# Managing Heat System Decarbonisation

# Comparing the impacts and costs of transitions in heat infrastructure

Final Report

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All errors and omissions are the authors' alone.

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# Contents

# Executive summary

Decarbonising heat at scale will need to be well underway by the 2030s and continue beyond 2050 to meet the legally binding carbon reduction targets set in the Climate Change Act, as well as to deliver on commitments made in the Paris Agreement to keep global temperature increases well below two degrees Celsius.

Although this may seem a long way off, planning and preparation for decarbonising the heat sector needs to be started now in order to pave the way towards reducing carbon emissions in this important sector cost-effectively, and with acceptable levels of disruption. This is particularly important in the case of space heating and hot water in domestic and commercial premises, which are responsible for between a fifth and a quarter of total carbon emissions,

Due to the scale of the heat sector and the number of properties involved, the task can seem daunting, but **with sufficient and timely preparation for the roll-out of an appropriate combination of approaches, and by spreading the delivery over suitable long term infrastructure programmes, heat decarbonisation can be made much more manageable.**

Due to the variation in geography, housing types and occupancy patterns as well as the characteristics of different means of heat provision, **no single solution suffices, so a variety of options will be needed to deal with this diverse range of application environments.** Early planning and action can create, or maintain flexibility and sensible levels of optionality around this.

Also reflecting this diversity, **it is recommended that service requirements and delivery methods should be established and decided locally, rather than seeking a single national level approach**. This has been difficult in the past, since little information was available about the specific costs and impacts of the different heat decarbonisation pathways. This paper fills some of these knowledge gaps to support those decision makers, designers and planners who may be charged with the development of credible pathways and action plans.

**The paper's main focus is on the enabling networks which provide the link between energy producers and end users. This element has not been extensively documented before, particularly with regard to the transitional impacts that will arise if new network infrastructures are installed.** The paper considers electric heat pumps and resistive heating, district heating schemes, decarbonising the gas grid and combinations thereof.

**To put each solution into its wider context, the paper also provides an overview of the costs and impacts for energy supply and domestic householder premises.**

Insulation and energy efficiency are also essential ("Efficiency First") and may be a prerequisite for success with novel heat supply solutions, but are already extensively discussed in the literature and are not the principal focus of this paper.

The main conclusions from the analysis are summarised below:

## Governance

Although this is not the main focus of the paper, it is clear that any specific recommendations about who should do what are difficult without having a proper governance system for the heat sector in place. Most of what currently exists relates to the centralised supply of fuel and energy – gas and electricity – and these **current governance arrangements are not fit for purpose in relation to the new and different challenges of heat decarbonisation**, where arrangements may, more often than not, be determined by regional and local requirements, and could reach into every home and business.

Future arrangements, which should also include national and local system design capability, will be needed to ensure that key decisions are made, delivery frameworks are put in place, and that the interests of residents, businesses and consumers are properly considered. Developing appropriate legislation and regulation to cover heat services, especially from district heating schemes, will be important to promote customer protection and supply competition, as well as to facilitate scheme development and operation at optimal financing costs.

**One of the first priorities should therefore be to agree the institutional and governance arrangements for heat.** This does not necessarily mean new organisations, but may involve a reallocation of responsibility and resources within existing ones. For instance, the National Infrastructure Commission would seem a natural home for establishing the appropriate national overview and frameworks – possibly including the proposed 'system architect' for design issues; Ofgem for regulating investment delivery and ongoing operations; and local authorities, have proven to be a key factor in the success of schemes in other countries, for the planning and roll-out of individual building and heating solutions.

**Many of the key delivery activities relate to networks and will need to be carried out by regulated monopolies** where there is no 'market' to make the decisions. Decisions should instead be made by the appropriate governance institutions, in order to allow private sector network operators to deliver timely investment in the measures needed to support heat users and producers. The gas Iron Mains Replacement Programme (IMRP) is a good example of an infrastructure programme of large scale and long duration, which could be followed.

## Heat energy demand and efficiency

Since over 90% of today's homes will still be in use in 2050, alongside the application of sensible measures and standards for new buildings, **a major retrofit programme will be required to improve energy efficiency levels and/or to decarbonise heat supply for about 25 million existing homes**.

**Energy efficiency investment in buildings can reduce the scale of the space heating challenge for all options and should be implemented on its own merits.** Indeed, most decarbonisation scenarios have at their basis a reduction of at least 20% in the energy required for space heating by 2030, without which the overall decarbonisation task will be much more challenging. However, with some notable exceptions, this would not fundamentally change the impact assessment ratings or choice of the decarbonisation options analysed in this paper.

Space heating and hot water demand are much greater than those of the electricity system – overall demand is about 150% of total electricity and **peak requirements in winter can be 5 or 6 times those for electricity**. **A particular challenge is the large seasonal variation in space heating demand**, currently managed with the help of flexible gas supply arrangements backed up by networks linked to daily and seasonal storage. Replacement solutions must be designed and costed to cope with these factors.

## Cost and impact assessments

The research and analysis results have been summarised in impact tables and, alongside quantification where possible, have been categorised as red, amber and green to symbolise the relative attractiveness of the approach as well as the level of cost or impact (red is highest cost/impact and green lowest). As the high level summary example below shows, there is at least one 'red' area for each of the three approaches analysed.

| Urban and suburban properties | Repurposed gas grids (hydrogen) | Electrification (heat pump) | District heating |
|---|---|---|---|
| Cost/impact of decarbonised heat supply | | | |
| Cost/impact of network activities | | | |
| Cost/impact of activities in customer premises | | | |
| Need for new regulation | | | |

This underlines that, **although there is no 'silver bullet', with further preparatory work and pilot schemes to address the highlighted issues, each solution can find application in suitable property types.**

Most supporting infrastructure, like networks, are hidden from view and limited in impact on daily life once installed. However, **the ubiquity of existing water, sewage, power, gas and telecoms networks make it challenging to modify or install any network, since this can have a significant impact on large numbers of people and businesses during the process. If a transition is not well managed, it could become a major social and political issue**, even where the technical and economic justification is favourable and the end outcome itself uncontroversial.

Full impact tables are included in the main report and show a more detailed breakdown for each solution across a range of property types. These highlight that **the choice of options and/or the rate of deployment may well be determined by the non-cost impacts and customer acceptance issues, rather than being made on the basis of least cost, market allocation principles.**

## Options for heat decarbonisation

The three main solutions analysed were:

- ### Repurposing the gas grids with hydrogen

As a consequence of the investment in the gas Iron Mains Replacement Programme (IMRP), **the repurposing of the gas grids for use with hydrogen has become feasible**, and could be an attractive option to avoid disruption from street works or in customer premises, especially for properties in urban and suburban environments, which comprise 80% of households.

The cost and disruption of conversion can be optimised by regulating for the installation of hydrogen ready appliances as early as possible.

Hydrogen has the advantage that it can be stored in similar facilities to those used for natural gas – salt caverns, disused gas fields and aquifers, albeit needing about three times the volume (or three times the pressure) due to its lower energy volume density.

However, **the most important precondition for using hydrogen would be the development of large scale, low cost production facilities.** This could be by electrolysis of water, although this is currently very expensive and not yet suited to large scale production, or through conversion of natural gas by steam methane reformation (SMR).

This second route is currently less expensive than electrolysis, but still more costly than natural gas. **SMR produces carbon dioxide as a by-product and its use would therefore be very dependent on the availability of CCS**, which is currently not commercially or technically proven in the UK.

To keep this option open, **pilot studies should be carried out to determine the feasibility of each of the hydrogen production processes** and, for steam methane reformation, the viability of CCS and availability of suitable storage facilities for carbon dioxide.

- ## Electrification

Decarbonising the electricity sector is well under way and **a low carbon electricity system could provide considerable future optionality for decarbonising the heat and transport sectors once sufficient extra low carbon generating capacity is in place.**

**Electrification, using highly efficient heat pumps, can be suitable for less densely populated environments, and where access and traffic disruption from electricity system upgrades can be minimised.** Disruption and cost to the householder could be a significant barrier to their adoption, but can be reduced by focussing on applications where no major energy efficiency improvements or radiator replacements are required.

The electrical effects of heat pumps will be particularly significant in the local, low voltage networks and their 11kV feeder circuits, since the ability to smooth out their impacts are much more limited than in the higher voltage distribution and transmission systems. **For reasons of network capacity and, more often, to avoid short term fluctuations in service quality, local networks could need upgrading to accommodate even modest penetrations of heat pumps**.

**Direct electric heating is suited to well-insulated properties, particularly flats and maisonettes in high rise buildings, where gas-fired boilers are not used and the space heating requirements are low.**

Since there is a high probability that electrification of heat and transport is likely to be a significant route for decarbonisation, a low voltage mains upgrade programme along the lines of the gas IMRP could be considered in those areas suitable for electrification. The justification for this could be stronger in areas that also have a high potential for solar PV roll-out where network upgrades may also be required.

Electricity is more difficult and expensive to store than gas, so consideration must be given at the design stage to storage, demand side management and back-up solutions that will provide a low cost, low carbon capacity, capable of dealing with the seasonal space heating requirements.

- ## District heating

**District heating can supply heat very efficiently and at low cost,** although **there are currently only limited sources of low carbon heat production,** even at limited scale – sustainable biomass, geothermal, waste heat and heat pumps (particularly ground and water source) - for this paper, the latter was used.

**It is well suited to areas of mixed use with strong anchor clients, such as municipal buildings, offices and leisure centres. Although most readily installed as part of new developments, district heating can also be suitable in less populated areas as part of community energy scheme as well as for flats and maisonettes in multi-storey buildings.**

**District heating would benefit from the introduction of regulation** to give consumers protection for service provision and to encourage supply competition where appropriate; to provide operators and developers with the statutory powers to aid access, land purchase and wayleaving; as well as to treat appropriate networks as regulated assets to lower the cost of capital, which currently makes many commercially funded schemes too expensive.

The seasonal fluctuations in space heating requirements can be reduced for mixed use district heating schemes and heat storage can be less expensive than electricity storage. Nevertheless, as in the electricity system, consideration should be given at the design stage to storage, demand side management and back-up solutions.

- ### Other solutions

Biomass and biogas have so far been the mainstays of renewable heat in the UK and wider EU and will continue to play an important role in future. However, due to concerns described in sections 1.3.6 and 1.3.7, about the sustainability and/or the future large scale availability of these fuel sources, they have not been considered in detail in this paper.

Solar thermal may have an important role in provision of hot water in some applications. However, it has limited applicability to space heating solutions and is also not considered in detail in this paper.

## Recommendations

The recommendations summarised below do not intend to favour any option. The aim is to indicate that ***if*** a particular option is chosen or decision made, ***then*** the recommended course of action should follow:

- ### Decision making and governance
  - National Government should at the earliest opportunity coordinate a process with the relevant interested parties to review and establish a system of governance for heat
  - in parallel to this it should initiate:
    - a national infrastructure programme for energy efficiency investment in buildings
    - a process to zone areas suitable for each heat decarbonisation option in each Local Authority area, building on heat mapping exercises already underway
    - pilot schemes to examine the detailed, technical and economic feasibility of each option.

- ### Repurposing gas grids with hydrogen
  - Set appropriate product standards to ensure that all new gas appliances are dual-fuel and hydrogen ready
  - develop safety standards for the use of hydrogen as a domestic fuel
  - develop a communication plan, along the lines of the 'digital switch over', to prepare consumers for any conversion
  - develop pilot schemes for a twin-track approach towards hydrogen production with both SMR + CCS and electrolysis, and encourage R&D to reduce the costs and increase the scalability of production facilities. For SMR, this must include a credible approach to CCS.

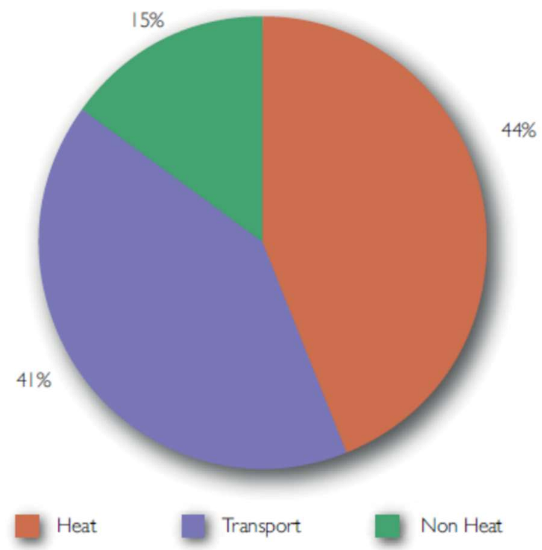
- ### Electrification
  - Consider a pre-emptive mains reinforcement programme, similar to the gas Iron Mains Replacement Programme (IMRP), to prepare for future electrification (also taking into account potential transport needs), especially for areas off the gas grid, or as identified for electrification by any zoning process
  - develop system design for varying levels of heat electrification to cover low carbon generation and flexibility/resilience/storage needs
  - consider regulating against the installation of new or replacement gas boilers in any areas zoned for electrification.

- ### District heating
  - Extend existing legislation and regulation for customer protection, clarifying the approach towards compulsory connection versus freedom to switch for district heating
  - introduce statutory development powers and a system to regulate assets for district heating
  - consider regulating against the installation of new or replacement gas boilers in areas zoned for district heating, but taking into account the need to provide an interim solution for consumers to bridge any delay before district heating becomes available.

# 1. Introduction

## 1.1 The importance of heat

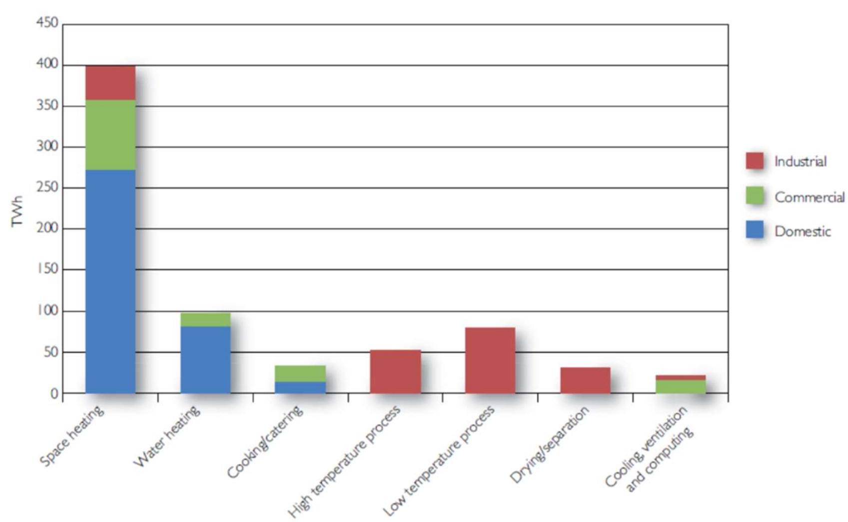
The heat sector[1] is where a significant proportion of energy consumption and carbon emissions arise, and where the infrastructure implications of decarbonisation could be most significant. The breakdown of energy consumption is shown in the figure 1 below:




Source: DECC

Figure 1 Energy usage for heat, transport and non-heat (mainly electricity for other purposes)

Figure 2 shows that the main use of heat energy is for the provision of space heating and hot water in the domestic sector – the focus of this paper:




Source: DECC

Figure 2 Energy consumption for heat by sub-sector in TWh

[1] For the purposes of this paper, the heat sector refers to space and water heating for domestic buildings, although many assessments and conclusions will be similar for space heating and hot water in the commercial sector. The very different and specific needs of industrial users is not within scope

Figure 3 from the ETI[2] shows that carbon emissions from buildings, primarily space heating and hot water, already represent over 20% of net carbon dioxide emissions, and that by 2020, this could become more significant than the power sector, which is currently particularly high due to the relatively high carbon intensity of fuels used and the relative inefficiency of its conversion processes.

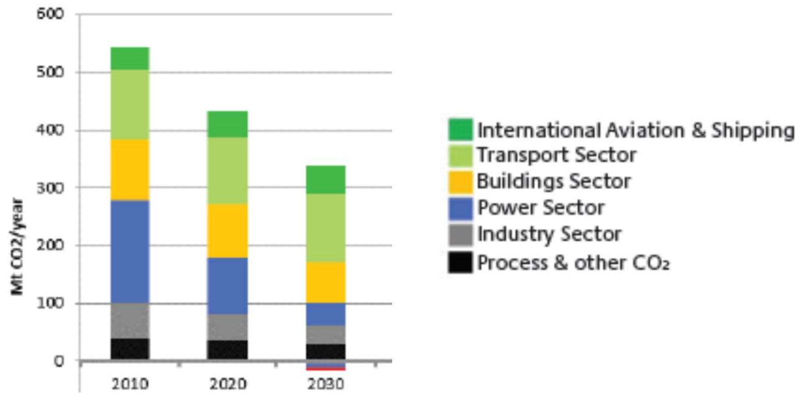



Figure 3 Net carbon emissions by sector

To meet the legally binding carbon reduction targets set in the Climate Change Act and to deliver on commitments made in the Paris Agreement to keep global temperature increase at or below two degrees Celsius, it will be essential to decarbonise the heat sector. The Committee on Climate Change has concluded that "meeting the 2050 target will be much more expensive, and may be impossible, without a near complete decarbonisation of heat."[3]

It is being increasingly recognised that heat will be a particular challenge[4] and decisions must actually be made earlier than previously considered to prepare for the long term transition measures which will be required, even though the main delivery programme may not ramp up until the 2030s. This is to allow and prepare for a cost effective and smooth transition which minimises disruption to households, businesses and neighbourhoods. This is especially true for the UK since:

- the UK is starting with the lowest level of renewable and low carbon heat in the EU[5] (4.8% in 2014)
- the UK has some of the worst housing with regard to energy efficiency - a report entitled the "Cold Man of Europe"[6] concluded: *"None of the 15 countries compared in this briefing performs as consistently poorly as the UK."*
- UK consumers are currently happy with the convenient and relatively affordable gas boiler solution that more than three quarters of households have adopted[7] and are therefore likely to be resistant to the desired changes.

