The path to zero carbon heat

Technical annex

Produced by the Net-Zero Infrastructure Industry Coalition

September 2020

Acknowledgements

This technical annex was produced as a supplementary document to The path to zero carbon heat report, and was developed by the Net-Zero Infrastructure Industry Coalition. This industry coalition was 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. 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 work was led by Mott MacDonald with support from a working group that comprised: Energy Systems Catapult, Engie, Leeds City Council, National Grid, Pinsent Masons, Delta-EE, University of Leeds, the UK Collaboratorium for Research on Infrastructure and Cities and the UK Green Buildings Council.

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A. Introduction

A.1 Objectives for the heat decarbonisation roadmaps

The UK's 2050 net-zero carbon target means not just that we must be building the UK's future infrastructure and assets in a way that supports a net-zero economy, but that we must be building at an accelerated pace in order to achieve it. The path to zero carbon heat report and its technical annex focus on one key aspect of this transformation: decarbonisation of heat.

The objective of the work was to develop infrastructure roadmaps for a range of heat decarbonisation pathways for the UK, in order to offer insight into the scale and complexity of this endeavour. We chose to explore a hydrogen-based pathway, an electric-based pathway, and a 'hybrid' pathway reflecting a more mixed approach. We considered the infrastructure value chain from energy generation, conversion and storage through to transmission, distribution and end-use. We have drawn out the key infrastructure components, timescales, challenges and requirements for each pathway, and identified key differences and commonalities. Our intention is to bring an infrastructure delivery perspective to better understand how the UK can decarbonise heat within three decades, supporting industry and government to plan, make decisions and take 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 further developed.**

This work was led by Mott MacDonald with support from a working group made up of businesses, institutions and public bodies (see page 2 for details). It was undertaken[1] independently through our industry net-zero coalition, formed in 2019. We engaged closely with the Department for Business, Energy and Industrial Strategy (BEIS), the Committee on Climate Change (CCC) and the Confederation of British Industry (CBI), but the conclusions remain our own.

The conclusions from the heat decarbonisation roadmaps work are summarised in The path to zero carbon heat[2] report, which highlights the scale and complexity of the endeavour the UK has embraced in committing to decarbonise heat by 2050, but also the key activities that must be undertaken over the next five to 10 years for the UK to remain on track to achieve its long-term goals. While the recommendations from the heat decarbonisation work are summarised in the main report, this technical annex is a supporting document to provide the technical background for the work. It includes more detailed considerations and a description of the assumptions behind the roadmaps, along with the methodology used to develop the work.

The technical report is split into five sections, covering a description of findings from the heat decarbonisation pathways literature review, considerations for each pathway and a cross-cutting section on the regulatory context, as well as energy efficiency measures and heat network considerations across all three pathways.

1. UKCRIC have undertaken the work under funding from EPSRC grant numbers EP/R017727/1 and EP/R013535/1.
2. https://www.mottmac.com/download/file?id=38783&isPreview=True

A.2 Roadmaps development methodology

In order to develop the heat decarbonisation 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. In developing the roadmaps we have adopted a top-down, nationally homogenous approach as the basis for our analysis. However, we recognise that in reality much more decentralised futures will also be possible. In practice, we might expect to see a palette of solutions and leadership emerge, with collaboration between central, regional, city and local institutions playing an essential role in addressing the scale of the heat decarbonisation challenge. We believe that a useful area for future work will be the exploration of more decentralised pathways, and that this, in turn, could challenge some of the findings made here, including by reducing the amount of new infrastructure and investment required. However, we also believe that useful insights can be drawn from our work about the decisions and actions we need to take as a country in moving this key aspect of a net-zero economy forward.

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.

The methodology used to develop the heat decarbonisation roadmaps was as follows:

1. **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. 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 (EE/UCL).[4]
3. 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 this technical annex – identify key activities, barriers, enablers and interdependencies on the route to a desired outcome.[5]
4. 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.

A.2.1 Literature review and pathway selection

The literature review undertaken by the University of Leeds covered almost 90 national heat decarbonisation scenarios developed over the last decade by government institutions, industry and academia. Not all of these pathways included consideration of a net-zero end point; many were oriented towards the previous Climate Change Act target of 80% emissions reduction by 2050.

Nevertheless, the review highlighted the vast range of possible approaches and the types of challenges that the industry expects to encounter. The scenarios were systematically organised to give a picture of the most common solutions, the degree to which they were expected to meet net-zero, and a summary of the anticipated technical and cost challenges, public acceptability and low regret actions.[6]

3. This literature review was undertaken by Josh Turner, Pepa Ambrosio-Albala et al from the University of Leeds.
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 on energy generation, transmission and distribution; the other on end-users. Two 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.
6. Refer to Turner et al (2020): https://doi.org/10.5518/824

Based on this review, and through discussion with BEIS and the CCC, we selected three pathways from the CCC 2019 net-zero technical addendum reports, which were undertaken by ICL, and EE/UCL. We used the 2050 quantum of infrastructure described in these reports as a starting point to explore the infrastructure delivery challenges for a full-electrification pathway, a hydrogen pathway and a hybrid pathway.

The assumptions for the 2050 quantum of energy generation, transmission and distribution for the three roadmaps was based on the ICL report Analysis of alternative UK heat decarbonisation pathways. For the electrification and hybrid scenarios, we followed the pathways from this research that have zero residual emissions, Electric[0] and Hybrid[0]. For hydrogen, the 10 million tonnes residual emissions pathway, H_2[10], was selected due to the financial challenges that were associated with the zero residual emission pathway based on electrolysis. However, it is acknowledged that electrolysis costs could fall more than expected or cheap hydrogen imports could be available in the future. For this reason we recommend a phased approach to the build-out of hydrogen production capacity, with regular review points.
The assumptions on 2050 end-user quanta, such as numbers of homes needing retrofit and scale of district heating roll-out, were based on scenarios in the EE/UCL study, the Further Ambition Central, Hydrogen-led and No Hydrogen options.

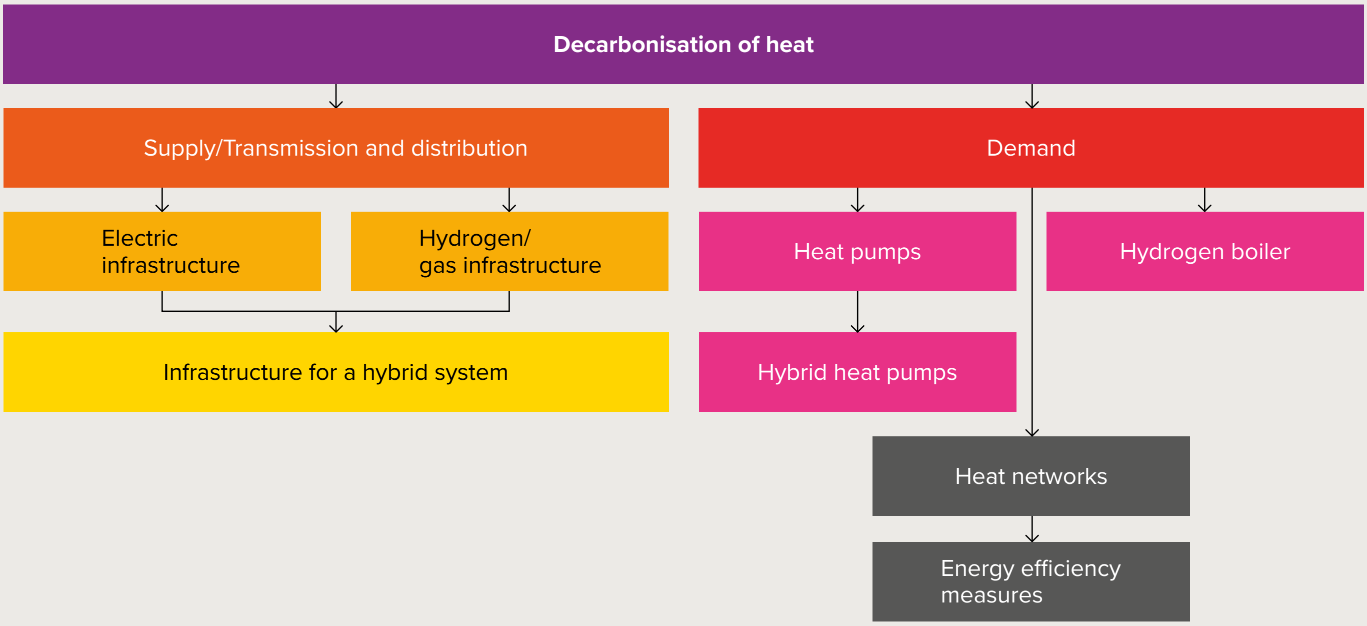
There are some variations between the assumptions in these two primary pieces of literature; these have been highlighted and discussed within this technical annex.

A.2.2 Dependency maps

Each roadmap considers the full span of the national energy system, covering hydrogen production, electricity generation, gas and electricity transmission and distribution, end-user systems, energy efficiency measures and heat networks.

In addition to this, delivering the infrastructure for a zero-carbon energy system involves technical, regulatory, market and end-user considerations in a complex interdependent system. To understand which of these aspects are likely to be primary drivers for each roadmap, and where the key relationships with other aspects lie, we developed conceptual dependency maps for six different aspects of the energy system. These six, and the hierarchy under which they were considered, are shown in the image below. From this we were able to extract the key components to take forward in developing the roadmaps.

Figure 1: Components of the decarbonisation of heat challenge



The maps do not define a strict timeline nor are they based on delivery quantities; they are a graphical and conceptual representation of the logical flow from one step to another and where there is dependency between different components.

As delivery steps were identified through this process, we highlighted potential blockers to the completion of that step and the enablers that may be able to resolve the constraint. The blockers and enablers were identified and colour-coded depending on type: regulatory, market skills, users, technical, digital and environmental.

We organised the dependencies maps in a chronological sequence, moving through feasibility (hydrogen only), prerequisites, implementation and operation and maintenance (O&M) as follows:

- The hydrogen dependency maps were the only ones to include a feasibility section, covering the steps needed to prove the safety case and feasibility of hydrogen.
- The prerequisite section covered some steps needed to enable the deployment of the infrastructure, with issues ranging from regulatory options to market and supply chain considerations.
- The implementation section covered the issues related to design and construction/installation.
- The O&M section looked at technology considerations once the infrastructure/systems are in use.

The dependency maps enabled key infrastructure delivery issues to be identified from among a very complex set of interdependent systems and taken forward into the roadmap development stage. For example, on the demand side they showed the importance of prerequisites for deployment of end-user systems such as the supply chain development and consumer confidence. On the supply side, key issues were the feasibility of hydrogen, defining the demand and market framework, the appropriate mix of technology and the network need for development.

A.2.3 Roadmaps

The dependency maps are a tool to set the context and understand the logic flow of the delivery steps. They do not give an indication of the scale and difficulty of achieving the outcomes or the timescales within which they may be achieved. The next step, therefore, was to create the associated roadmaps, taking the logical steps outlined by the dependency maps and considering these alongside the quantum of infrastructure expected for each pathway, in order to explore the infrastructure delivery challenge.

We developed one infrastructure roadmap for each heat decarbonisation pathway: electrification, hydrogen, and hybrid. The roadmaps were split chronologically, from 2020 to 2050. The quantum of infrastructure representing the 2050 endpoint was generally based on the selected ICL and EE/UCL pathways.

There are different types of delivery challenge depending on the infrastructure under consideration and they are mapped out in different sections of each roadmap. The component categories and their key areas of focus are summarised below and in Figure 2 (overleaf):

- **Cross-cutting:** This section considers general market and policy considerations that are applicable across all items in the roadmap.
- **Supply side:** The supply side components for hydrogen and electric infrastructure focus on the technology mix required to achieve sufficient energy capacity in 2050. The hydrogen map looks at steps required to prove the feasibility of using hydrogen instead of natural gas in the distribution and transmission system and for end-users. While policy decisions are not the focus of the roadmaps, some regulatory aspects are included in the roadmap as examples of regulatory stimulus required to achieve the delivery pace.
- **Demand side:** The demand side components provide more detail on some of the consumer, supply chain and regulatory aspects rather than the technological constraints for delivery. Generally, this is because the constraint to deployment of the end-user measures is not the time required for the installation of a system or its lead times, but supply chain and consumer considerations. The regulatory suggestions are only examples of the type of policy that may be needed to achieve the right delivery rate, such as policy required to stimulate demand, and are not the focus of the roadmaps.

