MOTT MACDONALD

The path to zero carbon heat

What we need to do, and when: three roadmaps for decarbonising UK heat by 2050

Produced by the Net-Zero Infrastructure Industry Coalition

July 2020

Acknowledgements

Net-Zero Infrastructure Industry Coalition
This report was produced as part of the work programme of the Net-Zero Infrastructure Industry Coalition, formed in 2019 in response to the UK government's 2050 net-zero greenhouse gas (GHG) emissions commitment. Our launch report, **Building a net-zero economy: planning and practical action to transition our economic infrastructure for a net-zero future** is available at www.mottmac.com. Coalition members include Mott MacDonald, Skanska, the UK Collaboratorium for Research on Infrastructure & Cities, UK Green Buildings Council, Anglian Water, Transport for London, Engie, Pinsent Masons, Carbon Trust and Leeds City Council.

The aim of our coalition is to harness our collective expertise to support the delivery of UK net-zero. Our belief is that net-zero must become an industry-wide mission that transcends traditional business relationships to become a fundamental part of the way we all work, much like health and safety has over recent decades. Our vision is that the UK's engineering and infrastructure sectors rapidly mobilise to meet the net-zero challenge.

Working group
This project was led by Mott MacDonald with support from a working group of: Energy Systems Catapult, Engie, Leeds City Council, National Grid, Pinsent Masons, Delta-EE, University of Leeds, the UK Collaboratorium for Research on Infrastructure & Cities and the UK Green Buildings Council.

Contacts
If you would like to discuss the contents of this report or the net-zero coalition please contact:

Monica Donaldson-Balan
Heat decarbonisation workstream lead
Monica.Donaldson-Balan@mottmac.com

Sam Friggens
Global practice leader, climate change
Sam.Friggens@mottmac.com

Ross Ramsay
Net-zero coalition project manager
Ross.Ramsay@mottmac.com

Contents

Summary

In 2019 the UK became the first major economy in the world to make a legally binding commitment to net-zero greenhouse gas emissions by 2050.

Achieving this goal will require a transformation of the UK's infrastructure system at a scale and pace that have few historical precedents. This report focuses on one key aspect of this transformation: the decarbonisation of heat. It has been produced by a coalition of leading infrastructure industry organisations with many decades of experience delivering infrastructure, internationally. The report is therefore written with deep understanding of technical and commercial realities as well as the challenges inherent in driving major programmes at pace.

The objective of our work was to develop infrastructure roadmaps for a range of heat decarbonisation pathways for the UK. We considered the infrastructure value chain from energy generation, conversion and storage through to transmission, distribution and use. We have drawn out the key infrastructure components, timescales, challenges and requirements for each pathway; and identified key differences and commonalities.

Our work highlights the scale and complexity of the endeavour the UK has embraced in committing to decarbonise heat by 2050, and the key activities that must be undertaken over the next five to 10 years for the UK to achieve its 2050 goal. Our intention is to assist industry and government in planning, making decisions and taking action. At the same time, we recognise that our findings reflect only our current understanding based on the inputs we have received. We expect them to be challenged and developed.

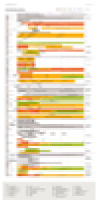
In developing this report we engaged with the Department for Business, Energy & Industrial Strategy, the Committee on Climate Change and the Confederation of British Industry.

Green growth

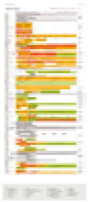
Our work was well underway before the emergence of the COVID-19 pandemic but its findings remain just as relevant today. Many of the critical actions that our report reveals are needed to ensure the UK decarbonises building heat by 2050 are also those that can deliver the jobs and investment needed for our economic recovery.

This report is supplemented by a technical annex as well as separate downloadable versions of our roadmaps.

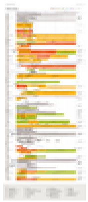
Download our roadmaps below.



Electrification



Hydrogen



Hybrid

Our technical annex is available below.

3 heat decarbonisation pathways

We chose to explore an electrification pathway, a hydrogen pathway and a hybrid pathway. We drew on analysis and modelling undertaken for the CCC to define the 'end-point' for each pathway in 2050, including indicative infrastructure quantities and requirements. Our work then focused on the milestones and activities needed to meet these requirements.

In doing this we have adopted a top-down, nationally homogenous approach as the basis for our analysis. However, much more decentralised futures will also be possible. In practice we might expect to see a palette of solutions and leadership emerge, with central, regional, city and local institutions collaborating to address the scale of the heat decarbonisation challenge.

We believe that future exploration of decentralised pathways would be beneficial, and that this could challenge some of the findings of this study – for example by reducing the amount of new infrastructure and investment required. But further work is not a prerequisite for action on the decarbonisation of heat. The insights in this report are intended to help in moving this key aspect of a net-zero economy forward.

We offer this work to the energy community for further debate and development.

Key infrastructure challenges

The three pathways explored as part of this work were all underpinned by common assumptions about the decarbonisation of heat and the wider economy.

Assumptions include increased demand for electricity over time as electric vehicles are rolled out, the critical need for hydrogen to help decarbonise heavy industry and peak power generation, and the need for widespread energy efficiency improvements to the UK's building stock alongside the deployment of district heat networks in densely populated urban areas.

1. Electrification pathway

The electrification pathway explores the widespread deployment of heat pumps in buildings across the UK, which when combined with the roll-out of electric vehicles leads to more than a doubling of total UK electricity demand by 2050.

The key infrastructure challenges here are:

Building enough new low-carbon electricity generation capacity to meet this demand
We assume this requires around 400GW by 2050 – four times more than today. The most difficult aspect of this is likely to be building large amounts of low-carbon baseload and mid-merit capacity, much of which would likely need to be in the form of nuclear power and natural gas with carbon capture, utilisation and storage (CCUS), as well as hundreds of gigawatts of renewables such as wind and solar. Large amounts of peaking capacity running on low or zero carbon fuels such as hydrogen will be needed to meet the challenge of peak heat demand.

Upgrading our electricity transmission and distribution networks to deal with much higher and more variable levels of supply and demand
Whilst upgrades to existing transmission lines will help boost capacity, the scale of electricity system expansion means new transmission capacity will also be required, most likely via sub-sea or underground high voltage direct current (HVDC) circuits. For distribution networks, essential measures to limit peak load and match local generation to demand must be implemented over the next five years, otherwise these networks could be overwhelmed by 2030.

Scaling up supply chains to deploy millions of heat pump systems and energy efficiency measures whilst ensuring standards and public support
In this scenario, by 2050 more than 19M homes have heat pump systems installed, in addition to the requirement for improved energy efficiency. A key challenge will be to scale up supply chains and train a workforce with the right skills.

2. Hydrogen pathway

The hydrogen pathway is based on the majority of buildings in the UK being directly supplied with hydrogen by 2050, which is combusted in hydrogen heating systems.

Key infrastructure challenges include:

Producing the huge quantities of hydrogen required to meet demand
Initially hydrogen production is assumed to be via autothermal reforming (ATR) of natural gas coupled with CCUS, with hydrogen produced from water through electrolysis coming on stream later. The complex early stage nature of these technologies means that deploying enough capacity by 2050 pushes the limits of what is realistically achievable from an infrastructure delivery perspective. CO_2 capture rates also imply some residual emissions in this pathway.

Building a largely new national hydrogen transmission system
If this is required alongside the UK's existing natural gas grid it will be a significant national infrastructure project in its own right, and one of the highest-risk critical-path challenges of this pathway.

Co-ordination throughout the hydrogen infrastructure value chain
Several national-scale infrastructure programmes will need to come together over 20 years, with new production and transmission infrastructure timed to integrate with the switchover of local distribution networks and buildings from natural gas to hydrogen.

Building public confidence
By 2050 17M homes are fed by hydrogen. A key challenge is likely to be public confidence in using hydrogen in buildings, the capability of installers and the safety of equipment. The workforce to deliver these conversions will be able to draw on existing skill sets (eg Gas Safe engineers) but retraining will be required alongside a trusted system of certification.

3. Hybrid pathway

The hybrid pathway explores the widespread deployment of hybrid heat pump systems. We assume the heat pump components of these systems meet most of a building's heat demand with the gas boiler components used at peak times, initially using natural gas but by 2050 mostly biomethane.

A hybrid approach
Combining electricity with low-carbon gases to meet heat demand has the potential to reduce the overall amount of infrastructure required by 2050 and, critically, reduce the required deployment rates for new technologies.

Infrastructure challenges
There are still major infrastructure challenges, however, with many of the same generation and network upgrade requirements as the electrification pathway. In addition, if there is an insufficient quantity of sustainable biomethane available to meet peak demand there would still be a requirement to convert and build hydrogen infrastructure (or risk not achieving zero carbon heating). A hybrid pathway also brings a risk of greater uncertainty about the UK's long-term heat decarbonisation strategy, making infrastructure planning decisions more difficult and delaying the mobilisation of supply chains.

Understanding hybrid pathways
Overall, our work points to the need for a better understanding of a range of hybrid pathways, including use of biomethane and hydrogen to meet peak heat demand and solutions tailored to local conditions and needs.

Critical activities for the next five years

Despite the long-term differences between the pathways, our roadmaps reveal they all require a set of common but urgent activities over the next five years:

Demonstrate critical new technologies at scale as early as possible in the 2020s so that mass-deployment can proceed from 2030 onwards (such as hydrogen production via ATR with CCUS, floating offshore wind, and advanced nuclear reactors).

Develop the regulatory, market and risk-sharing arrangements to support the mass-deployment of complex large-scale power generation, hydrogen production technologies, CCUS and CO_2 transport infrastructure – drawing on mechanisms such as the Regulated Asset Base model.

Continue to support major capacity upgrades to electricity transmission networks – for example by reinforcing existing lines with techniques used in other countries and developing and deploying new HVDC circuits.

Prioritise measures to manage peak load at electricity distribution network level, such as smart charging and time-of-use tariffs. Plan for more substantial upgrades by 2030.

Elevate energy efficiency in buildings to a national infrastructure priority – rapidly increasing installations, scaling up supply chains and building consumer confidence.

Increase deployment of heat pumps and hybrid heat pumps in line with the CCC's advice, at low-regret sites – via local initiatives, incentive schemes and trials in hard-to-convert buildings.

Accelerate the growth of district heat networks by developing regulatory and financial frameworks, enhancing consumer protection/ confidence and unlocking investment.

Build end-user confidence in heat decarbonisation measures by undertaking public engagement, installer training programmes, ensuring standards and compliance, and building local capability.

Provide clarity to supply chains and investors as soon as possible, for example by introducing a national digital heat map to show when and where different end-user solutions are preferred.

Keep hydrogen as an option by pursuing and expanding current studies into the feasibility of converting gas networks and end-user systems, with government taking a lead role co-ordinating activities.