Incorporating low carbon approaches into ***new*** buildings and localities can be relatively simple and driven by appropriate building standards and regulation. However, since over 90% of ***existing*** homes will still be in use in 2050, the transition away from established heat solutions will also require a large retrofit programme to develop new national and local systems for low carbon heat provision, converting roughly 20,000 homes a week, each and every week, for over 20 years – even though this programme may not begin large scale deployment until the late 2020s, important pilot studies and planning steps must be

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[2] http://www.eti.co.uk/wp-content/uploads/2015/03/Smart-Systems-and-Heat-Decarbonising-Heat-for-UK-Homes-1.pdf?dl=1

[3] https://www.theccc.org.uk/wp-content/uploads/2015/11/Fifth-Carbon-Budget_Ch3_The-Cost-effective-path.pdf

[4] http://www.ukerc.ac.uk/asset/8990F7A4-CCFA-4912-8C20113A240447F3/

[5] ec.europa.eu/eurostat/statistics-explained/index.php/File:Share_of_energy_from_renewable_sources_for_heating_and_cooling_-_2013.png

[6] www.ukace.org/wp-content/uploads/2013/03/ACE-and-EBR-fact-file-2013-03-Cold-man-of-Europe.pdf

[7] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf

carried out in the coming years to prepare for this and ensure that sensible levels of optionality are maintained and costs of deployment are kept as low as possible. It is these costs and the related impacts of such a retrofit programme that form the focus of this paper.

## 1.2 Background

A previous study by Imperial College, funded by The European Climate Foundation and published in October 2015, entitled "Energy System Crossroads – Time for Decisions"[8], concluded that putting the UK on a path of energy system change consistent with any of the various decarbonisation scenarios studied, would require a wide range of key decisions to be made in the parliamentary session to 2020, in order to prepare the way for the large scale measures to be deployed in the 2030s and thereafter. It also highlighted key interdependencies between the main energy sectors and their supporting infrastructure and networks, which could be better dealt with through timely planning and design. One of the key interdependencies highlighted was for the electricity system which could be overwhelmed by the electrification of heat and transport without proper prior consideration.

The paper concluded that, although there may be some debate on whether decisions about technologies for producers and end-users can be 'left to the market', this is certainly not going to be the case for local and national infrastructure, like heat, power or hydrogen networks. These are the responsibility of regulated monopolies rather than competitive markets. Therefore, key and timely decisions would be needed by government, both national and local, to facilitate the necessary investment, especially since networks often take longer to develop than the supply and demands side measures that they connect. There are path dependencies or 'chicken and egg' situations, where decarbonisation solutions require investment 'ahead of need' in the networks to allow users to connect, but this may in turn be hard to justify, unless there are larger numbers of users.

Nevertheless, it could be impractical to allow the uncontrolled deployment of multiple and very different heat infrastructure solutions in the same area. Even if there were the physical space in an already congested utility environment to allow this, such an approach could be unnecessarily expensive, disruptive and sub-optimal for the energy system as a whole.

Finally, it was concluded that in the important heat sector, the full implications of decarbonisation are least well analysed or understood, and the plans for decarbonisation are also least well developed. The approaches adopted towards the heat sector are likely to have important implications for other elements of the decarbonisation challenge, as energy systems become increasingly integrated and inter-dependent over time. This prompted the second phase of research into heat – the subject matter for this paper.

## 1.3 Research approach

The analysis in this paper is focussed on the costs and impacts as they stand at the time of writing. The aim of the quantification is only to establish the order of magnitude of today's costs involved and/or to estimate the relative scale of the impacts across the options.

In order to present a reasonably simple and clear comparison in the impact assessments, the raw data was kept as free as possible from assumptions and modelling influences. No attempt has been made to project forward and make predictions about how costs and impacts may, or may not, develop in future. Similarly, to avoid the potential impact of assumptions about inflation, discount or finance rates, most costs are quoted at their 2016 cash value.

Although this static approach was chosen for the impact assessments, it is recognised that developments will be dynamic and by 2030, the likely time-point for starting large scale deployment activities, undoubtedly some costs will, have changed. The need and scope for such future developments in cost

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[8] https://workspace.imperial.ac.uk/icept/Public/Energy%20System%20Crossroads.pdf

and cost of capital are discussed in the relevant technology assessments in Chapters 4 and 5 and, in some cases, form part of the recommendations.

The approach taken to key elements and options is outlined in the following sections:

### 1.3.1 Energy efficiency

The great importance of the 'efficiency first' principle and associate investment in the fabric of buildings should be recognised in all of the potential decarbonisation scenarios. The first phase of this work established that in most decarbonisation scenarios, between 20% and 30% efficiency savings were modelled. This level could be technically improved (e.g. by moving to a Passiv Haus standard[9]) but, as a recent report from Cambridge Econometrics[10] concluded, there is a natural limit to demand side efficiency measures before supply side measures prove more cost and carbon effective, particularly with regard to solid wall insulation where other, non-financial barriers to deployment also exist. According to the analysis from their paper, the average cost per home would be kept to £4,300 by capping individual investments for any household to £10,000. As part of any programme design, it would be sensible to evaluate more precisely the relevant cross-over points between demand and supply side investment.

There is a significant difference in the consumption patterns for hot water and space heating. The former varies significantly across the day, but very little across the year, whereas the latter varies across both and is the main driver for the very big swings in demand and peak demand shown in section 3.3.2.

In an average household, with an annual consumption of 12.5MWh, about 5MWh of this is used for hot water production, which is likely to remain at that level, since no significant efficiency savings are expected or shown in scenarios.

About 7.5MWh is used for space heating where the main efficiency savings are shown in all decarbonisation scenarios. A 20% reduction of this would equate to a future consumption level of 6MWh, which would continue to be subject to the extremes of seasonal variation and, as discussed in section 3.1.1, may not significantly change peak requirements.

In the methodology and analysis described later, even assuming the improvements in energy efficiency were reflected also in peak demand, this would not fundamentally change the ***relative*** rating of impacts for any of the decarbonised heat solutions, the main options for which are:

### 1.3.2 Electrification

A number of the early scenarios[11] foresaw significant uptake of heat pumps as the prime means of decarbonising heat where levels of space heating remained high (even after projected energy efficiency measures). For lower levels of space heating requirement, e.g. in newer, more energy efficient buildings, electricity could also be used directly using inexpensive electric radiators where, despite the higher unit costs of electricity, the consumption levels would be low enough that, when combined with the low capital costs of the heating appliances, the overall costs would be kept to an acceptable level.

As shown in the literature review (Chapter 2 and Section 13), there is little experience of heat pumps as a large scale ***retrofit*** solution, and a number of practical barriers to their adoption have become increasingly evident – a report for the CCC[12] concluded:

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[9] http://www.passivhaus.org.uk/standard.jsp?id=122

[10] http://www.energybillrevolution.org/wp-content/uploads/2014/10/Building-the-Future-The-Economic-and-Fiscal-impacts-of-making-homes-energy-efficient.pdf

[11] https://www.theccc.org.uk/archive/aws/IA&S/Element%20Energy%20-%20Decarbonising%20heat%20to%202050%20-%20Report.pdf

[12] https://www.theccc.org.uk/wp-content/uploads/2013/12/Frontier-Economics-Element-Energy-Pathways-to-high-penetration-of-heat-pumps.pdf

- the high capital cost of heat pumps relative to the conventional gas boiler alternative is a major barrier to uptake in existing homes on the gas grid
- in new build homes there has been a lack of uptake due to the relatively high costs of heat pumps, and the fact that they are not currently needed under building regulations
- another barrier to uptake has been consumer confidence. In particular performance of heat pumps has sometimes been below expectations, resulting in a lack of confidence among consumers
- consumer awareness around heat pumps is also limited and represents a barrier to uptake.

The majority of installations have been replacements for oil fired heating in well insulated homes and have reached installation rates of about 20,000 per annum compared to gas boilers at about 1,600,000.

This is leading to questions about the assumptions used in arriving at the high deployment rates shown in earlier models and scenarios, which may not have incorporated the issues outlined above and explored further in this paper regarding impacts in the distribution networks and in customer premises.

### 1.3.3 District heating

The main alternative to electrification in earlier scenarios was based on central heat generation using a variety of low carbon sources, e.g. large scale heat pumps, waste heat or biomass, combined with heat networks to provide space heating and hot water to individual buildings.

District heating is still relatively unusual in the UK. The examples which work well technically and economically are usually based on:

- a large proportion (based on the scheme potential)
- of mixed use consumers
- signed up to long term contracts.

However, each of these ‘success criteria’ raises issues which can make agreement harder:

- obtaining multiple signatories to a contract always makes it more difficult to conclude
- diverse user groups make it less likely that there is a common set of optimal criteria to which all can sign on
- the longer the contract term, the greater the commitment and the higher the hurdle to acceptance can become.

It is therefore not surprising that international experience has shown that a coordinating public service body which itself can sign up to and/or encourage the other necessary actors to do so, is often a prerequisite for the success of district heating schemes[13].

In a similar context it is also important to consider the potentially positive role that can be played by property developers who decide upon both original design features and specifications as well as by facilities managers for the energy service provision in multiple occupancy developments.

### 1.3.4 Repurposed gas networks

Thanks to the Iron Mains Replacement Programme (IMRP), by 2032 nearly all the low pressure mains pipes in the gas grid will be made from hydrogen compatible polyethylene. As a result, some more recent scenarios include repurposing of the gas grids to provide low carbon alternatives to natural gas, especially hydrogen, which can be used in individual properties using existing appliances[14].

[13] Bolton, R. and Foxon, T. (2015) Infrastructure transformation as a socio-technical process – Implications for the governance of energy distribution networks in the UK, *Technological Forecasting & Social* Change, 90:538-550

[14] https://www.bartlett.ucl.ac.uk/energy/research/themes/energy-systems/hydrogen/dodds-demoullin-2013-gas-network-conversion

Although hydrogen formed about half of the gas mix comprising town gas, which was extensively used for heating in the UK between the 1880s and 1970s, the concept of using 100% hydrogen is, as yet, unproven at scale, but appears attractive due to the reduced impact on distribution networks and customer premises, if the existing gas grids and suitably adapted appliances can be used. More details about how this might be achieved and what it would look like in practice are due to be published in May 2016 by Northern Gas Networks as part of a Low Carbon Network Fund project examining the conversion of Leeds to 100% hydrogen[15]. Clearly further pilot studies would be required for proof of concept, especially the CCS element, before any significant plans for deployment could be considered.

There have also been suggestions that hydrogen could be injected into the existing gas grid alongside natural gas. Current regulations only allow for 0.1% by volume of hydrogen to be blended into gas supplies[16]. Since the level is much higher in other countries, like Germany where it is over 10%, there appears to be no insurmountable technical or safety reasons for this low limit[17]. Upper end estimates of what could be added before adjustments would be required to appliances are about 20% by volume[18]. However, although hydrogen has a high energy density by weight, it has a very low density by volume – about one third of natural gas. Therefore, 20% by volume would only be equivalent to 6% by energy.

Considering the supply side and network developments needed to enable hydrogen use in any quantity, it may make better technical and economic sense to convert to 100% hydrogen in a limited number of locations, rather than to convert many more areas for a blended solution, especially if this remains limited to low levels.

### 1.3.5 Hybrid heat pumps

This solution, using a combination of electric heat pumps and gas boilers, has been considered by some scenarios[19], at least for a transitional period.

Hybrid heat pumps are a relatively new product and, as a consequence, there is very little practical or commercial experience with them. Nevertheless, they have been made eligible for subsidy in the UK under the Renewable Heat Incentive (RHI)[20].

One type integrates an air source heat pump (ASHP) with a condensing gas boiler. Another, commonly referred to as a bivalent system, separately utilises the existing gas boiler but provides controls to switch operation between the ASHP and gas boiler, as needed[21].

Hybrids operate mostly in heat pump mode with the gas boiler providing hot water (5MWh pa or about 45% of demand) and supplementing the space heating demand when required, e.g. as the air temperature falls, the heat pump becomes less efficient and may not be capable of delivering sufficient heat to meet the requirements of the building's occupants[22].

The capital cost of the heat pump could be lower than for a stand-alone heat pump, since the design allows for a lower rated unit to be used, e.g. $5kW_{th}$ versus $8.5kW_{th}$, with the gas boiler providing sufficient capacity to compensate for lower heat output. For the bivalent system, this would be in addition to the

[15] http://www.smarternetworks.org/Project.aspx?ProjectID=1630
[16] Health & Safety Executive. (1996) A guide to the Gas Safety (Management) Regulations 1996.
[17] https://documents.theccc.org.uk/wp-content/uploads/2015/11/E4tech-for-CCC-Scenarios-for-deployment-of-hydrogen-in-contributing-to-meeting-carbon-budgets.pdf
[18] http://www.hse.gov.uk/research/rrhtm/rr1047.htm
[19] fes.nationalgrid.com/fes-document
[20] www.gov.uk/government/uploads/system/uploads/attachment_data/file/212089/Domestic_RHI_policy_statement.pdf
[21] library.mitsubishielectric.co.uk/pdf/book/Hybrid_Application_Brochure#page-1
[22] www.domesticheating.mitsubishielectric.co.uk/information/brochures (page 22)

existing gas boiler.  With either version it would be less likely that new radiators would be required as may be the case with a stand-alone unit[23].

From an energy system perspective, hybrids potentially offer benefits in terms of reducing the additional electricity generation capacity that would have otherwise been required, but would still require the gas system to be maintained.

Although peak heat demand is provided by gas and not electricity, in terms of the electricity network the additional needs of the heat pumps are still likely to trigger low voltage (LV) network reinforcement, if not for thermal capacity reasons, then to deal with quality of service issues including flickering and due to loop impedance (see annex B).

The main drawback to hybrid heat pumps is that when operating on gas, which they would for hot water and peak heating, they will be emitting $CO_2$, and as a consequence they are generally seen to only offer benefits as a transition technology as opposed to an enduring low carbon solution.

Since they are unlikely to represent an enduring solution and due to the lack of experience and reliable data for this option, they have not been included in the cost and impact assessments.

### 1.3.6 Biomass

So far, the main means of producing renewable heat in the UK and wider EU (approximately 75% in the UK and 85% in the EU[24]) is with fuel from biological sources, mainly biomass.  However, estimates by the European Commission based on the Renewable Energy Action Plans from Member States suggest that current levels are unlikely to increase significantly to 2020 or beyond as shown in figure 4 below:

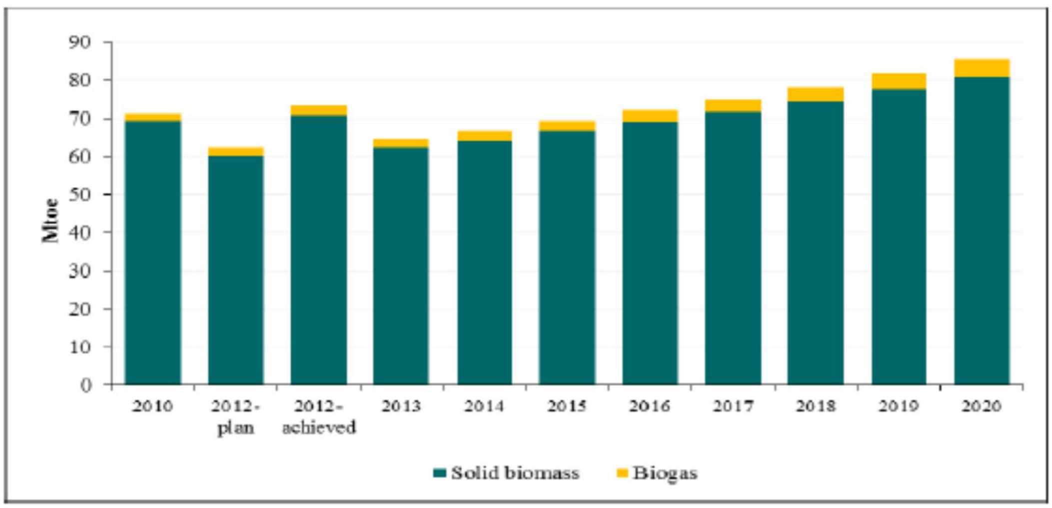


Figure 4 Outlook for total EU heat and cooling demand from solid and gaseous biomass[25]

This is mainly due to concerns about the viability of long-term, high volume, sustainable sources which lead to reservations about the extent to which bio-energy can offer a substantial and enduring solution. DECCs 2012 Bioenergy Strategy[26] also suggests that although bioenergy may contribute between 8% and 11% of UK primary energy demand by 2020, this may only grow to 12% by 2050.