Figure 2: Aspects of the different heat decarbonisation pathways

Key components of the pathways		
	Hydrogen infrastructure	• Feasibility • Production • CCUS
	Electric infrastructure	• Generation • Storage • Transmission • Distribution
	End-user systems	• Feasibility (for hydrogen only) • Prerequisites • Delivery • Performance where required
	District networks	• Prerequisites • Delivery • Installation
	Energy efficiency	• Prerequisites • Delivery • Installation

To develop the roadmap for each of the components we followed a number of steps:

- The **2050 outcome** was defined. This ranged from the final infrastructure capacity required – such as 90GW of hydrogen production or 15 million heat pumps – to a development outcome such as proving the technical feasibility of mass hydrogen deployment.
- The **steps and milestones** required to meet that outcome were defined, such as the type of infrastructure required to deliver 90GW of hydrogen and the steps needed for its installation, with lead times and deployment rates established.
- **Interdependencies** between components were identified, such as the spatial and temporal links between the development of the hydrogen transmission grid and the production of hydrogen. The previous steps were reviewed in light of these interdependencies.
- Each deployment step was **colour-coded** depending on the anticipated delivery rate risk. Most steps relating to infrastructure deployment are bookended on one side by the preparatory actions needed to be ready to deploy at large scale and by the 2050 end date at the other. The steps were colour-coded according to the change of pace needed to deliver the outcome: Green – a steady pace of delivery that should not incur significant challenges in the delivery process; Amber – a significantly faster pace compared with current practice; Red – an aggressive delivery pace that would require a shift in current market and regulatory frameworks.

Once the roadmaps were finalised we were able to highlight the commonalities between the pathways and also to understand the differences and tensions. A summary of this assessment is captured in the main report.

The following chapters describe in detail the mapping process and assumptions used in drawing up the roadmaps and, for each pathway, the key issues related to the deployment of the associated infrastructure.

B. Literature review

B. Literature review

B.1 Literature review summary

The literature review was carried out to understand the range of heat decarbonisation pathways that have already been proposed by industry, academia and other organisations, and identify any especially useful pathways to act as a starting point for further development. In total, almost 90 relevant pathways were identified from existing published reports.[7] Many other pathways were available but did not always have the detail required on certain aspects of the challenge.

The researched pathways were selected to span a full range of technology options and mixes, and deployment approaches. Pathways without sufficient information on the infrastructure requirements, including both cost and timeliness, for the supply side and demand side were rejected. Obtaining coverage in both the domestic and industrial sectors was also important.

Typically, the pathways identified were either developed by a consultancy or a university research group. They were usually commissioned by either an industry stakeholder or a governmental body. Given the short time elapsed since the release of the Committee on Climate Change's net-zero report (CCC, 2019), many of the pathways identified were not developed to meet the net-zero emissions target. Because of this, the literature review also included relevant pathways published between 2015 and 2019 that provided for 80% reduction in emissions by 2050 and therefore complied with the previous emissions target. Most of the pathways considered were national in scope, but some high-quality regional studies were also included, especially where they considered different deployment approaches, such as the role of technology expansion from regional industrial clusters.

7. 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

B.2 Key aspects from the literature review

Several pathways were usually published within single documents, often to provide a comparison between two or more options including an electrification pathway, a hydrogen-led pathway, and various hybrid pathways (Figure 3).

Figure 3: All reports reviewed

Name	Author	Pathway				
		Gas		Hybrid		Hydrogen
2050 energy scenarios: the UK gas network's role in a 2050 whole energy system	KPMG		●	●		●
Analysis of alternative UK heat decarbonisation pathways	Imperial College	●	●	●	●	●
Analysis on abating direct emissions from 'hard to decarbonise' homes, with a view to informing the UK's long-term targets	Element Energy and UCL		●		●	
Cost analysis of future heat infrastructure options	Element Energy and E4Tech	●	●	●		●
Delivering the transformation to hydrogen network	ENA	●				
Establishing a hydrogen economy: the future of energy 2035	Arup	●				
Future energy scenarios	National Grid			●	●	
H21 North of England	NGN, Cadent, Equinor	●				
Heat pumps in district heating	Element Energy and Carbon Alternatives			●		●
Hydrogen in a low-carbon economy	Committee on Climate Change	●	●		●	
Managing heat system decarbonisation: comparing the impacts and costs of transitions in heat infrastructure	Imperial College	●				●
Net-zero – technical report	Committee on Climate Change			●	●	
Next steps for UK heat policy	Committee on Climate Change	●				●
Pathways to low-carbon heating – dynamic modelling for five UK homes	Energy Technologies Institute			●		●
Pathways to net-zero – decarbonising the gas networks in Great Britain	Navigant			●	●	
Potential role of hydrogen in the UK energy system	ERP	●				
Sectoral scenarios for the fifth carbon budget	Committee on Climate Change		●	●		
The clean growth strategy: leading the way to a low-carbon future	BEIS	●				
Too hot to handle? How to decarbonise domestic heating	Policy Exchange			●	●	●
Transitioning to hydrogen	IET, with HSL, IChemE, IGEM, IMechE	●				●
UK energy system scenarios	Energy Technologies Institute		●	●	●	
UK scenarios for a low-carbon energy system transition	Energy Technologies Institute			●		
Zero carbon communities: understanding the transport, heat and energy infrastructure that communities across the UK need to reach net-zero	ScottishPower and Capital Economics			●		

Some of the specific technical challenges that were captured in the pathways research are included in the sections below.

B.2.1 Hydrogen-led pathways

Hydrogen pathways require the deployment of hydrogen-friendly appliances to replace existing systems, with a common challenge being the appropriate source of 'green' hydrogen. Autothermal reforming (ATR), steam methane reforming (SMR), and electrolysis are the three most prominent proposals with different pathways applying them in varying proportions. With both ATR and SMR, carbon capture, utilisation and storage (CCUS) at high capture levels is required, though this technology has not yet been proven at scale. The blending of hydrogen or biomethane with natural gas is commonly referred to as a short-term measure to reduce heating emissions. The implementation of biomethane as a long-term solution is also considered across a number of gas and hybrid pathways, though with varying degrees of utilisation.

B.2.2 Electrification pathways

Electrification pathways involve large scale roll-out of heat pumps, with one of the main challenges being the increased peak demand on the electricity grid in terms of generation and distribution. In particular, air source heat pumps are proposed for the majority of the residential sector, with resistive heaters often being limited to buildings with less space available or to meet additional peak demand, due to their relative inefficiency. Hybrid heat pumps appear in some electric pathways, often as a transitional technology before delivering fully electric heat pumps. In this scenario, the staggered roll-out is intended to allow the public to gain in confidence and understanding of heat pumps, as well as allowing the market time to develop. The generation of the additional low-carbon capacity required for the electrification of heat is assumed to come from a combination of renewable technology such as wind, solar and hydro, along with nuclear power. The relative contributions from each of these generation methods vary by pathway.

B.2.3 Hybrid pathways

Hybrid pathways reduce the demand and reliance on any one technology and would allow regional decisions on the most appropriate method. They can also benefit from the roll-out of hybrid heat pumps which use an electric heat pump to meet most of the heat demand, with a supplementary system used to deliver the peak heating demand, often through the combustion of hydrogen, natural gas, biomethane, or a blend.

Typically, hybrid pathways imply a strategy for the development and distribution of the low-carbon technologies that is government-led and nationwide. Contrastingly, a few reports investigated regional hybrid scenarios in which either (i) different technologies are applied by region but the strategy is still government-led, or (ii) the strategies are developed regionally depending on which technologies are available and best suited to that area. The decentralised scenarios can lead to a diverse portfolio of technologies with no dominant source of heat, which could make it easier to meet peak demand.

However, it would also mean that economies of scale for the individual technologies would be lost. It is also suggested that large-scale hydrogen deployment could fail to materialise without central leadership providing investment and driving innovation. Investigations into centralised regional scenarios show that in some cases overall costs could be reduced, though a like-for-like comparison across reports is problematic due to the varying assumptions and emission targets. Such regional scenarios include the use of hydrogen in the north of the UK and hybrid heat pumps elsewhere, or the use of large-scale heat pumps feeding district heating networks in urban areas.

It was of note that almost all the pathways studied are hybrid to some extent. While there are examples of fully electric pathways, typically the electrification pathways include some use of hydrogen for high temperature industrial processes. Similarly, the hydrogen pathways often include the roll-out of heat pumps to off gas grid dwellings.

B.2.4 Transmission and distribution grids

As the move is made away from natural gas, the quantity of generated electricity, hydrogen or both will increase significantly. The degree to which they are predicted to increase depends on such factors as the type of pathway, the efficiency measures implemented, and assumed rate of technology development and deployment.

Electric pathways invariably report the need for substantial grid reinforcement to cope with the additional demand, though it was noted that the reinforcement will be required to some extent in any pathway, due to the electrification of transport. One report suggests that as the majority of the cost for making the upgrade to the electricity network comes via the civil works, the cost is relatively insensitive to the size of reinforcement. Thus, as a reinforcement will be required for the transition to electric transport anyway, it would be cost-effective to reinforce at a substantial level to safeguard for a high-volume conversion to electrified heat (Committee on Climate Change, 2019). Cost estimates vary depending on the level of reinforcement assumed, though one report suggests that this could be reduced by 30-40% through the use of smart planning and management techniques (ScottishPower, 2019).

Similarly, the assumptions for the existing gas transmission and distribution grid are pathway dependent. For example, patchwork scenarios propose that by 2050 a proportion of the gas distribution grid is decommissioned due to the partial electrification of heat, another portion is converted for use with hydrogen, and the remainder is kept in its current state to continue supplying natural gas. If the distribution networks are required to be repurposed for hydrogen, a large portion of this cost is generally assumed to be covered by the iron mains replacement programme. The current National Transmission System (NTS) is commonly assumed to either remain operating as it is currently, or with less throughput, as it will be needed to provide gas for SMR or to supply industry or gas-fired electric generation. Many gas-based pathways propose a new hydrogen transmission network developed alongside the NTS.

B.2.5 Supplementary technologies

Additional technologies are indicated as being required to supplement heat pumps and hydrogen heating systems. Biomass heating systems and solar thermal systems could play a supporting role in achieving net-zero. Smart technologies are also proposed on the premise that more advanced appliances and controls will allow increased demand side response, introducing further flexibility and a reduction in peak heating loads.

The role of energy storage in the path to decarbonising heat is also consistently recognised due to its capability in matching supply and demand, both spatially and temporally. In this area, hydrogen pathways offer the advantage of increased flexibility and resilience, due to the increased capacity and the reduced cost for gas storage when compared to electricity storage. It is generally assumed that salt caverns will be used for storing large quantities of hydrogen, with pressurised tanks being proposed for local storage.

In addition, it is noted that heat storage is also generally more cost-effective than electricity storage and thus should also play a large part in reducing the peak demands. This can be achieved through heat batteries or hot water tanks. Heat storage can play a role in systems both large and small, but the difference it can make to sizing of plant can be constrained in terms of available space in existing buildings.

B.2.6 Low regret measures

Low regret measures, which are independent of a specific pathway, are also contained within most proposals. Generally, these include wide-scale retrofitting of energy efficiency measures in existing buildings and the adoption of high energy efficiency standards and fully adaptable heat distribution systems (e.g. larger heat emitters suitable for heat pumps) and low-carbon heating in all new buildings. The energy efficiency measures are particularly important for the application of heat pumps to facilitate higher efficiencies but are still highly relevant for the gas pathway as they would result in a reduction in the overall heat demand and can assist in addressing fuel poverty.

The development of hydrogen trials and application of hydrogen-ready boilers, which can later be adapted from natural gas to hydrogen with only a small conversion cost, are also highlighted as a low regret measure. At present, hydrogen-ready boilers are only at the prototype phase in programmes such as Hy4Heat, and even here only for domestic-scale equipment and only for a limited number of manufacturers.

Other measures frequently considered as low regret include installing low-carbon heating, such as heat pumps for existing properties not connected to the gas grid, and investment in low-carbon heat networks. The flexibility of heat networks to reduce emissions in the short term, through the utilisation of environmental and industrial waste heat, and in the medium to long term, through the distribution of low-carbon heat as it develops, make them an attractive proposition. These are noted to play a significant role particularly in dense urban areas.[8] Many of the reports that do not highlight heat networks as a low regret measure specifically still include assumptions about their use across the developed pathways.

Biomethane grid injection and biomass boilers are also reported as potential low regret measures, but their application will have to account for measures to capture or offset any residual emissions. Biomass boilers offer a way to offset any hard-to-decarbonise sectors when used in conjunction with CCUS, though their application is restricted by the evaluation of the best uses for biomass as a finite resource.