The need for leadership, co-ordination and urgency

Decarbonising heat by 2050 requires these critical actions to be undertaken in the next five years and ongoing co-ordination between multiple streams of infrastructure delivery over the next three decades.

This will require leadership and collaboration at all levels of government – national government and devolved administrations, cities and local authorities – to achieve strategic direction and co-ordination, allocation of powers and responsibilities, and regulatory and incentive frameworks. These are essential to deliver the right infrastructure in the right places at the right time.

In its own report, **Net-zero: the road to low-carbon heat,** the CBI recommends a new national delivery body to formulate and steer a national plan for heat decarbonisation and to work with regions and cities to co-ordinate efforts across scales, sectors and geographies.

We agree with this recommendation. It is critical that institutional arrangements are put in place to provide broad strategic co-ordination of heat infrastructure across the UK, while empowering local and regional authorities to deliver solutions appropriate to their context and respecting the principle of subsidiarity. Unless such institutional arrangements are implemented at the earliest opportunity, it is difficult to envisage heat decarbonisation being pursued and achieved with the urgency and at the scale required.

Our roadmaps reveal the huge scale and complexity of the endeavour the UK has embraced in committing to decarbonise heat by 2050. We hope that this report will help government and industry understand what is required to make this happen.

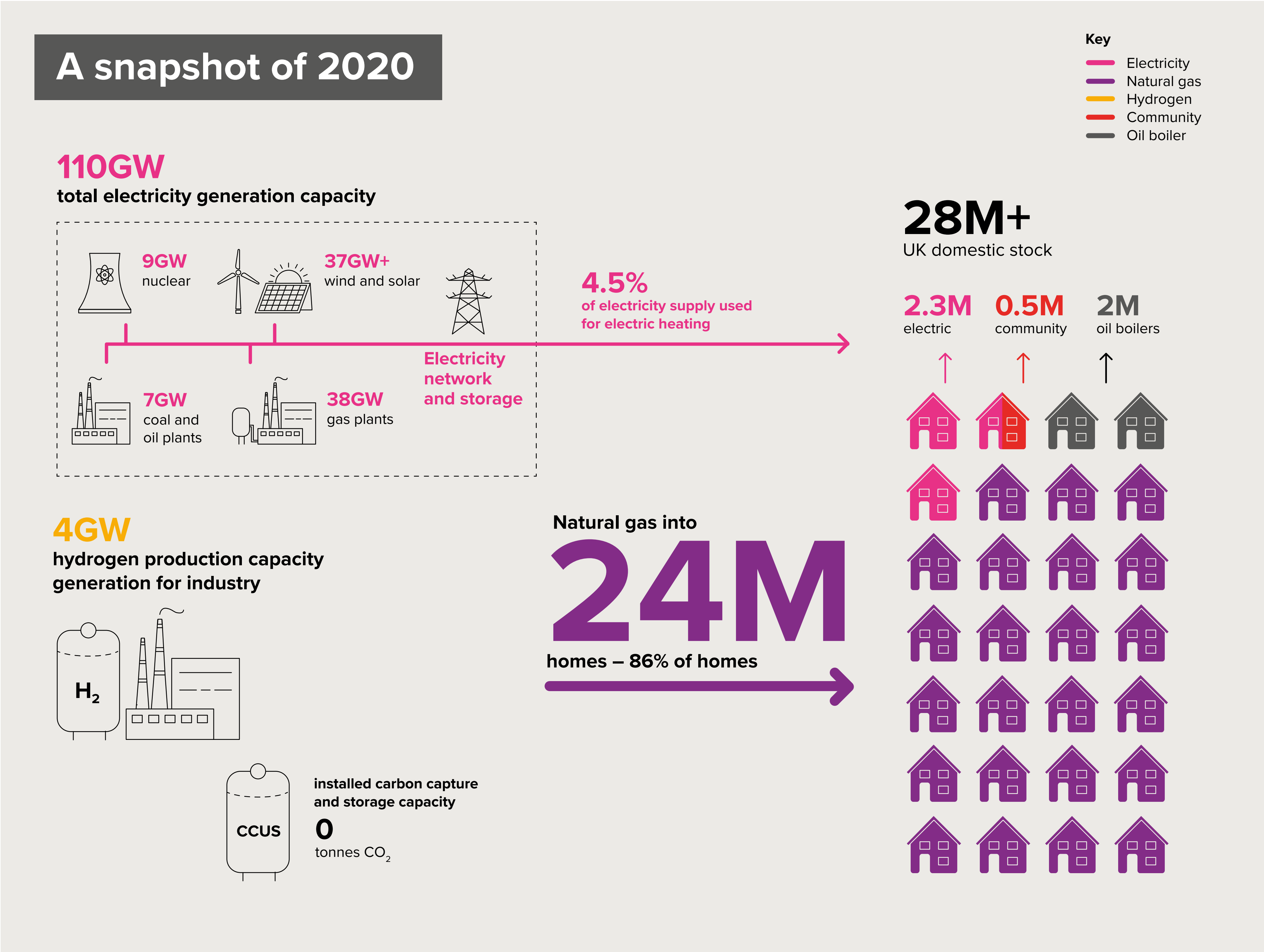
The challenge of heat decarbonisation

Heating and hot water for buildings make up around 40% of the UK's total energy demand, and 20% of its total GHG emissions.[1]

Most of this demand is met by natural gas that flows from North Sea production centres and import pipelines through a nationwide transmission and distribution system directly into our buildings. The rest is met through electricity, bioenergy and oil.

To fully decarbonise heat by 2050 this must completely change. Our use of fossil fuels to provide heat must be all but eliminated. Natural gas can no longer be used in our homes. New systems to provide virtually zero-carbon heat must be planned and implemented across more than 25M homes and millions more commercial and industrial buildings in less than three decades.

There are different potential solutions to this challenge, but none will be easy. The scale of infrastructure required, the urgent timescales, the complexity of co-ordination and the disruption to homes, institutions and businesses all make decarbonising heat one of the most difficult aspects of the UK's net-zero target. Only if leadership at all levels of government comes together with social buy-in and excellence in infrastructure delivery will this challenge be met. And only with a strategic, informed perspective now will the necessary actions be taken over the next five to 10 years.



1. CCC (2016) Next steps for UK heat policy

The CCC's advice to government

The CCC acknowledges the progress made since 1990 in reducing buildings' emissions – by more than 10% through efficiency improvements, grid decarbonisation and increased use of bioenergy – but says a far more ambitious approach is needed to fully decarbonise heat by 2050.

One of the CCC's core messages is that many measures are required under all of the UK's potential long-term heat decarbonisation pathways. Examples include requiring all new buildings to be energy efficient and zero carbon, the need to vastly improve the efficiency of the existing building stock, and the importance of large-scale district heat networks to supply heat in densely populated urban areas. It recommends that the government act now to implement these measures.

Beyond this, the CCC outlines options for how heat is generated and used in 2050. In its main net-zero scenario, most heat is generated from low-carbon electricity using heat pump technology with hydrogen playing a mostly niche role by topping up supply during the coldest periods of the year. However, the CCC also highlights alternatives such as the 'full-electrification' of heat and the possibility of hydrogen playing a much greater role.[2]

2. The most relevant CCC reports setting out these scenarios are: CCC (2019) Net zero technical report and CCC (2018) Hydrogen in a low carbon economy. In addition, CCC (2018) Biomass in a low carbon economy concludes that bioenergy should have only a niche role in providing building heat by 2050 because a finite sustainable supply of biomass will provide greater levels of GHG abatement when used elsewhere in the economy.

Uncertainty and the need for a strategic infrastructure perspective

Given the current uncertainties over the optimal approach to decarbonising heat, and recognising the long timescales associated with building and repurposing heat infrastructure, the CCC has recommended that the UK government develops a fully-fledged strategy for decarbonising heat in 2020 so that key strategic decisions can be taken in the 2020s.

As a step towards this goal, BEIS is currently undertaking work to explore different approaches to heat decarbonisation and is planning to publish a heat and buildings strategy later this year.

This report and its associated roadmaps are intended to inform and support the government's work in this space. By developing infrastructure roadmaps for three different heat decarbonisation pathways we aim to bring an integrated, strategic infrastructure delivery perspective to better understand what is possible, under what timeframes, and in what circumstances.

Uncertainty and urgency are the two key contextual themes that underpin decisions on heat decarbonisation that must be made in the next decade. Through our work we provide a grounded, practical view on how the tensions between these two themes can be navigated.

Our approach to developing infrastructure roadmaps

We selected three archetypal pathways as the basis for our analysis: a full-electrification pathway, a hydrogen pathway and a hybrid pathway.

The first two are intended to 'bookend' the range of possible scenarios from an infrastructure perspective, allowing us to explore a range of implications relating to infrastructure requirements and interdependencies. However, the reality is likely to lie between these two bookends.

Our hybrid pathway explores one set of possibilities, but there will be many others – including those using solutions and technologies not considered here.

None of our pathways are forecasts, and our work is not intended to endorse one scenario over another or to advocate a centralised future over more decentralised futures. We have drawn on existing studies and made our own assumptions and judgements where required. Our intention is to provide a transparent and sufficiently detailed set of infrastructure roadmaps to allow new insights to be developed. We did not examine the costs, benefits or wider trade-offs of each pathway; instead we focused on infrastructure delivery challenges and critical milestones in each case.

We proceeded in four stages:

1.

Review
We reviewed existing work to identify almost 90 decarbonisation pathways developed over the last decade by industry, academia and other bodies. This allowed us to understand the range of solutions already explored and extent of infrastructure analysis previously undertaken.[3]

2.

Select and define
Through discussions with BEIS and the CCC we selected and defined three decarbonisation pathways for our analysis. We based these on the CCC's net-zero report and drew on work undertaken by Imperial College London (ICL), and Element Energy and University College London (UCL).[4]

3.

Develop dependency maps
Through a collaborative process with a broad range of stakeholders we developed dependency maps for each pathway's infrastructure value chain, from generation to end-user. These maps – available in our technical annex – identify key activities, barriers, enablers and interdependencies on the route to a desired outcome.[5]

4.

Develop roadmaps
Based on key issues identified in the dependency maps we developed infrastructure roadmaps for each pathway from now to 2050, identifying the most challenging critical path activities. Our conclusions have been drawn through analysing and comparing these roadmaps.

By basing our pathways on analysis undertaken for the CCC we have adopted a 'top-down' nationally homogenous approach. Whilst this is useful for drawing insights and emphasising the need for a strategic approach, in reality we might expect to see different solutions in different areas, led by regions and cities. We also acknowledge that alternative more decentralised pathways are both possible and potentially desirable if heat decarbonisation can be achieved with greater benefits and at lower costs. We encourage future work in this area to explore a broader range of decentralised scenarios.

