Technical annex: hydrogen heating

NATIONAL
INFRASTRUCTURE
COMMISSION
Better infrastructure for all

October 2023

Contents

Introduction and approach

A significant amount of attention has been paid to whether hydrogen could play a role in decarbonising home heating. In the second National Infrastructure Assessment, the Commission recommends that government should not support the rollout of hydrogen heating. Recognising that there is a spectrum of views on the topic, this annex provides an explanation of the assessment underpinning the Commission's recommendation.

The first section sets out the framing of the Commission's assessment of whether there is a public policy case for hydrogen heating and therefore whether government should support it. The report then provides an overview of the assessment under each of the criteria: price, quality, delivery, environment, resilience and economy. The final section describes how the Commission has considered uncertainty in making its recommendation.

A holistic approach to assessing the public policy case

Electric heating will play a major role in decarbonising heating. Government has committed to delivering emissions limits under the Sixth Carbon Budget,[1] which it states will require a reduction in emissions from buildings of around 50 per cent by the mid 2030s.[2] Heat pumps are the most efficient form of electric heating and should therefore be the dominant electric solution. Hydrogen heating is not available today and will not be an option until the 2030s, as it would take time for the necessary network to be developed and to scale up the production of low carbon hydrogen.

Government is providing support to incentivise the switch to heat pumps and, while further action is needed, the electrification of heating is already in progress. The question explored in this report is whether hydrogen heating should be an additional part of the low carbon heating mix, in the medium to long term.

Government will need to decide how much support (policy and financial), if any, it provides for hydrogen heating alongside supporting deployment of heat pumps and heat networks. It should base its decision on whether there are public policy reasons for supporting the development of hydrogen heating, based on a holistic assessment of the impacts of systems with hydrogen heating and those without.

Future heating systems must meet emissions limits. Comparisons should therefore be made between systems with hydrogen heating and systems where heat is largely electrified.

Systems that include a continued reliance on natural gas heating are not low carbon and therefore cannot be used as a comparison. The analysis was focused on domestic heating, but the results are equally applicable to heating business premises. Industrial use of hydrogen and natural gas is not part of the assessment.

Systems with no hydrogen heating are assumed to be largely decarbonised through the deployment of air source heat pumps. However, they are not the only means of electrifying heat. Other electric technologies are available today, which could be better options for certain properties, under certain conditions.[3] Heat networks will also be an option for some properties.[4] These other technologies are included in the Commission's assumptions about how the heating mix will change over time.[5] Comparisons to technologies other than heat pumps are explicitly made where this is relevant to the Commission's analysis.

Property owners will always have a choice in what heating system to install, albeit that choice is restricted to ensure it is low carbon. Even without hydrogen heating, there will be different low carbon heat options for people to choose between, depending on their own priorities and their property's characteristics.

Criteria for assessing the public policy case

An assessment of the public policy case for hydrogen heating has been made against a set of criteria covering the range of impacts of different heating system choices:

- Price: energy system costs, system cost sensitivities, property-specific costs
- Quality: consumer ease, quality of heat provision, continuity of service
- Delivery: speed of rollout, coordination, supply chain capacity and capability
- Environment: greenhouse gas emissions, nitrogen oxide emissions, water use
- Resilience: system design, security of supply and vulnerability to shocks
- Economy: jobs intensity, development of the hydrogen sector

The safety case is clearly critical. While it is not sufficient alone to make a positive case, being able to be used safely is the minimum threshold for hydrogen heating to be considered. Health and safety assessments are outside the Commission's expertise, so safety has not been included in the Commission's analysis. The assessment covered by this report assumes that a decision on support for hydrogen heating follows a decision that it is safe.

For a public policy case for supporting hydrogen to be made, hydrogen heating would need to either:

- rate somewhat better than systems with no hydrogen heating across most (or all) criteria; or
- rate strongly better than systems with no hydrogen heating on one or more criterion, with no counterbalancing areas where systems with hydrogen heating rate negatively.

Based on the Commission's assessment of the evidence, there is no public policy case for hydrogen to be used to heat individual homes or other buildings. The Commission recommends that government should not support the rollout of hydrogen heating. Infrastructure solely for hydrogen heating should not be eligible for support under the hydrogen transport business model and gas consumers should not be expected to pay for the conversion of natural gas infrastructure to transport hydrogen through existing price controls. Figure 1 below summarises the Commission's assessment of the public policy case for hydrogen heating.

A decision by government not to support hydrogen for heating still leaves open the potential for commercial development of networks to provide hydrogen heating to those who want it. However, this will only happen if it proves commercially viable.

Figure 1: There is no public policy case for hydrogen heating

Criteria and summary of the assessment of hydrogen's role in heating

Criterion	Commission's assessment
Price	**Negative** • Energy system costs are lower without hydrogen heating. The cost of producing hydrogen is forecast to outweigh the greater in-building capital costs of heat pumps.
Quality	**Neutral** • No discernible difference in the quality of heat provided. • Hydrogen heating requires fewer in-building changes. • Continuity of service is a greater risk for hydrogen heating (initially and on an ongoing basis).
Delivery	**Negative** • The challenges of delivering a larger and decarbonised electricity system exist in all pathways. • Coordination challenges are greater in pathways with hydrogen heating due to the need for large numbers of properties to disconnect from natural gas and reconnect to a hydrogen supply at the same time. • Supply chain issues could arise in all pathways. For pathways without hydrogen, supply chains for equipment will be global and competition may affect access and price. For pathways with hydrogen heating, supply chains for hydrogen boilers are likely to be UK specific and could face thin market constraints.

Criterion	Commission's assessment
Environment	**Negative** • More adverse environmental impacts with hydrogen heating from both indirect greenhouse gas emissions (hydrogen leakage) and emissions of nitrogen oxides.
Resilience	**Negative** • Resilience to shocks to the electricity system does not differ. Both pathways require electricity to function and the same resilience standards can be set for all systems. • Exposure to volatile natural gas markets could be higher with hydrogen heating, if additional natural gas is required to produce hydrogen or to produce the additional electricity needed. • Geopolitical energy security risks would likely reduce in all pathways as reliance on fossil fuels overall decreases.
Economy	**Neutral** • The benefit to the UK is likely to be similar in all pathways as the proportion of economy activity that is UK based is broadly similar.

Source: Commission analysis

Criteria assessment

Price – energy system costs, system cost sensitivities, property-specific costs

The main aspect of the assessment under this criterion is a comparison of the cost of the whole energy system – electricity and hydrogen generation, electricity and hydrogen networks, storage and in-home appliances – between scenarios with hydrogen heating and without. The assessment also evaluates whether hydrogen heating may offer benefits for households in certain types of property, as the property-specific costs (appliances, their installation and fuel costs) will vary between systems with hydrogen heating and without.

Energy system costs

The Commission's analysis evaluates the cost of energy systems under alternative scenarios for decarbonising heat predominantly through two technologies: hydrogen and heat pumps. Calculating the whole system cost, which captures the cost of both the electricity system and heating system, allows for the fact that changes in heating technology have knock on impacts on the electricity system and hence the cost of electricity to all users, not just those using electricity for heat.

The analysis is based on the following heating technology deployment scenarios and associated electricity demand profiles:[6]

- **Scenario 1** – no hydrogen for heat: no buildings have hydrogen heating and by 2050 83 per cent have heat pumps
- **Scenario 2** – hydrogen for heat playing a niche role: by 2050 13 per cent of buildings have hydrogen heating and 71 per cent have heat pumps
- **Scenario 3** – hydrogen is a more mainstream option for heat: by 2050 38 per cent of buildings have hydrogen heating and 46 per cent have heat pumps.

Switches to electric resistive and district heat networks are also included in each scenario. Their contribution to the heating infrastructure mix across each scenario is held constant.

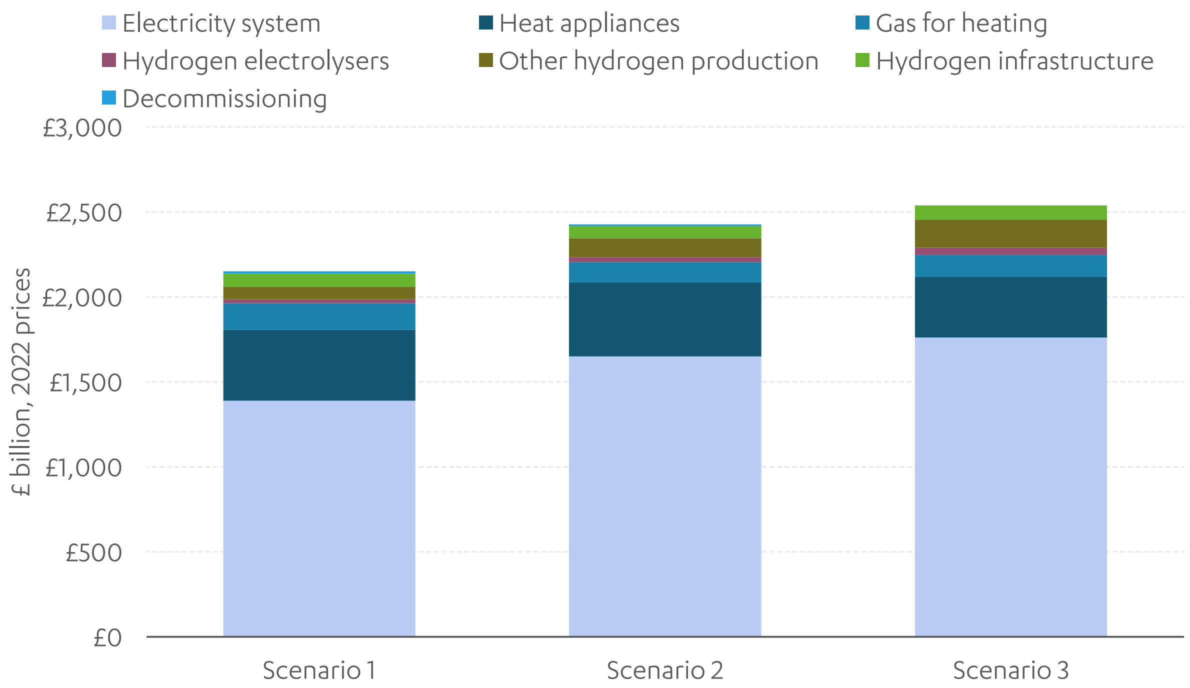
The analysis also uses assumptions for the hydrogen infrastructure that will be needed and the level of disconnection and decommissioning of the gas network that will be required for each of the three scenarios, based on research by Arup.[7] The number of properties on hydrogen heating in this research does not fully align with the scenarios described above, but is a reasonable indicator of the extent of gas infrastructure changes that will be needed if there is no hydrogen heating, if it plays a niche role and if it is a more mainstream option.