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[23] A gas boiler can heat the hot water to the radiator design flow temperature of circa 70°C thereby increasing heat output whereas for heat pumps the maximum water flow temperature is typically 55°C

[24] http://eur-lex.europa.eu/resource.html?uri=cellar:4f8722ce-1347-11e5-8817-01aa75ed71a1.0001.02/DOC_1&format=PDF

[25] Also from ref. 24

[26] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf

Concerns include[27]:

- unsustainable feedstock production
- emissions from land use
- land use change and forestry
- lifecycle GHG emission performance
- inefficient bioenergy generation
- concerns about emissions of local air pollution.

### 1.3.7 Biogas

Biogas is composed mainly of methane and carbon dioxide and is a product of the process of anaerobic digestion, whereby organic matter decomposes in the absence of oxygen. Feedstocks for the manufacture of biogas include animal slurries, municipal solid wastes, agricultural residues, energy crops and sewage.

Modelling undertaken for DECC suggests that a number of factors will limit the growth of biogas both in terms of scale and application. The 2012 Bioenergy Strategy suggests that whilst the injection of biomethane into the UK gas network may play a role it is unlikely there will be sufficient quantities of feedstock available to replace much of the natural gas in the grid. Some projections predict around 20TWh of biogas (3.5%) could be blended into the gas network in 2050 from the gasification of biomass, anaerobic digestion and landfill gas'.

Whilst bio-energy is likely to have an important role in decarbonisation, because of the limitations described above the paper does not evaluate biomass and biogas in detail.

## 1.4 Option evaluation

This paper aims to support the development of credible pathways and action plans for heat decarbonisation by informing decision makers, designers and planners about the costs and impacts associated with the large scale roll-out of each of the main heat decarbonisation options.

It does so by providing a high level overview which, as well as looking at the costs and impacts for energy supply and householder premises, focusses on the networks which provide the link between energy producers and the end users. These issues have not been extensively documented before, particularly with regard to the impacts over the transition that will arise for the very large scale and long duration investment programmes required in all of the studied options.

The paper examines the generic actions which can be taken to promote the decarbonisation process, as well as specific solutions that are better suited to a particular building type, or occupancy pattern and where, for each of these, cost and disruption can be minimised by further technical developments as well as proper programme planning and management.

Literature research together with modelling and original analysis by the project team have been combined with input from the advisory board and industry experts to inform the production of this paper, in which the key costs and impacts of each of the three main options are summarised and compared for each of four simplified housing types:

- urban
- suburban
- rural
- flats and maisonettes in high-rise buildings.

These have been defined specifically for the purpose of this study and detail of this is given in section 3.2.

[27] http://ec.europa.eu/energy/sites/ener/files/2014_biomass_state_of_play_.pdf

For each combination of network solution and housing type, a comparison between the existing natural gas solution is made and impact assessed using quantitative and qualitative analysis of a series of cost (based on current levels) and impact criteria including:

**Supply**

- efficiency of heat production
- gas/electricity/fuel price
- delivered heat cost
- production and supply issues (including sensitivity for CCS and storage)

**Distribution**

- cost per household of new and reinforced infrastructure
- property conversion rates
- trench size for cables and pipes
- access and traffic disruption

**Consumer premises**

- requirement for structural improvement/energy efficiency
- requirement for new/modified appliances
- cost per household to convert
- disruption
- customer acceptance
- regulation issues.

# 2. Literature research summary

A review of national and international developments has been carried out to identify and document:

- comparable examples of major infrastructure transition (i.e. non greenfield development), especially if/where this has happened in the context of liberalised markets
- other infrastructure transition studies that are being carried out
- peak heat consumption patterns, how these can be managed and reduced and dealt with by proposed decarbonised heat solutions
- options to 'decarbonise' the gas grid
- mass heat pump deployment in existing buildings
- heat network development in urban areas
- options for low/zero carbon heat generation for use with heat networks.

The detail of this is shown in the supplemental review in Section 13 and the main conclusions are as follows:

- literature more often discusses the establishment and configuration of infrastructure systems which develop over time rather than transitions from one system to another, on which less evidence is available
- historical examples rooted in transitions theory do not always address infrastructure and so are of limited relevance
- water networks have in the past grown more slowly in existing cities because of the cost of breaking up streets
- co-ordinated, concerted local action backed by central government greatly increases the chances of success
- projects tend to be driven by motivated and informed champions
- even where novel end-use technologies drive change, this starts off imperfectly and expensively before being scaled up to drive the transition forward
- technical standards can play an important role in network transitions
- gaining access to a large number of homes presents a challenge
- there has been relatively little research on managing peak heat demand in the context of low carbon heating provision
- options for biogas could be restricted by the availability of sufficient supply of sustainable fuel
- hydrogen can be produced through the reformation of hydrocarbons, or, electrolysis of water but is currently much more expensive than natural gas
- carbon capture and storage would be critical to any heat or fuel production based on carbon sources (hydrogen as well as electricity and heat generation for district heating)
- public ownership and local authority involvement appear to be important for success with district heating networks
- district heating works best if there is guaranteed demand, ideally starting with a blank canvas
- networks in general require a minimum customer and consumption density and are often developed more slowly in poorer areas where demand (or anticipated demand) is lower.

# 3. Potential costs and impacts

## 3.1 General considerations

With heat decarbonisation, the UK faces a challenging task as it is starting with the lowest deployment of renewable and low carbon heat in the EU[28], has some of the worst housing with regard to energy efficiency[29] and its consumers are currently happy with the convenient and relatively affordable gas boiler solution that more than three quarters of households have adopted[30].

Progress on implementing renewable heat has been very slow. As of December 2014, DECC reported that 32TWh of renewable heat energy was produced, equivalent to a share of 4.8%. However, three quarters of this came from the combustion of wood in domestic and industrial applications, most of which was accredited to historic installations predating renewable energy legislation and incentive schemes. In 2014, less than 5% of the 4.8% renewable heat contribution was supported by the Renewable Heat Incentive (RHI) or Renewable Heat Premium Payments (RHPP), the latter of which are no longer available (all data in this paragraph comes from DUKES[31] (Digest of UK Energy Statistics).

Many scenarios have relied heavily on the assumption that heat will be decarbonised through electrification, and heat pumps in particular. In 2012 and 2013 DECC, the Committee on Climate Change and National Grid foresaw over 380TWh heat production from heat pumps in 2050[32], equivalent to over two thirds of projected heat demand in 2050.

The cost optimisation and market allocation modelling undertaken in many low carbon scenarios did not have access to information about, or did not consider all of the impacts and costs explored in this paper, particularly with regard to distribution networks and domestic disruption[33]. More recent scenarios foresee considerably less penetration by heat pumps[34] with levels barely reaching 10% by 2032. Real world experience is now building and, despite the focus on heat pumps in the models, their actual contribution by the end of 2014 remained very modest at 4% of renewable heat and less than 0.2% of all heat production[35].

From the RHI in the ***non-domestic*** sector, over 98% of renewable heat energy is produced from biomass boilers or biogas, and from the much smaller ***domestic*** RHI scheme, 55% of energy is from biomass boilers. It is interesting to note that biomass and biogas are also projected to provide the vast majority of renewable heat production (about 85%) by 2020 across the EU as a whole[36].

Nevertheless, as discussed in section 1.3.6, the availability of sustainable biomass is likely to remain limited and there may be insufficient fuel available to significantly extend the use of this to make a further contribution to decarbonising the heat sector, especially if there is competition for the resource from other sectors.

In deciding which alternative approaches might be applicable, there are a number of important operational considerations for evaluating the impact of any potential decarbonisation options:

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[28] See ref. 5
[29] See ref. 6
[30] See ref. 7
[31] www.gov.uk/government/uploads/system/uploads/attachment_data/file/450298/DUKES_2015_Chapter_6.pdf
[32] See ref. 8
[33] See ref. 8
[34] The CCC in its 5th Carbon budget proposals models a combined share of district heating and heat pumps of 13%
[35] See ref. 31
[36] eur-lex.europa.eu/resource.html?uri=cellar:4f8722ce-1347-11e5-8817-1aa75ed71a1.0001.02/DOC_1&format=PDF

### 3.1.1 Peak requirement

It is the peak requirement rather than average or total consumption which determines the scale and resulting impact of the necessary supporting infrastructure, both generation and networks. It is important to consider the distributional impacts of heat load across the days and seasons, as well as how this could be influenced and managed to reduce residual peak impact. This will be demonstrated in more detail later in section 3.3.2.

The production and use of heat (as opposed to the fuel or energy vectors like electricity used for heat generation) is generally very localised and in many cases confined to a single building. It is possible to benefit from 'interconnection' with other users or areas with different peak requirements, especially where there are mixed use sites for district heating. However, even with electricity where wider interconnection and some smoothing of short term variations is possible, the interconnection is generally limited to other north-western European countries with similar weather patterns and heat requirements, so seasonal and some weather related variations are common across the area.

Peak heat requirements for space heating in well insulated new buildings are likely to be considerably lower than current levels in heating systems designed for older buildings.

In retrofitted buildings, peak demand may not reduce (fully) in line with any energy efficiency gains if, for instance, the appliance size for heat production is maintained for quick warm up, whereby only the running time and overall energy consumption would be reduced.

However, in either case, the capacity of the heating unit may in any case be sized to cope with the greater instantaneous demand for hot water production and may use this capacity for rapid space heating response, in which case space heating peaks may be unaffected by energy efficiency improvements in the building fabric. This is discussed in more detail in sections 13.8 and 13.9.

### 3.1.2 Flexibility and resilience

Currently, the natural gas system which has evolved in the UK provides an almost uniquely flexible part of the wider energy system – not only does it deliver the energy needed, but also the ability to supply, transport and store the fuel to meet the un-paralleled extremes of daily and seasonal heat consumption patterns[37], at the same time also providing wide geographical cover, and an actual or potential means of bridging supply across the three main energy sectors - heat and electricity as well as transport where compressed or liquid natural gas can be used.

Faced with big swings in heat demand, and the future challenges of increasingly intermittent and inflexible electricity generation, as well as meeting future transport needs, the ability to transport and store energy may be of increasing importance. The flexibility and resilience of the existing gas system is substantial and replicating it will be very challenging. Therefore, in any future scenarios, serious consideration should be given to how this capability can be maintained or replaced.

### 3.1.3 Infrastructure transition - end user implications

Most supporting infrastructure, like networks, are hidden from view and limited in impact on daily life once installed. However, the ubiquity of existing water, sewage, power, gas and telecoms networks make it challenging to modify or install any network. Regulation recognises that, "inevitably works in the street will interfere with road users and nearby residential and business premises to some extent. The aim should be to avoid serious disruption, where possible"[38].

If a transition is not well managed, it could become a major social and political issue, even where the technical and economic justification is favourable and the end outcome itself uncontroversial. It is therefore important to understand the transition pathway and not just the final desired outcome to

[37] See figure 5 later which shows the significant variation currently met by the gas system

[38] New Road and Street Works Act (1991) Code of Practice

successfully deliver any major project, or as will be necessary with heat infrastructure, a very large number of individual, smaller ones.

It is almost inevitable that a transition away from gas infrastructure for heating will involve substantial street works, and so the implications for the end-users as well as for neighbourhoods and businesses with regard to access and transport must be considered.

As was demonstrated by the Edinburgh Trams project[39], which seriously underestimated the time, cost and disruption associated with modifying utility services, transport disruption and delays arising from street works is a major source of complaints from the public and businesses.

Political barriers can develop even out of limited local opposition and, if not dealt with appropriately, this can prevent wider deployment, despite being a good technical and economic option, as has been seen with onshore wind.

### 3.1.4 Optimal governance

Costs should be optimised through adequate planning and preparation for any large scale, long duration infrastructure investment programme. Adequate governance structures should be put in place for delivery and this would need to be co-ordinated across the respective organisations, e.g. Ofgem, consumers, businesses, network companies, etc.

On an ongoing basis, national and local coordination of the approach(es) may be needed to avoid replication of effort and stranded assets, as well as to ensure that, over time, an adequate option is available to all homes and businesses in each locality, especially where this is combined with an energy efficiency investment programme in buildings. The zoning at a local level of areas suitable for each of the options would facilitate this process significantly. Further governance issues are discussed in more detail in Chapter 6.

## 3.2 Evaluating heat options

Rather than allocating incremental costs to new infrastructure, this study considers the specific impacts of what will be needed for each heat infrastructure solution as well as the scale, duration and non-incremental nature of the investments needed for a national programme, even if this is delivered locally in smaller units, and designed for each specific set of circumstances.

The result is a series of high level infrastructure impact assessments for the three main heat delivery systems: repurposed gas networks, electrification and district heating in deployment scenarios with four residential building types, defined for the purposes of this paper as:

- urban (~ 20% of housing[40]) – high population and traffic density city housing, on the gas grid and served by underground electricity cables with significant traffic and space restrictions
- suburban (~ 65%) - lower population and traffic density town and city housing, on the gas grid and served by underground electricity cables with fewer traffic and space restrictions
- rural (~10%) – off gas grid, low heat density and served by overhead electric lines
- high-rise (~5 %) – off-gas-grid flats and maisonettes in multi-storey buildings (which for reasons of safety or ownership and wayleaving rights do not have gas connections).

With the objective of identifying which solution is likely to be best suited to each housing type, the assessments include estimates of the costs and impacts of the transition, as well as the ultimate, ongoing costs in the following categories:

[39] Now the subject of a public inquiry: http://www.edinburghtraminquiry.org/the-inquiry/

[40] Estimated from DCLG: www.gov.uk/government/statistics/english-housing-survey-2013-to-2014-headline-report

**Supply**

- efficiency of heat production
- energy/fuel price
- heat supply cost
- production and supply issues (including storage and sensitivity for CCS)

**Distribution**

- cost per household of new and reinforced infrastructure
- property conversion rates
- trench size for cables and pipes
- access and traffic disruption

**Consumer premises**

- requirement for structural improvement/energy efficiency
- impacts of modifying or installing appliances and whether the existing radiators can be used
- cost per household to convert
- regulation issues
- customer disruption and acceptance
- other factors (e.g. hot water storage).

The choice of options, the rate of deployment and customer acceptance may well be determined by the non-cost impacts. A core objective is to consider the complexity of infrastructural change and to avoid oversimplifying the problem. It is hoped that this approach will yield insights that may not be easy to represent through cost optimisation models of decarbonisation – either because transition costs are difficult to capture and represent in models or because non-cost factors may be overlooked in cost-optimising approaches.

The heat transition will have to be driven by decisions at a number of levels by Government – local, national and international – as well as by those of individual households and businesses. In addition, standards and regulation will be needed, appropriate for each solution. This raises a number of questions about the system of governance and regulation that will be needed, which are examined separately in Chapter 6.

## 3.3 The starting point – existing gas networks

In order to evaluate and compare the new options it is useful to understand the current costs and benefits and impacts of the main current means of producing space heating and hot water - the gas boiler.

### 3.3.1 The costs

Natural gas has become so ubiquitous, in large part because it provides a relatively cost effective, flexible and convenient means of providing space heating and hot water, and because the UK has/had abundant reserves and easy access to natural gas through pipelines and liquefied natural gas (LNG) supplies.

Currently, in the absence of an appropriate carbon price to drive up the cost of gas fired heating and/or a subsidy to reduce the costs of alternatives, all of the low carbon options are going to appear more expensive to the householder, either in terms of running costs and/or up front capital required. It will be especially difficult to persuade householders to pay more for a new solution, if this causes disruption within the home and, potentially, in the local neighbourhood. Therefore, the challenge of making any transition happen should not be underestimated.

It should be stressed that this paper is based on current costs, so there may be significant potential for future savings in the costs of alternative means of heat provision.  However, where the cost increases are due to ***additional*** infrastructure and equipment, as with district heating or electricity system reinforcement, and/or to ***additional*** processes to produce fuel/energy and to remove carbon, for instance with SMR + CCS for hydrogen, this will only mean ***a reduction in the extra costs*** or financing requirements.

Optimisation of the costs and cash flow implications for consumers can certainly be achieved by spreading cost over time and minimising the cost of capital associated with the investments.  In this regard, as will be discussed later in chapter 6, it is important to examine the opportunities to structure and set up institutions for delivery which help lower overall costs. For example, if district heating networks were operated as regulated monopoly assets it would be possible to reduce investment risk and hence access lower costs of capital.

### 3.3.2 The functionality

The gas infrastructure that has developed in the UK is very resilient and includes significant volumes of low cost storage which allows it to meet the very large swings in demand, not only within day, but more challengingly, across the seasons.  Meeting this seasonal variation will be the most difficult issue for other solutions to deal with.