B.2.7 Reported costs

The cost indicators for the associated pathways were found to vary by report, causing difficulties in drawing direct comparisons. These indicators included the total incremental cost to reach the required emission reduction by 2050, the annual abatement cost per tonne of CO_2e, the annual costs of the systems up to 2050, and the annual costs as a snapshot at 2050. Many reports present a combination of these measures, with the more detailed reports offering a breakdown of the costs into categories such as capital or operating expenditure, appliance costs, or costs per household. Caution is required when a direct comparison of cost indicators is possible, as mismatched assumptions made in the generation of the pathways can still lead to incomparable values.

B.2.8 Selection of the pathways

Three key criteria were used to select pathways as a basis for full roadmap development:

1. It was important that the pathways considered the net-zero target, rather than the older 80% emissions reduction target.
2. At least two pathways were required to bookend the proposals; including a plausible extreme electrification and a plausible extreme hydrogen pathway ensures that the full range of possibilities in terms of technologies and infrastructure propositions are included.
3. It was important for the selected pathways to include detailed infrastructure requirements. This needed to include (i) the demand side, eg the number of heat pumps to be rolled out and associated timeline, costs, end use impacts, and supply chain and policy requirements; and (ii) the supply side, eg electricity generation split, timelines, and costs for implementation of generation and distribution enhancements.

On this basis, three reference pathways were chosen from the technical reports that accompanied the CCC's 2018 progress report to Parliament: Analysis of alternative UK heat decarbonisation pathways (Imperial College London, 2019) for the supply side, and the Analysis on abating direct emissions from 'hard-to-decarbonise' homes (Element Energy and UCL) for end-users. These reports were prepared for the CCC and include an electrification pathway primarily focused on heat pumps, a hydrogen pathway with hydrogen generation primarily from ATR with CCUS, and a hybrid pathway based on a combination of the technologies with the inclusion of hybrid heat pumps.

It should be noted that the pathways are based on modelling carried out in 2018, and progress may well have been made on technology availability, market capability and cost factors since then. We have stayed true to the details of the ICL pathways in developing each roadmap; however, as well as outlining the main components of each pathway, we have also provided commentary on where their details may differ in reality.

8. District Heat Networks in the UK: Potential Barriers and Opportunities

Figure 4: Key figures from the literature review

87 pathways identified

44 mention heat networks

23 reaching zero or very near zero residual emissions

38 pathways mention hybrid heat pumps

40 mention CCUS across both hydrogen and electric

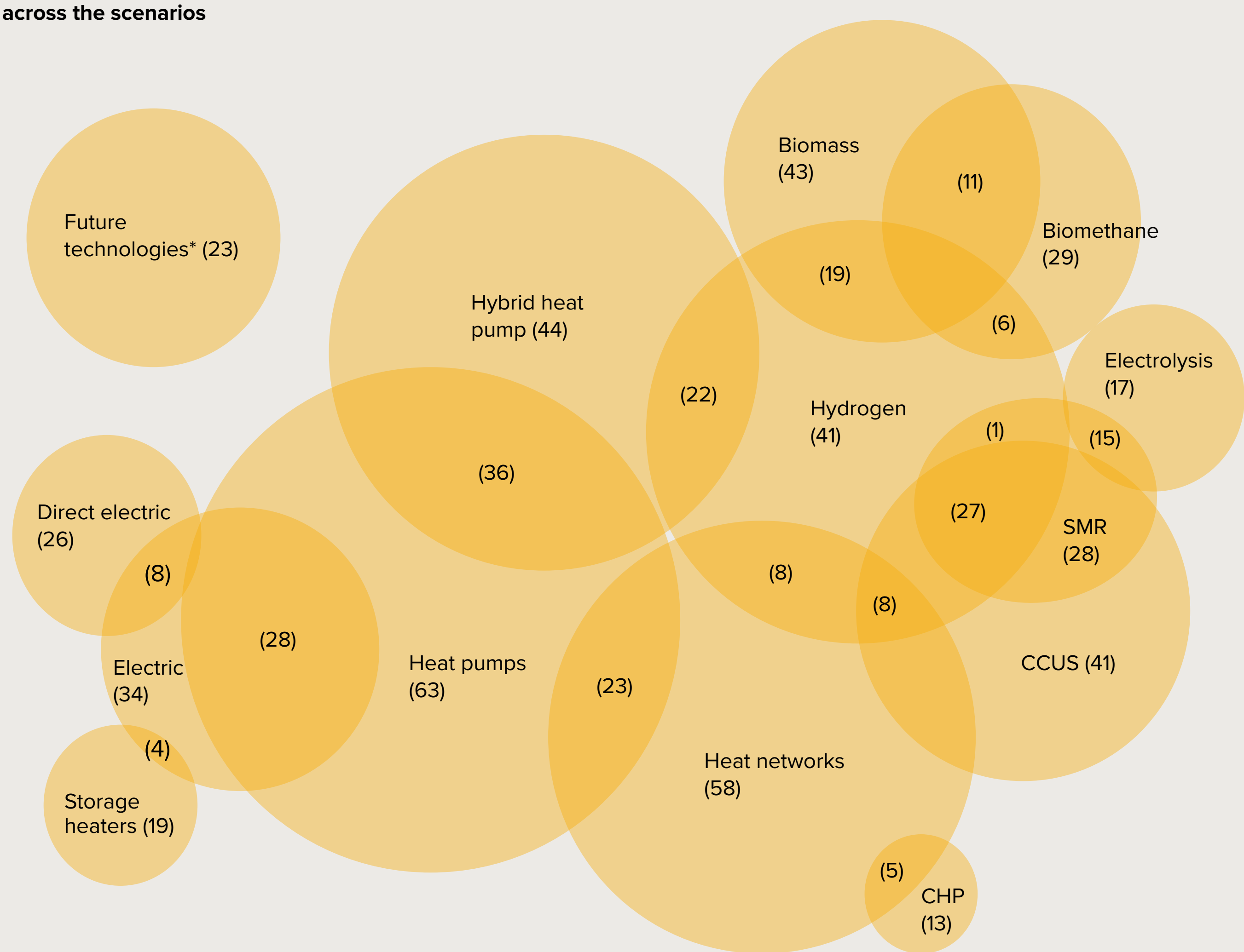
58 pathways mention heat pumps

41 hydrogen pathways, 15 with SMR/ATR, 16 with electrolysis

13 biomethane, 6 of these included within hydrogen pathways

Summary based on available information for pathways.
Not all pathways cover all technology aspects.

Figure 5: Venn diagram of the different technologies across the scenarios



*A series of the pathways have unidentified technology to deal with residual emissions or are lacking in specific detail.

C. Electrification pathway

C. Electrification pathway

C.1 Introduction to the scenario

Supply
In an electrified heat scenario, by 2050 most buildings in the UK 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. To meet this demand exclusively through low-carbon technologies, ICL's modelling suggests the UK's electricity generating capacity needs to quadruple from today's values 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 extended periods of still winter weather, over 100GW of this capacity may need to be in the form of peaking thermal plant (open-cycle gas turbines) running at very low capacity factors using hydrogen or other low-carbon fuels.[9] This assumes measures to reduce peak demand such as preheating (i.e. heating buildings earlier than would otherwise be done) and thermal storage systems (e.g. hot water tanks) are also widely deployed.

The pathway assumes a limited production of hydrogen for use in thermal plant for electricity generation but not for end-users.

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. Therefore, although we have used a 'top-down' nationally homogenous approach for the roadmaps, we recognise that in reality much more decentralised futures will also be possible.

End-user
It is assumed within this scenario that domestic and non-domestic users will convert to electric systems for heating by 2050. Heat pumps will likely represent over 70% of the end-user systems in 2050. In many cases, this will include adaptions to the buildings in question to include upsizing of heat emitters, upsizing of electrical capacity and addition of external plant.

The reason why heat pumps are predicted to be deployed so widely is both their high system efficiency and their versatility. Heat pumps can come in the form of air, ground or water source systems. They can also be connected to large district heat networks or make use of secondary sources such as waste heat recovered from sewers, underground transportation or industrial processes.

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. However, 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.[10]

9. The CCC suggests this could be through methane reforming of natural gas with carbon capture and storage (CCS).
10. 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, and electricity generation capacity increases from ~320 TWh p/a in 2019 to ~767 TWh p/a in 2050.

C.1.1 Pathway components

For the electrification pathway, one dependency map was developed for the heat pump aspect and one for the supply side aspects. These two maps detail the salient tasks that will define the basis of the infrastructure development pathway, capturing some risks together with the flow of activity from the inception/development phase to implementation phase. Some of the key issues captured are outlined below.

Prerequisites and feasibility

The main prerequisite components are ensuring a fit-for-purpose regulatory framework (working with the legacy framework, enhancing it or replacing it) and engaging with stakeholders (end-users, supply chain, etc) while being cognisant of market conditions.

On the feasibility side, the key components relate to the need to carry out technical studies and make decisions on issues such as:

- Modifying distribution network security standards for electric vehicle (EV) and heat pump roll-out.
- Co-ordinated planning of urban medium and low-voltage electricity distribution networks to accommodate heat pump and EV connections.

Generation

The main aspect for the implementation step is to select the appropriate balance of technology across generation, storage and other facilities. Each technology has its own set of attributes and associated set of challenges or barriers that needs to be overcome in order to be deployed.

The key components on the operational side are the ability of the system to meet generation adequacy standards, network adequacy, and a set of wider technical, economic and environmental impacts. A final aspect is the implication for service offerings.

Transmission and distribution

There is a need for substantial network upgrades at both transmission and distribution level associated with new generation and end-user loads, respectively, which will require forward planning.

The breadth and magnitude of requirements for new generation assets and associated storage and flexibility resources is challenging, whether these be CCUS, nuclear, wind or solar.

Heat pumps

Fundamental actions specific to the end-user that are required to deliver the full-electrification pathway have been categorised into: prerequisites, delivery and performance considerations. The dependency map highlights issues with respect to regulation and incentivisation schemes, engagement programmes, skills creation and technical constraints specific to the end-user.

Heat pumps are not yet widely used in domestic buildings in the UK. As such, building consumer confidence and enhancing the existing supply chain were identified as critical to unlocking potential deployment blockers for domestic users. Actions proposed to build and maintain the consumer confidence, and allow for a successful heat pump deployment at scale, cover items such as:

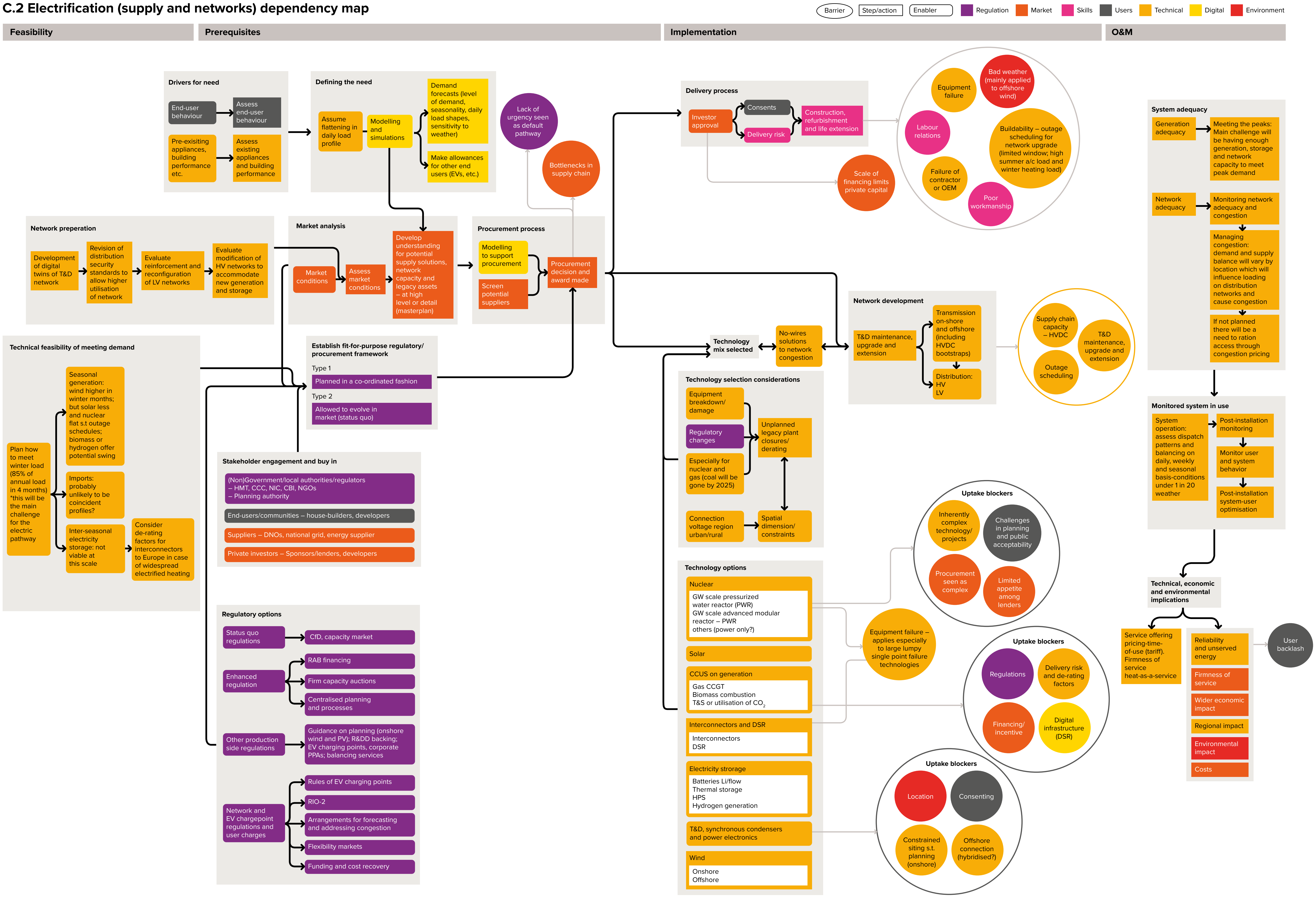
Reducing energy demand and energy cost:

- The development of standards and technical solutions to ensure performance in use and reduced running costs. One such example is the integration of smart controls able to respond to a range of potential signals such as local network pricing and time-of-use tariffs. Getting these elements right will have knock-on benefits to the pathway, eg in ensuring transmission and distribution size can be optimised, reducing overall system and end-user costs.
- The delivery of whole-house solutions, including energy efficiency where needed, is noted as a key enabling action for the pathway. This would require financial support to help with the capital cost not only for the heating system but also for the energy efficiency measures needed to maintain low energy cost and an efficient use of the equipment. This becomes an important element of optimising the overall energy system but also minimises end-user heating plant and equipment costs.

De-risking installations:
Upskilling the existing workforce and the delivery of early successful installations to build confidence during initial stages is noted as a key item for the successful delivery of heat pumps. For example, the success of early adopter projects can be enabled through the provision of on-site support to small installers by entities such as equipment manufacturers to de-risk initial installations. The technical support would incentivise small installers who would otherwise not want to increase their business risks by installing what is for them a new technology, limit the need for additional repairs should there be problems with the installation process, and limit the impact of poor installations on consumer confidence and in-use cost. Continued successful installation of heat pumps could be achieved through the development and provision of a certification scheme for installers, linked to a digital platform enabling consumers to find qualified installers. A scheme exists in the UK at present in the form of the Microgeneration Certification Scheme for domestic renewable heat; this could be expanded. Over time it would be hoped that such initiatives would embed good practice and high standards with installers, designer, maintainers and operators, much as is the case for conventional heating systems.

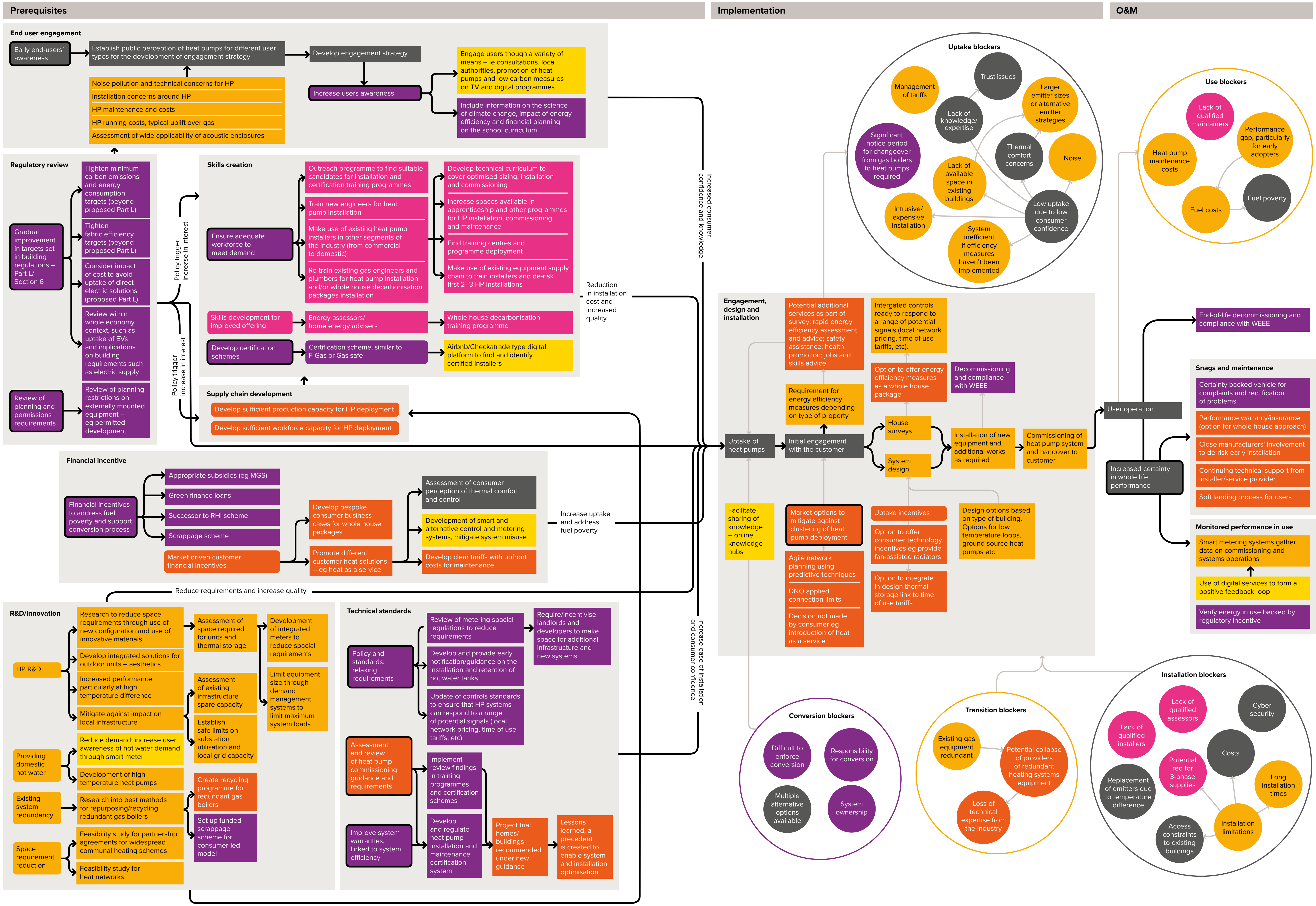
Consumer confidence:
For the electrification pathway, heat pumps need to become the favoured financial choice for consumers considering heating system replacement. More than this, there needs to be increased consumer confidence in the quality of installation and their ability to operate and maintain the systems over time. Regulation is hence required to provide a clear signal on the direction of the market and ensure that confidence in the approach is transmitted to manufacturers and consumers.

C.2 Electrification (supply and networks) dependency map



C.3 Heat pumps dependency map

Barrier | Step/action | Enabler | Regulation | Market | Skills | Users | Technical | Digital | Environment



C.4 Electrification roadmap – discussion

C.4.1 The 2050 technology mix

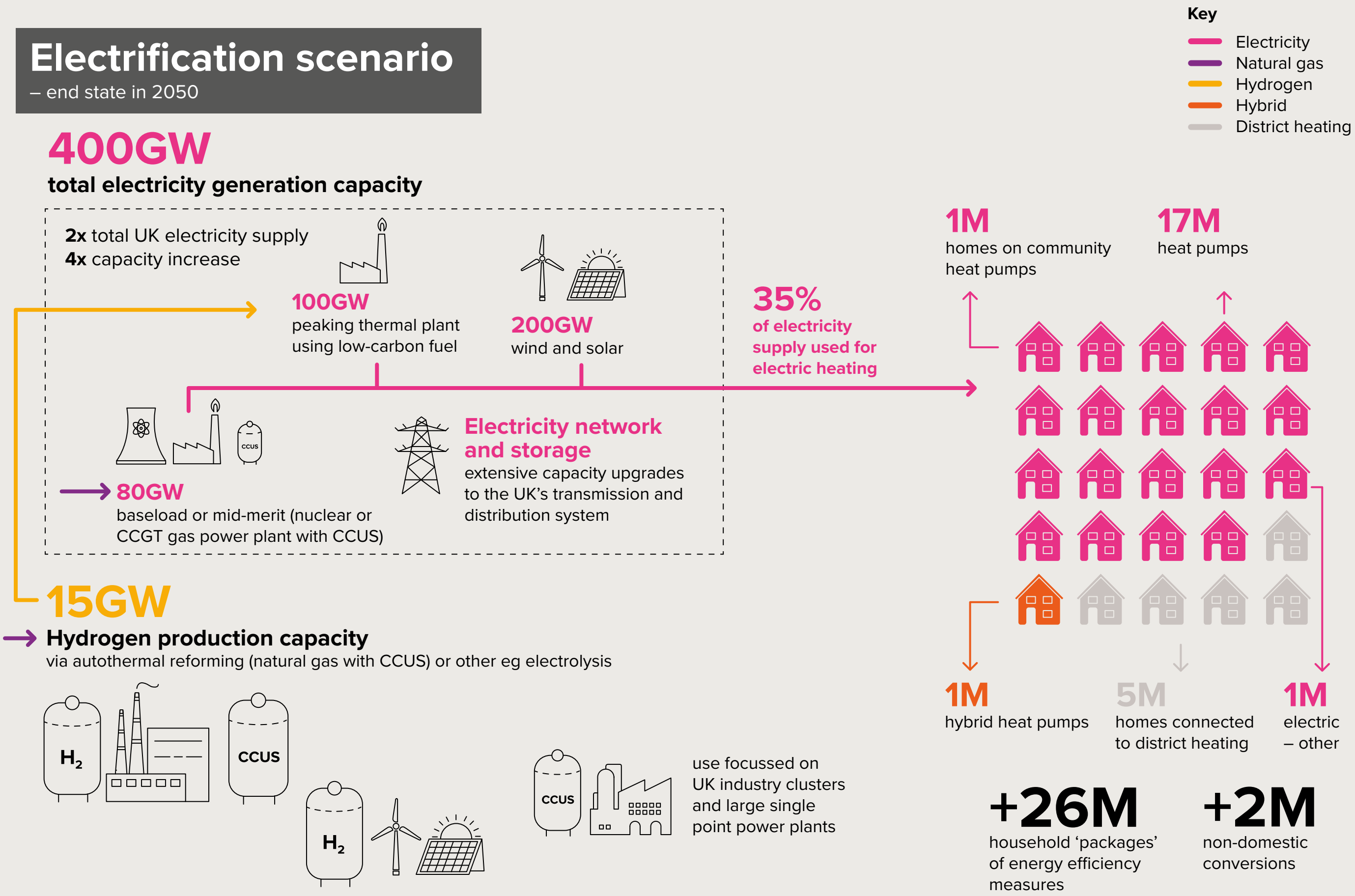
The 2050 technology mix for the electrification pathway is based on ICL's Electric[0] pathway as described in the supporting technical reports to the CCC 2019 net-zero report Analysis of alternative UK heat decarbonisation pathways.

The assumed electricity generation capacity in 2050 is made up of the following:

Table 1: Technology mix for the electrification pathway

Electricity generation	GW
H_2 CCGT	23
H_2 OCGT	24
NG CCGT	13
NG OCGT	79
Post-combustion CCUS	0
Nuclear	43
Wind	74
PV	129
Hydro	1
Storage	12
District CHP	0

Figure 6: The 2050 technology mix



The biggest challenge of the electrification pathway is building enough generation capacity to meet peak demand during cold periods and when renewables availability is limited. The electrification pathway assumes that by 2050 almost 400GW of generating capacity will be required, which is approximately four times the capacity available today. Over half of this capacity is assumed to be met by renewables such as wind and solar.

Compared with other electric pathways, the Electric[0] 2050 technology mix relies more on nuclear energy, which is quantified at 43GW, a capacity that will be challenging to reach by 2050 based on the historic scale of nuclear and the lack of identified sites for this scale of generation.

This nuclear capacity is supplemented by approximately 40GW of natural gas and hydrogen fired CCGT which is expected to operate in mid-merit. This plant will have significantly higher annual capacity factors than peaking plant which will mainly run when heating demand is very high and combined wind and solar output is low.