The cost of the energy system under alternative scenarios for heating technology deployment has been calculated over the 25 years from 2025 to 2050 with amortising of capital costs. This allows for a comparison of the costs that consumers will face in the years to 2050.[8]

The work brings together outputs from energy system modelling and analysis conducted for the Commission. The cost of heating appliances other than heat pumps or hydrogen boilers, for example heat networks or electric boilers, has been excluded because the magnitude is small and costs do not vary across the scenarios. Modelled costs for systems with hydrogen heating are higher than modelled costs for systems with no hydrogen heating – see Figure 2 (data available in Appendix A).

Figure 2: An energy system with no hydrogen heating is cheaper than one with hydrogen heating

Total energy system costs, 2025-50



Source: Commission analysis

The system cost components in Figure 2 cover:

- **Electricity system** – the cost of generation, transmission and distribution of the electricity needed across the economy. This is the largest component of costs, accounting for just under 70 per cent of the total costs considered.
- **Heat appliances** – the cost of installing and maintaining heat pumps, hydrogen boilers and gas heating systems (ahead of them being phased out). This is also a large component of costs, accounting for around 15 to 20 per cent of the total costs considered. The initial installation cost of heat pumps and hydrogen boilers includes the cost of additional transitional work that may be required. It also includes an assumed cost of energy efficiency improvements made when a heat pump is initially installed, but no improvements are assumed to take place when a hydrogen boiler is installed.

- **Gas for heating** – the cost of natural gas that will continue to be used by gas boilers is accounted for as the speed of switching from gas boilers to low carbon heat appliances varies across the scenarios. This is a minor component of costs, accounting for around five per cent of costs.
- **Hydrogen electrolysers** – the capital and operating costs of electrolysers producing green hydrogen. This is a minor component of the cost of producing hydrogen. The cost of electricity to produce hydrogen makes up around 90 per cent of the production cost and this is captured in electricity system costs.
- **Other hydrogen production** – the cost of producing all other hydrogen used across the economy. In the 2020s and 30s this is a mix of grey[9] and blue hydrogen, with grey hydrogen phased out entirely from the mid 2030s.
- **Hydrogen infrastructure** – the costs of creating a hydrogen pipeline network, providing hydrogen storage and in transitioning gas customers through either disconnection (scenario 1) or a mix of disconnection and transition to hydrogen (scenarios 2 and 3).[10] Hydrogen pipeline costs assume a mix of new build and conversion of existing gas infrastructure. This is a significant part of the system but only accounts for a minor component of the costs considered, at around three per cent of costs.
- **Decommissioning of the gas network** – the costs of permanently decommissioning the existing gas network, requiring grouting of the high pressure national transmission system and leaving the low pressure system in situ. This is a minor component of costs, accounting for less than one per cent of costs in scenarios where decommissioning is required. In scenario 1, with no hydrogen heating, not all pipelines are decommissioned as some are assumed to be in continued use for supplying industry. In scenario 3, no decommissioning occurs.[11]

The analysis takes into account the interaction between choices in different parts of the system, namely:

- heat pumps use around three times less energy than hydrogen boilers but have higher upfront in-building installation costs
- hydrogen heating reduces the direct use of electricity and peak electricity demand from heating but increases overall demand because electricity is used to produce hydrogen
- electricity demand for hydrogen production through electrolysis will affect the unit cost of electricity and the availability of 'spare' (i.e. curtailed) electricity will impact the cost of hydrogen production
- hydrogen heating requires a more extensive system of hydrogen pipelines and additional storage, but no hydrogen heating requires more decommissioning of the natural gas network.

The Commission has assumed that hydrogen used in heating will predominantly come from green hydrogen – produced by the electrolysis of water using low carbon electricity. This is because long term reliance on blue hydrogen – produced using natural gas with the carbon emitted in the process captured and stored – has more negative impacts for both the environment and resilience, which are discussed under those criteria.

Using electricity to produce hydrogen which is then used in boilers to produce heat requires five to six times more electricity than using the same electricity directly in a heat pump.[12] This is because more energy is lost in converting electricity to hydrogen, and heat pumps use less energy than boilers to produce the same level of heat. However, this does not result in a whole energy system with hydrogen heating being five times more expensive once all costs, efficiencies and interactions are accounted for. The Commission's analysis estimates that a system with hydrogen heating would be around 1.2 times as expensive than a system without (see Figure 2). Hydrogen consumers – which would make up a minority of households – would likely pay a significant proportion of this difference.

The difference in system costs is built up as follows:

- In isolation, the heating fuel costs of those properties that have hydrogen heating in scenario 3 are 6.2 times as expensive as if the electricity was used directly to fuel a heat pump. This result is to be expected due to the higher efficiency of using electricity directly to heat buildings rather than converting to hydrogen first.
- Adding in the costs of heating all buildings in Great Britain, a system with hydrogen heating is 2.7 times as expensive. This captures the impact above and the costs of all electricity used in heating, noting that the majority of heating is electrified, even in the scenarios with hydrogen heating.
- Initial switching to heat pumps will be more expensive than switching to hydrogen boilers because, in the near term, heat pumps are expected to be more expensive. This moves the cost of a system with hydrogen closer to 1.6 times as expensive than systems without.
- More hydrogen production assets are required in a system with hydrogen heating. This is a relatively minor component of costs and therefore a system with hydrogen heating remains around 1.6 times as expensive.
- The amount of hydrogen infrastructure (pipelines and storage) you need is greater when hydrogen is used in heating. But conversely there is additional cost for disconnecting customers and decommissioning natural gas pipelines when heat is electrified. Costs in this area are marginally cheaper for systems with hydrogen so the cost of systems with hydrogen become around 1.5 times as expensive.
- The remaining parts of the system, predominantly the costs of electricity demand from sources other than heat, are similar across the scenarios. Accounting for these costs results in a system with hydrogen heating as a more mainstream option being around 1.2 times as expensive than one without. This captures the spill over impacts of the price of electricity on other electricity consumers.

System cost sensitivities

Costs for delivering an energy system out to 2050 are uncertain, therefore sensitivity analysis has been used to assess the impact of uncertainty. The following has been tested and the results are presented in Figure 3:

- **Higher electricity distribution costs** – to reflect the potential need for greater investment in distribution network capacity enhancements when electrified heat is the only heating option, an increase of 30 per cent in investment in distribution networks in scenario 1 has been tested. Electricity distribution network costs would need to be four times higher than assumed in the base scenario to make systems with hydrogen heating a similar cost to a system without.
- **A slower rate of heat pump cost reduction** – to reflect the potential for the cost of heat pumps to reduce more slowly than assumed. Costs of heat pumps reduce by 17 per cent by the mid 2030s in the base scenarios, but only by six per cent in this sensitivity. Heat pumps are installed in all scenarios, so this sensitivity is applied to all.
- **A higher or lower cost of hydrogen production** – to reflect the uncertainty in the cost of producing hydrogen, a higher and lower capital cost has been tested. Increasing the capital cost of electrolysers by, on average, 75 per cent, or reducing the capital cost by, on average, 20 per cent has been tested on a base capital cost of £15 per MWh.[13] It has not been possible to test the consequential impact of this sensitivity on electricity system costs, which would be impacted by a higher or lower hydrogen price due to hydrogen being used to generate electricity. However, the impact is expected to be low as, if the price of hydrogen is high, cheaper alternative generation technologies would be used – for example gas generation with carbon capture and storage.
- **Customer gas disconnection process cost** – to reflect the uncertainty in the process for disconnecting large volumes of customers at the same time.[14] Systems with no hydrogen heating have higher costs as they require a greater volume of disconnections and the base scenarios include between £8bn and £28bn for the cost of disconnecting customers from the gas network.[15] These costs are based on an assumption that the existing ad hoc process, and resulting costs, continues, with some efficiency savings from economies of scale. There is high potential for the cost of this process to decrease further if a coordinated, national programme is developed. Arup's research for the Commission included a sensitivity looking at this, which is applied here.[16] For scenarios 1 and 2, a national programme is assumed, which reduces the cost of disconnection by over 50 per cent, based on both efficiencies and methodological changes. For scenario 3, where hydrogen use is higher and disconnections are more ad hoc, a ten per cent saving is applied to reflect the lower potential for savings, due to the continued use of the current methodology.