We used analysis by Imperial College London (ICL) and Element Energy and University College London (ICL) to define the 'endpoint' for each of our pathways in 2050, including indicative infrastructure quantities and requirements. The figures in this report for 2050 are mostly drawn from their analysis. Our work then focused on milestones and activities needed to meet these (or similar) requirements. The figures in this report for the period up to 2050 are our own, unless stated.

3. This literature review was undertaken by Josh Turner, Pepa Ambrosio-Albala et al. from the University of Leeds. Refer to Turner et al (2020): https://doi.org/10.5518/824.
4. See: ICL (2018) Analysis of alternative UK heat decarbonisation pathways, and Element Energy and University College London (2019) Analysis on abating direct emissions from 'hard-to-decarbonise' homes.
5. Dependency mapping is a tool used for planning and decision-making. It involves developing graphical representations of complex ecosystems of activities (and their interdependencies) for a project or objective. We developed two dependency maps for the electrification and hydrogen pathway – one focusing on energy generation, transmission and distribution; the other on end-users. Two cross cutting maps were developed for heat networks and energy efficiency measures. Our end-user maps drew on insights from UKGBC members via a workshop held on 9th January 2020.

What do the pathways look like? Endpoints and key infrastructure challenges

Common assumptions underpinning all of our pathways

All of our pathways are underpinned by common assumptions about the decarbonisation of heat and the wider economy:

Demand for electricity will increase as the economy is electrified
The expected switchover to electric vehicles in the 2020s and 2030s means that total UK electricity demand will substantially increase even without the electrification of heat.[6]

Hydrogen will be needed for the UK to reach net-zero even if it is not used to provide building heat
For example, it will be needed to decarbonise parts of industry and it is likely to be needed for peaking plant in the electricity system. This will require at least some hydrogen production and use in the UK by 2050, most likely in and around the UK's industrial clusters.

The energy efficiency of the UK's building stock will need to be substantially improved
Much of the UK's existing building stock is old and poorly insulated, and most of this will still be standing in 2050. We assume that over the coming decades measures such as loft insulation, cavity wall insulation and solid wall insulation are deployed in more than 20 million homes and millions more non-residential buildings, reducing total heat demand by around 25%.[7] These measures have the potential to bring other benefits such as lower consumer energy bills and warmer homes.

Meeting peak heat demand will be a major challenge
The UK's current natural gas based system is very effective at meeting big swings in heat demand and providing security of supply during cold winter weather. We assume that energy efficiency and thermal storage solutions will reduce but not eliminate these peaks in demand. The need to instantaneously balance heat supply and demand is a fundamental requirement for all our pathways.[8]

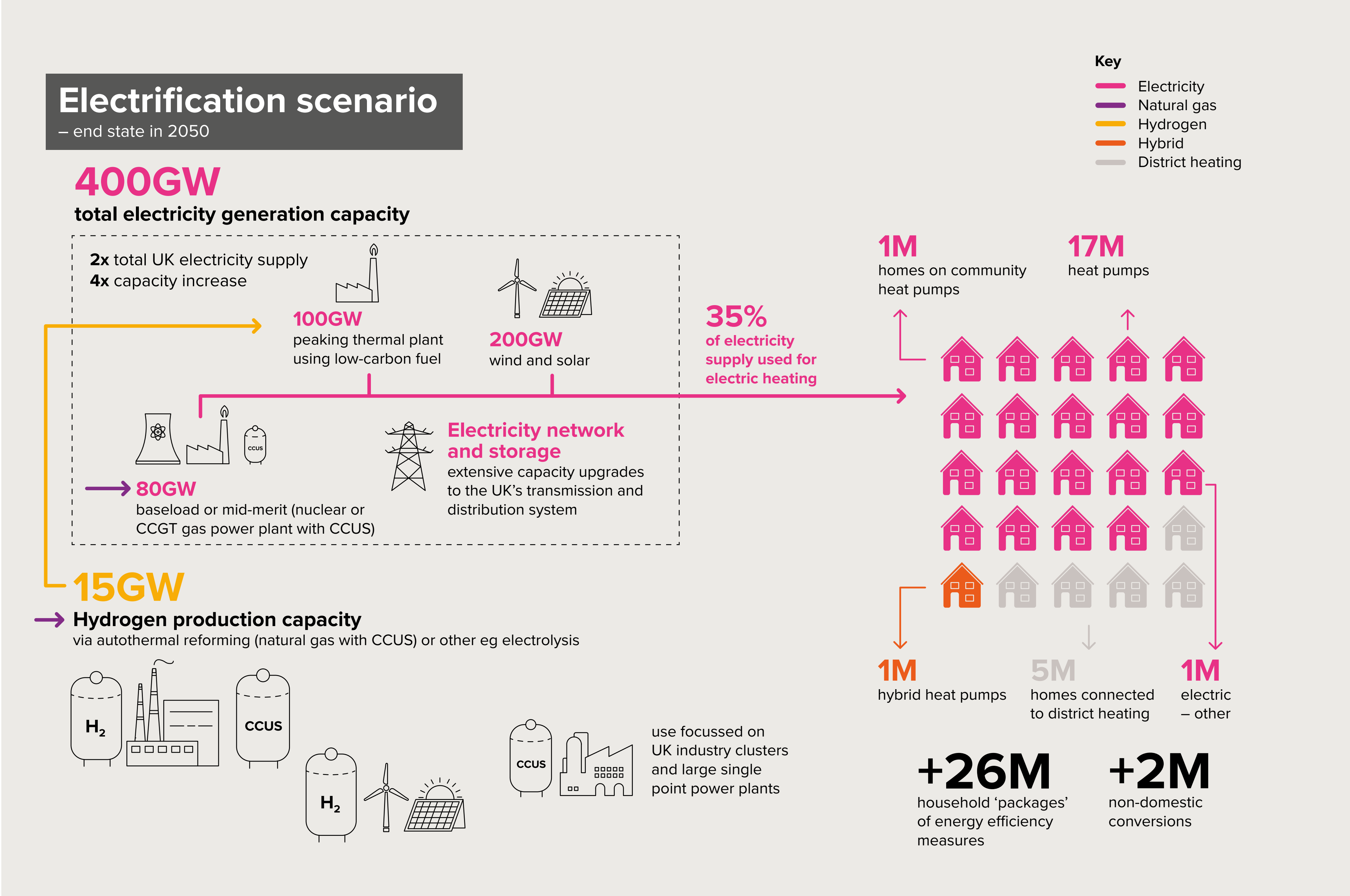
Large-scale district heat networks will be an effective way of delivering heat in dense urban areas
Analysis by the CCC, the Energy Systems Catapult and others points to large-scale district heat networks being the most effective way of delivering heat in dense urban areas, regardless of the mix of technologies that energises these networks. In all our pathways we assume that over 5 million homes are connected to district heat by 2050.[9]

A niche role for bioenergy
Sustainable biomass is a finite resource that should be used to maximise overall GHG abatement across the economy in 2050, including through its use with carbon capture, utilisation and storage (CCUS). This implies bioenergy will have only a relatively small long-term role directly supplying building heat (eg in small-scale local uses, top-up supply in off gas-grid homes, some limited use of biomethane into the gas-grid).[10]

There may be a trade-off between solutions for meeting the challenge of peak heat demand. 'In-home' measures to reduce peaks include energy efficiency, storage and smart technologies. Wider infrastructure solutions include more energy generation and network capacity. In reality both of these will be needed, but the optimal balance will need to be assessed over time, with implications for overall costs and end-user impacts.

6. ICL's analysis suggests total UK demand will increase by more than 50% by 2050 even in scenarios that do not see the widespread electrification of heat.
7. In line with the CCC's Further Ambition scenario in its 2019 net-zero report.
8. For a recent estimate of variations in the UK's heat demand see: Watson et al (2019) Decarbonising domestic heating: What is the peak GB demand? Energy Policy, Volume 126, March 2019, Pages 533-544.
9. In line with the CCC's net-zero report. For further reading see ESC (2018) District heat networks in the UK: potential, barriers and opportunities, and DECC (2013) The future of heating: meeting the challenge
10. See CCC (2018) Bioenergy in a low carbon economy

Electrification pathway



A snapshot of 2050

In an electrified heat scenario most buildings in the UK by 2050 will use heat pumps that draw on zero-carbon electricity from the grid to harness energy from the ground or air to provide decarbonised heat. Some systems will be based on 'hybrid' heat pumps, supplemented by electric resistive heaters or biofuels to meet peak demand. Several million buildings in cities will be linked to large-scale district heat networks comparable in size to those currently used in Copenhagen and Helsinki. These in turn will rely on community-scale heat pumps, combined heat and power (CHP) plants and 'waste' heat from sources such as industry or sewage water.[11]

To reduce and manage electricity demand, virtually every building in the country will have benefited from energy efficiency improvements. Storage, flexibility and smart technologies will have been widely deployed. Even with these measures, the electrification of heat alongside the roll-out of electric vehicles is likely to result in total annual UK electricity demand more than doubling by 2050.[12]

To meet this demand exclusively through low-carbon technologies, ICL's modelling suggests the UK's electricity generating capacity needs to quadruple to around 400GW by 2050. This implies a massive scale-up of technologies such as wind, nuclear, solar and natural gas with CCUS; and associated capacity upgrades to electricity transmission and distribution networks.

To meet peak heat demand on cold days and during long periods of still winter weather, over 100GW of this capacity comes in the form of peaking thermal plant (eg open-cycle gas turbines) running at low capacity factors using hydrogen or other low-carbon fuels. This requirement assumes measures to reduce peak demand such as preheating (ie heating buildings earlier than would otherwise be done) and thermal storage systems (eg hot water tanks) have already been widely deployed.

ICL's modelling includes large amounts of solar PV by 2050 (130GW vs 14GW today). Decentralised capacity can help meet demand locally and reduce burdens on transmission networks. However given the overall quantity of electricity required, large amounts of centralised generation will also be needed. ICL's modelling includes 75GW of wind in 2050 (vs 24GW today) and 45GW of nuclear (vs 9GW today).

11. An example of a technology that could potentially be used to provide both power to the grid and heat for district heat networks is Small Modular Nuclear Reactors (SMRs). See ETI (2015) The role for nuclear within a low carbon energy system.
12. These figures are derived from ICL's Elec [0] pathway. See: ICL (2018) Analysis of alternative UK heat decarbonisation pathways. The [0] implies there are zero $MtCO_2e$ emissions from heating UK homes in 2050. Electricity generation capacity increase from ~320 TWh p/a in 2019 to ~767 TWh p/a in 2050.

Key challenges

Our work highlights three critical infrastructure challenges in delivering the electrification pathway.