The requirement for peaking generators is significant, at 100GW, sized to meet demand spikes in severe weather and cover periods when wind, solar and/or other generation capacity or interconnectors have low availability. Building large amounts of peaking thermal plant in the form of open cycle gas turbines and reciprocating engines is manageable 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.

The pathway also has a much larger amount of PV capacity (129GW) than wind (74GW). Based on the availably of renewables resourcing and current development of the market, we would have expected a higher capacity for wind than solar. The pathway also has a lower reliance on storage when compared with other electric scenarios within the literature. Moreover, it assumes that industrial processes are electrified, which would be difficult to achieve and in reality it might be assumed that hydrogen or a similar zero-carbon gas will be required for some industrial processes.

However, the pathway represents a potential technology mix that could achieve zero carbon and has been used as the basis of our roadmap, with the comments above considered in the final recommendations.

End-users
For end-users, the electrification pathway assumes that the heat demand is met by the optimal deployment of heat pumps and other technologies such as electric storage, resistive heating and solar thermal systems deployed depending on the requirements and limitations of each building. The 2050 technology mix is based on the EE/UCL No Hydrogen Further Ambition scenario.

Heat pumps are seen as the most common technology for this pathway for end-users with almost 20 million heat pumps deployed for domestic users to 2050, of which 17 million are air source heat pumps. Because heat pump technology for domestic users is relatively new in the UK, this switch will require user acceptability and a significant increase in the current supply chain.

The EE/UCL report focuses on domestic users. Contrastingly, the roadmaps developed in this body of work have also included non-domestic buildings as these are seen as important to the delivery of the roadmap. While the large-scale challenge lies with domestic users, it is assumed that the greatest individual site complexities will arise in the non-domestic sector. It is expected that not all non-domestic buildings will be capable of an easy shift towards full electrification (due to issues such as spatial constraints for new plant and emitters, compatibility with equipment such as domestic hot water (DHW) raising plant and air handling equipment, planning constraints for external plant, and electrical capacity for individual buildings), and this will have to be taken into account in any preparatory work for the scaled deployment of electric heat technology.

While the EE/UCL report signals a significant increase in the overall number of heat pumps required, it does not include a high number of ground source heat pumps (GSHP) – these account for only 38 installations. It is assumed that this is driven by a cost-optimised model, and the fact that GSHP capital costs are higher and there is uncertainty surrounding the financial incentives available for these systems in the future. Based on current market and industry developments, we expect the number would be significantly higher in practice as this technology can give a significant increase in efficiency, particularly when used with low temperature water systems, and can provide a solution where planning and space for external plant is otherwise an issue. However, an increased prevalence of GSHP is not seen as likely to lead to increased timescales needed for heat pump deployment.

C.4.2 Assumptions for the roadmap

The roadmap was developed to achieve the ICL and EE/UCL 2050 technology mix. We have made assumptions regarding key mobilising actions and the deployment rates that are possible for various interventions. These are captured below for the electric infrastructure and electric end-user systems, as these are the driving components for the electrification pathway. Assumptions made for energy efficiency measures and heat networks are presented in the cross-cutting section.

Assumptions on the process of deploying renewable generation

Based on the quantification and lead times for various technologies, we have assumed that the deployment and construction of the renewable generation will take the following phases:

1. Demonstrate at scale new technology designs such as offshore floating wind, small modular reactors and GW scale nuclear plants.
2. Reinforce transmission networks, especially north-south transmission.
3. Ramp up industry capacity to deliver new renewable and nuclear capacity.
4. Reinforce distribution networks, especially at LV.
5. Continue to build renewable and nuclear capacity.

Wind assumptions

- Floating offshore wind will be proven as a commercial reality and supply chain established.
- Fixed offshore wind will be developed initially prior to floating systems.
- The planning 'ban' on onshore wind will be lifted.

Solar assumptions

- Sufficient consented land area will be made available between the present and 2050 to develop required capacities.
- The current supply chain will be able to provide market requirements until a UK supply chain is developed.

Thermal generation assumptions

- Peaking and back-up generation capacity comprising some combination of gas turbine and reciprocating engines which can run on clean fuel (hydrogen, biomethane or other) are comparatively easy to procure, consent and build.
- Hydrogen open and closed cycle gas turbines are proven as a technology with suitable mitigations put in place for the release of NO_x gases.

Nuclear assumptions

- Some combination of new GW-scale reactors and advanced modular reactors will be granted design approval and will be successively demonstrated in operation, such that series order can proceed.
- Hinkley Point C is successfully commissioned by 2027.
- The build time for GW-scale nuclear plant post-2020 is up to seven years; this is highly ambitious and assumes an improved timeframe due to a mature design and co-ordinated planning of approvals from the government.
- Small modular reactors reach commercial maturity by 2030 and new small modular reactor sites are acceptable to the public.
- Existing nuclear sites have space to install 35GW of GW-scale nuclear energy capacity (as per ETI (2015) The role for advanced nuclear within a low-carbon energy system). The remainder of the installations are small modular reactors.
- From 2030 to 2050, the UK has the capacity to build two to four 3-4GW nuclear projects concurrently (this would require an upskilling of the current market).

Transmission network assumptions

- HVDC will become a proven technology within the UK market and will be utilised by the offshore wind industry as standard.
- Transmission infrastructure is likely to be driven by requirements of new power generation (in particular offshore wind). Thermal and nuclear generation is likely to be sited on location of existing generation (and hence transmission infrastructure). Solar generation is likely to be predominantly distributed or behind the meter connected. As such, transmission requirements will predominantly be related to connecting offshore wind, upgrading N-S flow (to accommodate wind transmission to load centres) and reinforcing existing networks to accommodate additional generation.
- Multiple major new overhead line transmission circuits are unlikely to be built and that bulk power transportation from the remote and offshore site are likely to use underground (or offshore) HVDC cabling. This is in line with the 'bootstraps' being installed by National Grid for new Scotland to England interconnection.
- Reinforcement of existing lines may be by using conductors with greater capacity (either high temperature, super conducting, or great cross-sectional area), or could look at introducing ultra-high voltage systems (e.g. 750kV as used in Canada or 1000kV as used in China).

Distribution network assumptions

- There will be a major roll-out of EVs from 2025, but smart charging and time-of-use tariffs will limit the impact on peak load, with major mitigation measures only required post 2030.
- To drive this mitigation, we have assumed that different security of supply requirements or some other prescriptive measures are put in place for EVs and heat pumps to enable district network operators (DNOs) to manage load.
- We have assumed that DNOs will use the increase in controllable load (EVs and heat pumps) to allow greater utilisation of their medium voltage networks (e.g. security achieved by managing load smartly rather than simple redundancy). This will mean that the major reinforcements will be required on the low voltage (LV) and 11kV networks.
- We assume that rather than wholesale upgrading of the LV networks to accommodate additional load, existing cables are used with circuits divided into smaller groups. We note this may not be possible where tapered circuits have been used.
- To minimise disruption, we have assumed that cities and utilities would seek to plan and co-ordinate reinforcements to minimise disruption (as well as cost). This may require the rules around DNO investment to be modified to allow reinforcement for anticipated demand.

End-user assumptions

- The appropriate regulatory framework will be in place to ensure the stimulation of demand and consumer protection.
- A clear signal from the government, as aforementioned, is likely to be sufficient in ensuring installers retrain in low-carbon technologies. Assuming an average of five person-days per installation, this equates to 1.4 million person-days of installer time in 2025, increasing up to roughly 6 million person-days in 2035. Installations are focused on new build and homes off the gas grid during first half of this decade.
- Heat pump installations would only become dependent on mass reinforcements of the distribution grid by 2030.
- Full electrification beyond 2025 would see the majority of installations being in retrofit – up to a (peak) annual installation rate of circa 1.15 million in 2035 as estimated by the Heat Pump Association (HPA).[11] It is of note that research by Delta-EE[12] covering how the heat pump market is likely to develop to 2025 under current conditions forecasts that we could see a doubling in size by 2050 achieving just under 50,000 installations per year. This is well below the deployment rate noted in the HPA report, strengthening the point that significant incentives will be required to achieve the required deployment rates, as noted in the HPA report.

11. See HPA (2020) Delivering Net-zero: A roadmap for the role of heat pumps
12. See Delta-EE UK heat pump market likely to double by 2025 [online] accessed 06/2020 https://www.delta-ee.com/delta-ee-blog/uk-heat-pump-market-likely-to-double-by-2025.html

C.4.3 Roadmap description

Critical aspects
The electrification roadmap generally shows a large deployment of electrical generation capacity and network expansion and upgrades. The main aspects that appear challenging are: nuclear deployment – both for GW-scale plants and small modular reactors; the development of HVDC north-south bulk transmission and subsea cables to access offshore wind; and the reinforcement of the distribution networks.

Nuclear
The first GW-scale plant and the first demo small modular reactors would be commissioned by 2029. This allows for standardised designs to be established prior to phase 2 and would enable construction teams to move on to successive GW-scale projects. The small modular reactor programme would have four years between 2025 and 2029 to build the small modular reactors and from 2029 to 2033 to build additional supply chains, prior to the locations being agreed and roll-out. The outcome by 2050 is 43GW of generation to be provided by the nuclear sector.

Thermal generation
For thermal energy generation, trial of hydrogen OCGTs is from 2025 to 2029 with roll-out from 2031 for natural gas and hydrogen OCGTs and CCGTs.

Wind
In the early 2020s, floating wind must be demonstrated and then commercialised from 2024 to 2030, including a scale-up of supply chains for fixed and floating offshore wind. From 2030, we must start the large-scale delivery of deep/floating offshore wind and fixed onshore wind to deliver collectively a 74GW capacity. To be achievable, this is deemed to need a high deployment rate comparable to existing rates.

Solar
After a review of existing policy to support renewable energy growth, 2023 is seen as a milestone to establish the procurement method for delivery. 129GW of solar is needed across the UK, and since this is deemed to be high, it will therefore need widespread implementation across the public and private sectors.

Storage (electric)
Storage is seen to be one of the easier aspects to this roadmap, because of the low storage capacity assumed by the pathway. However, the development of a clear and robust regulatory regime is needed in 2021 to continue supporting markets for capacity and ancillary services to incentivise electrical storage.

Transmission
Critical to supporting the development of offshore wind, the UK needs to build capacity in HVDC and subsea cables urgently between now and 2025, which is seen as highly ambitious. This allows us to plan and build HVDC bootstraps from 2026 for offshore wind connection and to allow for north-south power flows by 2040. From 2033, reinforcement of the transmission network to accommodate nuclear and thermal generation is also needed. Both of these actions need a high deployment rate in order to reach the needed milestones.

Distribution
For the 2020s, most of the activities are for planning, projections and establishing market flexibility. The period from 2024 to 2030 gives a bracket for trials of flexible connection agreements for domestic customers as well as some reinforcements for EVs. By the end of the 2020s, we must have established city-wide plans for electrical reinforcement, based on projections for load profiles. From 2030, mass reinforcement of the DNO network needs to begin.

Hydrogen
The feasibility of hydrogen generation and storage must be proven within the next three to five years using existing and new trials and testing, including development of the safety case. This concludes with establishing the regulatory and procurement framework for hydrogen by 2028.

Biomass
Between 2020 and 2025, biomass gasification will focus on construction of a ~5MW plant and the front end engineering design (FEED) studies for a ~50MW plant. This ~50MW first of its kind plant will be constructed by 2035, and thereafter these plants will be deployed at scale. This deployment at scale and the scaling up of biomass plants (which can begin now) are seen as the key challenges in hydrogen production. The Green Gas Levy is also utilised to support biomethane production.

CCUS
CCUS needs to have a critical strong market signal for deployment from 2020 to 2027. This runs parallel to CCUS demonstration projects from 2021. Demonstration of CCUS within industrial clusters is needed within the period 2021 to 2026 and allows a scale-up from 2026 onwards. There is a more significant phase on build-out in the 2030s and even more significant again in 2040s in line with increasing hydrogen generation. However, the required capacity and pace is less here than in the hybrid or hydrogen pathway.

CO_2 storage is a critical element of the demonstration CCUS plants and is seen as a highly critical aspect of this component.

Storage (hydrogen)
In order to supply hydrogen to meet peak demands, storage is a vital element to achieve demand response. In the early 2020s we must define storage requirements and geographical mapping, closely followed by proof of concept at small scale between 2021 and 2026 and through industrial clusters from 2024 to 2030. Preparation of depleted gas fields and salt caverns are also needed between 2026 and 2030 to allow for the development of storage infrastructure; local and large-scale centralised storage to balance demand and supply is assumed developed from 2030 to 2037. This is seen as ambitious and accelerated in terms of delivery period. Further storage is brought online from 2038, but in line with regional demands.