Based on energy output, peak gas demand for heat at 300GW is:

- 5 times greater than the level would be if it were spread evenly over the days and seasons
- 12 times the summer maximum
- between 5 and 6 times the current peak in the electricity system.

This is illustrated in figure 5 below which compares GB actual half hour electricity demand in 2010 with a synthesised half hourly heat demand.

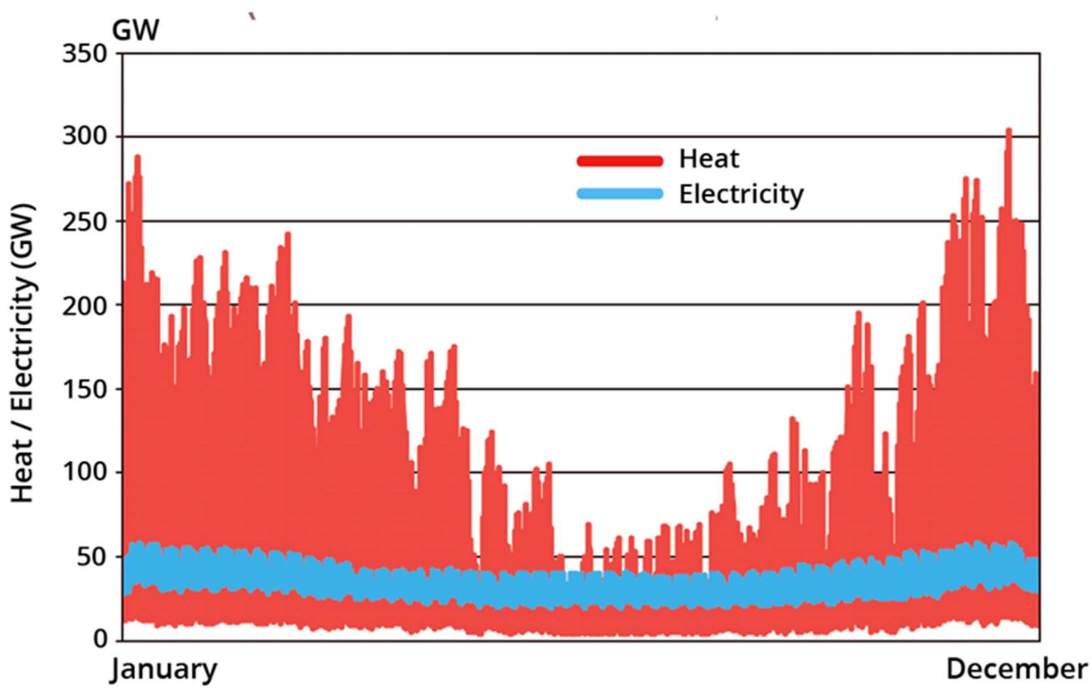


Figure 5 Heat and electricity demand comparison[41]

[41] https://spiral.imperial.ac.uk/bitstream/10044/1/25503/1/Sansom-R-2015-PhD-Thesis.pdf

Table 1 summarises other interesting comparators for the UKs natural gas and electricity systems:

| | Gas (for heat) | Electricity |
|---|---|---|
| **Annual energy delivered (TWh)[42]** | 675 | 350 |
| **Peak demand (GW)[43]** | 300 | 60 |
| **Storage duration (h)[44]** | 900 | 9 |
| **Storable energy (GWh)** | 50,000[45] | 27[46] |
| **Storage cost (£/MWh)*** | 30[47] | >60,000[48]<br>120,000 – 1,400,000[49] |
| **Retail energy cost (£/MWh)[50]** | 48 | 154 |
| **Heat carbon intensity ($gCO_2$/kWh)[51]** | 185 | 375 |

Table 1: Comparative statistics of the gas and electricity systems

(* The costs of storage in this table, and in the impact assessments reflect what would be needed if storage were the chosen or necessary route to balance, or partly balance supply and demand. There are other means of achieving this, although more limited for large scale or seasonal variations.

For instance, traditionally in the electricity system back-up generation using low(er) capital cost, high(er) fuel cost plant has been the chosen method. The current costs of this using fossil fuelled plant (as measured in the levelised cost of electricity) could be £50 - £250/MWh depending on assumptions about the load factor and carbon price. It is unlikely that this can be seen as a future solution, since without CCS, this would not be consistent with decarbonisation targets and with CCS, would become more economically and potentially technically challenging.)

[42] See ref. 31
[43] See ref Figure 5 and Ref. 41
[44] Authors' estimate
[45] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2013/01/NG-72.pdf
[46] http://erpuk.org/wp-content/uploads/2014/10/52990-ERP-Energy-Storage-Report-v3.pdf
[47] See ref. 45
[48] https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf
[49] ScottishPower pumped storage project at Cruachan (6.7GWh for £400m)
[50] www.gov.uk/government/uploads/system/uploads/attachment_data/file/487856/QEP_final_Dec_15.pdf
[51] www.defra.gov.uk/environment/business/envrp/pdf/conversion-factors.pdf for gas, http://www.earth.org.uk/_gridCarbonIntensityGB.html for electricity over recent months

# 4. Impact assessments

The tables in sections 4.3 to 4.6 summarise the results of the impact assessments for each of the three network solutions in the four property types. Since, by the definitions used in this paper to simplify the assumptions around property types, rural properties and flats are not connected to the gas grid, only an electric or district heating solution is considered. Furthermore, it is assumed that for flats, an electric solution would be a combination of direct resistive heating and, potentially, modern storage heaters. This is for the following reasons:

- a flat is likely to have a lower heat demand and this can make direct electric heating potentially more economic
- air source heat pumps require hot water storage for efficient operation and there is likely to be more limitations on water storage and space (internal and external) in flats
- there is significant potential for (cumulative) visual and noise impact from heat pumps.

## 4.1 Impact assessment summary tables

The tables are split into three cost and impact categories:

- **Supply side** – this section covers all of the elements required to produce the fuel or energy which will be transported to, and paid for by end users through energy bills – equivalent to existing gas and electricity costs
- **Distribution** – additional costs and impacts which are the responsibility of the respective network owners – Gas Distribution Networks (GDNs) for gas solutions, Distribution Network Owners (DNOs) for electricity, and heat network owners for district heating. These costs would subsequently be recovered through energy bills, but are treated separately for this exercise
- **Consumer premises** – all the non-energy/fuel costs and impacts directly affecting the householder which relate to the transition to the new solution as well as the ongoing operation.

Each assessment segment is characterised with a colour to indicate the change in cost or the significance of the impact. These were allocated on the following basis:

- Green – cost similar to natural gas; little or no impact
- Amber – increased cost; noticeable impact
- Red – significantly increased cost; significant impact

In some instances, a 'bright red' classification is used to further differentiate the enhanced adverse potential or significance when compared to other deployment areas. A 'deep green' rating is used where a solution is a marked improvement over the status quo.

Where possible and applicable, approximate quantification of the cost or impact is also included in the table, explanations for these are given in the results section and in the separate annexes A, B and C.

## 4.2 Definitions

Each of the impact assessment categories used in the assessments is explained below.

### 4.2.1 Heat production efficiency

The heat efficiency is a relative measure of how much energy must be input to produce a unit of heat. For gas and hydrogen, it is the boiler efficiency, and for the two heat pump solutions it is the coefficient of performance (CoP) which represents how much heat can be extracted from the heat sink for each unit of electricity used by the pump.

For some heat pump solutions, it is almost a pre-condition for its proper functioning that a minimum level of building energy performance is achieved and this cost is included in the upper range of "appliance costs per household" shown in the tables. Otherwise, for the purposes of the evaluation in this paper, energy efficiency investment in the building is assumed to be driven and paid for separately, although it obviously makes sense to have an integrated approach to the design and delivery of both of these elements in practice.

### 4.2.2 Energy/fuel supply cost

The figures quoted show the delivered unit cost of the proposed fuel/heat energy production methodology to the household. It is based on the components that comprise the retail gas and electricity tariffs[52] with adjustments for specific usage and features, as well as the capital and operating costs of the centralised fuel/heat production technology itself. For hydrogen it includes the capital cost of the SMR + CCS (or electrolysis), and for district heating it includes the capital and operating cost of the heat pump.

These estimates do not take into account the potential for future price developments whether from fuel price changes or from system cost changes. For example, the extra demand created by electrification of heat (and transport) could increase the cost of electricity to cover additional capacity requirements, system service and storage costs (see below in section 4.2.5).

### 4.2.3 Heat supply cost

This value represents the resultant cost (from 4.2.1 and 4.2.2) to produce a heat output of 1MWh.

It is important to note that this is a unit cost of heat produced and does not equate to the end user cost until combined with the appropriate consumption levels.

The quoted values do not include the consumer premise investment costs, or the ***additional*** capital costs of the new or reinforced distribution systems, which ultimately may well be recovered through network charges in the energy bill, as for ***existing*** distribution costs. Both of these costs are instead shown separately in the respective categories of the tables for the purposes of this analysis.

### 4.2.4 CCS criticality

This is an assessment of the role that CCS would have to play in ensuring that each particular solution is viable and/or reduces carbon.

### 4.2.5 Storage

As was shown previously in Table 1, the current contribution to resilience and flexibility provided to the gas system through large daily and seasonal storage facilities is relatively inexpensive and readily available when compared with alternative solutions.

Satisfying winter peak loads with electricity, or other non-fossil fuel solutions, must take into account the availability and cost of storage or alternative flexibility, back-up and resilience solutions in the energy system.

The European Commission recently estimated that heat storage is about 100 times more expensive than fuel storage and electricity storage is 100 times more than heat[53]. The estimates in the assessments confirm this approximation and summarise the capital cost ranges applicable to longer term storage facilities suitable for seasonal storage. On this basis, replacing energy service requirements currently derived from gas storage with similar services using other forms of storage could increase the capital cost by a factor of 1,000 - 10,000, and this has to be seen in the context of the overall system costs for each particular solution.

[52] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/511316/QEP_Mar_2016_V2.pdf

[53] http://www.svenskfjarrvarme.se/Global/EU-fr%C3%A5gor/Consultation%20Forum%2009092015%20-%20Issue%20Paper%20IV%20-%20Linking%20heating%20and%20cooli.pdf

### 4.2.6 Network investment cost

These are the costs that will be borne by the network owner/operator for each respective solution and include the material, staff and overhead costs associated with the long term network transition for each solution. More detailed explanations are provided for the three solutions in annexes A, B and C.

For the infrastructure comparisons, no attempt was made to model the impact of different financing costs or discount rates. It was assumed that, as infrastructures are most likely to be owned and operated by regulated monopolies, similar principles would be applied to each and therefore would not change the relative assessments of the costs. This assumption is clearly not currently applicable to district heating which, due to the much higher costs of commercial rates, is almost impossible to finance on the scale required. This is indeed highlighted later in chapter 5.3.4 as one of the regulatory issues that would have to be addressed in order to make district heating a viable option. Without this assumption, district heating network costs would be considerably higher.

### 4.2.7 Homes converted per year

This is an estimate of the likely maximum rate that a transition programme at scale might take place and only considers the activities and impacts relating to the networks. (It is recognised that there will be other related activities such as the construction of power plant, steam methane reformers, or the household energy efficiency improvements and that these may further constrain the rate of deployment.)

It is important to emphasise that the rates of household connections estimated here are primarily for comparative purposes in order to illustrate the resources required and the extent of the programme to be undertaken. They are not meant to imply an upper limit, but to indicate the extent of the 'effort' that may be required, or the higher level of disruption that would need to be accepted, to raise the limit.

For comparison, in the IMRP, a programme to replace the mains for the remaining 13 million homes over 30 years, the annual rate of replacement was limited to 3,580 km as this was judged to "represent an achievable level of replacement that would not cause excessive disruption to the public"[54]. This was an important recognition of the importance of maintaining public acceptability and that this, rather than cost or resource levels, may be the rate-limiting factor for infrastructure transition.

### 4.2.8 Trench size

This simple measure provides a means of comparing the scale of excavation works which will be associated with each type of network and an indication of the potential restrictions on applicability.

### 4.2.9 Traffic and access disruption

This relative comparison combines the scale of the excavation required, with the degree of existing utility network congestion and the density of homes businesses and traffic for each area to compare the scale and duration of disruption that will be experienced in a particular locality.

### 4.2.10 Criticality of energy efficiency

It is assumed that ongoing energy efficiency investment in buildings must be pursued for all scenarios in order to reduce energy consumption and carbon emissions. This evaluation only examines the criticality of this for the basic functioning and ongoing operational efficiency for each of the solutions.

### 4.2.11 Household appliance costs

This section estimates the costs that each householder will have to pay directly to upgrade or replace existing systems within each property. These will be one-off capital purchases and do not include

[54] "10 year review of the Iron Mains Replacement Programme." Prepared by Cambridge Economic Policy Associates Ltd for the Health and Safety Executive and Office of Gas and Electricity Markets 2011

equipment installed by network operators, which are accounted for in the "Network Investment Costs" (section 4.2.6).

As will be discussed later in chapter 5.2.4, for some heat pump solutions, it is almost a pre-condition for functionality and achieving the quoted coefficient of performance that a minimum level of building energy performance is achieved and this cost is included in the upper range shown in the tables.

Otherwise, for the purposes of the evaluation in this paper, energy efficiency investment in the building is assumed to be driven and paid for separately, although it obviously makes sense to have an integrated approach to the design and delivery of both of these elements in practice.

### 4.2.12 Household disruption

This is an estimate of the extent of the modification and installation work that will be required in each property. In some instances, for example hydrogen boilers, it should be possible to reduce or eliminate some elements of disruption by ensuring appliance standards are introduced early enough to ensure that appliances will be 'dual-fuel' or 'hydrogen ready' by the time the switch-over is carried out.

### 4.2.13 Customer acceptance

This is an estimate of the likely customer reaction to each of the solutions – on the whole, the greater the disruption, the lower the likely acceptance, but there may also be ongoing non-technical elements like 'heat experience', and/or regulatory issues like customer protection or ability to switch which will also play a role, particularly for district heating.

### 4.2.14 Visual and noise impact

This provides an estimate of the likely local visual and noise impact of the solutions after the transition, on an ongoing individual and cumulative basis.

### 4.2.15 Regulation issues

This is an assessment of the regulatory and governance issues that will arise in transitioning to a large scale roll out of each of the options. This includes regulations needed for product and appliance standards, statutory rights of access and compulsory purchase for developers and operators as well as customer protection. It also takes into account the impact on cost of capital that network ownership models will have – lower rates if the asset is owned by a regulated monopoly, like the existing gas and electricity networks, or much higher for commercial owners, as is the case currently for private wires and heat networks.