Generation capacity
400GW of installed low-carbon capacity by 2050 implies deployment rates of more than 10GW every year for the next three decades. For comparison, between 2016 and 2019 actual deployment was around 4GW p/a – principally from wind, biomass and solar.[13] Achieving 400GW by 2050 will require recent successes in offshore wind delivery to be scaled up and extended to a wide range of low-carbon technologies.[14] Supply chains will need to be rapidly developed, which in turn will require reliable financing and delivery mechanisms, a strong industrial strategy, skills development and investment in emerging technologies such as floating wind and HVDC submarine cable circuits.

The most difficult aspect of this generation challenge is likely to be deploying the large amounts of low-carbon baseload and mid-merit capacity (between 50GW and 80GW) that ICL's modelling suggests is needed.[15] Much of this capacity would likely need to be in the form of nuclear power and natural gas with CCUS.

- In terms of technology development this will require radical changes to industrial norms to compress "typical" timelines for demonstrating complex capital-intensive new technologies and bringing them to market. This is a common challenge for new technologies across all our pathways and implies a level of risk beyond that which the private sector is normally willing to accept, in turn requiring an active role for government.
- In terms of deployment, the nature and size of the technologies in question mean both site selection and financing will be major challenges. Overcoming the former will require a strategic, flexible approach to site identification and consenting that addresses public safety concerns while facilitating a regular drumbeat of projects. Overcoming the latter will require the timely implementation of suitable financing approaches such as a Regulated Asset Base model.

Over 200GW of wind and solar capacity is deployed by 2050 in this pathway, up from below 40GW today. While challenging, the nature of these technologies means that this increase is considered achievable provided siting and planning issues are managed and the right incentive frameworks are in place (building on the UK's Contracts for Difference framework):

- ICL's modelling has over half of this renewable capacity in the form of solar PV – implying considerable land take in parts of the UK with higher levels of irradiance, even if rooftop space is widely exploited. This may not be acceptable to the public from a land-use perspective but localised capacity can also bring benefits by limiting the need for transmission network upgrades.
- Recent deployment rates and costs reductions suggest offshore wind has a major part to play in the future of the UK's electricity system, and its high capacity factors mean it can displace solar PV capacity by a factor of four or five. Offshore wind also benefits from fewer siting constraints and a seasonal generation profile that closely matches heating demand, making it particularly important for our heat electrification scenario. It does, however, imply a need for major transmission network upgrades – a key infrastructure challenge.

Building 100GW of peaking thermal plant in the form of open-cycle gas turbines and reciprocating engines is potentially achievable provided the challenges of plant siting and fuel supply are overcome. These are established and relatively easy-to-deploy low-impact technologies, with some manufacturers already producing variants that can run on hydrogen blends and natural gas equivalents:

- Where hydrogen is used, these plants will likely need to be located near to hydrogen supply infrastructure (eg near to the UK's industrial clusters). Alternatively, given these plants will operate only very occasionally it may be possible to produce hydrogen locally via electrolysis or to deliver compressed hydrogen to local storage facilities by ship or land-based transport.
- Biogas and synthetic natural gas are often produced at more local scales implying peaking plant using these fuels could be more distributed around the electricity network.
- Depending on the outcome of these siting decisions and provided peaking plants are located close to demand or where existing transmission capacity exists, they would not necessarily put undue additional pressure on the electricity transmission network (unlike new large-scale renewable capacity such as offshore wind).

13. Total UK renewable capacity increased from 35.7GW in 2016 to 47.4GW in 2019 (provisional). See BEIS (2020) Energy Trends.
14. Offshore wind deployment has been driven by a combination of factors including the Contracts for Difference scheme and the Offshore Wind Sector Deal.
15. Baseload plant generate electricity most of the time and do not quickly change their power output. Mid-merit plant has more variable output and is able to adjust its power output relatively easily throughout a day or week.

Three different 'third generation' nuclear reactor designs already have approval under the UK's generic design assessment (GDA) and some – such as the advanced boiling water reactor – have proven operational records. Other newer technologies such as advanced modular reactors are yet to gain approval under the GDA. These will require accelerated deployment and joint licensing approaches with other countries in order to unlock their full potential.

Currently five sites appear feasible for new large nuclear plants in the UK, delivering around 15GW capacity: Hinkley Point C, Sizewell C, Wylfa Newydd, Moorside and Bradwell. Other designated sites – such as Oldbury, Heysham and Hartlepool – have space and/or water cooling constraints. To meet the levels of nuclear capacity assumed in our electrification and hybrid scenarios for 2050 more viable nuclear sites will be needed.

The UK is one of the world's largest offshore wind markets and recent auctions have seen the cost of electricity associated with new projects fall to below £40/MWh – making it one of the cheapest forms of electricity available. The UK government is committed to a large scale-up of offshore wind, targeting 40GW by 2030 – a rate of deployment broadly consistent with delivering the level of renewables needed in 2050.

During the UK's 'dash-for-gas' in the 1990s, deployment of gas turbines often reached 2-3GW p/a. This is broadly comparable to the levels needed to deploy 100GW low-carbon peaking capacity by 2050.

Networks

Connecting hundreds of gigawatts of generation capacity – particularly offshore wind situated in remote locations – to distant demand centres implies major capacity upgrades to the UK's electricity transmission system and reinforcements to existing networks. This is challenging but achievable given the timescales involved.

- Some of the required upgrades will come from reinforcing existing transmission lines, for example, by using conductors with greater capacity, and by increasing voltage levels. These have been used in countries such as China and Canada and could be implemented in the UK too.
- We would expect a significant amount of new capacity to be delivered via sub-sea or underground HVDC circuits, similar to the recently completed 2.2GW 'bootstrap' between Western Scotland and North Wales. We estimate that several multiples of these existing projects could be needed over the coming decades along with several dozen offshore wind connections. When combined with growing global demand for HVDC solutions, this places supply chain scale-up as a major critical path issue, particularly given the current skills gaps and mixed track record of new HVDC projects.

Impacts on electricity distribution networks will be driven by increases in demand from electric vehicles and heat pumps and increases in supply from solar PV installations. During the 2020s these impacts are likely to be manageable with modest infrastructure reinforcements, provided measures to limit peak load and match local generation to demand are implemented with urgency over the next five years. If they are not, distribution networks could be overwhelmed by 2030.

- From a hard infrastructure perspective the challenge for distribution networks is likely to escalate from 2030 onwards.
- At that point it may be possible for distribution network operators (DNOs) to increase their utilisation of medium voltage networks by using the current redundancy in the network to supply managed loads such as heating and electric vehicles (eg during faults these loads would be rationed or curtailed). Upgrades – which could be extensive – would be focused on low voltage parts of the system which are closer to end-users and where no redundancy exists.
- It will be essential to minimise disruption to communities from local network upgrades and to integrate reinforcements with heat pump deployment and energy efficiency measures. Physical works will also need to be co-ordinated between geographical areas.

The 2020s must be used to plan and prepare for these changes. Particularly important will be enabling DNOs to take advantage of smart systems and demand-side management at the end-user level (particularly domestic heating and EV charging). This could be via flexibility markets and end-user financial incentives.

End-users

As an indication of the scale of change required within buildings themselves, Element Energy's and UCL's assessment suggests that by 2050 in an electrification scenario heat pumps would be installed in up to 19M homes across the UK, with a further 1M using communal heat pump systems and over 5M connected to district heat networks. This implies a deployment rate of over 1M low-carbon heating systems a year from 2030, even before accounting for the non-residential sector. Currently, under 30,000 heat pump units are deployed in the UK each year.[16]

Installing heat pumps can often require intrusive interventions to people's homes, including to central heating systems (eg replacement with larger radiators), and may require planning permission due to impacts on the external appearance of buildings and neighbourhood noise levels. Heat pumps also perform better in buildings with high levels of energy efficiency where peaks in demand are lower and easier to manage. This creates a need for widespread building efficiency improvements, which in turn can affect both living space and aesthetics. These factors mean that heat pump deployment has substantial impacts on end-users that will require careful management if public acceptability and buy-in is to be achieved.

Given the scale of heat pump deployment required in an electrification scenario and the evident need to ensure standards of installations which ensure consumer satisfaction, reliability and energy-efficient operation, a key challenge will be to scale up supply chains and train a workforce with the right skills. To meet this challenge, government must use the next five years to support an escalating deployment rate of heat pump and energy efficiency measures while working with supply chains to ensure the right products, skills, standards and financial incentives are in place.

16. The UK Heat Pump Association estimates that there were around 27,000 heat pump unit sales in the UK in 2018. See: Heat Pump Association (2019) Delivering net-zero: A roadmap for the role of heat pumps.

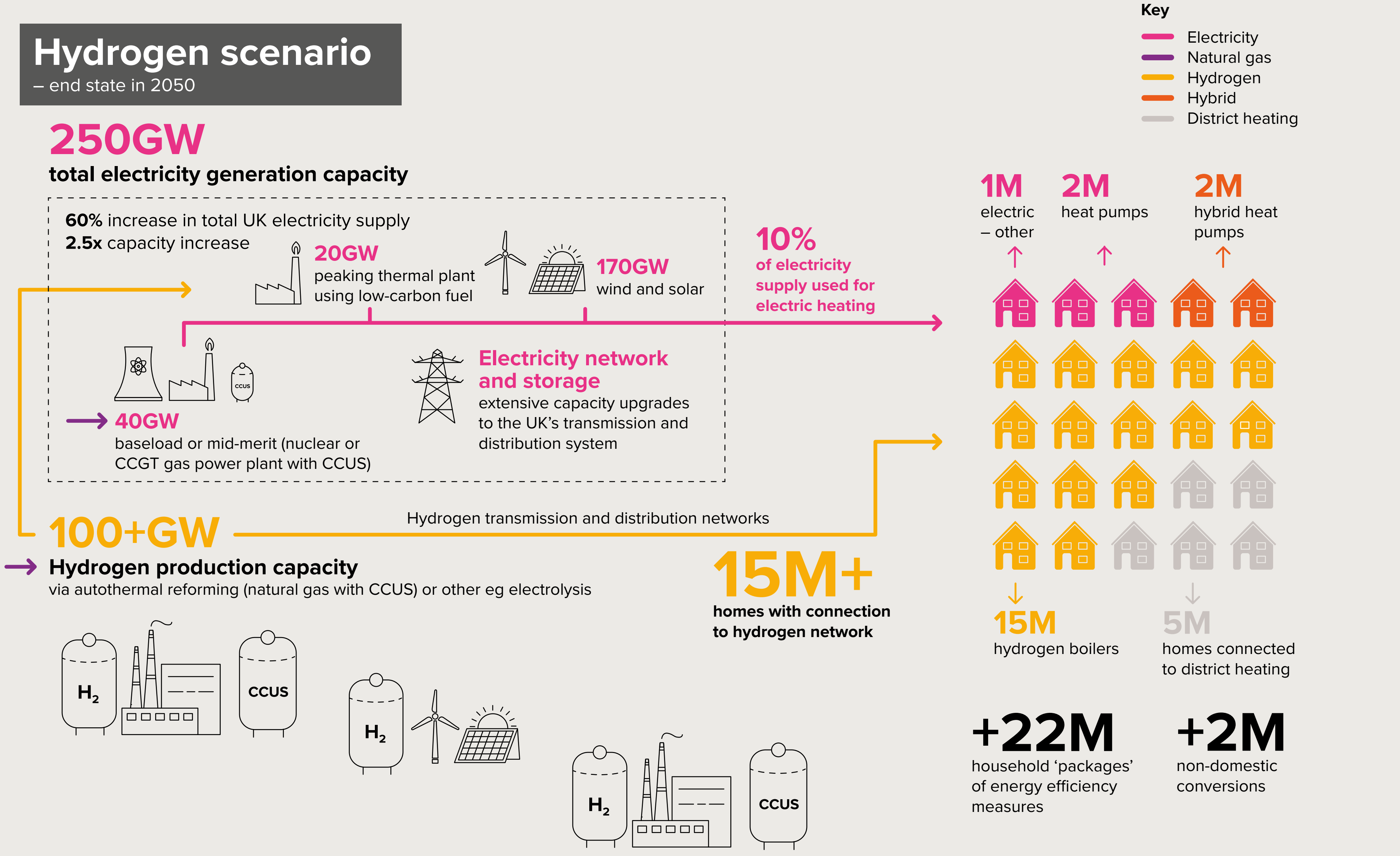
The scale of power generation and network infrastructure required in this electrification pathway points to the role that **more decentralised solutions** could potentially play. With more power generated and stored locally there could be opportunities to reduce the overall amount of infrastructure needed over time.