Heat pumps – prerequisites
In the early 2020s, a series of regulatory and market drivers need amendments or changes to enable the delivery of heat pumps across the UK. This includes preparing evidence for and consulting on revisions to the Building Regulations between 2020 and 2025, so that by 2025 heat pump installations are favoured and low performance/high energy consumption assets are significantly discouraged. This is coupled with inadmissibility of gas boilers in new builds from 2025. We would propose these changes will be signalled well in advance of 2025 through consultations and other engagement actions to allow both the supply chain and end-user to prepare for the change. Examples of financial incentives are noted, such as the low-carbon heat support scheme, a potential scrappage scheme and incentives at near end of existing asset lifespan. Similar incentives should be considered in parallel for energy efficiency measures.

Major training of installers needs to take place rapidly and as soon as possible, promoting early retraining of existing boiler installers if possible, to allow for ~7,000 installers by 2025-2026. This is seen as highly accelerated but critical, particularly with the requirement for a high quality install and reputation for early adopters in the 2020s. Further retraining of boiler installers is noted between 2026 and 2031. From 2031, there is a reducing rate of additional yearly installers to reach ~30,000 installers by end of 2035. Throughout this whole period it is also imperative to have engineers within the design, manufacture and research sectors to keep driving improved performance.

Engagement with end-users is also critical for the roll-out of change in the energy system, especially given the number of heat pump systems needed for the electrification pathway. The criticality here is not about achievable pace but about end-user acceptance as a potential blocker of delivery and uptake.

Supply chain engagement is needed early in the 2020s to respond across the domestic and non-domestic sectors. Stock characterisation between 2020 and 2022 would help demonstrate the pipeline for the supply chain and the different types of energy system conversion needed across the geographical regions of the UK. Early trials of ‘hard to convert’ buildings and those in the non-domestic sector will help bring some clarity to the other technologies required for these types of stock, i.e. non-electric solutions such as hydrogen or biomass. These steps will ensure that the supply chain will react to increasing heat pump demand from 2025 at a high ambition and pace of roll-out.

Heat pumps – delivery
Incentives for early adopters should be accelerated, especially for those customers who are able and willing to adopt low-carbon heating early. This has a high importance and is very ambitious. Initially the focus is on new builds and homes off the gas grid up to 2025. From 2025-2030, retrofit takes up greatest proportion of yearly installs. The estimated yearly installation rate is 1.15 million from the end of 2035. From 2025, retrofit needs to start occurring in housing stock with unfavourable conditions and where homeowners cannot afford the necessary modifications. This is by far the hardest aspect to achieve and requires very ambitious delivery rates for these types of homes – which will be expensive and time consuming.

Parallel to the delivery of heat pumps it must be ensured that the performance of these schemes is maximised. Between 2020 and 2025, it will be important to develop commissioning procedures for existing heat; a digitalised system evaluation will help this process. From 2025, a widescale roll-out of yearly performance reviews is recommended to ensure continued best practice, and digitalisation of the process would provide effective feedback to the end user.

C.4.4 Key risks and challenges

The following table summarises the key risks and issues of this pathway. This is not a comprehensive list of risks, but some of the main aspects that came out of the development of the roadmap. It is also of note that these risks relate to the specific pathway we have mapped, and different electrification pathways could have different risks.

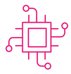
We have categorised the risks under four categories – scale and delivery, technology, complexity and public acceptance – to help understand the differences between these pathways and the issues present.

Key

Scale and delivery | Complexity | Technology | Public acceptance

Table 2: Risks and challenges

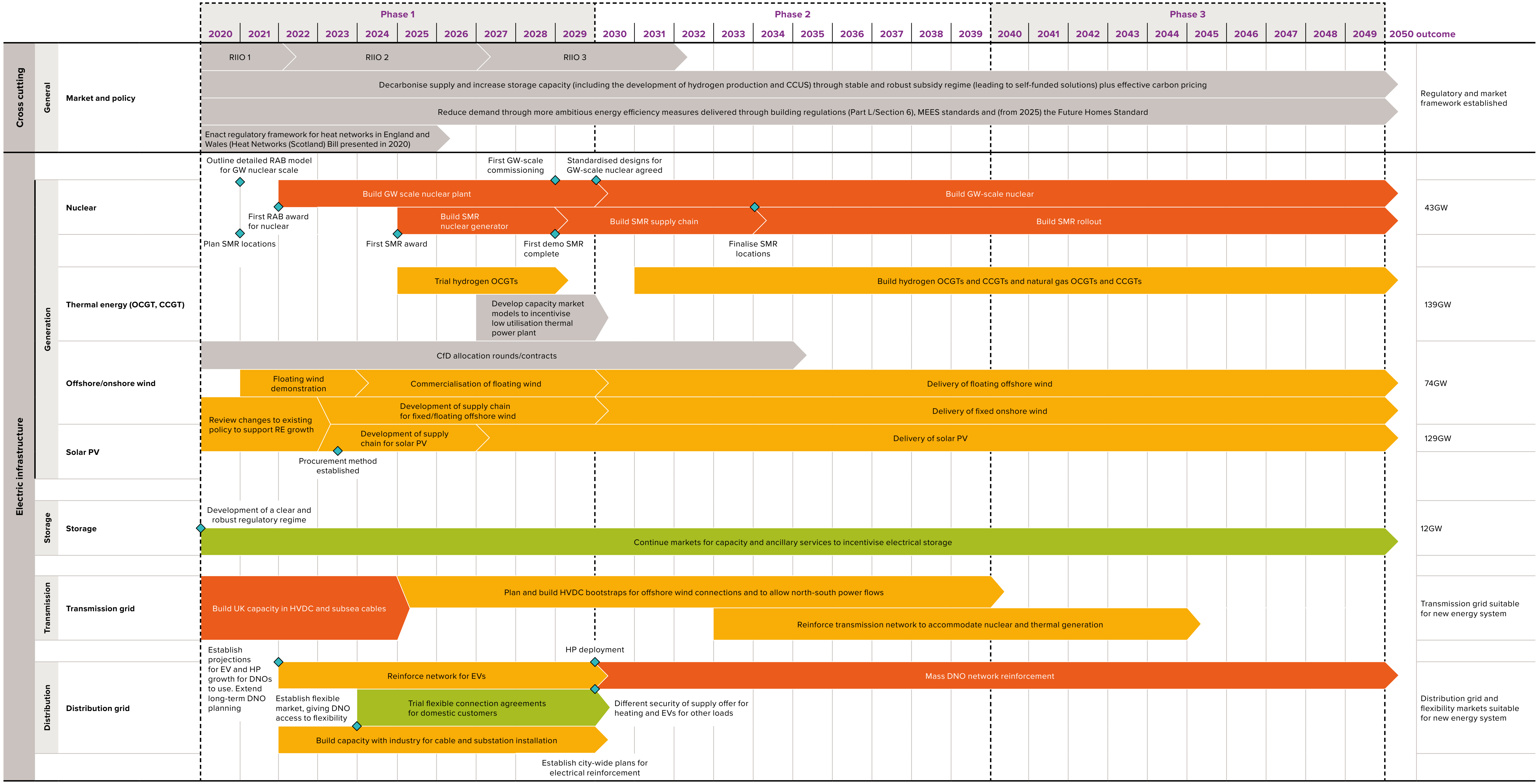
Risk/challenge	Type	Solution
Current limited capacity of supply chains within UK for a range of technologies such as HVDC, new nuclear, offshore wind and solar generation, which will require substantial build up.	Scale and delivery	Ensure the skills are appropriately planned and rewarded within the UK. Create training and career paths for these kinds of roles, as well as retraining paths for those already in the industry. This should be included within the UK industrial strategy as an immediate priority.
There is a very large amount of peaking plant needed for back-up and to cover demand spikes. Locations for these plants, preferably near load centres, will need to be secured so as not to put undue pressure on the transmission network. Fuel supply logistics will also need to be considered.	Scale and delivery	Undertake planning to determine the locations of this thermal plant close to demand. Where hydrogen is used these plants will likely need to be located near to hydrogen supply infrastructure. 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.
To achieve nuclear roll-out at both GW scale and by using small modular reactors, technologies must be proven to deliver economically and reliably. SMR technologies need to be demonstrated by early 2030s. If this is not completed alternative investments in more renewables and storage may be required.	Technology	GW scale nuclear power needs to deliver first schemes by late 2020s (~2027) and agree standard designs for wider implementation shortly afterwards. Industry needs commitment to technology to invest and scale up R&D and deployment. Planning for future scenarios needs to be undertaken, to bring online alternative solutions if some technologies are not realised at scale.
Negative societal perception of major infrastructure projects, especially transmission lines and substations, may slow the planning and consenting process. Similar issues apply to new nuclear projects , both GW scale and small modular reactors, given the perceived risks associated with nuclear.	Scale and delivery, Complexity, Public acceptance	Use planning phases to begin stakeholder engagement. National scale communications regarding future rolls of technology to deliver net-zero. For small scale nuclear seek to develop reduced exclusion zones.
Floating and deep-water offshore wind needs to be proven to allow the scalability and financial feasibility of wind power; without this it will be difficult to deploy the targeted wind capacity.	Technology	Industry needs government commitment to such technology and incentives to invest and scale up R&D and deployment.
Very large areas of consented land will be required (most notably for solar PV, and mainly in the southern half of the UK) to enable generation capacity to be deployed. This will require a change in mindset among many planning authorities, otherwise sites may not be made available.	Scale and delivery, Public acceptance	Low-carbon generation must be viewed favourably by planning authorities and areas for development actively encouraged as part of local development plans.