## 4.3 Impact assessment for urban properties

| URBAN | | Network type | | | | |
|---|---|---|---|---|---|---|
| | | Gas grid | | | Electricity | District heating |
| | | Natural gas | Hydrogen | | Heat pumps | Large heat pump |
| | Evaluation criteria | | SMR+CCS | Electrolysis | | |
| Supply side | Heat production efficiency (%) | 85% | 85% | 85% | 270% | 340% |
| | Energy supply cost (£/MWh in 2016) | 50 | >75 | >125 | 130 | 100 |
| | Heat supply cost (£/MWh in 2016) | 60 | >90 | >150 | 50 | 45 |
| | CCS criticality | | | | | |
| | Seasonal storage cost (£/MWh) | 30 - 80 | 100 - 250 | | > 50,000 | 80 - 8,000 |
| Distribution | Network investment cost (£k/home) | | 0.3 | | 2 | 9 |
| | Homes converted per year (thousand) | | 1,000 | | 400 | 100 |
| | Trench size (m) | | N/A | | 1 | 3 |
| | Traffic and access disruption | | | | | |
| Consumer premises | Criticality of energy efficiency | | | | | |
| | Appliance costs per household (£k) | | 0 - 1 | | 5 - 15 | 0 - 1 |
| | Household disruption | | | | | |
| | Customer acceptance | | | | | |
| | Visual and noise impact | | | | | |
| Regulation issues | | | | | | |

## 4.4 Impact assessment for suburban properties

| SUBURBAN | | Network type | | | | |
|---|---|---|---|---|---|---|
| | | Gas grid | | | Electricity | District heating |
| | | Natural gas | Hydrogen | | Heat pumps | Large heat pump |
| | Evaluation criteria | | SMR+CCS | Electrolysis | | |
| Supply side | Heat production efficiency (%) | 85% | 85% | 85% | 270% | 340% |
| | Energy supply cost (£/MWh in 2016) | 50 | >75 | >125 | 130 | 100 |
| | Heat supply cost (£/MWh in 2016) | 60 | >90 | >150 | 50 | 45 |
| | CCS criticality | | | | | |
| | Seasonal storage cost (£/MWh) | 30 - 80 | 100 - 250 | | > 50,000 | 80 - 8,000 |
| Distribution | Network investment cost (£k/home) | | 0.3 | | 2 | 9 |
| | Homes converted per year (thousand) | | 1,000 | | 400 | 100 |
| | Trench size (m) | | N/A | | 1 | 3 |
| | Traffic and access disruption | | | | | |
| Consumer premises | Criticality of energy efficiency | | | | | |
| | Appliance costs per household (£k) | | 0 - 1 | | 5 - 15 | 0 - 1 |
| | Household disruption | | | | | |
| | Customer acceptance | | | | | |
| | Visual and noise impact | | | | | |
| Regulation issues | | | | | | |

## 4.5 Impact assessment for rural properties

| RURAL | | Network type | | | |
|---|---|---|---|---|---|
| | | Gas grid | | Electricity | District heating |
| | | Natural gas | | Heat pumps | Large heat pump |
| | **Evaluation criteria** | | | | |
| **Supply side** | Heat production efficiency (%) | 85% | | 270% | 340% |
| | Energy supply cost (£/MWh in 2016) | 50 | | 130 | 100 |
| | Heat supply cost (£/MWh in 2016) | 60 | | 50 | 45 |
| | CCS criticality | | | | |
| | Seasonal storage cost (£/MWh) | 30 - 80 | | > 50,000 | 80 - 8,000 |
| **Distribution** | Network investment cost (£k/home) | | | 2 | 11 |
| | Homes converted per year (thousand) | | | 400 | 100 |
| | Trench size (m) | | | 1 | 3 |
| | Traffic and access disruption | | | | |
| **Consumer premises** | Criticality of energy efficiency | | | | |
| | Appliance costs per household (£k) | | | 5 - 15 | 0 - 1 |
| | Household disruption | | | | |
| | Customer acceptance | | | | |
| | Visual and noise impact | | | | |
| **Regulation issues** | | | | | |

## 4.6 Impact assessment for flats

| FLATS | | Network type | | | |
|---|---|---|---|---|---|
| | | Gas grid | | Electricity | District heating |
| | | Natural gas | | Resistive | Large heat |
| | **Evaluation criteria** | | | heating | pump |
| **Supply side** | Heat production efficiency (%) | 85% | | 100% | 340% |
| | Energy supply cost (£/MWh in 2016)* | 50 | | 155 | 100 |
| | Heat supply cost (£/MWh in 2016) | 60 | | 155 | 45 |
| | CCS criticality | | | | |
| | Seasonal storage cost (£/MWh) | 30 - 80 | | > 50,000 | 80 - 8,000 |
| **Distribution** | Network investment cost (£k/home) | | | 0 - 2 | 6 |
| | Homes converted per year (thousand) | | | 400 | 100 |
| | Trench size (m) | | | 1 | 3 |
| | Traffic and access disruption | | | | |
| **Consumer premises** | Criticality of energy efficiency | | | | |
| | Appliance costs per household (£k) | | | 0 - 2 | 0 - 1 |
| | Household disruption | | | | |
| | Customer acceptance | | | | |
| | Visual and noise impact | | | | |
| **Regulation issues** | | | | | |

*** For electric resistive heating, this is based on standard electricity tariff, but could be less on Economy 7, dependent on heating system and usage patterns**

# 5. Discussion of impact assessments

In the following sections, 5.1, 5.2 and 5.3, the results for each of the three main solutions are summarised and discussed individually. Potential issues and solutions are identified and discussed.

The aim of this analysis is to identify the applications particularly suited to each option and the actions necessary to remedy any shortcomings recognised. For clarity and focus, the comparisons are segmented into the three main categories – supply, network and customer premises.

No attempt has been made to create an integrated basis for evaluation, only to compare individual elements across the options and to highlight the particular areas of concern for future action and development.

## 5.1 Repurposing the gas grids with hydrogen

### 5.1.1 Summary

Perhaps not surprisingly, an approach based on repurposing the existing network and reusing existing appliances scores very well on minimising network and household costs and disruption. In this regard, it is fortuitous that a programme of gas iron mains replacement is well advanced, and will create a low pressure gas distribution network well suited for use with hydrogen. Nonetheless, the concept must be proven in reality with particular regard to safety, practicability, cost and customer acceptance.

The solution could be well suited to the 85% of properties currently connected to the gas grid, approximately 22 million homes. On the basis of the definitions used in this paper, it is assumed that this would not be a solution for properties which have no existing connection to the gas grid.

Even though the focus of this paper is on hydrogen, rather than on bio-methane or alternative gases, none of which appears to offer the potential for sufficient scale (see sections 1 and 13.7), the main issue that will determine the viability of this solution is still on the supply side - it would be necessary to find a means to build facilities capable of producing hydrogen in the very large amounts needed and at a cost that would be financially and politically acceptable – this is not yet in sight.

For electrolysis to become a large scale means of hydrogen production, the costs of low carbon electricity generation must reduce very significantly.

Alternatively, CCS will be critical to the viability of hydrogen if production from natural gas remains the favoured means of providing hydrogen.

Safety and acceptance factors would also have to be dealt with, for example:

- Network and appliance standards
- Training and experience of network staff and installer/maintenance networks
- Odourisation and visualisation of hydrogen flames, if used for open flame appliances
- Public concerns about hydrogen (images of the Hindenburg) could be negative, despite historic use of hydrogen 'disguised' as town gas and increasing familiarity with it for transport.

### 5.1.2 Supply side assessment

There are no differences in the assessments for urban and suburban properties for the supply side impact assessments. Comments on each criterion are summarised below:

- **Heat production efficiency** – this is assumed to be similar to natural gas at the end user level, based on 85% boiler efficiency.

- **Energy/fuel supply cost** – the cheapest current form of large scale hydrogen production is steam methane reformation (SMR) – the combination of methane (from natural gas) and water to produce hydrogen and carbon-dioxide. Taking into consideration an increase in costs for CCS facilities and efficiency losses totalling 10-15%, the hydrogen cost is currently at least twice the wholesale cost of the equivalent amount of natural gas and means that the delivered price to the consumer, including all of the non-energy elements, would be at least 50% higher than the equivalent cost for a unit of heat from natural gas.

  It is also possible to produce hydrogen without the carbon dioxide by-product through electrolysis of water – the use of electrical energy to split it into its component parts of hydrogen and oxygen. However, since a unit of standard electricity is three times the retail price of natural gas and there are efficiency losses in the conversion process, the overall cost of hydrogen from this source is at least four times that of natural gas, and even more if low carbon electricity is used[55].

  The levelised cost of electricity production from renewables or other low carbon sources would have to come down to about £20/MWh to be cost competitive. In the context of current renewable energy costs in the US where onshore wind is coming in as low as £30-60/MWh and PV between £45-60/MWh[56] this could be feasible, especially for the period 2030 to 2050 when the higher volumes are needed.

  If electrolysis is used for hydrogen production, the cost evaluation is 'bright red' for the UK, where renewable costs are much higher than in the US even though, at times of high output and low demand, wholesale prices do come down to low or even negative levels which has led to consideration of 'power to gas' in which this excess renewable electricity could be considered as a partial source of hydrogen[57].

  For example, if the electricity system requirements were 400TWh each year, with intermittent renewables providing 75% of this output, then if 15% of this were 'spilt' (when production exceeds demand), and instead used for hydrogen production, then after accounting for process losses, this would equate to about 32TWh – about 8% of projected space heating and hot water requirements, after accounting for projected energy efficiency improvements. However, for this hydrogen to be 'free' or low cost, the operator would need to forego the earnings for 15% of the output, which in current economic models is compensated for by constraint or curtailment payments.

  To be capable of meeting more significant demand from the heat sector, hydrogen production would require dedicated electrolysers. For instance, if 25% of domestic and commercial space heating and hot water requirements (roughly 100TWh) were to be supplied by hydrogen from electrolysis, this would require the following (based only on energy output and assuming adequate overall hydrogen supply and storage facilities):

  - 15GW of dedicated nuclear or
  - 25GW of dedicated offshore wind or
  - 40GW of dedicated onshore wind or
  - 95GW of dedicated solar PV.

[55] Theoretically, at £80/MWh and an efficiency of 70%, the cost would be about £115/MWh
[56] https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf
[57] Championed in the UK by ITM Power

- **Heat supply cost** – the overall cost for heat produced from hydrogen is also affected by the efficiency of the boiler, which will be similar to that of natural gas boilers, but the dominant impact on the cost of a unit of heat will be the higher costs of hydrogen fuel.
- **CCS criticality** – CCS will be absolutely critical for steam methane reformation (SMR), which combines methane and water to produce hydrogen as well as carbon dioxide. This is currently the least cost technology. If production is based on electrolysis using low carbon electricity, which results in little or no carbon dioxide, the criticality evaluation is 'deep green'.

  It is also worth considering that hydrogen production from natural gas might be a more effective way of deploying CCS. For the capture stage of the process, steam reformation of gas provides continuous and high concentrations of $CO_2$, which could be efficiently captured. In comparison, the capture phase for use in the power sector is less efficient due to relatively low concentrations of $CO_2$ in flue gases, especially from gas generation (when compared to coal), and due to the intermittent running of the plant in anything other than guaranteed baseload electricity production. Nevertheless, there are significant remaining uncertainties about CCS which would have to be clarified before embarking on the steam reformation of gas + CCS route and which could fundamentally undermine this pathway. It is interesting to note that the largest scale plant combining steam reformation of gas and CCS was set up in Texas[58] for the purposes of Enhanced Oil Recovery, which requires reliable and continuous sources of carbon dioxide.

- **Storage** - One key benefit of a hydrogen solution is the flexibility and resilience provided to the system by having a storable fuel. Hydrogen can be stored, albeit less effectively than natural gas since the volume energy density is much lower (about one third). This can be done under pressure in the network to provide short term storage, as well as in salt caverns, depleted reservoirs etc. to provide the large capacity, long duration facilities for seasonal storage[59]. The costs will be about three times higher due to the lower energy density of hydrogen for a given volume and pressure[60].

  NB Hydrogen has potential added benefits that have not been evaluated here, in that it also could allow cross-sectoral synergies with the transport and electricity sectors – e.g. use of hydrogen for vehicles, or as a source of balancing and system services for electricity.

### 5.1.3 Distribution assessment

The assessments for urban and suburban properties for the distribution impact assessments are the same. More detail is given in Annex A and comments on each criterion are summarised below:

- **Network investment –** the bulk of the costs of making the low pressure gas network suitable for hydrogen are already being covered by the Iron Mains Replacement Programme (IMRP) where the old metal pipes are being replaced with polyethylene ones that are capable of transporting hydrogen at low pressure with very low losses (<0.001%[61]), although this figure would have to be assessed in practice for the UK gas network. However, in addition to this there is potential for hydrogen leakage from the connections between polyethylene pipes and other equipment which would also need to be assessed. This programme is due to be complete by 2032, although further work would still be needed by the gas network companies to prepare each individual part of the network for conversion to hydrogen.

  Work would also have to be carried out in each household in order to check and commission appliances as well as to install hydrogen meters. There would be other costs associated with

[58] http://www.netl.doe.gov/File%20Library/factsheets/project/FE0002381.pdf
[59] http://www.eti.co.uk/wp-content/uploads/2015/05/3380-ETI-Hydrogen-Insights-paper.pdf
[60] See ref. 14
[61] See ref. 14

conversion and upgrades to other parts of the gas network. Overall the model shows an undiscounted cost will be about £300/household. This is lower than the figure of £490 per household estimated by Dodds and Demoullin in 2013[62], but section 5.1.4 separately identifies a further potential cost of up to £1,000 for some households for appliances not covered by the distribution programme which means that the total average costs are more comparable.

Further clarification of the technical and economic aspects of a conversion programme will be published soon by Northern Gas Networks, who have been developing a fully costed and detailed plan for the conversion of Leeds to hydrogen.

- **Homes converted per year** – it is to be expected that the conversion rate for this process involving no excavation works on the networks can be considerably faster than for other options. However, there are likely to be other constraints associated with the deployment of upstream assets such as SMR deployment, CCS or electrolysers. For these reasons the maximum annual rate of conversion has been limited to 1 million homes. Comparison with the 10-year programme to convert homes from town gas to natural gas in the 1960s/70s and the 30-year programme to complete the IMRP for gas to an estimated 13 million homes currently underway suggests that this rate is reasonable.

  Another way of looking at the conversion rate is to take a unit for changeover comprising 2,500 households, based on easily isolatable part of the network which could be worked on and converted without impact on other users, where if each gas technician converts 3 households per day, it would take a team of 40 technicians a month to complete. So for a modest size city with 300,000 households it would take 3 teams just over 3 years to complete the conversion.

- **Trench size** – this is not relevant since no further pipes need to be replaced or installed for hydrogen conversion, although there may be some upstream replacement of assets not considered under the IMRP but which would need replacing for hydrogen.
- **Traffic and access disruption** - this is not relevant since no further pipes located in the street and adjacent to households would need to be replaced or installed for hydrogen conversion.

### 5.1.4 Consumer premises assessment

There are no differences in the assessments for urban and suburban properties for the consumer premises impact assessments. Comments on each criterion are summarised below:

- **Criticality of energy efficiency** – in the absence of a more cost effective production process for hydrogen, the energy costs for the end user will be more expensive than natural gas and therefore will become more sensitive to the energy efficiency performance of each building. (NB as stated elsewhere, cost-effective energy efficiency measures are always worthwhile and lowering energy consumption will also reduce the volumes of hydrogen that need to be produced and of any carbon dioxide that must be stored.)
- **Appliance costs** – as with the conversion programme in the 1970s to move from town gas to natural gas, it is assumed that in a move to hydrogen, the bulk of the household gas appliance conversion cost would be included within the gas network conversion programme. Up to an additional £1,000 may be required in some households to cover open flame gas appliances, such as gas fires and cookers, that may need to be replaced by the householder. This is likely to be necessary in relatively few homes and the overall costs of conversion can be considerably reduced if product and appliance regulation is introduced early enough to ensure most equipment is already hydrogen compliant.

[62] See ref. 14

- **Household disruption** – if dual-fuel appliances have been mandated sufficiently in advance of the conversion programme, then there is virtually no impact on householders beyond a safety check and recommissioning of the supply. Even where the householders' gas appliances do still have to be converted for hydrogen, then the level of disruption is likely to be little more than they would experience with an annual service. If older appliances cannot be converted this may inconvenience the customer.
- **Customer acceptance** - once converted, the output from the appliances running on hydrogen should be similar to natural gas and the customer 'heating experience' should be similar. It is possible that there will be issues of consumer concern about hydrogen which could impact adversely on acceptance, and this should be considered as part of any roll-out programme. If hydrogen becomes a more common sight for use as a 'clean fuel' in vehicles, this may aid acceptance of its use for heat.
- **Visual and noise impact** – there will be no adverse effects from the conversion.
- **Regulation issues** – existing regulation covers both networks and supply. Changes would be required for hydrogen, e.g. it would be necessary to incorporate the natural gas conversion technology (steam methane reformation or electrolysis) in the use-of-system charge. The costs associated with assets for carbon dioxide transmission and storage are likely to be a separate regulated activity, particularly if they support other assets such as power generation. Regulation in the form of appliance standards could be introduced early to minimise the cost and disruption from the switch-over. New health and safety regulations will be needed to cover specific aspects of hydrogen usage.

## 5.2 Electrification of heat

### 5.2.1 Summary

There are two main routes to electrify heat – heat pumps and resistive heating (with or without storage heaters – dependent on consumption patterns and the availability and attractiveness of off-peak tariffs like Economy 7).

Heat pump solutions use energy very efficiently and, as a result, consume less overall than direct resistive heating solutions, offsetting the higher cost of electricity and meaning that the overall running costs can end up being similar to those of natural gas, as shown in this paper. In terms of performance, heat pumps could be used to replace gas boilers or liquid/solid fuel solutions in urban, suburban and rural areas. In order for this to be possible, it will be necessary to overcome the hurdles to deployment – heat pumps are currently costlier to purchase and install than gas boilers, and have the potential to cause significant disruption in and around the consumer premises during the transition due to the need to install the sometimes bulky fan unit and, in some cases to replace the radiators[63].

Resistive heating is a low cost solution and easy to install. It is particularly suitable where the space heating requirement is already low, as with well insulated modern flats and maisonettes in multi-storey buildings, or where a suitable retrofit programme can be carried out in conjunction with the conversion. The inherently lower energy consumption levels, combined with the lower capital costs of equipment and installation can offset the higher costs of electricity (approximately three times the equivalent unit cost of natural gas). There may also be further scope to reduce cost since resistive heating offers considerable potential for demand side management to take advantage of low tariff periods.

For any significant transition to either electric solution, there will be a need to reinforce the electricity network, to source additional low carbon generation capacity as well as to provide a means of dealing

[63] http://www.energysavingtrust.org.uk/domestic/air-source-heat-pumps

with, and paying for the additional seasonal variation that heat demand will impose on the electricity network.