Figure 3: Sensitivities tested do not change the result that a system with no hydrogen heating is cheaper than one with

Relative costs of systems with hydrogen heating compared to a system without

Sensitivities	Scenario 2 (niche role for hydrogen) vs scenario 1 (no hydrogen heating)	Scenario 3 (more mainstream option for hydrogen) vs scenario 1 (no hydrogen heating)
Base case	1.13	1.18
Scenario 1 has higher electricity distribution costs	1.11	1.16
A slower rate of heat pump cost reduction	1.13	1.18
A higher cost of electrolysers	1.13	1.19
A lower cost of electrolysers	1.13	1.18
A lower cost of customer disconnection	1.13	1.19

Source: Commission analysis

Property-specific costs

The Commission has also considered how property-specific costs for heating and hot water provision could vary by heating option across different property archetypes. This analysis considers the direct costs to households – the upfront installation cost and the annual running cost. Cost assumptions for appliances, installation (including hot water provision), maintenance and fuel are aligned across the Assessment.[17] The archetypes analysed were an 'average' house,[18] a small, space constrained flat[19] and a large, leaky house.[20] All costs are exclusive of any subsidies that may be available for the upfront cost of purchasing low carbon heat appliances.

The future running costs of all heat appliances are uncertain, but the cost of hydrogen is more uncertain than electricity because it is not currently produced at the volumes needed to supply to homes and none of the infrastructure is yet in place. In 2035 the cost of hydrogen is assumed to be between £0.10 and £0.17 per kWh. This assumption is based on:

- A cost of producing hydrogen with a lower estimate of £0.07 per kWh and a higher estimate of £0.13 per kWh[21]

- A cost of transmission and distribution of the hydrogen of £0.01 per kWh, in line with the network component of natural gas bills today[22]
- An addition of 25 per cent to cover supplier operating costs, supplier margin and VAT.[23]

The running cost of electric heating is calculated based on a variable unit rate price for electricity in 2035 of £0.13 per kWh.[24] The annual costs of different heating technologies based on these fuel cost assumptions and assumed capital and installation costs are summarised in Figure 4.

This analysis suggests that there will be an electric heating option that is of equivalent or lower cost to hydrogen heating across a range of property archetypes. The upfront cost of a heat pump is significantly higher than a hydrogen boiler, but their lower running costs (due to greater efficiency) offsets this in most archetypes. Other electrified heating options could also be installed and offer a comparable or cheaper system than a hydrogen boiler.

Figure 4: Hydrogen heating is expected to be more expensive in a range of property archetypes

Annual heating costs in 2035 for different property archetypes

Property archetype	Heating technology (annual cost, 2022 prices)				
	Hydrogen boiler	Electric resistive	Electric boiler	Air source heat pump25	High temp. heat pump
Space-constrained flat – inefficient	£1,040 to £1,510	£1,170	£1,040	£1,120	
Space-constrained flat – efficient	£860 to £1,200	£940	£840	£1,020	
Average home	£1,550 to £2,370			£1,320	
Large, leaky house	£1,990 to £3,120				£1,880

Source: Commission analysis

The analysis shows that a lower estimate for the future price of hydrogen could result in hydrogen heating being a similar cost to electric heating in space constrained flats. However, space constrained properties (under 50m²) are often not connected to the gas network making them unsuitable for conversion to hydrogen heating. Currently, 42 per cent of space constrained properties are not connected to the gas network and the proportion for newer properties is even higher with more than half of such properties built since 1983 not connected to the gas network.[26]

The potential for a small number of households to find hydrogen heating to be a comparable cost is not sufficient to make a case that government should support the rollout of hydrogen heating. If society as a whole is better off with electrified heat (as the analysis of total energy system costs shows it would be), then government's focus should be on supporting households where the barriers to electric heating are greatest, rather supporting a hydrogen option that raises the costs of the system overall.

The costs above also reflect the cost of the initial installation of a heat pump and the transition costs that would be incurred, including radiator replacements. Transition costs are one off costs that would not be incurred again. This means that when it comes to replacement of either a heat pump or a hydrogen boiler the gap will be even more in the favour of heat pumps or other forms of electrified heating.

Quality – consumer ease, quality of heat provision, continuity of service

Consumers should expect a high quality and reliable service. This criterion compares aspects of the service that consumers should expect from different heating systems throughout the process – from installation through to continuing use. Key aspects are the relative levels of disruption caused by the installation of different heating technologies (the 'hassle factor'), whether consumers will be able to maintain a warm home and how likely they are to be exposed to fuel supply risks.

Consumer ease

In most properties, it appears likely that installing a hydrogen boiler would require less in-home changes than installing a heat pump for the first time. The range of possible changes required for a hydrogen boiler and a heat pump are summarised in Figure 5. Interventions will vary by property, depending on its characteristics, and the type of heating appliance installed.

Figure 5: Interventions needed will vary by property

Potential in-home changes required for a hydrogen boiler or an air source heat pump

	Hydrogen boiler	Air source heat pump
All homes	• Excess flow valves – one in the meter and one upstream to ensure safety[27] • Boiler – replacement of boiler, or (if in place) adjustments to a hydrogen ready boiler to run on hydrogen instead of natural gas	• Heat pump installation – external installation of unit and connection to existing wet system, electricity supply and hot water cylinder
Some homes	• Ventilation – additional ventilation in rooms with hydrogen appliances and pipes for a small number of homes[28] • Pipework – replacement where pipes do not meet the current natural gas standards[29]	• Radiator replacement – where these are not large enough to provide sufficient heat with the lower flow temperature[30] • Hot water infrastructure – installation of hot water cylinder (or similar) where this does not already exist or replacement if the existing cylinder is unsuitable[31] • Energy efficiency – insulation to reduce heat loss and increase efficiency

Source: Commission analysis

Replacement of an existing natural gas boiler with a hydrogen ready boiler would take one, or occasionally two, days.[32] Conversion of an already installed hydrogen ready boiler could take around an hour,[33] but that is only part of the conversion process, which is likely to require the property to be without a gas supply for up to 48 hours – see delivery section.

Other changes could be more invasive, if required. Installation of additional ventilation is likely to be disruptive, though this is only expected to be required in a very small number of properties. The need for replacement of internal pipework would only be identified through pre-installation checks and testing, which makes it difficult to estimate what proportion of homes it may apply to.[34] If required, pipework replacement would be disruptive due to it being within the fabric of the property. An installation with new pipework is likely to take two to five days, based on estimates for a natural gas boiler system today.[35]

For a heating supply via a heat pump, first time installation averages two to four days.[36] The exact length of time will vary by property depending on, for example, the size of current radiators and the type of heat pump chosen. The heat pump will need to be installed outside the property and connected to the electricity supply, with the natural gas boiler removed and the heat pump connected to the existing wet system.

A hot water tank (or alternative hot water provision) will also need to be installed at the same time. In many properties a replacement of some or all of the radiators will be needed, with over 90 per cent of properties in the Electrification of Heat Demonstration Project replacing at least one.[37] Where required, new radiators could be installed while the existing gas boiler is in place, as could installation of any energy efficiency measures.

There is growing evidence that heat pumps are suitable in a wide range of building types.[38] While low cost, low disruption energy efficiency measures – such as loft and cavity wall insulation – could be helpful in reducing running costs they are not expected to be required in most homes.[39] There is also increasing confidence that high temperature heat pumps could reduce or remove the need for energy efficiency measures and radiator replacement in some properties.[40] The appliance could be more expensive than a standard heat pump and they can require more energy to run, but overall could be cheaper if it removed the need to replace radiators or install additional energy efficiency measures.[41]

The installation requirements of a heat pump would only apply for the initial installation, as these are one off costs and hassle. Replacement at the end of a heat pump's life would be much faster and more straightforward, which means the advantage hydrogen boilers have for consumer ease will diminish over the course of the heat transition. Recent survey evidence also suggests that views on the relative disruption impacts of heat pumps and hydrogen boilers may not be that different, especially once factors such as provision of networks (covered below in the delivery section), are factored in.[42]

Quality of heat provision

In terms of operation, hydrogen boilers offer more of a 'like-for-like' replacement for natural gas boilers than heat pumps. The difference in operation of heat pumps (largely the production of lower temperature heat) will require some adjustment for users. However, evidence suggests heat pump users have broadly the same level of satisfaction as natural gas boiler users.[43] There are also alternative electric heating technologies, like electric boilers, which can be operated much the same as a gas boiler.

Continuity of service

Continuity of service is a key risk for hydrogen. Consumers will need a guarantee that the necessary network build and conversion happens so that hydrogen is supplied to their property both initially and that they will have access to a continuous supply. Demand uncertainty for hydrogen is high and there is a risk that suppliers or networks could fail if demand fails to materialise. This is especially true for heating, which will be the main rationale for hydrogen distribution networks.[44]

It is possible that a hydrogen supply may never materialise – for example, if it becomes clear that there will not be sufficient demand because many consumers have already chosen an alternative low carbon heat source. Were this to be the case, households who had made plans to use hydrogen would have to install an alternative low carbon heating system, potentially at short notice.

The German Government's draft legislation to amend the Building Energy Act45 proposes measures to manage this continuity of service risk of hydrogen heating. If the hydrogen network is not operational and compliant with the required standards by 2035 then the proposed legislation would require the hydrogen network owner to compensate households for the installation of an alternative, compliant heating system. If equivalent rules were applied across Great Britain, it would only require a failure in supply to less than 100,000 customers (under 0.5 per cent of total properties) for the liability to reach £1 billion.[46]

If energy supply companies fail, government would likely continue to step in to support the provision of supply (likely at a cost to consumers), as has happened to date with failed energy suppliers.[47] This risk exists for both suppliers of electricity and hydrogen. The customers of a failed electricity supplier could be purchased by an alternative electricity supplier. But it could be more challenging to find an alternative supplier of hydrogen due to the market being considerably smaller, leaving a higher risk and cost of failure sitting with government.