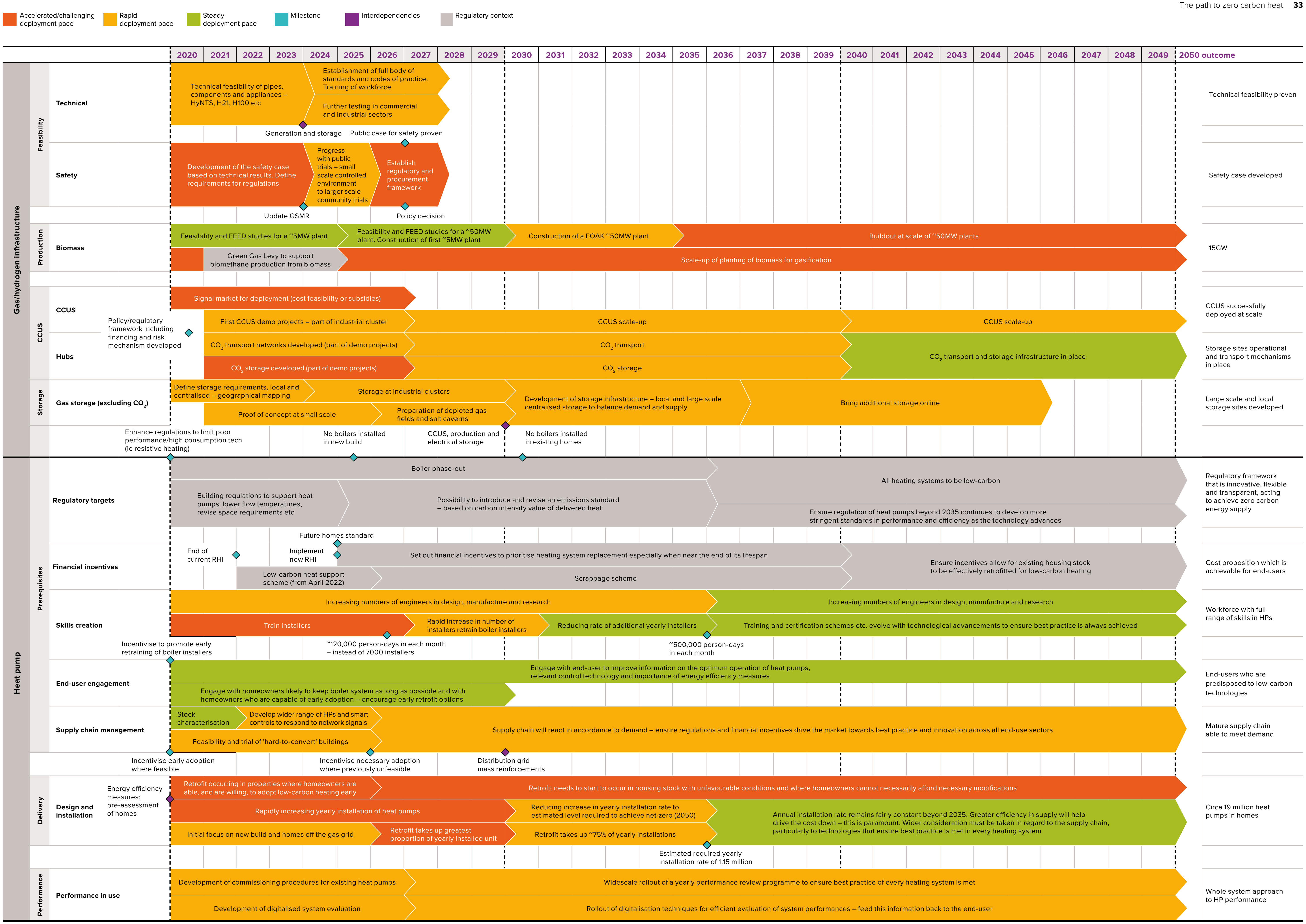
Risk/challenge	Type	Solution
Impacts on distribution networks will be driven by increases in demand from electric vehicles and heat-pumps and increases in supply from solar PV installations. During the 2020s, these impacts are likely to be manageable with modest infrastructure reinforcements. If they are not, distribution networks could be overwhelmed by 2030.		Implement with urgency over the next five years measures to limit peak load and match local generation to demand.
Impacts on distribution networks past 2030, driven by accelerated uptake of heat pumps and EVs.		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. Focus upgrades – which could be extensive – on low voltage parts of the system which are closer to end-users and where no redundancy exists. Minimise disruption to communities from local network upgrades. Co-ordinate physical works between geographical areas.
Quality of heat pump installation and whole-system co-ordination (ie suitable energy efficiency measures, suitable heat emitters, etc.) is effectively managed for the scale of delivery required.	 	Ensuring suitable certification schemes are established is critical in this regard. The capacity of the Microgeneration Certification Scheme (MCS) will have to be increased and potentially a comparable scheme for non-domestic installations might be required. Eventually, installer skills would become established as per conventional heating.
Energy efficiency measures deployment requires an immediate increase in installation rate.		Revision of the Building Regulations (Part L/ Section 6) needs to legislate implementation of energy efficiency measures and low-carbon heating and provide a clear direction.
Supply chain risk may be impacted by developments overseas which could reduce the capacity of OEM and EPC contractors to service the UK market.		Strengthen own UK supply capacity, engage early with international suppliers and seek commitments but ensure diversity of providers for back-up.
Large scale roll-out of yearly performance reviews of energy efficiency measures will require co-ordination to ensure systems are not neglected, this is in the interest of achieving best operating practice. Managing the need for system reviews alongside the increasing rate of required installations and the number of suitably trained installers requires attention.	 	Aftercare, monitoring and potentially a 'soft landings' type approach to be included within robust plans for roll out.
Low consumer uptake of heat pumps and energy efficiency measures.		End-user incentivisation schemes are likely to require a shift from current payment methods to one which involves upfront grants to combat the capex involved with electrification.
Not all non-domestic buildings will be capable of a shift towards full electrification.		Heat pumps suitable for use in non-domestic applications need to be investigated and trialled.
Complex non-domestic buildings are very difficult to convert.		Early market characterisation and conversion plan required.

Risk/challenge	Type	Solution
There is a risk that heat pump systems will not be used in a manner that promotes the highest efficiencies and performance characteristics, due to operating requirements differing to conventional technologies that end-users are familiar with.		Engagement initiatives will be required to inform and instruct end-users, installers and designers on best practices for low-carbon heating installations.
Co-ordination of energy efficiency measures and implementation of heat pump systems.		Planning needs to be undertaken via a central organisation/group that has responsibility for the co-ordination and oversight of implementation across regions.
Overall power system operations will become much more sensitive to weather patterns, especially in the heating season. This will increase the incidents of periods when the overall demand/supply balance comes under stress.		Sophisticated forecasting of demand and supply should enable the system operator and the market to provide signals to flexible generation, interconnectors, storage and demand side response to ensure the system manages.
Poor management of incentive schemes in conjunction with regulatory decisions. For example, if incentives stimulate demand beyond what is achievable (based on the number of trained installers at the time), the quality of installation is likely to be impaired.		Manage the incentivisation schemes such that the necessary interventions are suitable in scale and timing to achieve the desired result, in a manner that is feasible in a logistical sense.
Installations could be seen as being risky by end-users.		Upskill the existing workforce and the delivery of early successful installations to build confidence during initial stages. Ensure continued successful installation of heat pumps through the development and provision of a certification scheme for installers linked to a digital platform enabling consumers to find qualified installers.
High energy costs for end-users.		Develop standards and technical solutions to ensure performance in use and reduced running costs. One such example is the integration of smart controls able to respond to a range of potential signals such as local network pricing and time of use tariffs. Deliver whole-house solutions, including energy efficiency, where needed. This would require financial support to help with the capital cost required not only for the heating system but also for energy efficiency measures to maintain low energy cost and an efficient use of the equipment. As complementary to whole-house solutions, encourage Heat as a Service (HaaS) type business models to enable providers to innovate in how they provide and charge for heat and improved efficiency.

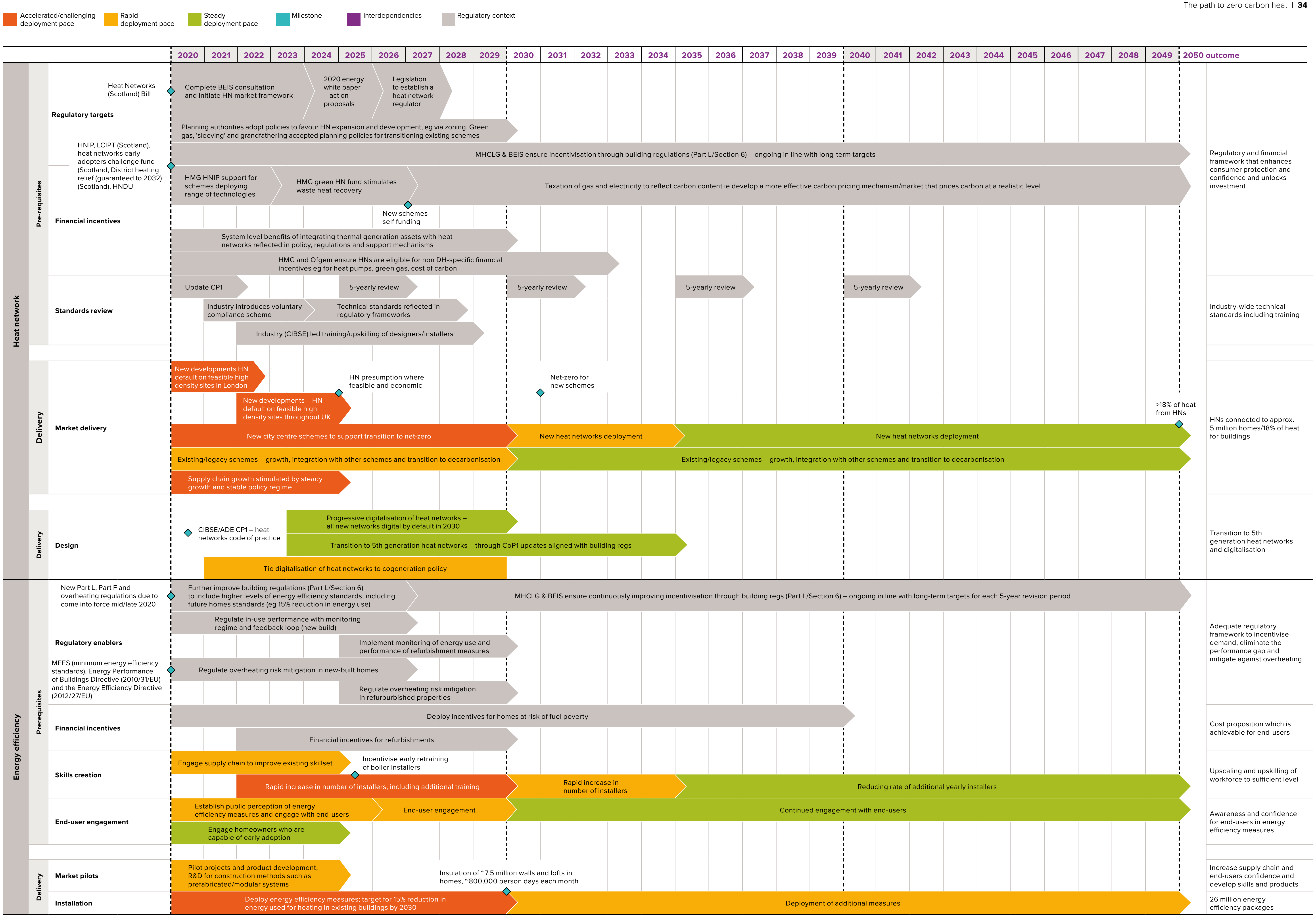
C.5 Electric pathway roadmap

Accelerated/challenging deployment pace | Rapid deployment pace | Steady deployment pace | Milestone | Interdependencies | Regulatory context





Accelerated/challenging deployment pace
Rapid deployment pace
Steady deployment pace
Milestone
Interdependencies
Regulatory context
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049
2050 outcome
Gas/hydrogen infrastructure
Feasibility
Technical
Technical feasibility of pipes, components and appliances – HyNTS, H21, H100 etc
Establishment of full body of standards and codes of practice. Training of workforce
Further testing in commercial and industrial sectors
Technical feasibility proven
Generation and storage
Public case for safety proven
Safety
Development of the safety case based on technical results. Define requirements for regulations
Progress with public trials – small scale controlled environment to larger scale community trials
Establish regulatory and procurement framework
Safety case developed
Update GSMR
Policy decision
Production
Biomass
Feasibility and FEED studies for a ~5MW plant
Feasibility and FEED studies for a ~50MW plant. Construction of first ~5MW plant
Construction of a FOAK ~50MW plant
Buildout at scale of ~50MW plants
Green Gas Levy to support biomethane production from biomass
Scale-up of planting of biomass for gasification
15GW
CCUS
CCUS
Hubs
Policy/regulatory framework including financing and risk mechanism developed
Signal market for deployment (cost feasibility or subsidies)
First CCUS demo projects – part of industrial cluster
CCUS scale-up
CCUS scale-up
CCUS successfully deployed at scale
CO_2 transport networks developed (part of demo projects)
CO_2 transport
CO_2 transport and storage infrastructure in place
CO_2 storage developed (part of demo projects)
CO_2 storage
Storage sites operational and transport mechanisms in place
Storage
Gas storage (excluding CO_2)
Define storage requirements, local and centralised – geographical mapping
Storage at industrial clusters
Development of storage infrastructure – local and large scale centralised storage to balance demand and supply
Bring additional storage online
Proof of concept at small scale
Preparation of depleted gas fields and salt caverns
Large scale and local storage sites developed
Enhance regulations to limit poor performance/high consumption tech (ie resistive heating)
No boilers installed in new build
CCUS, production and electrical storage
No boilers installed in existing homes
Heat pump
Prerequisites
Regulatory targets
Boiler phase-out
All heating systems to be low-carbon
Building regulations to support heat pumps: lower flow temperatures, revise space requirements etc
Possibility to introduce and revise an emissions standard – based on carbon intensity value of delivered heat
Ensure regulation of heat pumps beyond 2035 continues to develop more stringent standards in performance and efficiency as the technology advances
Regulatory framework that is innovative, flexible and transparent, acting to achieve zero carbon energy supply
Future homes standard
Financial incentives
End of current RHI
Implement new RHI
Set out financial incentives to prioritise heating system replacement especially when near the end of its lifespan
Ensure incentives allow for existing housing stock to be effectively retrofitted for low-carbon heating
Low-carbon heat support scheme (from April 2022)
Scrappage scheme
Cost proposition which is achievable for end-users
Skills creation
Increasing numbers of engineers in design, manufacture and research
Increasing numbers of engineers in design, manufacture and research
Train installers
Rapid increase in number of installers retrain boiler installers
Reducing rate of additional yearly installers
Training and certification schemes etc. evolve with technological advancements to ensure best practice is always achieved
Workforce with full range of skills in HPs
Incentivise to promote early retraining of boiler installers
~120,000 person-days in each month – instead of 7000 installers
~500,000 person-days in each month
End-user engagement
Engage with end-user to improve information on the optimum operation of heat pumps, relevant control technology and importance of energy efficiency measures
Engage with homeowners likely to keep boiler system as long as possible and with homeowners who are capable of early adoption – encourage early retrofit options
End-users who are predisposed to low-carbon technologies
Supply chain management
Stock characterisation
Develop wider range of HPs and smart controls to respond to network signals
Feasibility and trial of 'hard-to-convert' buildings
Supply chain will react in accordance to demand – ensure regulations and financial incentives drive the market towards best practice and innovation across all end-use sectors
Mature supply chain able to meet demand
Incentivise early adoption where feasible
Incentivise necessary adoption where previously unfeasible
Distribution grid mass reinforcements
Delivery
Design and installation
Energy efficiency measures: pre-assessment of homes
Retrofit occurring in properties where homeowners are able, and are willing, to adopt low-carbon heating early
Retrofit needs to start to occur in housing stock with unfavourable conditions and where homeowners cannot necessarily afford necessary modifications
Rapidly increasing yearly installation of heat pumps
Reducing increase in yearly installation rate to estimated level required to achieve net-zero (2050)
Annual installation rate remains fairly constant beyond 2035. Greater efficiency in supply will help drive the cost down – this is paramount. Wider consideration must be taken in regard to the supply chain, particularly to technologies that ensure best practice is met in every heating system
Initial focus on new build and homes off the gas grid
Retrofit takes up greatest proportion of yearly installed unit
Retrofit takes up ~75% of yearly installations
Circa 19 million heat pumps in homes
Estimated required yearly installation rate of 1.15 million
Performance
Performance in use
Development of commissioning procedures for existing heat pumps
Widescale rollout of a yearly performance review programme to ensure best practice of every heating system is met
Development of digitalised system evaluation
Rollout of digitalisation techniques for efficient evaluation of system performances – feed this information back to the end-user
Whole system approach to HP performance


