of the population away from using fossil fuels for heating. On the other, it might lock in incumbent technologies and prevent other nascent technologies from breaking into the market.

6. CONCLUSIONS

There is clearly a role for hydrogen heating in the UK energy system. The size of this role is unclear from an economic perspective as it depends on assumptions about economies of scale in a conversion programme and is also likely to be sensitive to the level of residual emissions. Hydrogen conversion is the most cost-optimal option for at least part of the UK housing stock, but for many residences might be intermediate option in the medium-term. The most appropriate long-term heating technology is unlikely to be boilers for all houses.

It appears that mandating HyReady boilers would not provide a substantial economic benefit, but they could reduce the size of the peaks and troughs in the number of boilers required in future years. If they can be produced as cheaply as natural gas boilers, and with similar levels of efficiency, then they would nevertheless be a no-regrets option.

Capital costs have an important influence on the cost-competitiveness of various low-carbon technologies. An important question is whether economies of scale can be realised in a gas network conversion programme, while being fair to gas users in terms of like-for-like technology replacements and socialising conversion costs. If proposed economies of scale cannot be achieved then the case for gas conversion across the whole stock is much weakened.

ACKNOWLEDGEMENTS

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7. KEYWORDS

natural gas; hydrogen; gas networks; boilers; heat; optimisation model