While the scale of the risk of hydrogen not being available for heating when needed is hard to quantify, it is higher than electrified heat where the stranding risk is close to zero. The electricity network will need to carry additional capacity to meet the demand of heat pumps and other forms of electrified heat. Increasing the capacity of the electricity network for heating, to support electric vehicles and to provide for electrification of other parts of the economy, will be necessary. There is some risk that high levels of demand could create short term constraints on electrification before upgrades are made – see delivery section for further details.

Delivery – Speed of rollout, coordination, supply chain capacity and capability

Decarbonising the heating systems of around 29 million homes in Great Britain by 2050 is a major delivery challenge which will require significant coordination.[48] Whether hydrogen heating looks likely to make the delivery challenge faster, less complicated or reduce risks is therefore a key factor in whether government should support its use.

Speed of rollout

Decarbonising heating is going to require major infrastructure investment and careful planning and coordination no matter what technologies are used. The Sixth Carbon Budget in the mid 2030s is the initial milestone to meet. Timely delivery is therefore critical.

The need for at least some upgrades to electricity distribution networks exists regardless of whether heat is electrified – for example, to ensure there is sufficient electric vehicle charging infrastructure.[49] The existing capacity of distribution networks is not well understood and this situation needs to be improved through the gathering of more data on network capacity and usage.[50] Trial evidence suggests that electrified heat will be a larger driver of investment in electricity distribution networks than electric vehicles, but also that neither is expected to have more than a minor impact.[51]

While there is some uncertainty around the precise level of electricity network investment required for the energy transition, investment will be needed regardless of whether hydrogen heating plays no role, a niche role or becomes a more mainstream option. The Commission's recommendations support the timely deployment of infrastructure to support decarbonisation.[52] Without the necessary action there could be a short term constraint on heat pumps (albeit likely before hydrogen could provide an alternative). Any constraints are likely to be localised, depending on both the capacity of existing infrastructure and the pace of electrification in the local area.

The need to scale up hydrogen production and provide pipelines means it is not possible to begin at scale conversion of homes to hydrogen until the mid 2030s. Research suggests that national conversion could start in 2036.[53] This is in order to provide sufficient time to build a hydrogen transmission network and undertake the necessary enabling works on the existing gas distribution network, without jeopardising security of supply.[54]

Hydrogen heating is the main driver of investment in hydrogen distribution and so the rollout requirements and challenges will be determined by heating deployment. This is distinct from upgrading electricity networks, which will be a challenge for all future systems, including those with hydrogen heating.

Coordination

The process of taking a customer off natural gas and connecting them to a hydrogen supply requires multiple properties to be converted at the same time, as distribution networks carrying gases are shared infrastructure. The distribution network would need to be divided into segments, so that natural gas could be removed from each segment and replaced with hydrogen.[55] As all homes have an electricity supply there is not a coordination challenge for switching to heat pumps.

The size of the segment, and therefore how many properties would be affected at the same time, is driven by both the engineering design of the network and by the need to limit the length of time properties have no access to fuel for heating and producing hot water – 48 hours is expected to be the maximum time window feasible.[56] The process would therefore likely require activity across thousands of properties per segment.[57] To reach the level of hydrogen heating deployment in scenario 3 of the price analysis (38 per cent in 2050) around 800,000 homes would need to be converted every year from 2036 to complete the transition by 2050.[58]

Converting homes during a 48 hour window is reliant on enabling works both inside and outside the home happening in advance. This includes both replacing network components that are incompatible with hydrogen and the installation of hydrogen ready appliances. This assumption relies on these appliances being able to operate using natural gas ahead of conversion. Actions during the conversion window could then be focussed on removing natural gas from the network and from people's homes and replacing it with hydrogen.

Having hydrogen ready boilers would not reduce the need for access to individual properties within the same window. Hydrogen ready boilers would require manual adjustments to switch them from running on natural gas to hydrogen and properties would need to have natural gas removed from internal pipes before hydrogen could be introduced.[59]

In order for this process to happen smoothly, surveys and pre-engagement with customers would be needed.[60] This would check whether internal pipework and appliances are hydrogen ready, meaning they just require adjusting, or if they would need replacing. Repeated engagement with customers was a key part of the town gas conversion, which changed the fuel source to properties connected to the gas network in the 1960s and 70s.[61]

The shared conversion process means that engineers would need to be able to access every property in each segment of the network during the 48 hour conversion window. This has long been flagged as a challenge for hydrogen heating.[62] It was also a regular challenge during the town gas conversion. While that transition was broadly seen as successful, access still caused problems and some customers were unhappy with the level of intrusion, which required significant effort to smooth over.[63]

The current context is very different to when the town gas conversion took place. The structure of the industry is not the same, with many more actors involved across the whole value chain, compared to the centralised oversight the Gas Council had at the time. And social and economic changes mean property access could be more difficult. Firstly, there are more buildings today – around 14 million were converted to town gas[64] but in 2021 there were estimated to be over 24 million domestic gas connections across Great Britain.[65] Secondly, greater workforce participation means that less of the population are at home during the day to provide the necessary property access.[66] The rise of remote working may provide some counterbalance against this, but only for a minority of the working population.[67]

Where a property could not be accessed on the day of conversion, one of two mitigations would have to be employed, neither of which is desirable:

- **Disconnect inaccessible properties.** This would allow the conversion of other properties in the area to proceed. However, temporary welfare measures would need to be provided to disconnected customers (e.g. so that they can cook) who are unlikely to be happy to return home and find that they have been disconnected. The property would then need to be converted and connected to hydrogen at a later date, which would add further cost and delay.
- **Enforcing conversion.** Gas network operators could use their powers to access properties for safety reasons to enter and enforce the conversion, subject to receiving a warrant from a magistrates' court.[68] This could potentially allow access during the conversion window but would be extremely controversial.

Enforced conversion is unlikely to be acceptable today. The Energy Bill will provide gas network operators with powers to access homes for the purpose of safety during hydrogen trials, in line with the powers they have today. As this has proved controversial, government has provided assurances that no property will be forcibly converted during a trial.[69] It is reasonable to think that this position would hold for a national rollout too.

In comparison, heat pumps (or other electric heating) can be installed independently of gas disconnection and boiler removal. Property owners could schedule different elements of the transition as and when it is convenient for them. There may be some short term constraints to heat pump deployment if network capacity needs to be increased but, as set out above, these constraints will likely be addressed before hydrogen is an option.

In systems without hydrogen, it would also be critical that the necessary decommissioning of gas networks is programmed in an orderly fashion and the impacts on vulnerable customers would need to be carefully managed. This is recognised in the Commission's recommendation on phasing out the use of natural gas.[70] Ultimately the natural gas supply to buildings will need to end by 2050 in order for the net zero target to be met.

Realistically, there will be some properties that do not plan to undertake the transition in advance of a gas supply no longer being available and there will therefore be a difficult 'tail' of customers that need to be transitioned late in the process. Past analogous transitions, such as the switch to digital television show how switchovers can be managed effectively and that there is scope to manage the size of the potential tail of transitions.[71]

Supply chain capacity and capability

While some hydrogen and hydrogen ready boilers have been produced for the purposes of trials, no UK manufacturer is currently making hydrogen ready boilers at scale. Stakeholder engagement has suggested that this could change relatively quickly if government were to make a positive decision on hydrogen heating. Even with scaled up manufacturing, the supply chain for hydrogen boilers is likely to be relatively thin, as there are very few other countries with an interest in hydrogen heating, whereas the majority of countries are supporting deployment of heat pumps (see box 1). This means hydrogen boilers are likely to be produced by a small number of manufacturers serving a relatively small market. A relatively small and potentially UK focussed supply chain could have advantages, as it may be partially insulated from international disruption, but thin markets also pose supply chain resilience risks.

Heat pump demand and therefore supply chains are likely to be much more global than for hydrogen boilers,[72] though inter-regional trade is currently relatively low.[73] This has positive benefits, for example competition in supply can drive cost reductions. There is some risk of global shortages as has been experienced in other technology sectors, for example, the ongoing challenges around the availability of semiconductors.[74] But experience suggests that a global market is much more likely to be able to match supply to demand.

Box 1: Global interest in hydrogen heating

The main European countries with interest in hydrogen heating are Germany and the Netherlands, although both countries see electrification as the primary means of decarbonising heat and have seen heat pump sales increase.[75]

Outside of Europe, Japan is interested in hydrogen heating (as it too has a high level of gas connections) although this is more focussed on use in fuel cells rather than boilers, which are already being deployed, albeit in relatively low numbers.[76] The Republic of Korea also has some interest in hydrogen fuel cells for heating, which is more nascent than Japan.[77] It is possible that interest in hydrogen heating could emerge in future in other countries with extensive domestic gas networks, but this is not currently the case.

Having the right workforce will also be critical to the heat transition and an increase in heat engineers and installers will be needed under all scenarios. A large increase in heat pump installers will be needed this decade to deliver the government's target of 600,000 heat pump installations per year by 2028.[78] And this workforce will likely need to increase further given the centrality of electrification to meeting the Sixth Carbon Budget. This means that a large heat pump workforce will need to be in place regardless of government's decision on hydrogen heating and significantly before hydrogen could become an option in the 2030s.

However, there are significantly more gas engineers than there are heat pump installers today.[79] There is evidence that the existing gas workforce would prefer to retrain for hydrogen,[80] but the time requirements for retraining gas safe engineers for heat pump installations or hydrogen boiler installations are expected to be similar. As part of the Hy4Heat programme, Energy & Utility Skills estimated that the minimum additional training time for hydrogen would be three to four days.[81] Additional training time for heat pumps could be comparable, as courses are available from around three days – though they can be longer depending on installers' existing skills and experience.[82]

The existing gas workforce is also disproportionately older. In 2019, 82 per cent of gas safe registered engineers were 41 or older, 58 per cent were 51 or over and only six per cent were under 35.[83, 84] Large numbers of new installers will therefore need to join the workforce, especially as there will be continued demand for gas engineers as the system is wound down.