### 5.2.2 Supply side assessment

There are no differences in the assessments of using heat pumps for urban, suburban and rural properties in the supply side impact assessments. The assessment in flats is for direct resistive heating which does show differences to the other property types. Comments on each criterion are summarised below:

- **Heat production efficiency** – this will be considerably enhanced for heat pump use, where a relatively low level of electrical energy extracts up to three times as much heat from the ground, from water or from the air. This effect is measured by the pump's seasonal performance factor (SPF)[64] which is the average efficiency of the heat pump over the heating season and takes into account its coefficient of performance (CoP) as well as other factors such as de-frosting. For this analysis the SPF has been set at 2.7 to reflect the likely average level that will be achieved by air-source heat pumps over the year (see more detail in section 5.2.4).

  For resistive heating the end user consumption level will be slightly better than for natural gas due to its 100% heating efficiency.

- **Energy/fuel supply cost** – in most electrical solutions, as was shown in Table 1 earlier, the domestic retail unit cost of electricity is about three times that of natural gas. For direct electrical heating the unit cost will be about three times higher. (NB This may be reduced by switching to an overnight, 'Economy 7' style tariff, depending on heating system and usage patterns – this has not been assessed for this paper).
- **Heat supply cost -** The overall costs of heat delivered can be attractive in comparison to natural gas for both heat pumps and direct heating, in the former due to the efficiency of the heat pump and in the latter, despite high unit costs, due to the low capital costs of the radiators in combination with low consumption levels.
- **CCS criticality** – Despite the Government recently announcing the ending of support for the CCS demonstrators, it is reportedly still promoting a role for CCS as one of the three potential routes to decarbonise electricity supply[65]. Therefore, CCS may still have to play a role in reducing the carbon intensity of electricity production alongside renewable and nuclear generation. Indeed, with the recently announced Government ambition for a significant new-build programme of gas-fired CCGTs, and the continuing push for shale gas development, CCS appears to remain a key requirement, if legally binding carbon targets are to be met. Since, as shown in Table 1 earlier, the carbon intensity of heat produced by electricity is currently still more than double that of heat from natural gas, it is essential that further decarbonisation of the electricity system is achieved to ensure that heat pumps, let alone resistive electric heating are providing a carbon reduction benefit.
- **Storage** – There is limited storage capacity in the electricity system (30GWh compared to 50,000GWh in the gas system) and the cost of new storage is very high in comparison to fossil fuels, hydrogen or even heat. This is borne out by comparing the costs of new gas storage investment for salt caverns or depleted reservoirs from about £30/MWh[66] with estimates for large scale electricity storage, which start from £120,000/MWh[67]. Even a recent example of the

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[64] www.gov.uk/government/uploads/system/uploads/attachment_data/file/225825/analysis_data_second_phase_est_heat_pump_field_trials.pdf

[65] http://www.businessgreen.com/bg/interview/2438510/lord-bourne-eyes-new-path-for-uk-ccs-supremacy

[66] See ref. 47

[67] See ref. 48

well-established, but geographically and regulatory limited pumped storage, with a scheme costing about £400m and providing 6,700MWh of storage equates to nearly £60,000/MWh[68].

Because the energy density of traditional fuels is very high, it has been possible to store large quantities of energy to bridge large seasonal changes in supply and demand patterns. Even with a shift from a 'just in case' approach based on stockpiles of fuel, to a more 'just in time' approach balancing electricity use and production short term or in real time, there is currently no equivalent in the electricity system which is able to combine the high energy output and extended duration needed to help manage seasonal variations in space heating demand. It is therefore critical that the system design and cost implications of managing the daily and, more significantly, seasonal swings of heat requirements are incorporated into any scenario for large scale electrification.

it is important to note that any electrification of heat will compound the challenge that is already developing within the electricity system itself, as coal generation comes to an end. The system resilience cost difference will be even more significant as coal storage has to be replaced – most coal stations have traditionally maintained 2–3 months' stock, roughly 20,000GWh in total, and this at little more cost than associated with the working capital deployed.

### 5.2.3 Distribution assessment

Annex B contains a detailed summary of the potential suitability as well as the resultant costs and impacts of electrification on distribution networks. Comments on each criterion are summarised below:

- **Network investment –** the prime localities to prioritise for electrification will have building types, local geography and occupation patterns that are most compatible with heat pumps, so it is assumed that for each of these locations it would be the dominant solution. Consequently, heat pump clustering on a circuit will be high and in many cases the affected circuits will require reinforcement to address thermal capacity, circuit voltage drop[69] and loop impedance[70]. Loop impedance could be particularly problematic with heat pumps kicking in frequently and causing local voltage dips. Therefore, it may often be the trigger for reinforcement, rather than thermal capacity.

  Reinforcement will be primarily required to support air source heat pump installation in detached, semi-detached and terraced properties, connected to underground LV circuits in urban and suburban areas. The installation of heat pumps will not only significantly increase overall household electricity demand but also the peak coincidence factor. This is because the heat pump will be operated at specific peak times and for sustained periods, particularly under cold weather conditions, with particularly high space heating and hot water demand in the morning and early evening periods in the winter.

  This will drive the need for extensive reinforcement of the low voltage and 11kV networks as well as for upgrading substations. Costs include measures for traffic management and street works. In the reference case, total costs per converted property are about £2k. This appears credible when compared with the equivalent cost for the IMRP of about £1k per property and, over 40 years, would equate to an undiscounted annual household cost of £50, in comparison to the current annual total network costs of approximately £150.

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[68] See ref. 49

[69] Voltage drop is a function of circuit loading and should not exceed 6%.

[70] When inductive devices such as heat pumps are switched on they can draw a starting current which may be several times normal levels. This can give rise to a temporary voltage dip or flicker which is predominantly determined by the loop impedance of the circuit and which should not exceed specified standards.

- **Homes converted per year** – For electricity it is assumed that a limit on the rate of network reinforcement will be necessary to minimise householder and wider local disruption to access, transport and business. From the analysis described in Annex B, a network reinforcement programme covering 10 million households over 25 years is achievable without the constraints used for IMRP being violated. This conversion rate would be equivalent to 400,000 homes a year.
- **Trench size** – at about 1m, this requires significant excavation which, unlike the gas IMRP, is not possible using directional drilling to reduce the length of open trenching, and is one of the reasons for the higher cost in comparison.
- **Traffic and access disruption** - the chosen reinforcement methodology would minimise the cable length needed and, in many instances, this could be accommodated in the footpath rather than the carriageway. However, in either case traffic and access disruption would ensue. The more densely populated the area, whether in terms of homes and businesses, utility infrastructure and/or traffic, the greater the disruption. This is reflected in the highest impact rating for urban settings, reducing for suburban and further still for rural ones.

### 5.2.4 Consumer premises assessment

Comments on each criterion are summarised below:

- **Criticality of energy efficiency** – both heat pump and resistive heating solutions are very sensitive to the energy efficiency performance of the building, albeit for different reasons.

  As discussed previously, the retail unit price of electricity is more than three times that of natural gas therefore direct heating with electricity can be very expensive in an inefficient building.

  Although heat pumps use much less electricity, this is only when they operate efficiently. For an air source heat pump (which must be used in most retrofit scenarios in urban and suburban environments due to lack of space for ground sourced ones) the efficiency or CoP falls with air temperature as shown in figure 5 below. For example, it can be seen that the CoP ranges from above 3.5 during the summer down to nearly 1.6 during the winter when usage it greatest.

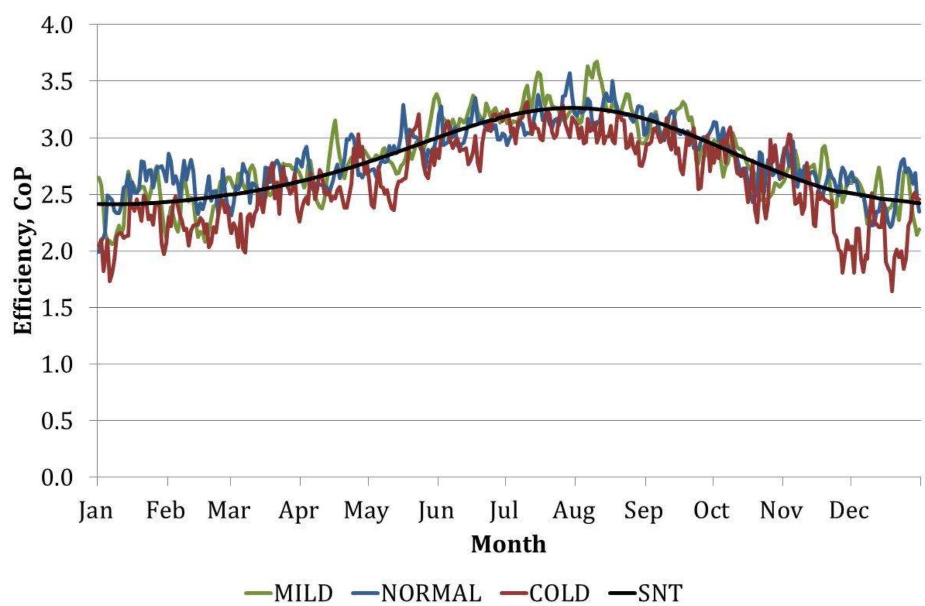


Figure 5 ASHP impact on efficiency (CoP) for different temperature scenarios[71]

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[71] See ref. 41

Changes in the CoP will have a direct impact on the heat output of the heat pump and this is illustrated in figure 6 below.

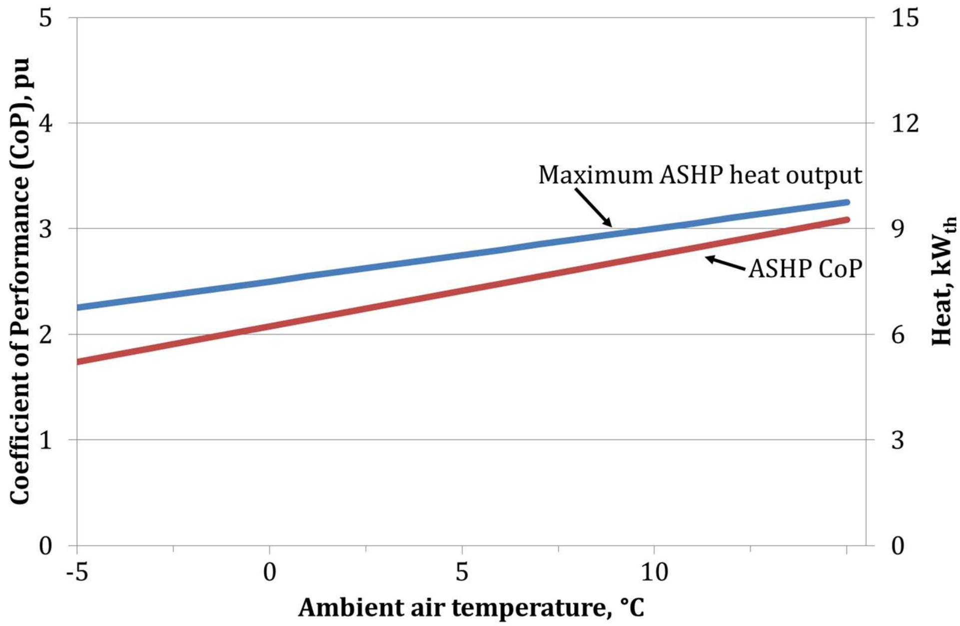


Figure 6 Coefficient of performance and heat output against temperature for 8.5kWth ASHP[72].

It can be seen that with a heat pump rated at 8.5 $kW_{th}$ the output will drop to below $6kW_{th}$ when the ambient air temperature falls to below $0^oC$. This means that they may not be able to meet demands for thermal comfort in poorly insulated or draughty properties and as a result will be expensive to run and/or ineffectual in providing the heat comfort needed.

- **Appliance costs** – the appliance costs for heat pumps are still expensive and currently have to be financed by the consumer with up-front capital or a loan. Furthermore, as discussed in the preceding section, in some properties it will be essential at the time of heat pump installation to additionally invest in energy efficiency measures. Most heat pumps produce hot water at a lower temperature ($55^oC$) than a gas boiler ($70^oC$) and so it may also be necessary for the consumer to replace existing radiators with new ones suitable for a heat pump[73].

  In contrast, the capital costs for resistive heating equipment are relatively low – this is why, despite the higher running costs, the overall cost to the consumer can be acceptable, especially where consumption levels are lower, as with well insulated properties.

- **Household disruption** – the level of householder disruption will be relatively low for direct electric heating solutions but much more significant for heat pumps, which are larger than modern gas boilers - space will need to be found for installation and/or a different location must be used. For ground source heat pumps, the land outside the building must be excavated for the installation of the heat exchange piping, while air source heat pumps require the installation of

[72] See ref. 41

[73] See ref. 41

an external heat exchanger plus fan unit and the drilling of external walls to bring the pipework into the home.

At present, nearly two thirds of gas boilers are combination boilers[74] which provide both space heating and instantaneous hot water at mains pressure. As these do not need hot water storage, it is reasonable to assume that most of these households no longer have hot water storage. Heat pumps require a buffer hot water tank of circa 200 litres for efficient operation, and the output of a heat pump would not be sufficient to meet the hot water demand of a typical household. Consequently, an immersion heating system (including tank) or some form of instantaneous hot water production will be required. Further disruption will be associated with replacing the radiators, if this is necessary for performance reasons, as discussed in the previous section.

- **Customer acceptance** – the disruption during the transition is likely to create significant customer acceptance issues. Moreover, the perceived 'heat experience' may be very different to a gas boiler - the heat output is substantially lower and so it can take much longer to warm the house to the desired temperature if the system is not operated continuously.
- **Visual and noise impact** – Air source heat pumps require the installation of external heat exchange and fan units. These look similar to large air conditioning units and can have both a visual and a noise impact. The noise from an individual unit will be regulated to an acceptable level, however in more densely populated areas, the cumulative visual and noise impact may become unacceptable.

  There will be no adverse effects for the use of resistive heating systems in flats.

- **Regulation issues** – No particular energy regulation issues arise with regard to either electrical solution. It is likely that product and performance standards for heat pumps will need to be developed further and it is also conceivable that planning restrictions may be imposed to deal with visual and noise impact, especially for cumulative effects.

## 5.3 District heating

### 5.3.1 Summary

District heating can provide a very energy efficient means of supplying heat. Since the heat production is centralised there is the potential to modify or exchange the heat source, either for better efficiency or lower costs and/or to improve carbon abatement potential. A system approach to design also allows for heat stores to be incorporated which help significantly to reduce the overall size and cost of the system by spreading peak demand over time.

The potential heat sources include, for example, CHP plant, geothermal, solar thermal and waste heat. CHP in particular has previously been used extensively for district heating across Europe, mainly driven by gas engines, coal or biomass. Although this may continue to provide a solution in the short term, for large scale, low carbon development, unless combined with CCS none of these fuels is likely to be sustainable in the volumes required in the long term. Since there is less experience with alternatives and there may also be potential complications in cost allocation between heat and power, or in assessing the wider power system impacts that may arise, CHP has not been assessed further in this paper.

In practice there may well be a mixture of heat sources used to feed district heating systems, but for the purposes of this study, the heat source chosen for illustration is a large heat pump installation. This is seen as a viable and enduring source of low carbon heat, and suitable for large scale deployment. This could include water source heat pumps using sea water, river, sewage or any other water facility suitable

[74] See ref. 7

for extracting heat[75]. It could also be a ground source heat pump supplying heat to a community based scheme, such as a block of flats or, in a rural area, a group of houses.

The distribution of heat to individual properties through relatively large insulated heat pipes means that space must be available and accessible under footpaths or road carriageways. The main heat network infrastructure will comprise twin pipes, each typically 500mm in diameter (including insulation), in a trench 2m wide. These will connect to smaller diameter pipework with final building service connections of about 100mm in diameter with insulation, so in some instances, total trench width may be up to 3m. These space requirements can limit the applicability of an otherwise efficient solution.

Theoretically, a scheme can be installed in any environment if there is sufficient, accessible space, but this can be challenging in more densely populated urban areas, which may be already highly congested with existing utility infrastructure. For example, it might require pipe works to be installed in tunnels which could be very expensive.

District heating schemes tend to work best in mixed use areas where the different consumption patterns of domestic, commercial, public service and leisure buildings are balanced out over the day and week. Historically, they have most effectively and extensively developed where there has been significant local or public authority involvement, and where there are key anchor load clients. However, as an alternative to the installation of a large number of individual household heat pumps a district heating or community based heating scheme could provide a viable option even in areas of low heat density such as rural housing[76].

District heating may be the only alternative to electricity for use where there is no current or proposed gas supply and could benefit from the introduction of appropriate new regulation to improve customer protection, facilitate scheme development and reduce both capital costs and the cost of capital.