Key measures to prevent distribution networks being overwhelmed in the 2020s include **smart charging for electric vehicles**, time-of-use tariffs for consumers, local energy markets, use of new business models such as 'heat as a service', and the co-location of storage with solar PV generation (at both household and utility scales).

Heat pump technology is well understood but will require further development to decrease space requirements, improve efficiency and controls (such as integrated solutions for domestic hot water and exhaust air), and integrate with smart controls and phase changing materials for thermal storage.

Installation processes for **solid wall insulation** are labour and time intensive. Modular systems could be designed and prefabricated based on 3D point cloud surveys and energy assessments, reducing installation times, cost and snags, and improving quality.

Hydrogen pathway



A snapshot of 2050

In a predominantly hydrogen scenario by 2050 the majority of buildings in the UK will be directly fed by hydrogen combusted in hydrogen boilers that have directly replaced today's natural gas boilers, with associated upgrading of meters and possibly internal gas pipework. The resulting heat can be distributed using existing central heating systems, reducing disruption for end-users. In locations not connected to the natural gas grid, hydrogen will not be an option and heat pumps are likely to remain the preferred solution. Like the electrification scenario, millions of buildings in densely populated urban areas will be connected to large-scale district heat networks. But in a hydrogen scenario much of the heat for these networks will be provided by large-scale hydrogen boilers and fuel cells alongside other sources.

Huge quantities of hydrogen will need to be produced to meet demand across the economy. The CCC's and ICL's analysis suggests using electrolysis for hydrogen production at this scale may be expensive and place large additional burdens on the electricity system. So here we use ICL's assumption that most of the UK's hydrogen is produced via autothermal reforming (ATR) with CCUS, using natural gas as a feedstock.[17] ICL's modelling indicates that around 100GW ATR capacity will be needed by 2050, requiring the co-development of large-scale CCUS infrastructure.

There is currently uncertainty as to whether it is feasible and desirable to transition the UK's existing natural gas transmission system (NTS) to hydrogen in the future (see below). Here we assume that a largely new hydrogen transmission system is required alongside the natural gas system. We have made this assumption to allow us to explore the infrastructure requirements for this scenario. Depending on the outcome of research in the coming years, it may be that parts of the existing NTS could be repurposed. At the distribution level we assumed that local networks can be systematically and safely switched from natural gas to hydrogen, with some alterations to pipework and equipment.[18]

There is a question over residual GHG emissions for this type of hydrogen scenario, estimated by ICL to be around 10Mt CO_2e p/a in 2050, principally due to CO_2 capture rates on ATR + CCUS facilities. The CCC's analysis suggests that once upstream emissions associated with natural gas production and transportation are also considered, then this type of pathway becomes potentially incompatible with net-zero objectives.[19]

In the UK the CCC expects **hydrogen production from electrolysis** to be more expensive than from autothermal reforming, mainly due to the costs of electricity itself. However, electrolysis costs could fall more than expected or cheap hydrogen imports could be available. For this reason we recommend a phased approach to the build-out of hydrogen production capacity, with regular review points.

17. Using ICL's H2[10] pathway. See: ICL (2018) Analysis of alternative UK heat decarbonisation pathways. The [10] implies there are 10Mt CO_2e residual emissions from heating UK homes in 2050. An alternative to ATR that also used natural gas as a feedstock is steam methane reforming, sometimes referred to as SMR.
18. For more on this topic, see: Institute of Engineering and Technology (2019) Transitioning to hydrogen: Assessing the engineering risks and uncertainties.
19. CCC (2018) Hydrogen in a low-carbon economy.

Key challenges

Our work highlights a number of critical infrastructure challenges in delivering the hydrogen pathway.

Proving the feasibility of hydrogen use for heat

The most urgent challenge associated with a hydrogen pathway is the need to demonstrate the technical and economic feasibility of hydrogen infrastructure along the whole value chain, from production to end-user. This must be prioritised to allow strategic decisions on the future of hydrogen by the mid-2020s. These issues include the application of CCUS, the feasibility of converting the existing natural gas networks and in-building pipe systems, and the extent of disruption required for different types of end-users.

While government and industry are currently undertaking activities to address these questions, more urgency and co-ordination with different stakeholders across sectors is required. A 'business-as-usual approach' will not suffice. Without a concerted effort over the next five years to undertake all the required investigations and preparation activities, there is a risk that heat decarbonisation by 2050 via a hydrogen pathway becomes unachievable.

Hydrogen production with CCUS

Building almost 100GW of ATR by 2050 is in itself a huge undertaking but combining this with CCUS implies a deployment rate of new industrial-scale technologies that is arguably without historical precedent in the UK. Ensuring end-to-end CCUS infrastructure is in place at the right time and performs at the scale required is the most challenging aspect of all, compounded by the urgent timescales required and the fact that only a limited number of commercial-scale CCUS plants are currently in operation worldwide.

To achieve this, it will be critical that a number of 'first-of-a-kind' ATR plants with CO_2 capture facilities are commissioned before 2030 so that technologies can be demonstrated and costs reduced as lessons are learned. Then, in order to reach 100GW ATR capacity by 2050, a very ambitious escalating 'drumbeat' of 'nth-of-a-kind' plant deployment will be required. This should be based on a phased approach with reviews to avoid stranded assets and allow a switch to electrolysis or imports if desirable. The first phase of mass roll-out must begin by 2030 and deploy 1-2GW ATR capacity p/a. From the mid-2030s this will need to increase to more than 5GW p/a.

Reaching and maintaining these build out rates will require a clear long-term vision from government to provide supply chains with the certainty they need to scale up. Unlocking the investment required will require a market and procurement framework that provides investors with long-term revenue certainty and acceptable levels of risk.

Even with these measures in place, however, the rates of CCUS deployment implied by this scenario push up against the limits of what is realistically achievable from an infrastructure delivery perspective, particularly when wider CCUS deployment across different sectors of the economy is also considered (eg for power generation and industry). This potentially makes a UK-wide hydrogen heat decarbonisation pathway unachievable unless more emphasis is given to electrolysis as a production method over time.

CO_2 transport and storage

Putting to one side the very ambitious rate of CCUS deployment required for our hydrogen pathway, from a technical perspective the construction of CO_2 transport networks – which is likely to be focused around specific geographic locations – is not in itself a major challenge. The UK's expertise in the oil and gas sector means that these are well-understood areas and work by the Energy Technologies Institute suggests the UK has enough CO_2 storage capacity for the next 30 years.[20]

Instead a key challenge here relates to risks, regulation and incentives. Given the 'natural monopoly' nature of this type of infrastructure and the importance of allowing access to multiple users, the government has a critical role putting in place a supportive regulatory framework while working with industry to develop effective business models, financing arrangements and risk-sharing mechanisms. This could be based on a Regulated Asset Base model or equivalent approaches.

20. See: ETI (2016) Progressing development of the UK's strategic carbon dioxide storage resource.

The research and development on hydrogen distribution and end-use should culminate in **demonstration trials** involving the conversion of several hundred homes, these ideally being undertaken before 2025. Beyond this, in the second half of the 2020s, larger trials of several thousand homes may be warranted. Alternatively, it may be possible to move straight to a wider roll-out phase, targeting areas favourably located near to hydrogen production facilities.

Each **hydrogen production facility** with autothermal reforming and carbon capture utilisation and storage will be a complex large-scale industrial infrastructure project in its own right, comparable in size to today's oil and gas refineries. Many of these facilities would be needed to deliver our hydrogen pathway – strategically located with access to bulk natural gas supply and CO_2 storage facilities – most likely in or close to industrial clusters.

CO_2 storage must be permanent (eg 'deep' geological storage via injection into porous sandstone) and located offshore (eg in depleted oil and gas reservoirs or saline aquifers). The UK's CO_2 storage potential has been mapped through the UK CO_2 storage atlas and is estimated to exceed 70 billion tonnes CO_2.

The regulatory framework for hydrogen is currently underdeveloped. Significant regulatory development is needed in terms of network development, gas safety regulation, and hydrogen production and CCUS, alongside a programme of changing appliances in properties currently connected to the gas grid.

Hydrogen storage

The 100GW ATR hydrogen production capacity assumed in this pathway is broadly sized to meet winter peak demand, but substantial amounts of hydrogen storage will still be needed to balance hydrogen supply and demand on an intra-day and intra-seasonal basis. This is particularly important given the highly variable nature of heat demand, even over short time periods.

ICL's modelling suggests that around 20,000GWh hydrogen storage will be needed in 2050, roughly double the level of natural gas storage in the UK today. This will be frequently charged and discharged and is likely to be best located onshore and close to demand. We expect this to be met principally through a combination of salt caverns and localised above-ground storage similar to the old town gas storage vessels. However, some offshore depleted oil and gas fields may also be needed if storage over longer time periods (inter-seasonal) is required.