For new installers, training routes ought to be comparable across technologies. It takes between six months, via a training centre, or up to four years, via an apprenticeship, to qualify as a gas safe engineer[85] and heat pump apprenticeships are expected to last for a similar length of time.[86] There may also be lessons that can be learned from the town gas conversion. To enable this transition 13 schools were set up to teach four to six week basic courses and significant resources were put into maintaining a skilled workforce.[87]

Environment – greenhouse gas emissions, nitrogen oxide emissions, water use

Given the overarching objective to reduce greenhouse gas emissions, the pace of heat decarbonisation in reducing greenhouse gas emissions has to be considered. Binding legal targets mean the Commission has assumed that, regardless of technology choices, all systems follow an emissions pathway compliant with carbon budgets and the achievement of net zero by 2050. This criterion therefore covers differences in how greenhouse gas emissions are managed and the risk of fugitive emissions for systems with and without hydrogen. The potential for in-home pollution through nitrogen oxide emissions also needs to be considered, both for the health of households and due to the potential aggregate impacts on local air quality.

Greenhouse gas emissions

Hydrogen produces no carbon dioxide when it is burned, but it is an indirect greenhouse gas, meaning it affects how long greenhouse gases, such as methane, remain in the atmosphere. This means that if it leaks then it has a higher global warming potential than carbon dioxide.[88] As hydrogen will be used in industry and to generate electricity, managing leaks will be important with and without hydrogen heating. If leakage cannot be minimised, there could be challenges for a wide range of hydrogen applications and leaks will need to be managed for safety reasons as well. While this is therefore not a unique risk for hydrogen heating, the higher volumes of hydrogen used and more extensive network required, would increase the risk relative to systems without hydrogen heating.

Estimates of gas network leakage today are limited, although it is generally predicted to be very small as a proportion of gas transported.[89] Past and ongoing investment through the Iron Mains Risk Reduction Programme has reduced leakage from the gas network.[90] Estimates for future hydrogen network leakage are similarly low.[91] However, leakage across the value chain also needs to be considered as leakage in some parts of the value chain, e.g. production, is expected to be higher.[92] This means systems with higher demand for hydrogen would likely result in higher levels of leakage. In-home hydrogen leakage would also be a risk to systems with hydrogen, but not those without. It is predicted to be low,[93] but would also be challenging to monitor.

Production emissions will depend on the type of hydrogen production used. In the long term the Commission expects that hydrogen supply will be predominantly from green hydrogen produced using decarbonised electricity. This is both desirable from an emissions standpoint and a reflection of the cost reductions that are expected to be realised for green hydrogen production.[94] This is reflected in the Commission's analysis, with growing heat demand assumed to be met predominantly from green hydrogen.[95] However, if blue hydrogen production is higher in systems with hydrogen heating then this would entail higher emissions.[96] Some increase is plausible given the challenges around hydrogen supply – see resilience section.

For systems with electrified heating, the electricity supply will be increasingly decarbonised and should ultimately be decarbonised by 2035, in line with the government's target.[97] Losses from electricity supply will therefore have no or very little impact on greenhouse gas emissions. Hydrogen use in other parts of the economy will still be required, including in electricity generation. However, the lower levels of hydrogen demand and smaller network required would mean greenhouse gas emissions from hydrogen would be lower than systems with hydrogen heating.

There is one greenhouse gas emission risk associated with heat pumps directly, as fluorinated gas (F-gas) refrigerants, used in some designs, have a very high global warming potential. This risk is currently small given low deployment but could increase as heat pumps are deployed more widely.[98] However, analysis suggests the greenhouse gas benefits of switching from a gas boiler to a heat pump will "far outweigh" the potential increase in F-gas emissions.[99] There is also optimism that heat pumps that use refrigerants with much lower global warming potential (such as propane) could meet a significant proportion of demand.[100]

Nitrogen oxide emissions

Burning hydrogen creates nitrogen oxide emissions. This issue is recognised by the government and discussed in its boiler standards and efficiency consultation.[101] There is currently uncertainty about exactly what level of nitrogen oxide emissions would be produced from hydrogen boilers, with studies indicating a wide range.[102]

There may be trade-offs between reducing nitrogen oxide emissions and appliance efficiency.[103] However, it is expected that appliance design standards and regulation will be able to ensure nitrogen oxide emissions meet international standards and are equal to, or below, the levels produced by gas appliances today.[104]

Nonetheless, this would still mean that systems with hydrogen heating produce more domestic nitrogen oxide emissions than systems without hydrogen heating. Electric heating and cooking do not produce any nitrogen oxide emissions in the home.

Water use

Hydrogen production uses water. Both blue and green hydrogen require water, but the demands of green hydrogen are more significant, and the Commission expects that this will become the dominant hydrogen production technology. There is a wide range of estimates for the total water demand (including factors like water purification and cooling) from green hydrogen production through electrolysis. Manufacturers suggest between ten and 16 litres of water are required per kilogram of hydrogen produced,[105] however some research suggests it could be significantly higher.[106] Based on a central assumption of 16 litres of water per kilogram of hydrogen, heating a home with hydrogen would require around 5,800 litres of water per year.[107] This represents an additional five per cent on an average household's water demand.[108]

This is not necessarily prohibitive, but it does need to be factored into decisions about green hydrogen production, particularly its location. The design of the electrolysis system and avoiding water stressed regions can minimise the amount of water required and its impact on the local water system.

For electrified heat, the move to increasingly renewable generation will reduce the amount of water required. There will still be water demand from hydropower and future thermal generation (hydrogen or gas with carbon capture and storage), but there will be a gradual decline from today's level of thermal generation.[109] The majority of this water is also returned to the environment.[110] The potential to repurpose current gas generation sites would also further reduce the local impacts, as access to water would already be in place.

Resilience – system design, security of supply and vulnerability to shocks

Resilience is a core characteristic of good infrastructure. In the case of heat, resilience matters as it ensures a supply of reliable heat to people's homes. Resilience standards for both hydrogen and electrified heating can be set and maintained. The other key impact when considering resilience is how a system copes when faced with shocks to either supply or to the cost of that supply. The test is whether hydrogen heating provides opportunities to increase resilience, or makes it more difficult to maintain, than systems without hydrogen heating.

System design

There should be no inherent difference in energy system resilience between systems with hydrogen heating and without. Currently the natural gas network must be operated to meet a one in 20 year peak demand[111] and an appropriate level of resilience will need to be maintained in all circumstances, either as the system is wound down ahead of decommissioning, or prior to conversion to hydrogen.

Like the natural gas network, a hydrogen network would need to be designed to the desired level of resilience (whether that is one in 20 peak demand, or a different standard). As hydrogen will be required for other uses, this will be true regardless of whether it is used for heating. However, additional demand from heating would need to be accounted for in setting resilience standards. Likewise, any additional electricity demand from electrified heating would also need to be factored into resilience standards for the electricity system.

Maintaining the resilience of the electricity system, by ensuring supply and demand are balanced at all times, will be critical to all future systems. Firstly because, a hydrogen boiler will require electricity to operate – just like a heat pump, or a natural gas boiler does today. Although, depending on the circumstances, heat pumps may take longer to deliver the same level of heat after a power cut – especially if the power is cut for a long period of time.[112] Secondly, because significant electricity will be required to produce green hydrogen. It is possible that, to meet demand for green hydrogen, the electricity system could need to expand more quickly in systems with hydrogen heating than in systems where heat is solely electrified.[113] The impacts of this are captured elsewhere in the assessment – see price section.

Great Britain's existing electricity and natural gas networks have a strong overall record of delivering a reliable service to consumers.[114] Average interruptions to electricity supply (measured as minutes lost per customer) have been falling since 1990.[115] Since 2002, when Ofgem introduced incentives for companies to improve reliability, there has been an almost 50 per cent reduction in the frequency of power cuts and an almost 60 per cent reduction in the length of power cuts.[116] The reliability of natural gas is similar, with all gas networks significantly exceeding their targets for minimising unplanned supply interruptions in 2021-22.[117]

Systems with and without hydrogen heating can be built to the same standard of resilience (loss of load) and the properties of hydrogen that make it useful for resilience can be harnessed through the electricity system – hydrogen produced during periods of cheap, abundant renewable supply can be stored, at scale, ready to produce electricity at times of high demand and/or low supply. Converting stored hydrogen to electricity (rather than using directly in boilers) provides greater resilience because electricity is a significantly more efficient form of energy.

Security of supply and vulnerability to shocks

Vulnerability to economic and geopolitical shocks will be lower in all future systems. This will be driven by a move to increased domestic renewable electricity production, reducing reliance on internationally traded fossil fuels which are inherently more price volatile. This reduces the vulnerability of domestically produced green hydrogen to shocks, as well as electricity. However, the risks will differ between heating systems with and without hydrogen due to the greater size of the overall system.

Scaling up domestic green hydrogen production will be challenging. The ambitious build rates required to decarbonise the electricity system by 2035 (in all future systems) mean there is limited potential for dedicated electrolysis in the medium term.[118] And while creating hydrogen using curtailed electricity is likely to be the cheapest way of producing it, there will not be enough of it to produce sufficient volumes of hydrogen to serve all potential heating demand.[119] Any hydrogen supply gap – which the Climate Change Committee has predicted is likely even without heating demand – would need to be filled through imported energy and/or blue hydrogen production.[120]

There are drawbacks to either of these options as they would both increase vulnerability to economic and geopolitical shocks, relative to supply through domestically produced green hydrogen or systems without hydrogen (see Box 2).