### 5.3.2 Supply side assessment

Comments on each criterion are summarised below:

- **Heat production efficiency** – due to the potential for efficient heat generation through large scale heat pumps and other low carbon sources like geothermal and waste, the consumption levels can be significantly lower than for conventional natural gas boilers. A heat pump operating at this scale could have a Seasonal Performance Factor[77] (SPF) of 400% meaning that for each unit of electricity input, an average of four units of heat can be extracted from the ground or a suitable water source. However, there will also be losses in the heat network. Depending on the design and operation of the heat network these can vary significantly and range from 10% to over 20% but overall European heat losses are estimated to be 14%[78], although with modernisation they can be lower. For the purposes of this analysis the losses have been set at an average of 15%, reducing the overall efficiency to 340%.
- **Energy supply cost** – Due to the potentially different heat generation technologies, there will be a range of capital costs and unit energy prices. The costs included in this section are the fuel/energy costs for the chosen heat pump solution. In this assessment using a large scale heat

[75] www.gov.uk/government/publications/water-source-heat-map
[76] http://cied.ac.uk/files/file.php?name=3525-cied-policy-briefing-01-heat.pdf&site=440
[77] Explanation here or elsewhere The CoP is the instantaneous efficiency of the heat pump. It is normally specified at a water flow temperature (35, 45 and/or 55 Celsius)) and an ambient air temperature (7 Celsius). SPF is the average efficiency over a period of time typically a year and will include auxiliary loads such as de-icing and a mix of hot water and space heating load. Note: SPF has multiple definitions and this is well described in https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/225825/analysis_data_second_phase_est_heat_pump_field_trials.pdf
[78] https://setis.ec.europa.eu/system/files/1.DHCpotentials.pdf

pump, the 'medium' business tariff for electricity of £91/MWh has been used which, together with the Climate Change Levy gives an energy unit price of £97/MWh.

- **Heat supply cost** - Combining the consumption efficiency of the heat pump, the energy supply cost and 5% VAT gives an overall equivalent cost of about £30/MWh of heat delivered which increases to about £45/MWh when an allowance for the capital and operating costs of the heat pump are added.
- **CCS criticality** – if biomass and biogas are discounted, district heating will, to a degree, be dependent on CCS, whether indirectly through electricity consumption, as in this example, or directly for fossil fuel based heat generation or CHP. However, due to the range of heat generation sources and inherently lower energy consumption, this should be less critical than for other solutions. For instance, with the current carbon intensity of electricity at under 400g/kWh and a heat pump with average SPF of 4, the resultant carbon intensity of heat is just over 100g/kWh (after distribution losses) – just over half of natural gas boilers. Even if the carbon intensity of the electricity system only falls to 200g/kWh (not far below where a combination of unabated gas with renewables and some nuclear could achieve), the resultant carbon intensity of heat could be around 50g/kWh.
- **Storage** – The ability to incorporate heat storage into district heating schemes is a distinct advantage in dealing with daily fluctuations in heat demand, especially when mixed use schemes are in operation. Heat storage in various forms can provide short term, and where sufficient space is available, even seasonal storage. Nevertheless, the availability of energy sources to initially generate for the district heating scheme will depend on a flexible and resilient supply chain. If natural gas or hydrogen is used as fuel sources, then adequate storage will form part of the solution. If the energy source is electricity based, the commentary from section 5.2.2 must also be considered for district heating.

### 5.3.3 Distribution assessment

Annex C contains a detailed summary of the potential costs of district heating networks. Further comments are summarised below:

- **Network investment –** the costs of heat distribution networks are driven by the size of the insulated pipes (both supply and return), their costs and the labour and overheads needed for their installation. The values shown in the table comprise the capital cost of heat network infrastructure (including all labour and overheads), street heat network, connections to heat sources, network ancillary plant such as heat storage, pumps and heat substations, household service connections and the heat interface unit to be installed in each property. It should be noted that the household specific items - service connections and heat interface unit - form the majority of the cost of installation and are directly affected by the heat density resulting in higher costs for rural areas with low heat density, and lower costs for flats with high heat density.
- **Homes converted per year** – it is difficult to estimate the number of households that could be connected each year to district heating. An annual connection rate of 100,000 households would mean that by 2050 just over 3 million homes could be connected. This would amount to less than 10% of total households, which is below projections made by CCC and DECC[79]. Denmark is often cited as one of the leading examples of district heating, but it should be noted that when Denmark started its planned development in the 1980s it already had 30% of households connected to district heating networks[80]. It has subsequently taken 30 years to increase the number of connected households to the current level of about 1.7 million or 64% (March 2016). Over that period the average rate of connection was 30,000 homes pa with a maximum of

[79] https://documents.theccc.org.uk/wp-content/uploads/2015/11/Frontier-Economics-for-CCC-Research-on-district-heating-and-overcoming-barriers-Annex-1.pdf
[80] Expert evidence for this paper from Birger Lauerson

60,000 in 1993. Hence an annual roll out rate of 100,000 households for the UK would be more than three times that achieved by Denmark. This is not to say that a higher rate would not be possible but, considerably more effort would be required to address many of the constraints that are likely to be encountered if such a rate were to be achieved.

- **Trench size** – at up to 3m this can require very extensive excavation works which, unlike the gas IMRP, are not possible using directional drilling to reduce the length of open trenching, and is one of the reasons for the much higher cost. Indeed, in congested areas it may be necessary to use deep burial or tunnelling which would add very significantly to the cost.
- **Traffic and access disruption** – In all cases significant traffic and access disruption will ensue. The more densely populated the area, whether in terms of homes and businesses, utility infrastructure and/or traffic, the greater the disruption. This is reflected in the highest impact rating for urban settings, reducing for suburban and further still for rural ones.

### 5.3.4 Consumer premises assessment

Comments on each criterion are summarised below:

- **Criticality of energy efficiency** – Energy efficiency investment is always a sensible measure to carry out. However, since the cost per energy unit of a district heating scheme is lower than for other solutions, the relative criticality of the investment for the economic and technical functioning of district heating is less than in other options.
- **Appliance costs** – on the assumption that the existing space heating system can be linked to the district heating scheme and that the cost of the heat exchanger is covered in the distribution costs, only gas appliances like hobs, ovens or open fires would need to be considered for replacement with an electric alternative. The upper cost range of up to £1,000 should cover this, although it is expected that the full sum would not to apply to all households.
- **Household disruption** – The level of householder disruption will be limited to the installation of a heat exchange unit and some form of heat metering.
- **Customer acceptance** – on the assumption that the household's heating system can be directly connected to the heat interface unit, then the level of disruption can be kept to a minimum. Any gas appliances will need to be decommissioned and this will require their replacement with an alternative, e.g. gas hob, etc. Hot water storage is not essential but there will be design implications, e.g. higher rated district heat service connection.

  The customer 'heat experience' should be very similar to that with a gas boiler, with the system being just as flexible and controllable through the use of thermostatic valves and electronic heating controls. However, customers may be unfamiliar with heat being provided 'remotely' and the concept of losing the 'independence' offered by a gas boiler. At present district heating customers are locked in to a single provider and so the lack of supply competition might be an issue for customers. Nevertheless, in other countries, district heating arrangements have become the norm, rather than the exception, where customers conversely look at gas appliances with suspicion. However, none of this should distract from the challenge that customer and wider public perceptions could represent for the ability to implement such solutions.

- **Visual and noise impact** – there should be little or no adverse effects for the use of district heating schemes if underground pipes are used. (NB in some countries, heat networks are installed over ground and are visually intrusive).
- **Regulation issues** – at present heat networks are not regulated which leaves them at a disadvantage in comparison with other heat solutions with regard to customer protection and standards, powers of compulsory purchase, access and way-leaving for developers/operators and means that financing costs are significantly higher than for regulated network assets.

## 5.4 Impact assessment summary

### 5.4.1 General observations

All of the three options covered in this paper can be applied to decarbonising heat, but none is a 'silver bullet' that can be applied effectively everywhere. All three have attractive features and each also has a particular challenge to overcome, albeit in different areas.

As a consequence of the investment in the gas IMRP, the repurposing of the gas grids for use with hydrogen has become feasible, and could be an attractive option, especially for the 80% of properties in urban and suburban environments where the alternatives could cause significant disruption.

The most important precondition for using hydrogen would be the development of large scale, low cost production facilities. This could be by hydrolysis, which is currently very expensive, or through conversion of natural gas by steam methane reformation, but this would be dependent on the availability of CCS, which is currently not commercially or technically proven in the UK.

Electrification, through heat pumps, can be suitable for environments which are less densely populated and where access and traffic disruption from electricity system upgrades can be minimised. Disruption and cost to the householder can be reduced in applications where no energy efficiency improvements or radiator replacements are required and where hot water storage is available.

Direct electric heating is suited to well insulated properties, particularly flats and maisonettes in high rise buildings, where the space heating requirements are lower.

District heating can produce heat very efficiently and at low cost. It is well suited to areas of mixed use with strong anchor clients, ideally public sector bodies. Although most readily installed as part of new developments, district heating is also suitable in less densely populated areas as well as for flats and maisonettes in multi-storey buildings.

The choice of options, the rate of deployment and customer acceptance may well be determined by the non-cost impacts, rather than being made on the basis of least cost, market allocation models.

### 5.4.2 Urban housing

The repurposing of the gas grids is particularly suited to buildings in this category which together with suburban dwellings, for which it is also well suited, accommodate over 80% of the UK population[81]. This approach could avoid the significant disruption potential for individual households as well as for local access, transport and business activities associated with the other options. If (and it remains a big if) a solution can be found for the large scale, cost effective, low or zero carbon production of hydrogen, this solution would be ideal for this environment.

The costs and impacts of transition can be reduced by regulating in advance for the introduction of 'hydrogen ready' appliances capable of operating on dual fuels. Despite the roll out predominantly taking place after 2030, regulation would need to be introduced quickly to ensure that as many appliances as possible are in place, since they are typically replaced every 10 to 15 years.

### 5.4.3 Suburban Housing

The main difference between urban and suburban housing is the applicability of alternatives to repurposed gas grids. The lower population and traffic density in suburban areas mean that the adverse impacts of the transition to electrification or heat networks may be reduced. The enduring visual and noise impacts from individual and cumulative heat pump solutions would also be reduced.

[81] See ref. 40

### 5.4.4 Rural Housing

In rural areas, the choice narrows down to one between electrification, particularly for isolated rural properties, and district heating for some rural towns and villages. Electrification offers an opportunity for individual properties to decarbonise with less disruption and lower network costs than would be the case in urban and suburban environments. Hence the choice could simply come down to the specific economics of installing many heat pumps in individual households along with energy efficiency improvements and low voltage network reinforcement, compared to community based heat pump installation with a local heat network.

Small scale 'micro-nets', district heating schemes with a low thermal capacity operated by agricultural cooperatives for themselves and a few local users, have proved popular and easily implementable in other countries, like Austria[82], where, despite the poorer economics, the more manageable size of the developments has meant that they can be delivered more easily than larger, more economic schemes that generally involve a greater number of decision makers. Although there are other key drivers to the adoption of this approach which are more country specific and not immediately applicable to the UK, they will be important in understanding how barriers can be overcome and how the adoption of a district heating approach can be incentivised and delivered.

### 5.4.5 Flats and maisonettes in high rise buildings

The choice in this category of housing narrows down to one between electrification and district heating. Although for some applications there will be a clear favourite, in others the choice between approaches is polarised between the perceived independence, albeit at lower efficiency and greater operating cost, of electrification, versus the greater efficiency and lower operating cost of district heating, where there is the requirement to contract for the long term and give up switching rights.

[82] See ref. 78

# 6. Regulation and governance

## 6.1 Introduction

One of the greatest weaknesses in the current approach to governing the various elements of energy, is the lack of the decision making and design capability needed for heat, let alone for a full cross sector development of a decarbonised energy system.

As matters currently stand there is a significant risk, that either nothing happens, or that a piecemeal approach could develop and, in the worst case scenario, a consumer could be persuaded to replace a gas boiler with a heat pump, only to find that a new district heating scheme will be on offer shortly, and/or that after some have switched to heat pumps and others to the heat network, a new scheme replaces natural gas with hydrogen and the original gas boiler could have been retained and reused at a fraction of the cost.

Individual fuel and energy inputs, e.g. gas and electricity networks and appliances, are the subject of historic regulation and product standards, but an approach to the much more diverse and localised heat production requirements, or which recognises the scope and scale of the new decarbonisation challenge in the sector does not yet exist. As was mentioned in section 5.3.4, district heating in particular lacks the regulation that exists for other networks, leaving schemes at a disadvantage with regard to:

- customer protection and standards
- supply competition
- powers of compulsory purchase, access and way-leaving for developers/operators
- financing costs which are significantly higher than for regulated network assets.

## 6.2 New governance frameworks are needed

A new approach to the governance and regulatory framework for heat should be considered urgently to prepare for and then deliver the measures needed to meet the challenge of decarbonising heat. In particular, the review of arrangements should consider that:

- many of the current decision making frameworks relate to centralised energy and fuel supply, and have already evolved well beyond what they were originally created to do
- the changes needed for decarbonisation require a whole systems approach and current frameworks are based on an unbundled and fragmented one
- for the scale of the challenge, an unplanned incremental approach will be ineffective and inefficient
- there is very little at all with specific regard to the more local and differentiated requirements for heat
- the scale and extended duration of the transition requires long term clarity which is not provided currently.

## 6.3 Approach to heat governance

Due to the scale of the heat sector and the number of properties involved, heat decarbonisation can seem daunting, but with sufficient and timely preparation for the roll-out of an appropriate combination of approaches, and by spreading the delivery over suitable long term infrastructure programmes, heat decarbonisation can be made much more manageable.

As suggested by most decarbonisation scenarios, it is likely that delivery will need to begin in the 2020s but that the main large scale roll-out will take place in the 2030s and 2040s. The preparation should begin as early as possible, since many of the key elements for this may take many years to complete. For example, if hydrogen ready boilers are to be in place for the 2030s, it will be necessary to regulate for this almost immediately since the replacement cycle for a boiler can be 10 – 15 years.

Preparation is particularly important to allow the network owners and the regulator to establish the necessary plans to invest in sufficient time to enable the measures to be deployed to support heat producers and consumers.

The following sections explore the potential to develop a suitable approach to governance and regulation for the energy system as a whole and for the heat sector in particular.

### 6.3.1 Local and regional aspects

Although national standards and support are important, many elements of the energy system can, and should develop at a local and regional level. Local authorities also have responsibility for local planning, administration and policing of building standards, council tax and a number of other administrative functions which could be central to the success of decarbonisation investment.

For instance, a significant proportion of the necessary carbon emissions reduction from the heat sector needs to come from energy efficiency investment in buildings. Local authorities could be empowered to have better access to information about housing and occupancy, as well as to many of the tools needed to implement, support and police the necessary investments. They could then be well positioned to coordinate the delivery of such investment and, in many instances as building owners, will themselves have the direct responsibility for making the investments.

In contrast to the electricity system where many future developments are based on the ***de***-centralisation of energy production, most current heat solutions are already highly decentralised with, for instance, individual gas boilers in about 85% of homes[83], and decarbonisation solutions based on district heating would actually require a ***re***-centralisation of heat production.

With a variety of potentially mutually exclusive infrastructure solutions to decarbonise space heating and hot water provision, local authorities could play a critical role in determining which solutions are best suited to which areas, building types and occupier profiles and use this knowledge for zoning the solutions into appropriate areas, planning the transition and communicating with those affected.

With regard to heat solutions local authorities may be able to act as anchor clients and could be given powers to coordinate with other public and private bodies, and through the planning system to maximise the use of municipal buildings like schools, hospitals, offices and leisure facilities to provide some guaranteed demand for heat providers (potentially themselves as investors). In general, mixed-use heating systems (commercial, leisure and domestic) spread peak load better across the day and the week providing additional benefits.

It would be beneficial for capability to be developed in local authorities to enable them to make the necessary investments, not only in the energy system, but in the necessary human resources. To avoid every authority replicating the expertise and support facilities, national or pooled schemes should be considered – some examples of this already exist[84].

Overall, it is important to look at the most effective and efficient means of achieving the objectives, and experience in other countries has shown that, for investment in buildings and heat infrastructures, this is through the involvement of local authorities[85].

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[83] www.delta-ee.com/images/downloads/pdfs/Delta-ee_ENA_Full_Report.pdf
[84] www.districtheatingscotland.com
[85] Bolton, R. and Foxon, T. (2015) Infrastructure transformation as a socio-technical process – Implications for the governance of energy distribution networks in the UK

### 6.3.2 System design

Perhaps one of the greatest weaknesses in current governance and regulation of the energy sector overall is that none of the agencies or companies involved currently has responsibility to consider the full cross sector development of the energy system.

There have been suggestions by the IET for a fully independent system architect[86]. The role of an architect embodies a number of concepts which could be well suited to an energy system designer:

- develop the outline ideas into a concrete design and delivery plan
- pull together the necessary expertise from the individual specialisms (rather than having to be an expert in everything)
- develop budgets
- maintain an overview of delivery and deals with unplanned issues as they arise
- feed back to the client on an ongoing basis, agree any revisions and refine the plans accordingly.

To work for the energy system, the IET's basic idea would have to be extended to also cover gas transmission and all distribution networks, as well as national level issues covering the energy impacts of the heat and transport sectors. This could be further enhanced through a network of local architects working with, or for, local authorities and dealing with the regional aspects of distribution, heat and transport as well as energy efficiency investment in buildings.

Only with such a comprehensive approach to design will it be possible to recognise and value the system characteristics, and to optimise the respective costs, benefits and values for the whole system (local and national, where appropriate) rather than just its individual parts, which risks a higher overall cost and sub optimum system performance.