The initial challenge will be finding enough suitable bulk hydrogen storage opportunities. While studies suggest there is substantial potential within the UK's exclusive economic sea zone,[21] more work is needed in the early 2020s to quantify and map this capacity and understand any potential overlaps with CO_2 storage requirements. This must be followed by proof-of-concept pilots by the mid-2020s and preparation of large-scale stores in the late 2020s.

Mandating the installation of 'hydrogen-ready' boilers once the feasibility of hydrogen use in buildings has been proven (likely 2025) will be an important low-regrets measure, with the potential to reduce future disruption and avoid premature boiler replacements during a hydrogen conversion. A voluntary market-driven hydrogen 'health check' – undertaken at the same time – could also help increase preparedness by checking the general compliance of pipe systems and safety features well in advance of conversion.

Hydrogen transmission system (HTS)

If it is technically and economically feasible to repurpose substantial parts of the existing NTS for hydrogen, then this aspect of the hydrogen pathway becomes less challenging from an infrastructure perspective (although still far from easy). If it is not, then building a largely new HTS – a significant national infrastructure development project in its own right – will become one of the highest risk critical-path challenges of this pathway.

Ongoing work by BEIS, National Grid and others is aiming to develop a better understanding of the options for the future of the natural gas grid. Potential barriers to its conversion to hydrogen include:

- Technical issues, such as the safety and compatibility of materials and components.
- Operational issues during conversion, such as the feasibility of blending/deblending hydrogen and natural gas at different points in the network.
- The possibility that in 2050 parts of the NTS will still be required for natural gas (eg to supply hydrogen production facilities) and/or CO_2 transport (as part of CCUS infrastructure systems).

If these barriers cannot be overcome in an acceptable way, the widespread use of hydrogen as a decarbonised energy vector in 2050 will potentially require the construction of over a thousand kilometres of new high-pressure pipelines to transport hydrogen throughout the UK. This is the scenario we have assumed in our roadmap and its delivery starting in 2030 would pose a huge challenge, particularly from planning and public acceptability perspectives. Much of this new HTS will need to be in place by 2040 to integrate with hydrogen production facilities coming online and to support regional switch-overs. To achieve this, detailed preparations must be made between 2025 and 2030 (once current feasibility work is complete).

Distribution and end-use

From a technical perspective, local hydrogen distribution and the conversion of end-user systems are likely to be more manageable than the generation and transmission challenges. While work is still needed over the next few years to investigate the safety and feasibility of converting natural gas distribution networks and different end-user systems, we ultimately anticipate that solutions are likely to be found, although there clearly remains a risk that the safe conversion to hydrogen could be more expensive and involve more work than envisaged here (for example, it is possible that hydrogen could require significant alteration to in-building pipe systems, increasing the cost and time for conversion).[22]

Overall we anticipate the hydrogen pathway may have lower end-user impacts than the electrification pathway, but nonetheless a key challenge is likely to be public confidence in relation to both the notion of using hydrogen in buildings and the capability of installers and reliability/safety of equipment. Element Energy and UCL estimate that around 17M homes could be fed by hydrogen in 2050, implying an average of over 850,000 home conversions every year for two decades.[23] While these conversions will be less disruptive than those required for heat pump systems (they do not involve changes to 'wet' heating systems), they will nonetheless require some changes to natural gas pipes and meter arrangements, probably on a street-by-street basis, as well as the systematic switch-over of end-user appliances.

The workforce to deliver these conversions will be able to draw on existing skill sets (eg Gas Safe engineers) but retraining will be required alongside an increase in the number of engineers and a trusted system of certification. Widespread hydrogen conversions are unlikely before 2030 so the coming years must be used to develop the standards, regulations and training to scale up supply chains.

Certification schemes for installing hydrogen heating systems will be required, similar to Gas Safe (the UK's official gas registration body). Automatically linking this to digital vetting platforms could increase confidence and help consumers find certified installers.

Local production of 'green' hydrogen using renewable energy – if it could be deployed at sufficient scale and within the required timescales – could reduce reliance on autothermal reforming and the potential scale of hydrogen gas pipeline infrastructure.

Co-ordination throughout the hydrogen infrastructure value chain

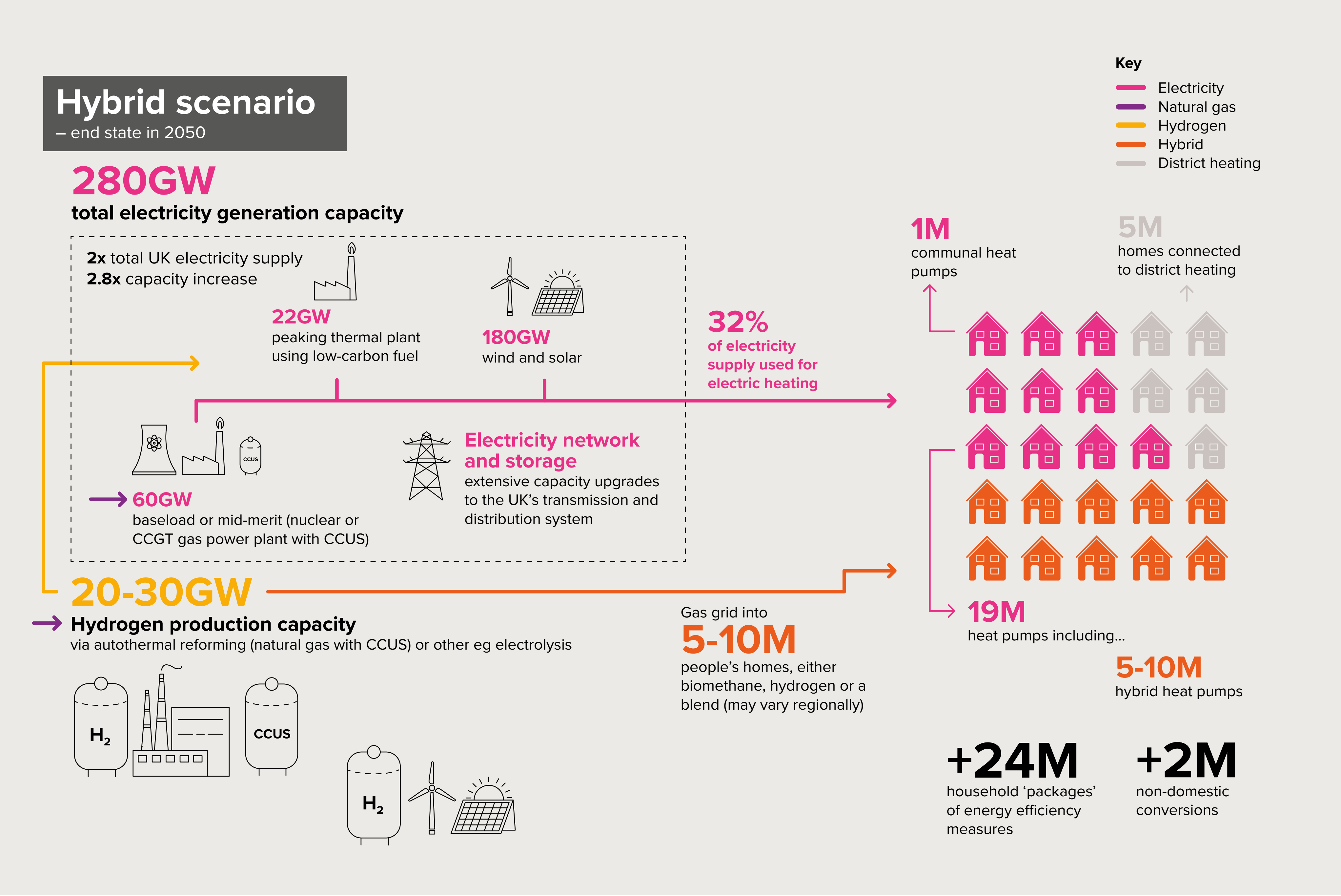
Successfully implementing a hydrogen pathway will require several national-scale infrastructure programmes to come together in an integrated way over a 20-year period. New industrial-scale hydrogen production facilities with CO_2 capture will need to sequentially begin operation alongside the relevant sections of a hydrogen transmission network and CO_2 transport and storage networks. This, in turn, will need to be timed to integrate with the switch-over of local distribution networks and buildings from natural gas to hydrogen (probably on a street-by-street basis).[24]

Maintaining security of supply and public support during this transition will be a critical challenge, requiring careful co-ordination and planning underpinned by strong institutional arrangements. Government will need to take a leadership role here, drawing on lessons learnt from historical transitions, such as the switch from town gas to natural gas, while recognising the greater scale and complexity that a hydrogen switch-over presents.

---

21. See: Energy Technologies Institute Hydrogen: The role of storage in a clean responsive power system.
22. For larger non-residential buildings (eg hospitals, offices with multiple end-users and critical uses of heat), the conversion process could be complex and expensive. Alternative approaches (eg heat pumps) may be preferred.
23. For comparison around 1.67 million natural gas boilers were purchased in the UK in 2019, according to the Energy and Utilities Alliance.
24. We would expect hydrogen production and CCUS infrastructure to be concentrated around the UK's industrial clusters. These may provide the anchors around which the hydrogen transmission system is rolled out.

Hybrid pathway



A snapshot of 2050

Our hybrid pathway explores the widespread deployment of hybrid heat pump systems in buildings across the UK. Like our electrification pathway, by 2050 around 19M homes in the UK have heat pumps; the difference here is that between a quarter and a half of these systems include both heat pumps (to provide most of a building's heat) and a gas boiler (used more occasionally to meet peak demand).

In line with ICL's work we have assumed that the heat pump components of hybrid systems are sized to meet over 95% of a building's heat demand.[25] For the remaining fraction we have assumed that gas boilers transition over time to use biomethane or potentially, small quantities of natural gas blended with hydrogen. This has the advantage of utilising the existing gas grid but could imply low levels of residual CO_2 emissions in 2050.

In terms of upstream infrastructure, by 2050 our hybrid pathway has:

- Lower levels of peaking power generation capacity than our electrification pathway (~10GW compared to ~100GW) but similar levels of renewable and baseload generation capacity and electricity network upgrades.
- Less hydrogen production capacity than our hydrogen pathway (~25GW compared to ~100GW), with around one-fifth as much demand for hydrogen across the economy as a whole and no national hydrogen transmission system.

We have focused on one type of hybrid pathway here – based on hybrid heat pumps – but many others are possible. For example, we might expect **different parts of the UK to pursue different approaches** based on their specific local context, with areas close to industrial clusters prioritising hydrogen and other areas choosing a more electric-based pathway.

25. Using ICL's Hybrid[0] pathway.

How our hybrid pathway compares to the CCC's hybrid pathway

The CCC's core scenario for decarbonising heat, set out in its 2019 net-zero report, is in many respects similar to the hybrid pathway we have explored here. In both cases, hybrid heat pump systems are installed in millions of homes by 2035 and these systems continue to use natural gas to meet peak demand over the next decade or two.