Systems without hydrogen heating are therefore less vulnerable to shocks, given both the efficiency of electrification – lowering the amount of energy required – and because electricity generation will be increasingly renewable and therefore domestic (as set out above green hydrogen would also have lower risks for the same reason). Where fossil fuels are required to produce electricity to power a heat pump it is around three times more efficient than using those fossil fuels to produce blue hydrogen and then combusting it in a boiler.[121] This difference in efficiency means a lower volume of imported natural gas would be required to meet the equivalent heating demand.

This is also reinforced by the fact that the electricity system is expected to be bigger in systems with hydrogen heating, because the volume of electricity used to produce hydrogen is greater than the volume of electricity saved in having fewer heating systems powered by electricity.[122]

Box 2: Alternative hydrogen supplies

Blue hydrogen. Even if, counter to expectations, blue hydrogen proves to be cheaper in the long term, there are energy security drawbacks to using it to fill a hydrogen supply gap. A greater reliance on blue hydrogen means a greater dependence on imported natural gas. The UK is a net importer of gas[123] and this is likely to continue even as demand falls.[124] So increasing blue hydrogen production increases exposure to global natural gas prices. The potential impact of this was illustrated in the Office for Budget Responsibility's 2023 Fiscal Risks and Sustainability report. This analysis found that, were reliance on natural gas to continue, future global gas price spikes "could be as expensive fiscally as completing the transition to net zero".[125]

If blue hydrogen were to remain dominant in the long term, it would mean higher emissions, which would need to be mitigated elsewhere in the economy to meet emissions targets. And capturing emissions from blue hydrogen production will be reliant on the development of sufficient carbon capture and storage infrastructure.

Imported hydrogen. Global trade of hydrogen could become significant.[126] But blue hydrogen production requires a source of fossil fuels and so would be subject to many of the same resilience challenges of domestically produced blue hydrogen. However, if trade develops, green hydrogen imports are most likely to come from countries with high levels of renewable potential (and therefore cheap electricity).[127] This offers increased diversity in comparison to relying on natural gas or blue hydrogen but does not mitigate the inherent geopolitical risks of relying on imported energy.

The low maturity of both global low carbon hydrogen production and the means of transporting hydrogen over long distances (where pipelines are not an option) means there is uncertainty about when imports could become competitive with domestic production. The full costs of importing low carbon hydrogen would need to reduce significantly to compete with projected domestic production prices. This is likely to take time, with the Climate Change Committee predicting it could take until the 2040s.[128] Trade is likely to be limited to near neighbours via pipelines unless hydrogen transportation via shipping advances significantly. Global trade of liquified natural gas may provide a useful example of market growth and competitive pricing for shipping over longer distances. While growth in this market has been strong, it took several decades to reach the level of trade today.[129]

Any increased reliance on imported hydrogen could also have additional global emissions risks, given leakage may be higher in the exporting country than domestically – as can be the case with natural gas today.[130]

Economy – jobs intensity, development of the hydrogen sector

Many of the economic impacts of heating technologies are captured under the previous criteria, including system costs. However, the transition to low carbon heat could also support wider economic benefits, including job creation or supporting the development of new sectors. Whether there is a meaningful difference in the potential for wider economic benefits between systems with and without hydrogen heating has implications for whether government should support it.

Jobs intensity

Regardless of the heat decarbonisation pathway, the majority of economic activity is likely to take place within the UK. All systems will require large capital items, such as wind turbines, carbon capture and storage, and hydrogen fuelled electricity generation, along with millions of heat pumps and, potentially, hydrogen boilers. Many of these will be imported, as the UK is not specialised in production of components for these technologies. One exception may be hydrogen boilers, where manufacturing could be largely UK based – as discussed in the delivery section. However, capital is only part of system costs. Government analysis shows construction costs make up about half the cost of offshore wind and a quarter of the cost of gas with carbon capture and storage electricity generation.[131] Pre-construction planning, operation and maintenance are similar in magnitude and will necessarily be mostly UK based.

The specific activities under each scenario with and without hydrogen will differ, but activity will be needed in the following parts of the energy system:

- **Electricity supply:** is the largest overall element of costs in all scenarios
- **Electricity network upgrades:** will be required in all scenarios for non-heat electrification, although more capacity is likely to be needed with electrified heat
- **In-home installations:** are the other main component of costs, which is to be expected given it is an area of significant activity today – around 1.7 million gas boilers are installed every year[132]
- **Gas network:** in all scenarios this will need to be converted to hydrogen, decommissioned, or a mix of both
- **Hydrogen production and network:** electrolysers and blue hydrogen production, transmission and cluster pipeline networks and large scale storage will be required in all scenarios to serve electricity generation and industry although more will be needed if hydrogen is used for heat.

Even if hydrogen boilers are manufactured in the UK and heat pumps are imported, the overall impact on the economy would be small, as appliance costs account for only 15 to 20 per cent of the total energy system costs.[133] For heat pump installations, analysis suggests that the heat pump itself may only be 30 to 40 per cent of the installation cost, with other items like radiators and the labour costs of installation making up the rest.[134]

Employment effects are also likely to be similar in systems with and without hydrogen. All future systems will require large numbers of installers and associated trades to upgrade home heating systems and insulation, providing skilled and semi-skilled jobs throughout the country. Published job figures tend to be gross, rather than net, so it is difficult to identify what jobs are likely to represent additional activity, rather than displacement of activity in another part of the economy.[135] It is worth noting that both UK and international estimates suggest that heat is relatively less job intensive than other uses of hydrogen.[136]

The electricity and gas sectors today are both capital intensive, but the electricity system is more so, meaning it generates fewer jobs than gas, but those jobs may be higher paid.[137] How the nascent hydrogen sector as a whole develops will affect the economic impacts of hydrogen heating. While it may seem straightforward to expect that the hydrogen sector will look like the natural gas sector does today, there are some characteristics that mean it could be closer to electricity in capital intensity. For example, hydrogen needs to be produced and, like the electricity system, production and associated assets may be more geographically dispersed than natural gas today.[138]

Even if the hydrogen sector is more capital intensive than natural gas today, it is likely to be less capital and more labour intensive than the electricity system.

Development of the hydrogen sector

A hydrogen sector is going to be required to meet net zero. Hydrogen pipeline networks and storage will be critical to decarbonising the electricity system and industry, and hydrogen will also play a role in the decarbonisation of transport. The Commission has recommended that government supports the development of a core hydrogen pipeline network and a minimum of eight TWh of large scale storage by 2035.[139]

Along with successfully scaling up production, it is the development of the core network and storage that will determine the hydrogen sector's success, not whether it has a role in heating. These are the areas where activity can happen more quickly and there is potential for early mover advantages to be gained, whereas hydrogen heating cannot be deployed until the 2030s. The limited global interest in hydrogen heating (see delivery section) also means heating is unlikely to be an area where UK knowledge can be exported.

Electrification of heat would still see an important role for the hydrogen sector as it is needed to support the electricity system, helping to provide the persistent supply required to meet longer shortfalls in renewable supply.

The scale of pipeline, storage and production infrastructure required for these core activities is significant. Given the long lead times for planning and construction and the challenge of deploying any new technology, getting this investment in place to support meeting the Sixth Carbon Budget must be the priority for hydrogen. Were a focus on hydrogen heating to detract from these priorities, it could undermine the development of the broader hydrogen sector.

Managing uncertainty

There is uncertainty inherent in looking at any major socio-economic transition and the transition to low carbon heat is no exception. However, this is not an excuse for inaction and delayed decision making. Maintaining optionality can be beneficial, but it can also lead to higher costs. It is critical that a case for action is made in spite of uncertainty,[140] especially as acting late is also likely to increase the cost of the transition to net zero.[141] It is in this context that the Commission recommends that government does not support the rollout of hydrogen heating.

There is not full certainty that a future without hydrogen heating will be more beneficial than one with it. Assumptions must be made to assess the public policy case for hydrogen heating. For example, forecasting the cost of the energy system over the long term is inherently uncertain. Work is also ongoing to develop the evidence base of using both hydrogen boilers and heat pumps.

However, the Commission considers that the direction that the evidence takes is unlikely to change in a way that changes the assessment of the public policy case. The basic parameters of the heat transition are increasingly clear and the Commission's position that hydrogen heating should not be supported is robust across a range of scenarios, as summarised above in the assessment.

The laws of thermodynamics and the relative efficiencies of boilers and heat pumps are not going to change and, from a technical standpoint, there are no properties for which hydrogen represents the only means of decarbonisation. It looks challenging to produce sufficient low carbon hydrogen to supply heat demand (as well as other sources of hydrogen demand) at a price that could make systems with hydrogen cheaper. And it appears even more challenging to do this without trading it off for unpalatable resilience and environmental risks.

The evidence leads to the same conclusions when considering potential benefits as well as risks. For example, higher than projected reductions in the cost of hydrogen produced via electrolysers could be realised, but not in the near term. By the time it is known whether projections were cautious the electrification of heat will be well advanced. But electrifying heat does not mean these benefits cannot be accessed, as cheaper hydrogen would also mean cheaper electricity generation, as the majority of the cost of using hydrogen to generate electricity comes from the fuel.[142]

The main argument made by hydrogen's proponents is that there is value in maintaining optionality and that ruling it out could miss opportunities to make the heat transition cheaper or easier. Conversely, other stakeholders have argued that keeping the option open for hydrogen heating is slowing progress on switching to heat pumps and creating confusion amongst consumers on the choice they should make.[143] Government reports have strongly implied that electrification will be the dominant technology for decarbonising heat, but this is not explicit policy and so sufficient measures are not in place to deliver the required volume of switches to electrified heat, even for systems with some hydrogen.