### 6.3.3 Regulation, oversight and policing of delivery

The current regulatory system is generally recognised to work well for monopoly networks. The role going forward could also be to independently oversee the delivery of the high level objectives set by the Government. This would be more akin to the successful work carried out by the Monetary Policy Committee and the Committee on Climate Change, as well as with regard to the responsibilities that Ofgem has carried out for monopoly network regulation and the administration of schemes like the RO, feed-in tariffs and the RHI.

The principles embodied in the regulatory regime and statutory frameworks that currently apply to other utility networks should be extended to cover heat networks in order to support developers and operators in their activities, as well as to protect consumers with regard to service provision, billing etc. and network investors with regard to price controls and regulated returns, in a manner they are accustomed to in other sectors.

This does not mean to say that identical regulatory arrangements for gas and electricity should be adopted for heat. Heat is in many respects different and there is relatively little existing infrastructure. The level of capital investment required is substantial in comparison to what would be traditionally needed for gas and electricity, where the assets have existed for many years and where capital investment can be recovered from existing users.

Heat should be treated in an equitable manner when compared with other options and it would seem sensible for the arrangements to be encompassed within a single regulatory environment along with gas and electricity and therefore logical to extend the remit of the existing regulator for gas and electricity to cover this, rather than to create a separate body.

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[86] www.theiet.org/factfiles/energy/brit-power-page.cfm

### 6.3.4 Effective market delivery – development, construction and operation

The role of the private sector, and competition within it, should be clarified and strengthened so that it can be used to maintain a downward pressure on costs as well as an efficient approach to delivery. This can be best achieved by encouraging private sector organisations to respond competitively to tenders for the element(s) of the delivery process for which they are best suited.

Combining this with a decision making framework that provides long term clarity and a governance structure that removes, or at least lowers political risk, and which suitably allocates the residual risks will bring further optimisation to the cost of capital.

Long term clarity about the Government's objectives can also encourage collaborative investment in innovation and standardisation as well as efficient production facilities in the supply chain, and allow these to develop over the many years and decades needed to bring them to readiness for deployment at scale. Therefore, a considered strategy and coherent policy framework which focusses support and resource on a limited number of options in the short term, can actually lead to greater diversity and competition in the long term, in a way that competition from the outset may not.

## 6.4 Additional actions

As well as the immediate need for Government to coordinate the development of a suitable governance and institutional framework, a number of sensible steps can be taken by the Government in parallel:

- engage the National Infrastructure Commission in developing strategies and governance arrangements for heat
- set up a national infrastructure programme for energy efficiency investment in buildings
- start a process to zone areas suitable for each heat decarbonisation option in each Local Authority area, building on heat mapping exercises already underway
- set up pilot schemes to examine the detailed, technical and economic feasibility of each option
- engage the regulator to consider a low voltage mains replacement programme for areas with a high likelihood of heat and transport electrification.

# 7. Conclusions and recommendations

## 7.1 General findings

To meet the legally binding carbon reduction targets set in the Climate Change Act and to deliver on commitments made in the Paris Agreement to keep the global temperature increase at or below two degrees Celsius, it will be essential to decarbonise the heat sector and, in particular, to focus on space heating and hot water requirements.

Incorporating energy efficiency and low carbon approaches into ***new*** buildings can be relatively simple and driven by appropriate building standards and regulation. However, since about 90% of ***existing*** homes will still be in use in 2050, the transition away from established heat solutions will require a large retrofit programme for energy efficiency in buildings and the development of new national and local systems of low carbon heat provision.

Energy efficiency investment in building infrastructure which reduces energy demand is one of the most cost effective means of reducing carbon emissions and should be carried out, as foreseen in all decarbonisation scenarios, as a national infrastructure priority.

The estimates for reductions in energy demand due to energy efficiency from the various scenarios range from 20 to 30% by 2030. These are significant, but do not fundamentally change the choice or impacts of any of the decarbonised heat solutions, all of which will require their own investment programmes. Even if these do not ramp up until the 2030s, decisions should be made during this parliament to allow suitable preparation for the large scale, long term transitions which will be required. This is essential for an efficient and smooth transition where cost and disruption to households, businesses and neighbourhoods is minimised.

It will be important to clarify and apportion responsibility for heat governance in a way that encourages a process of local zoning to ensure that at some point, a decarbonisation option will be available to each locality and household. It is important to avoid the uncontrolled deployment of multiple and very different heat infrastructure solutions in the same area, potentially undermining the business case for some or all options.

The private sector will play a central role in the delivery of low carbon heat. In some instances, competitive markets will continue to play a key role. However, network infrastructures retain the characteristics of a natural monopoly – and in future this will extent to heat distribution as well as electricity and gas. If new and upgraded network infrastructures are to emerge on a timeframe consistent with decarbonisation goals, then key decisions are needed in a timely fashion to facilitate the necessary infrastructure investment. In many cases networks take longer to develop than the supply and demand side measures that they connect.

Heat solutions and related energy efficiency investments are particular to each housing type, occupancy pattern and local geography, so the role of Local Authorities in coordinating and driving developments could be key.

The choice of options as well as the rate of deployment may well be determined by customer acceptance and the non-cost impacts, rather than being made on the basis of least cost, market allocation models.

## 7.2 Previous experience

There is little evidence of large scale retrofit infrastructure transitions in the UK, or internationally. The literature more often discusses the establishment and configuration of new infrastructure systems which develop over time, rather than transitions from one system to another. Some reports may cover transitions, but not infrastructure.

Co-ordinated local action backed by central government greatly increases the chances of success. Public ownership as well as local authority involvement appear to have been particularly important for success with district heating networks, which also work best if there is guaranteed demand, and ideally working with new developments.

Networks in general require a minimum customer and consumption density to be economically viable which has meant that, if left to the market, they develop more slowly or not at all in poorer areas.

## 7.3 The challenge

Heat provision is currently dominated by natural gas. The gas system, which has evolved over decades in the UK provides an almost uniquely flexible part of the wider energy system – not only does it deliver the energy needed, but also the ability to transport and store the fuel to meet the un-paralleled extremes of daily and seasonal heat consumption patterns, at the same time also providing wide geographical cover.

Particularly for heat, it is the peak requirement rather than average or overall consumption which determines the scale of the necessary supporting infrastructure for production, networks and storage. Replicating the sheer scale and cost effectiveness of the current gas system to achieve this would be challenging, and meeting the seasonal variation, particularly in peak requirements, may be the most difficult issue for alternative new solutions.

## 7.4 The contenders

All of the three options covered in this paper can be applied to decarbonising heat, but none is a 'silver bullet' that can be applied effectively everywhere.

All three have attractive features – avoided disruption in homes and roadways for hydrogen; universal availability for electrification; and efficient, low cost energy production for district heating.

Nevertheless, each also has a particular challenge to overcome, albeit in different areas – on the supply side for hydrogen; in the home for electrification with heat pumps; and in heat distribution networks for district heating.

### 7.4.1 Repurposed gas grids with hydrogen

By reusing the existing local gas grid and appliances, this option significantly reduces the impact of transition for householders, neighbourhoods and businesses. This makes the solution particularly attractive for more densely populated urban and suburban areas.

The conversion can be carried out relatively quickly by the gas network companies and the work needed in most buildings for conversion would be no more onerous than an annual gas boiler service. The overall costs of conversion can be reduced if product and appliance regulation is introduced early enough to ensure most equipment is already hydrogen compliant.

The main issue that will determine the viability of this solution is the technical and economic challenge of providing facilities capable of producing hydrogen in the very large amounts needed and at an affordable price for the end user.

SMR + CCS is currently the lowest cost means of (low carbon) hydrogen production, but adequate CCS facilities locally and nationally will be critical to the viability of this approach – without confidence in the availability of suitable carbon dioxide storage capacity it makes little sense to pursue this option.

This route would also be dependent on the availability and cost of natural gas, and always be more expensive, due to the equipment and processing costs, as well as the efficiency losses and $CO_2$ storage needs.

Electrolysis has been suggested as an alternative, especially 'power to gas' - using excess electricity from renewable electricity production. As shown in section 5.1.2, the sheer volumes of hydrogen required for a significant share of the heat demand would need the development of many dedicated, large scale renewable electrolysers to meet the enormous challenge. There are also questions about how low the cost of 'spilt' or excess electricity would be.

Apart from the potential for lower cost hydrogen at times of excess production, electrolysis is currently very much more expensive than SMR + CCS so, to be competitive, low carbon electricity generation costs would need to reduce considerably, although they do, at least theoretically, have the potential to be lower than existing gas costs at some point in the future.

One additional benefit of a hydrogen solution is the flexibility and resilience provided to the system by having a fuel which can be stored to cover seasonal variations using relatively low cost existing gas facilities.

### 7.4.2 Electrification

There are two main routes to electrify heat – direct resistive heating and heat pumps. The choice between them is dependent on consumption patterns and the availability and attractiveness of off-peak tariffs.

Simple resistive storage heating is a low cost, low impact solution which is easy to install. Since it uses electricity costing at least 50% more than natural gas (if an Economy 7-night rate tariff is available, otherwise up to 300%), and has none of the inherent low consumption benefits of heat pumps, its main use will be in off-gas-grid properties that are well insulated and have low space heating requirements. In such buildings, like well insulated flats – new build or the result of a targeted retrofit program to facilitate electrification - the very low capital costs offset the higher running costs, in comparison with the lifetime costs of other, higher capital cost options. Electric storage heaters provide opportunities for demand side management as well as greater utilisation of electricity generation and infrastructure assets possibly leading to lower levels of additional investment, but this has not been explored further.

Heat pumps can offer the benefit of high efficiency heat production, extracting nearly three times as much heat energy from their heat sink as the electric pump consumes. This can entirely offset the higher cost of electricity in comparison to gas. Because of the disruption to the household during installation they may face customer acceptance issues. The need for a high standard of energy efficiency for them to function may limit their applicability, or increase the costs. However, in low density rural areas not connected to the gas grid, they may provide the only low carbon heat solution.

For any significant transition to either electric solution, there will be a need to reinforce the electricity network which will add to the cost of the solution and lead to disruption, although upgrades to the network may anyway be partly justified on the basis of transport needs, solar PV installation or an age and condition related refurbishment. Minimising the impact of this will limit the rate at which roll-out can occur. The more densely populated the area, whether in terms of homes and businesses, utility infrastructure and/or traffic, the greater the potential disruption.

To deal with the increased need for electricity, it will be necessary to source additional low carbon generation. Perhaps the greater challenge will be to provide a low carbon means of dealing with, and paying for, the additional seasonal variation that heat demand will impose on the electricity network. It is therefore critical that the system design and cost implications of managing the swings of heat requirements are incorporated into any scenario for large scale electrification.

### 7.4.3 District heating

District heating can provide a very energy efficient means of supplying heat. It is also flexible - since the heat production is centralised, there is the potential to modify or exchange the heat source without disrupting individual users.

The distribution of heat to individual properties through large, insulated heat pipes means that space must be available and accessible under footpaths or road carriageways. In practice lack of space and/or the disruption to traffic and access can significantly limit the applicability of an otherwise efficient solution and will make it much slower than the other two options to roll-out. It may be the only alternative to electricity where there is no current or proposed gas supply.

Schemes work best in mixed use areas where the different consumption patterns of domestic, commercial, public service and leisure buildings are balanced out over the day and week. Historically, they have most effectively and extensively developed where there has been significant local or public authority involvement, and where there are key anchor load clients.

The 'heat experience' is very similar to that from natural gas and, with suitable thermostat valves and electronic heating controls, just as flexible and controllable. However, customers may be unfamiliar with heat being provided 'remotely' and still have the perception of losing the 'independence' offered by a gas boiler.

District heating faces a number of barriers that the other, more established networks do not, and could benefit from the introduction of appropriate new regulation to improve customer protection, supply competition, facilitate scheme development and reduce both capital costs and the cost of capital.

## 7.5 Governance and regulation

The changes needed for decarbonisation require a whole systems approach and current frameworks are focussed on an unbundled and fragmented one. Due to the scale of the challenge, an unplanned incremental approach could be ineffective and inefficient. The extended duration of the transition requires long term clarity which is not provided currently.

Current energy governance and regulation arrangements do not explicitly include heat. Where regulation exists, it is aimed at either the supply of gas and other fuels, or at product and appliance standards.

Many of the changes will require decades to complete and many years to prepare. It is therefore essential to begin the process quickly and to clarify and allocate responsibilities in a heat governance framework, in order to give consumers and the supply chain the necessary overview and opportunity to adapt. This is particularly important to allow the network owners and the regulator to establish the necessary plans to invest in sufficient time to enable the measures to be deployed.

Heat networks are particularly in need of regulation to provide adequate customer protection, to provide developers and operators with the necessary statutory powers of compulsory access and wayleaves as well as to regulate the asset base to reduce the cost of capital for the investment. To avoid regulation becoming a barrier, or something that delays district heating schemes, care should be taken about how it is introduced.

## 7.6 Local and regional aspects

Although national frameworks, standards and support are important, many elements of the heat system can, and should develop at a local and regional level.

With a variety of potentially mutually exclusive infrastructure solutions to decarbonise space heating and hot water provision, local authorities could play a critical role in determining which solutions are best suited to which areas, building types and occupier profiles and use this knowledge for zoning the solutions into appropriate areas, planning the transition and communicating with those affected.

In contrast to the electricity system where many future developments are based on the ***de***-centralisation of energy production, most current heat solutions are already highly decentralised with, for instance, individual gas boilers in about 85% of homes. Decarbonisation solutions based on district heating would actually require a ***re***-centralisation of heat production.

With regard to district heating solutions, local authorities could coordinate with other public and private bodies and utilise the planning system to maximise the use of municipal buildings like schools, hospitals, offices and leisure facilities to provide some guaranteed demand for heat providers (potentially themselves as investors).

Capability should be developed in local authorities to enable them to make the necessary investments, not only in the energy system, but in the necessary human resources. To avoid every authority replicating the expertise and support facilities, national or pooled schemes should be considered.

## 7.7 System design

One of the greatest weaknesses in the current system is the lack of the design capability needed for a full cross sector development of the energy system. Therefore, decision making could be further improved by having a body responsible for designing the system, and which could also provide expert, informed advice to decision makers. This aligns with the principle of a 'System Architect' but would need the concept to be extended to cover all aspects of the energy system and incorporate a network of local participants.

## 7.8 Recommendations

The recommendations summarised below do not aim to favour any particular option. The aim is to indicate that ***if*** a particular option is chosen or decision made, ***then*** the recommended course of action must be put in place:

### 7.8.1 Decision making and governance

- National Government should at the earliest opportunity coordinate a process with the relevant interested parties to review and establish a system of governance for heat
- In parallel to this it should initiate:
    - a national infrastructure programme for energy efficiency investment in buildings
    - a process to zone areas suitable for each heat decarbonisation option in each Local Authority area, building on heat mapping exercises already underway
    - pilot schemes to examine the detailed, technical and economic feasibility of each option.

### 7.8.2 Repurposing gas grids with hydrogen

- Set appropriate product standards to ensure that all new gas appliances are dual-fuel and hydrogen ready
- Develop safety standards for the use of hydrogen as a domestic fuel
- Develop a communication plan, along the lines of the 'digital switch over', to prepare consumers for any conversion
- Develop pilot schemes for a twin-track approach towards hydrogen production with both SMR + CCS and electrolysis, and encourage R&D to reduce the costs and increase the scalability of production facilities. For SMR, this must include a credible approach to CCS.

### 7.8.3 Electrification

- Consider a pre-emptive mains reinforcement programme, similar to the gas Iron Mains Replacement Programme (IMRP), to prepare for future electrification (also taking into account potential transport needs), especially for areas off the gas grid or as identified for electrification by any zoning process
- Develop system design for varying levels of heat electrification to cover low carbon generation and flexibility/resilience/storage needs
- Consider regulating against the installation of new or replacement gas boilers in any areas zoned for electrification.

### 7.8.4 District heating

- Extend existing legislation and regulation for customer protection, clarifying the approach towards compulsory connection versus freedom to switch for district heating
- Introduce statutory development powers and a system to regulate assets for district heating
- Consider regulating against the installation of new or replacement gas boilers in areas zoned for district heating, but taking into account the need to provide an interim solution for consumers to bridge any delay before district heating becomes available.

## 7.9 Potential areas for further research

Based on the findings of this report, it would be helpful for further work to be undertaken to:

- Develop whole system cost comparison models for heat decarbonisation options
- Examine governance and regulation models appropriate for the heat sector – both in the decarbonisation transition and in the ongoing operations
- Analyse EU and international developments of low carbon heat solutions and how these might aid the approach for the UK
- Investigate the whole system requirements for flexibility and resilience and how these can be maintained in decarbonised scenarios
- Investigate low cost, high volume production of hydrogen, particularly with regard to the potential criticality of CCS
- Investigate low carbon heat generation options for use with district heating, building on the work already done on heat mapping.

# Annexes and Literature Review (available in separate document)