The main difference relates to the long-term use of the natural gas grid. We have assumed no major upgrades to the existing gas grid and that mostly biomethane is used to top up hybrid heat pumps in areas on the gas grid. Conversely, the CCC has assumed that pure hydrogen is used by 2050 – an approach that will ultimately depend on the technical and economic feasibility of converting gas networks for potentially small amounts of hydrogen.

A hybrid heat pump system refers to the installation of an electrically-driven heat pump alongside a secondary heat source (such as a gas boiler) and control system – all in the same building. Typically, the heat pump component is sized and controlled to meet most of a building's heat demand with the secondary source only activating at times of high demand.

A hybrid pathway enables cross vector solutions for end-users which can help **control and optimise energy demand**. Smart controls will play a key role in enabling hybrid heat pump systems and fuel cells used in combined heat and power applications to support wider energy system flexibility and reduce end-user costs. Further development of smart controls and updates to standards will be required to allow hybrid heat pumps to respond to a range of signals such as local network pricing or time of use tariffs.

The rationale for deploying hybrid heat pumps

The widespread deployment of hybrid heat pump systems has a number of potential advantages over other pathways:

End-user acceptability
Heat pump solutions are unknown to most households so the option of introducing hybrid systems that retain existing gas boilers may help to build confidence, increase end-user uptake and accelerate overall heat pump deployment.

Lower levels of end-user disruption
Hybrid heat pumps can, depending on their design, reduce the work involved in conversion compared to full heat pump systems, especially for some older, less efficient buildings and larger non-residential buildings. They can also be installed in advance of efficiency improvements, which may be attractive to some end-users.

Reducing near-term CO_2 emissions
By operating alongside natural gas over the next 10-20 years, hybrid heat pumps can provide greater levels of near-term emissions reductions while uncertainties over the best long-term heat decarbonisation strategy are being resolved.

System flexibility
Hybrid heat pump systems can be operated flexibly to support efficient operation of the wider energy system, for example, switching to use gas boilers at times of peak power demand.

Lower overall infrastructure requirements
By substantially reducing the need for peaking power generation capacity and hydrogen production capacity (compared to our other pathways), widespread use of hybrid heat pumps offers a route to heat decarbonisation with lower overall infrastructure requirements.

Key challenges

Meeting peak heat demand while eliminating emissions
The widespread deployment of hybrid heat pumps with natural gas boilers implies that further measures will be needed over time to completely eliminate CO_2 emissions. These measures will be needed to replace the use of natural gas for meeting peak demand. Without careful planning they could prove as challenging from an infrastructure delivery perspective as our electrification and hydrogen pathways.

In our hybrid pathway, we assume that biomethane is available to meet peak heat demand via the existing gas grid, potentially blended with some hydrogen and/or small quantities of natural gas (so small that any residual emissions do not compromise the UK's overall net-zero target). This allows the benefits of a hybrid pathway to be realised, including lower overall infrastructure requirements.

However, if this approach proved to be unachievable – for example if gas demand were higher than assumed here and/or insufficient quantities of biomethane were available – other solutions would be needed. This could mean converting parts of the gas network to run on pure hydrogen, which would in turn imply some of the same hydrogen transmission, distribution and co-ordination challenges as our hydrogen pathway.

Alternatively it could mean conversion of hybrid heat pump systems to full electric systems, which would in turn imply some of the same electricity system challenges as our electrification pathway. In practice we might expect a patchwork of regional solutions across the UK to be most effective at meeting this challenge in ways that reduce overall national infrastructure requirements.

Planning and decision making in a context of uncertainty
A hybrid pathway brings more flexibility and allows greater levels of near-term emissions reductions, but it also brings a risk of prolonged uncertainty about the UK's long-term heat decarbonisation strategy. This in turn could make infrastructure planning decisions more difficult and delay the mobilisation of supply chains and critical investment decisions.

To reduce uncertainty and support the evolution of optimised infrastructure systems it will be critical that clear signals are given to both infrastructure providers and end-users on the expected mix and regional distribution of heat decarbonisation solutions. A clearer picture of the best mix of long-term solutions is likely to emerge over the coming decade as the feasibility of hydrogen is tested and as the deployment of heat pumps and district heat networks progresses. As learning from these activities is integrated into whole energy system analysis, easily accessible information must be combined with policy instruments to steer choices at the building level to align with the long-term planning of networks and generation assets.

End-user complexity
Hybrid heat pumps are not a new technology and have been applied in various non-domestic buildings for many years. They do however have a mixed operational record with heat pump output often falling below expected levels due to sub-optimal installation and maintenance and greater complexity for end-users.

Remedying these issues requires increased practical and design experience for installers and improved packaged systems and controls to simplify the proposition for end-users; thereby ensuring systems are operated in the way intended (with the secondary source only used for 'top-up' situations), and achieving a positive consumer experience. The first half of the 2020s should be used to escalate deployment of hybrid heat pumps in a low-regrets way that facilitates an increased skills base and practical experience of design, installation and operation. Installation and maintenance providers should evolve to provide integrated single-point-of-service offerings.

As home heating systems become more complex, there will be a need for heat service providers to focus on **ease-of-use and simplicity for end-users**. Recent field trials by the Energy Systems Catapult explored new models such as 'heat as a service', where end-users purchased 'warm hours' based on their desired levels of warmth and comfort, with the service provider then helping to pick the best solution for their situation. Such approaches may improve customer acceptability and promote the uptake and efficient use of low-carbon systems.

Common issues and requirements

Despite their differences the roadmaps for each of our pathways share a number of common features. These point to the critical low-regrets actions that should be undertaken in the next 5-10 years regardless of longer-term decisions and outcomes.

Leadership and urgency
Decarbonising heat by 2050 requires critical actions to be undertaken in the next five years and ongoing co-ordination between multiple streams of infrastructure delivery over the next three decades. In its recent report, 'Net-zero: the road to low-carbon heat', the CBI has recommended a new national delivery body to deliver a national plan for heat decarbonisation and to work with regions and cities so that efforts are co-ordinated across scales, sectors and geographies. We agree with this recommendation. It is critical that institutional arrangements are put in place to provide broad strategic co-ordination of heat infrastructure across the UK, while simultaneously empowering local and regional authorities to deliver solutions appropriate to their context and respecting the principle of subsidiarity. Unless such institutional arrangements are implemented at the earliest possible opportunity, with close working between governments at central, regional and local levels, it is difficult to envisage heat decarbonisation being pursued with the urgency and at the scale required.

Demonstrating critical technologies at scale
All of our pathways rely on the development of technologies that either still need to be successfully demonstrated at scale, such as CCUS, ATR and some forms of new nuclear; or still need further innovation to fulfil their potential, such as floating offshore wind and HVDC lines. To enable widespread deployment to begin by 2030 – essential in the case of most of these technologies if heat is to be fully decarbonised by 2050 – multiple full-scale demonstration projects will need to be commissioned by 2025 or soon after. Meeting these timescales will require major government-backed innovation programmes, industry leadership and risk sharing arrangements between the public and private sectors.

Rapid mass deployment of technologies with substantial levels of risk
One of the biggest infrastructure challenges common to all pathways is the requirement to have begun the mass deployment of complex large-scale technologies by 2030, some of which will still be relatively immature. For example, both the electric and hybrid pathways require several gigawatts of nuclear or gas CCUS power generation capacity to be deployed every year for two decades; and the hydrogen scenario assumes that 1-2GW AMT+CCUS hydrogen production capacity is deployed each year from 2030, scaling up to 5GW+ each year from 2035. Given the size, costs and complexity of such projects there is unlikely to be sufficient market appetite to deliver at the pace required without considerable government involvement and risk-taking that go beyond levels seen in the UK in recent decades. The 2020s must be used by government and industry to develop, test and refine suitable delivery arrangements.

Building supply chain capability at local level will support energy area planning and low-carbon infrastructure investment, and also drive consumer engagement. The UK100 report Financing the Transition: Harnessing UK Cities' Ambition for Clean Energy recommends the creation of **Clean Energy Action Partnerships** to achieve this. These are technical assistance facilities that offer access to technical and development expertise for clean energy projects from a central team with regional reach. They would empower local authorities to offer scalable and replicable clean energy projects and develop commercial standard business cases, facilitating the delivery of local infrastructure.

Transforming the UK's electricity networks
The expected electrification of large parts of the UK's economy over the coming decades (including surface transport) means that a major transformation of the UK's electricity system is required regardless of the heat decarbonisation pathway chosen. Even in our hydrogen pathway, for example, electricity demand increases by over 50% by 2050 compared to today, with generation capacity more than doubling. Renewables – especially offshore wind – are likely to contribute a major part of this increase and as a result the UK's transmission network will need major upgrades throughout the 2020s and beyond. These upgrades are on the critical path for all our roadmaps. At the distribution level major reinforcements can be delayed in many cases until the 2030s, provided essential measures to limit peak load are implemented with urgency in the 2020s, such as smart charging and time of use tariffs. Without these measures, distribution networks could be overwhelmed by 2030.

National energy efficiency programmes to reduce heat demand
All of our pathways assume ambitious nationwide energy efficiency programmes to reduce heat demand are implemented across the UK's existing building stock, most of which will still be standing in 2050. Measures such as loft insulation, cavity wall insulation and solid wall insulation must be applied to over 25M homes and millions more non-residential buildings, reducing total heat demand by around 25%. Achieving this deployment rate will require a year-on-year increase in the supply chain capacity sustained well into the 2030s. Without such measures the huge infrastructure challenge reflected in all of our pathways would become even more expensive and difficult. The 2020s must be used to elevate energy efficiency to a national infrastructure programme in its own right – rapidly increasing installations, introducing regulatory and financial incentives, developing supply chains and ensuring standards and compliance to build consumer confidence and uptake.

Deploying heat pumps and building supply chains
Even our hydrogen pathway has over 4M homes with heat pumps or hybrid heat pumps by 2050, principally those not connected to the gas grid. The CCC's central scenario in its advice to government for the UK's fifth carbon budget has over 2M residential heat pumps by 2030. A clear and immediate low-regrets action for government is to substantially increase deployment of heat pumps and hybrid heat-pumps – to both reduce emissions in the short term and build the supply chains and consumer confidence for greater levels of long-term roll-out. The recent commitment to phase out natural gas boilers in all new homes by 2025 is a major step towards this objective. Other critical near-term activities include regulatory changes (eg to building regulations), incentive schemes for existing homes, installer training programmes, a decision on the application of hydrogen ready boilers and trials in hard-to-convert buildings.