Private companies may believe they can make a case for investing in hydrogen heating and that a sufficient number of consumers are willing to pay for the choice of hydrogen. If government were to set up the necessary regulatory regime private companies could be allowed to offer hydrogen heating, but the Commission considers that there is not a case for them receiving billpayer or taxpayer support for this investment. The Commission's full recommendation on hydrogen heating specifies that infrastructure solely for hydrogen heating should not be eligible for support under the hydrogen transport business model and gas consumers should not be expected to pay for the conversion of natural gas infrastructure to transport hydrogen through existing price controls.

There are currently barriers to electrifying heating but these can be addressed, as the Commission has recommended.[144] Along with confusion over options, a lack of clear information, higher upfront costs, and fear of higher running costs all disincentivise switching away from fossil fuels.[145] Government actions should address this and be in line with the scale of the challenge and the pace of change required.

Appendix A: Total energy system costs, 2025-50

£ billion, 2022 prices	Scenario 1	Scenario 2	Scenario 3
Electricity system	£1,390	£1,650	£1,760
Heat appliances	£420	£435	£360
Gas for heating	£155	£120	£125
Hydrogen electrolysers	£20	£30	£45
Other hydrogen production	£75	£110	£165
Hydrogen infrastructure	£80	£70	£85
Decommissioning	£15	£10	-
Total	**£2,155**	**£2,425**	**£2,540**

References

1 HM Government (2021), **UK enshrines new target in law to slash emissions by 78% by 2035**
2 Department for Energy Security and Net Zero (2023), **Carbon Budget Delivery Plan**
3 Department for Business, Energy & Industrial Strategy (2021), **Cost-Optimal Domestic Electrification (CODE): Final Report**
4 Heat networks could be powered by a variety of sources, including heat pumps or boilers: Department for Business, Energy & Industrial Strategy (2023), **What is a heat network?**
5 Hybrid heat pumps have not been considered in this assessment. Hybrid heat pumps could combine the benefits of both heat pumps and hydrogen. See for example: Climate Change Committee (2018), **Hydrogen in a low-carbon economy**. But the costs of a system with hybrid heat pumps would need to capture the cost of operating a predominantly electrified heating system and the cost of developing and operating a hydrogen network.
6 All three scenarios are derived from Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)**
7 Arup (2023), **Future of GB Gas Networks Assessment**
8 Costs are calculated up to 2050 as this is the year the government has committed the UK to achieving net zero by. They cover the full cost of systems and so are not just the 'additional' costs of decarbonising heat (e.g. they include 'business as usual' investment like the replacement of gas boilers before they are phased out).
9 Blue and green hydrogen are defined later in the report. Grey hydrogen is also created from natural gas but is not low carbon as the carbon emitted during the process is not captured and stored.
10 Arup (2023), **Future of GB Gas Networks Assessment**. For scenario 1, Arup's 'low' scenario is used. For scenario 2, Arup's 'balanced' scenario is used. For scenario 3, Arup's 'high' scenario is used.
11 Arup (2023), **Future of GB Gas Networks Assessment**
12 Leti (2021), **Is Hydrogen a decarbonisation route for heat in buildings?**; Hydrogen Science Coalition (2022), **Hydrogen for Heating? A comparison the heat pumps (Part 1)**
13 Commission analysis of Department for Energy Security and Net Zero (2021), **Hydrogen Production Costs 2021**
14 Arup (2023), **Future of GB Gas Networks Assessment**
15 Arup (2023), **Future of GB Gas Networks Assessment**
16 See section 7.3 in Arup (2023), **Future of GB Gas Networks Assessment**
17 Aurora Energy Research (2023), **Decarbonising heating systems: evidence and options (B)**
18 Average annual heat demand of 10.14MWh assumed for an efficient, not space constrained house: see Aurora Energy Research (2023), **Decarbonising heating systems: evidence and options (B)**
19 Average annual heat demand of 4.24MWh for an efficient flat and 5.81MWh for an inefficient flat: see Aurora Energy Research (2023), **Decarbonising heating systems: evidence and options (B)**
20 Average annual heat demand of 13.89MWh for an inefficient, not space constrained house: see Aurora Energy Research (2023), **Decarbonising heating systems: evidence and options (B)**
21 Commission analysis of Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)** and Department for Energy Security and Net Zero (2021), **Hydrogen Production Costs 2021**
22 Commission analysis of data in Ofgem (2023), **Energy price cap (default tariff): 1 October to 31 December 2023**
23 Commission analysis of data in Ofgem (2023), **Energy price cap (default tariff): 1 October to 31 December 2023**
24 Commission analysis based on Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)**
25 Air source heat pumps may not be able to be fitted in all space constrained flats. It is included here as a comparator and to show its relative attractiveness for any properties where there is sufficient space.
26 Commission analysis of Department for Energy and Climate Change (2013), **Special feature – NEED analysis December 2013: Areas and types of properties off the gas grid** and Department for Energy and Climate Change (2013), **Off gas NEED table creator December 2013**

27 The Hy4Heat programme recommended two excess flow valves are installed at every meter point, one upstream and one within the smart meter installation: Hy4Heat and Department for Business, Energy & Industrial Strategy (2021), **Safety Assessment: Conclusions Report**
28 Additional ventilation is only expected to be required in a small subset of properties which do not have sufficient ventilation – likely around 4 per cent of total properties: Hy4Heat and Department for Business, Energy & Industrial Strategy (2021), **Safety Assessment: Conclusions Report**
29 Pipework would also need to be tested for tightness to ensure it met the standards for natural gas, which has been found to be sufficient to also manage hydrogen. Where this was not the case, remedial work would be required: Hy4Heat and Department for Business, Energy & Industrial Strategy (2020), **Safety Assessment: Experimental Testing - Domestic Pipework Leakage**
30 LCP Delta for Energy Systems Catapult (2022), **BEIS Electrification of Heat Demonstration Project: Home Surveys and Install Report**
31 The heating coil in many existing systems is too small to heat the water sufficiently quickly when heat is provided by a heat pump: LCP Delta for Energy Systems Catapult (2022), **BEIS Electrification of Heat Demonstration Project: Home Surveys and Install Report**
32 Boiler Guide (2023), **How Long Does It Take to Fit a Boiler? - Installation Timescales**
33 Worcester Bosch (2023), **Hydrogen-Fired Boiler**
34 These pipework changes would also be required for fitting a replacement natural gas boiler
35 Boiler Guide (2023), **Cost to Install Central Heating in the UK: Full Breakdown**
36 LCP Delta for Energy Systems Catapult (2022), **BEIS Electrification of Heat Demonstration Project: Home Surveys and Install Report**
37 LCP Delta for Energy Systems Catapult (2022), **BEIS Electrification of Heat Demonstration Project: Home Surveys and Install Report**
38 House of Lords Environment and Climate Change Committee (2023), Boiler upgrade scheme inquiry: **Written evidence from the Department for Business, Energy & Industrial Strategy (BEIS)**
39 LCP Delta for Energy Systems Catapult (2022), **BEIS Electrification of Heat Demonstration Project: Home Surveys and Install Report**. 85 per cent of homes in this study required no further energy efficiency measures.
40 Energy Systems Catapult (2023), **Electrification of Heat Demonstration Project: Interim Heat Pump Performance Data Analysis Report**
41 Nesta (2022), **How to reduce the cost of heat pumps**
42 Thomas, Pidgeon and Henwood (2023), **Hydrogen, a less disruptive pathway for domestic heat? Exploratory findings from public perceptions research**, Cleaner Production Letters
43 Nesta (2023), **Heat pumps: a user survey**
44 Hydrogen distribution networks would supply hydrogen at low pressure. This is distinct from a hydrogen transmission network, which would move hydrogen at high pressure between different parts of the country, but with very few users directly connected. In the Assessment the Commission is recommending that a core hydrogen transmission network is developed to support the decarbonisation of power and industry.
45 Federal Ministry for Economic Affairs and Climate Action (2023), **Draft of a law amending the Building Energy Act, amending the Heating Costs Ordinance and amending the Sweeping and Inspection Regulations**
46 Commission analysis using assumptions in Aurora Energy Research (2023), **Decarbonising heating systems: evidence and options (B)**
47 Ofgem (2021), **How you're protected when energy firms collapse**
48 26.4 million dwellings in England and Wales and 2.7 million in Scotland. Office for National Statistics (2023), **Housing in England and Wales: 2021 compared with 2011** and National Records of Scotland (2023), **Households and Dwellings in Scotland, 2022**
49 Regen (2023), **Preparing Britain's electricity network for net zero**
50 Ofgem (2022), **RIIO-ED2 Final Determinations**
51 UK Power Networks (2014), **Impact of Electric Vehicle and Heat Pump loads on network demand profiles**
52 National Infrastructure Commission (2023), **Second National Infrastructure Assessment**
53 Arup (2023), **Future of GB Gas Networks Assessment**
54 Arup (2023), **Future of GB Gas Networks Assessment**

55 Arup (2023), **Future of GB Gas Networks Assessment**. This is based on the assumption that the existing natural gas network is converted to supply hydrogen. If a parallel network to supply hydrogen was built there would not be a need to convert multiple properties at the same time. Though this would come with a significant cost and could cause additional disruption as homes would need to be connected to the new network.
56 Arup (2023), **Future of GB Gas Networks Assessment**
57 Arup (2023), **Future of GB Gas Networks Assessment**
58 Start date based on Arup (2023), **Future of GB Gas Networks Assessment**
59 Arup (2023), **Future of GB Gas Networks Assessment**
60 Energy Systems Catapult (2022), **Inclusive Innovation: Safeguarding the Switch to Domestic Hydrogen**
61 Williams (1981), A History of the British Gas Industry
62 Frazer-Nash Consultancy (2018), **Logistics of Domestic Hydrogen Conversion**
63 Arapostathis, Laczy and Pearson (2019), **Steering the 'C-Day'_ Insights from the rapid, planned transition of the UK's natural gas conversion programme**, Environmental Innovation and Societal Transitions
64 Williams (1981), A History of the British Gas Industry
65 Department for Business, Energy and Industrial Strategy (2022), **LSOA estimates of properties not connected to the gas network**
66 The economic inactivity rate for working age adults has steadily fallen since the 1970s. See, Office for National Statistics (2023), **LFS: Economic inactivity rate**
67 Office for National Statistics (2022), **Homeworking in the UK – regional patterns: 2019 to 2022**
68 Houses of Parliament (2023), **Public Bill Committee, Energy Bill**
69 Hansard (2023), **Energy Bill: Second Reading**
70 National Infrastructure Commission (2023), **Second National Infrastructure Assessment**
71 House of Lords Communications Committee (2010), **Digital switchover of television and radio in the United Kingdom**
72 Department for Business, Energy & Industrial Strategy (2020), **Heat Pump Manufacturing Supply Chain Research Project: Final Report**
73 International Energy Agency (2023), **Energy Technology Perspectives 2023**
74 World Economic Forum (2022), **When the chips are down: How the semiconductor industry is dealing with a worldwide shortage**
75 Commission analysis of European Heat Pump Association (2022), **European Heat Pump Market and Statistics Report 2022**
76 CMS (2023), **Hydrogen Law, Regulations & Strategy in Japan**
77 CMS (2023), **Hydrogen Law, Regulations & Strategy in South Korea**
78 HM Government (2021), Heat and Buildings Strategy
79 CITB (2021), **Building Skills for Net Zero**
80 Social Market Foundation (2022), **Installing for time**; Heating & Hotwater Industry Council (2023), **Skills, Training and the Future of Heat**
81 Energy & Utility Skills (2021), **Hy4Heat Competence Framework: Hydrogen Transition Training Specification**
82 Department for Energy Security and Net Zero (2023), **Notice: Apply for the Heat Training Grant: discounted heat pump training**
83 Sustainable Energy Association (2019), **Heating Installers Have Their Say**
84 Macdonald (2019), **The heating workforce is shrinking and that's a problem**, Heating Venting and Pluming
85 Teach a Trade (2023), **How long does it take to become a gas engineer?**
86 UK Government (2023), **Apprenticeship training course: Refrigeration air conditioning and heat pump engineering technician (level 3)**
87 Williams (1981), A History of the British Gas Industry
88 Warwick, Nicola et al (2022), **Atmospheric implications of increased hydrogen use**; Sand, Maria et al (2023), **A multi-model assessment of the Global Warming Potential of hydrogen**, Communications Earth & Environment
89 Ofgem (2022), RIIO-GD1 Supplementary Data File 2020-21; Cadent (2023), **Converting wind into hydrogen for heating homes**

90 Energy Networks Association (2020), **Replacing Britain's old gas pipes and laying the foundations of a zero-carbon gas grid**
91 Estimated at 0.5 per cent in Cadent (2023), **Converting wind into hydrogen for heating homes** and 0.4 per cent in Fan, Zhiyuan (2022), **Hydrogen Leakage: A Potential Risk for the Hydrogen Economy**
92 Fan, Zhiyuan (2022), **Hydrogen Leakage: A Potential Risk for the Hydrogen Economy**; McFarlane, Sarah and Bousso, Ron (2022), **Has green hydrogen sprung a leak?**
93 Estimated at 0.8 per cent in Fan, Zhiyuan (2022), **Hydrogen Leakage: A Potential Risk for the Hydrogen Economy**
94 Bloomberg (2021), **'Green' Hydrogen to Outcompete 'Blue' Everywhere by 2030**
95 Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)**
96 Whereas green hydrogen could use electricity from a decarbonised power sector (in line with government's 2035 target), once fugitive emissions are accounted for, as well as capture rates, blue hydrogen could only result in lifecycle emissions savings of 60 to 85 per cent compared to unabated gas. Climate Change Committee (2023), **Delivering a reliable decarbonised power system**
97 Department for Business, Energy & Industrial Strategy (2021), **Plans unveiled to decarbonise UK power system by 2035**
98 Department for Environment, Food and Rural Affairs et al (2022), **F gas regulation in Great Britain: Assessment report**
99 Climate Change Committee (2020), **The Sixth Carbon Budget: F-gases**
100 Dern (2023), Will the government risk the rollout to make heat pumps greener? Utility Week
101 Department for Business, Energy & Industrial Strategy (2023), **Improving boiler standards and efficiency: consultation**
102 Wright and Lewis (2022), **Emissions of NOx from blending of hydrogen and natural gas in space heating boilers**, Elementa: Science of the Anthropocene
103 Lewis (2021), **Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NOx emissions**, Environmental Science: Atmospheres
104 Hy4Heat and Department for Business, Energy & Industrial Strategy (2022), **Hy4heat Report: Final Progress Report**; Lewis (2021), **Optimising air quality co-benefits in a hydrogen economy: a case for hydrogen-specific standards for NOx emissions**; Environmental Science: Atmospheres
105 Watersmart! (2020), **Water for the Hydrogen Economy**. Some of the water used in production of hydrogen is taken from the environment whereas some will be taken temporarily and returned, e.g. that used for water purification and cooling.
106 See Irena (2020), **Green Hydrogen Cost Reduction Scaling Up Electrolysers To Meet The 1.5°C Climate Goal**; Ramirez et al (2023), **Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption**. Full estimates include factors such as de-ionisation and water used for cooling.
107 Commission analysis based on meeting a heat demand of 12,000 kWh per year
108 Commission analysis based on average household consuming around 127,000 litres of water a year, as per Energy Saving Trust (2013), **At home with water**
109 Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)**
110 Environment Agency (2013), **Water use and electricity generation**
111 National Grid (2014), **Gas Transportation Transmission Planning Code**
112 Baxi (2023), **How to restart your air source heat pump again after a power cut**
113 Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)**
114 An overview of electricity resilience was set out in National Infrastructure Commission (2021), **Second National Infrastructure Assessment: Baseline Report, Annex B: Energy**
115 Analysis of Ofgem Data Request in National Infrastructure Commission (2021), **Second National Infrastructure Assessment: Baseline Report, Annex B: Energy**
116 Ofgem (2017), **What do energy networks do for you?**
117 Ofgem (2022), **RIIO-GD1 Supplementary Data File 2020-21**
118 Climate Change Committee (2023), **Delivering a reliable decarbonised power system**
119 Commission analysis of Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)**
120 Climate Change Committee (2023), **Delivering a reliable decarbonised power system**

121 Leti (2021), **Hydrogen: a decarbonisation route for heat in buildings?**
122 Aurora Energy Research (2023), **The impact of decarbonising heating on the power sector (C)**
123 North Sea Transition Authority (2023), **NSTA Overview 2023**
124 Climate Change Committee (2023), **Delivering a reliable decarbonised power system**
125 Office for Budget Responsibility (2023), **Fiscal risks and sustainability**
126 Irena (2022), **Global hydrogen trade to meet the 1.5°C climate goal: Trade outlook for 2050 and way forward**
127 Irena (2022), **Global hydrogen trade to meet the 1.5°C climate goal: Trade outlook for 2050 and way forward**; Irena (2022), **Geopolitics of the Energy Transformation: The Hydrogen Factor**
128 Climate Change Committee (2023), **Delivering a reliable decarbonised power system**
129 Pirrong (2014), **Fifty Years of Global LNG: Racing to an Inflection Point**
130 Abnett and Nasralla (2021), **Gas infrastructure across Europe leaking planet-warming methane**
131 Department for Business, Energy & Industrial Strategy (2020), **Electricity Generation Costs 2020**
132 Heating & Hotwater Industry Council data shared with National Infrastructure Commission
133 Commission analysis of system costs – see price section
134 Nesta (2022), **How to reduce the cost of heat pumps**
135 Hydrogen Taskforce (2020), **Hydrogen Economic Impact Assessment**
136 Hydrogen Taskforce (2020), **Hydrogen Economic Impact Assessment**; CE Delft (2021), **Work through investments in green hydrogen**
137 Turner, Katris, and Corbett (2023), **What will investing in hydrogen transmission infrastructure mean for the UK economy?**
138 Turner, Katris, and Corbett (2023), **What will investing in hydrogen transmission infrastructure mean for the UK economy?**
139 National Infrastructure Commission (2023), **National Infrastructure Assessment**
140 National Infrastructure Commission (2022), **Managing uncertainty in the second National Infrastructure Assessment**
141 Office for Budget Responsibility (2021), **Fiscal risks report**
142 Department for Energy Security and Net Zero (2023), **Electricity Generation Costs 2023**
143 House of Lords Environment and Climate Change Committee (2023), **Letter to Lord Callanan: The Boiler Upgrade Scheme and the wider transition to low-carbon heat**
144 National Infrastructure Commission (2023), **National Infrastructure Assessment**
145 Thinks Insight & Strategy (2023), **Social research for the National Infrastructure Commission to inform the second National Infrastructure Assessment**; UK Collaborative Centre for Housing Evidence (2023), **Motivations and Barriers Associated with Adopting Domestic Heat Pumps in the UK**

NATIONAL
INFRASTRUCTURE
COMMISSION
Better infrastructure for all

Windsor House
Victoria Street
London SW1H 0TL

nic.org.uk / @NatInfraCom

October 2023