Facilitating large-scale heat networks in densely populated areas
All scenarios require the connection of over 5M homes to large-scale district heat networks by 2050; this is a significant challenge that will require a year-on-year scaling-up of the supply chain and unprecedented growth in both domestic and large-scale heat pump deployment. To achieve this the 2020s must be used to remove barriers and develop supportive policy, regulatory and financial frameworks. Critical near-term actions include: finalisation of policy/regulatory framework to improve consumer protection and confidence and provide greater demand assurance, such as establishing a heat network regulator; levelling of the playing field between heat supply and gas/electricity supply in terms of issues such as rights of access; and achieving policy clarity and consistency to sustain investor confidence in district heating as a long-term infrastructure asset investment.

Providing market certainty
At the current time there is uncertainty across heat supply chains as to the UK's long-term approach to decarbonising heat. This is a barrier to investment and co-ordinated action and means that decisions being made now by market players (for example on the types of heating system incorporated into new buildings) may not be aligned with the approach eventually adopted at a local or regional level – with implications for costs and disruption. To resolve this it will be important for government to provide clear and stable long-term signals (similar to its approach to phasing out sales of new petrol and diesel cars) to unlock the private sector investment needed. More clarity to the market on when and where different types of solution should be deployed and the associated infrastructure needs could be achieved through an end-user heat map – updated over time – to give guidance on preferred solutions in different areas and local area energy plans.

Building public acceptability
All heat decarbonisation pathways have substantial impacts on end-users and require the adoption of new technologies in homes and businesses. Public acceptability will therefore be key, and factors such as cost, benefits, perceived risks, levels of consumer protection and even social and cultural factors will all affect the level of public buy-in ultimately achieved. The use of participatory methods will help to ensure that public perceptions are included in the development process for different future heat technologies, and ultimately boost levels of public acceptance.

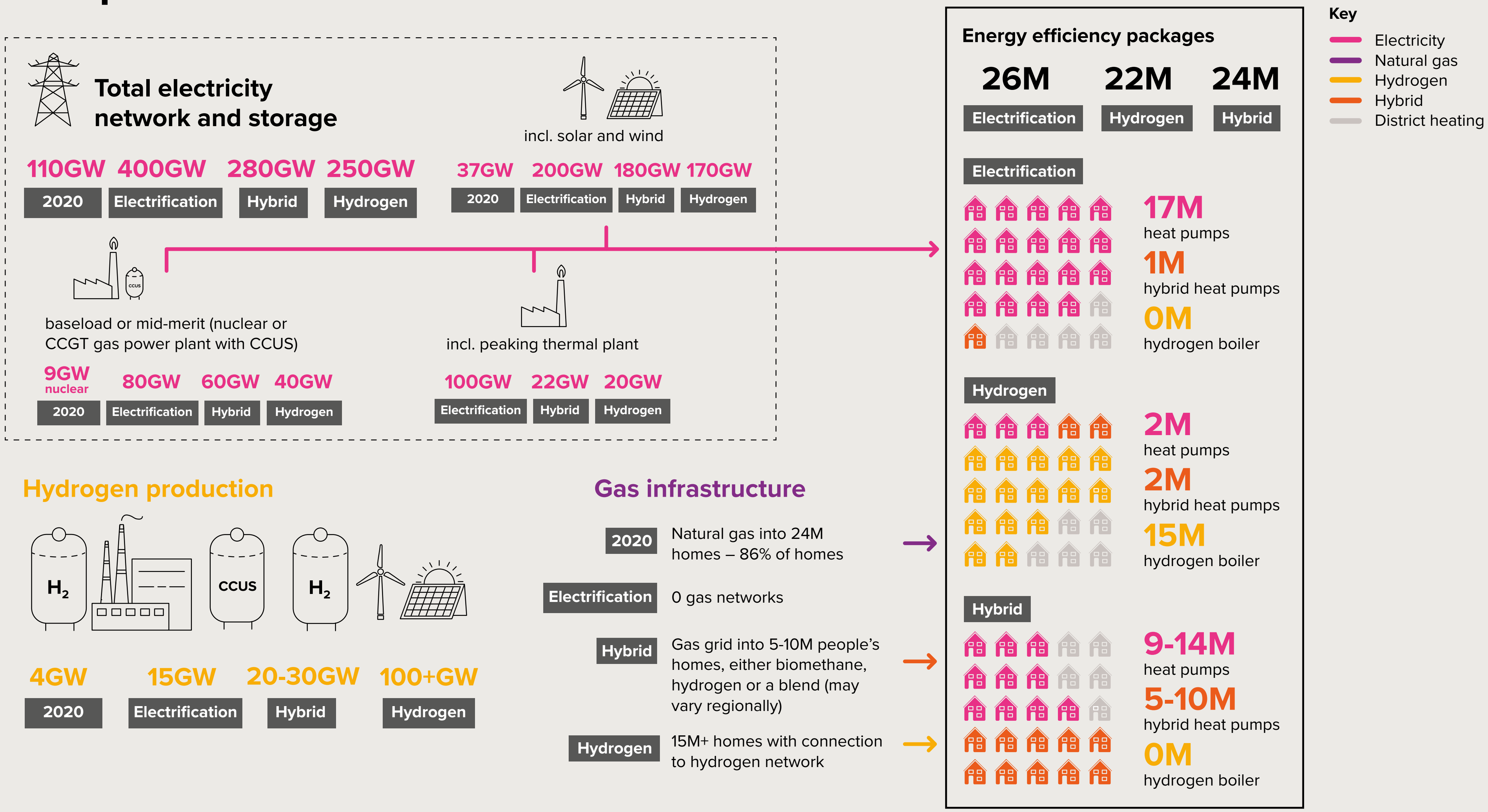
Fourth generation district heating systems can deliver improved operational efficiency, share energy between heating and cooling demand, and integrate multiple low and zero carbon energy sources on the same network. Digital technologies such as smart controls, energy planning systems or network digital twins, will be a key to the efficient delivery of future heat networks, and should be developed with improved intercompatibility and made widely available across the industry.

A UK digital heat map – informed by national and regional heat strategy – could offer impartial and easily accessible information for end-users, designers, developers and network operators on the most appropriate heat solutions for a given location. This could support long-term network planning, facilitate market coordination (between heat pump installation, network upgrades and energy efficiency measures), facilitate planning approvals and help link end-users to certified installers.

Differences and tensions

Our roadmaps also reveal differences in the type, scale and pace of infrastructure delivery required under different pathways.

Comparison of the scenarios



Need for a national hydrogen economy

The CCC's work shows that at least some hydrogen will be needed to decarbonise the economy by 2050, regardless of the heat pathway chosen. However using hydrogen to directly provide building heat moves the infrastructure challenge from one primarily focused on a limited number of industrial clusters to one requiring large regional or national scale hydrogen economies with complex transmission, distribution and end-user arrangements. In both cases the critical activities for the first half of the 2020s remain the same – ie demonstrating and scaling-up hydrogen production facilities and investigating the feasibility and safety of converting natural gas networks. Later in the 2020s, key decisions will be needed on the future of the gas grid and the deployment of large-scale hydrogen production facilities.

Amount of 'firm' low-carbon electricity generation capacity

While all net-zero pathways require large increases in power generation capacity by 2050, the type of capacity varies between pathways. In particular heat scenarios primarily reliant on electricity are likely to have a greater need for reliable 'firm' capacity, for example to ensure demand is met during occasional long windless periods in winter. Our electrification pathway assumes around 80GW of nuclear and natural gas CCUS capacity by 2050, compared to almost 40GW in our hydrogen pathway (although these numbers could potentially be reduced with more ambitious deployment of efficiency measures and interseasonal storage). Despite these long-term differences, all our pathways have common requirements for most of the 2020s – ie demonstrating technologies at scale and establishing the regulatory and financial arrangements for higher levels of deployment from the late 2020s onwards.

Level of end-user disruption and complexity

While all pathways require interventions to almost every building in the country over the next 30 years, the extent of change and potential disruption to end-users varies. In particular, we would expect the electrification and hybrid pathways to result in more disruption than the hydrogen pathway because heat pumps require more changes to central heating system, building fabric and space than hydrogen boiler systems. Nonetheless, all pathways require broadly equivalent actions in the short and long term: ensure the right skills and standards are in place for installers and manufacturers, stimulate demand, engage end-users to build public confidence, and co-ordinate and minimise intrusive physical works and cost.

26. See Energy Research Partnership (2015) Managing flexibility while decarbonising the GB electricity system

Conclusions

The infrastructure roadmaps we have developed highlight the scale and complexity of the endeavour the UK has embraced in committing to decarbonise heat by 2050. Our work sheds new light on what it will take to achieve this. We draw the following overarching conclusions:

1.

There are different ways the UK can decarbonise heat, but all will require a transformation of our infrastructure systems

Whether the focus is a huge expansion of our electricity system, as in our electricity and hybrid pathways, or the construction of a national hydrogen economy, as in our hydrogen pathway, the levels of infrastructure deployment and supply-chain mobilisation required have few historical precedents.

2.

Decarbonising heat is a true system challenge

Not only will it require the rapid deployment of complex large-scale energy generation assets and upgrades to electricity and gas networks, but it means installing new heating systems into virtually every building in the country. Infrastructure delivery must be integrated and co-ordinated across multiple sectors and along the entire infrastructure value chain over a 30-year period.

3.

Leadership is required at all levels of government

The scale, pace and complexity of infrastructure transformation required to decarbonise heat means that leadership will be required at all levels from UK government and devolved administrations down to cities and local authorities. This must involve clear strategic direction and co-ordination, appropriate allocation of powers and responsibilities, and regulatory and incentive frameworks to deliver the right infrastructure in the right places at the right time.

4.

Urgent action is needed now to ensure the UK stays on track

Despite the long-term differences between our pathways they all require a set of common but urgent activities over the next five years. These are set out in our report and include (but are not limited to): making building energy efficiency improvements a national infrastructure priority; increasing deployment of heat pumps, hybrid heat pumps and district heat networks; implementing measures to manage peak load in electricity distribution networks, completing investigations into the feasibility of using hydrogen for heat; and building end-user confidence through public engagement.

5.

A hybrid pathway could reduce the overall infrastructure challenge

Our work reveals the huge infrastructure delivery challenges associated with decarbonising heat either exclusively through electricity or principally through hydrogen. It suggests that a hybrid approach combining electricity with low carbon gases has the potential to reduce the overall amount of infrastructure required by 2050 and, critically, reduce the required deployment rates for complex new technologies. Our work points to the need for a better understanding of a range of hybrid pathways, including those that explore the requirements and implications of using biomethane and hydrogen to meet peak heat demand; and those that explore how different regions of the UK can harness solutions specific to their local context. In this way, decarbonising heat can become a more achievable infrastructure transformation for the UK as a whole.

Opening opportunities with connected thinking.