Accelerated/challenging deployment pace
Rapid deployment pace
Steady deployment pace
Milestone
Interdependencies
Regulatory context
2020
2021
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2040
2041
2042
2043
2044
2045
2046
2047
2048
2049
2050 outcome
Heat network
Pre-requisites
Regulatory targets
Heat Networks (Scotland) Bill
Complete BEIS consultation and initiate HN market framework
2020 energy white paper – act on proposals
Legislation to establish a heat network regulator
Planning authorities adopt policies to favour HN expansion and development, eg via zoning. Green gas, 'sleeving' and grandfathering accepted planning policies for transitioning existing schemes
HNIP, LCIPT (Scotland), heat networks early adopters challenge fund (Scotland, District heating relief (guaranteed to 2032) (Scotland), HNDU
MHCLG & BEIS ensure incentivisation through building regulations (Part L/Section 6) – ongoing in line with long-term targets
Financial incentives
HMG HNIP support for schemes deploying range of technologies
HMG green HN fund stimulates waste heat recovery
Taxation of gas and electricity to reflect carbon content ie develop a more effective carbon pricing mechanism/market that prices carbon at a realistic level
New schemes self funding
System level benefits of integrating thermal generation assets with heat networks reflected in policy, regulations and support mechanisms
HMG and Ofgem ensure HNs are eligible for non DH-specific financial incentives eg for heat pumps, green gas, cost of carbon
Regulatory and financial framework that enhances consumer protection and confidence and unlocks investment
Standards review
Update CP1
5-yearly review
5-yearly review
5-yearly review
5-yearly review
Industry introduces voluntary compliance scheme
Technical standards reflected in regulatory frameworks
Industry (CIBSE) led training/upskilling of designers/installers
Industry-wide technical standards including training
Delivery
Market delivery
New developments HN default on feasible high density sites in London
HN presumption where feasible and economic
Net-zero for new schemes
New developments – HN default on feasible high density sites throughout UK
>18% of heat from HNs
New city centre schemes to support transition to net-zero
New heat networks deployment
New heat networks deployment
Existing/legacy schemes – growth, integration with other schemes and transition to decarbonisation
Existing/legacy schemes – growth, integration with other schemes and transition to decarbonisation
Supply chain growth stimulated by steady growth and stable policy regime
HNs connected to approx. 5 million homes/18% of heat for buildings
Delivery
Design
CIBSE/ADE CP1 – heat networks code of practice
Progressive digitalisation of heat networks – all new networks digital by default in 2030
Transition to 5th generation heat networks – through CoP1 updates aligned with building regs
Tie digitalisation of heat networks to cogeneration policy
Transition to 5th generation heat networks and digitalisation
Energy efficiency
Prerequisites
Regulatory enablers
New Part L, Part F and overheating regulations due to come into force mid/late 2020
Further improve building regulations (Part L/Section 6) to include higher levels of energy efficiency standards, including future homes standards (eg 15% reduction in energy use)
MHCLG & BEIS ensure continuously improving incentivisation through building regs (Part L/Section 6) – ongoing in line with long-term targets for each 5-year revision period
Regulate in-use performance with monitoring regime and feedback loop (new build)
Implement monitoring of energy use and performance of refurbishment measures
MEES (minimum energy efficiency standards), Energy Performance of Buildings Directive (2010/31/EU) and the Energy Efficiency Directive (2012/27/EU)
Regulate overheating risk mitigation in new-built homes
Regulate overheating risk mitigation in refurbished properties
Adequate regulatory framework to incentivise demand, eliminate the performance gap and mitigate against overheating
Financial incentives
Deploy incentives for homes at risk of fuel poverty
Financial incentives for refurbishments
Cost proposition which is achievable for end-users
Skills creation
Engage supply chain to improve existing skillset
Incentivise early retraining of boiler installers
Rapid increase in number of installers, including additional training
Rapid increase in number of installers
Reducing rate of additional yearly installers
Upscaling and upskilling of workforce to sufficient level
End-user engagement
Establish public perception of energy efficiency measures and engage with end-users
End-user engagement
Continued engagement with end-users
Engage homeowners who are capable of early adoption
Awareness and confidence for end-users in energy efficiency measures
Delivery
Market pilots
Pilot projects and product development; R&D for construction methods such as prefabricated/modular systems
Insulation of ~7.5 million walls and lofts in homes, ~800,000 person days each month
Increase supply chain and end-users confidence and develop skills and products
Installation
Deploy energy efficiency measures; target for 15% reduction in energy used for heating in existing buildings by 2030
Deployment of additional measures
26 million energy efficiency packages

D. Hydrogen pathway

D. Hydrogen pathway

D.1 Introduction to the scenario

Hydrogen production, transmission and distribution

The pathway considers the wide-scale integration of hydrogen in existing gas infrastructure with the intention of displacing natural gas as the main source of supply for heating in buildings. The pathway was chosen as it poses several key long-term benefits including the repurposing and thus continued use of our extensive gas distribution system in the future decarbonised energy landscape (though the same may not necessarily be true of the gas transmission system). Hydrogen has the potential to act as an energy vector with applications extending beyond heating, including use as a transportation fuel source and a component in industrial and chemical processes.

Following the selected pathway, large scale hydrogen production will be primarily based on SMR (steam methane reformation) or ATR (auto thermal reforming) technology to convert natural gas, combined with carbon capture, utilisation and storage (CCUS) with a smaller amount being produced from biomass using gasification and/or pyrolysis. The facilities will be placed at strategic locations determined through modelling and optimisation. Bulk hydrogen and carbon storage will be required and will make use of salt cavern formations, depleted offshore gas fields and purpose-built bulk storage facilities at selected locations.

An alternative route is through the production of 'green' hydrogen, either via electrolysis using renewable or nuclear power, or through other processes. It is recognised that as this technology improves and the required cost reductions are achieved, more can be deployed, reducing the reliance on natural gas reformation to produce hydrogen. Our selected hydrogen pathway has taken this into account by introducing a phased approach whereby the asset deployment base is reviewed and adjusted to accommodate these developments. The centralised production option using ATR and CCUS was used as a basis to identify some of the challenges associated with deploying these systems at scale; however, it is recognised that 'green' hydrogen production is a preferred option to meet decarbonisation and sustainability targets.

There is currently ongoing work to establish whether it is feasible to transition the UK's existing natural gas transmission system (NTS) to hydrogen in the future. Here we assume that a largely new hydrogen transmission system (HTS) is required alongside the natural gas system. We have made this assumption to allow us to explore the infrastructure requirements for this scenario. This will be a significant national strategic undertaking requiring extensive and very challenging accelerated planning and approval processes involving various stakeholders. Depending on the outcome of research in the coming years it may be that parts of the existing NTS could be repurposed whereupon these will transition to hydrogen as demand-supply balancing through the conversion process takes place. Options such as deblending are being explored to determine feasibility to accelerate and simplify the transition process to 100% hydrogen in the gas infrastructure. 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.[13]

To enable this new hydrogen industry, the safety case for hydrogen will need to be established and the required modifications to protocols, procedures and mechanisms developed and put in place to allow conversion to commence. A new regulatory framework is also to be established to underpin the sector.

End-user hydrogen systems

For end-users, the hydrogen pathway assumes that both domestic and non-domestic systems that are currently run on natural gas will be replaced with equivalent systems that run on hydrogen. Domestic and non-domestic end-users will have different challenges, which depend on the type of heating systems and end-user equipment that is already in place and the complexity of each site and building. In the domestic sector, all end-users that currently use natural gas to meet their heating needs, and who represent almost 85% of domestic properties, are assumed to use hydrogen boilers, cookers and other domestic appliances. In this pathway, nearly 17 million (if the small number of hybrid heat pumps as well as dedicated boilers are taken into account) hydrogen boilers for domestic properties are deployed by 2050.

13. For more on this topic see: Institute of Engineering and Technology (2019) Transitioning to hydrogen: Assessing the engineering risks and uncertainties.

D.1.1 Pathway components

Two dependency maps were developed (page 39 and 40), one for the supply side of the hydrogen pathway and one for hydrogen heating systems. The components of the pathway are shown within the dependency map and are generally placed in a sequence that correlates to the timelines.

The development of the infrastructure required to deploy hydrogen in this pathway at scale is a significant national undertaking that will require planning co-ordination and policy/regulatory decisions at specific stages during the pathway timeline. The dependency map for the supply side details the salient tasks that will define the basis of the infrastructure development pathway, detailing some risks and the flow from the inception/development phase to implementation phase, whilst the dependency map for the demand side looks at the tasks needed for the roll-out of end-user hydrogen heating systems.

Planning

The planning phase is dependent on the outcomes of the feasibility phase as shown on the dependency map. The hydrogen pathway assumes that certain policy decisions will be made to allow the development to progress. These decisions will rely on the outputs of the different programmes that are currently being run or planned by various organisations to test the feasibility of deploying, or repurposing, the requisite infrastructure. Specific examples include the safety and operational requirements that must be taken into account when dealing with hydrogen in installations. These are currently being assessed, and organisations such as the HSE will define what measures must be introduced to achieve safety. Programmes such as HyNTS, Hy4Heat and others are currently in progress, while others that include production, storage and CCUS have been initiated or are being developed.

The planning phase is initiated by some form of master planning that will evaluate the whole system architecture. The demand analysis and transitional approach forms the basis for this phase as various possible scenarios must be accounted for. This includes the management of various flow regimes in the piping infrastructure as the demand transition from hydrogen to natural gas takes place.

Implementation

For a hydrogen scenario, the interdependencies related to the implementation are numerous and span across various aspects. Some of the key points that were incorporated into the maps are as follows:

- Roll-out strategy will need to be strategically managed on a regional and national basis and will be timed to manage complexities related to the switchover, some of which were encountered during the town gas transition.
- The delivery process will require interaction with a developing supply chain and workforce, requiring market and government-controlled mechanisms to co-ordinate and manage.
- The scale of the infrastructure that will be potentially deployed is significant and will require continuous monitoring and revision during the implementation phases to ensure that aspects such as stranded assets are minimised.

Regulatory

The UK current regulatory frameworks for gas and electricity provide no specific material support for hydrogen production, transport or use, and if this situation were to persist there would be no incentive for any move towards the hydrogen economy. However, the government recognises this and is already supporting innovation programmes and technology demonstrations. At the time of writing the government was looking to support planning and outline design of new regional low-carbon industrial clusters, all of which plan to include hydrogen production, transport and use. The government is also expected to release an energy white paper, which should outline support for CCUS and potentially for hydrogen production. While we do not know the timing and the specifics of this – the dependency map outlines several different options – it is clear that putting in place a fit-for-purpose regulatory regime will be a key early prerequisite for implementing the hydrogen pathway.

Hydrogen heating
The hydrogen heating dependency map (page 39) looks at steps required to deploy the systems at scale, and the prerequisite actions that can be undertaken. These prerequisites include the regulatory incentives required to stimulate demand and streamline deployment, financial incentives, the development of the supply chain including skills creation and the required technical development for hydrogen systems. In addition to these, the hydrogen systems dependencies map includes a feasibility stage.

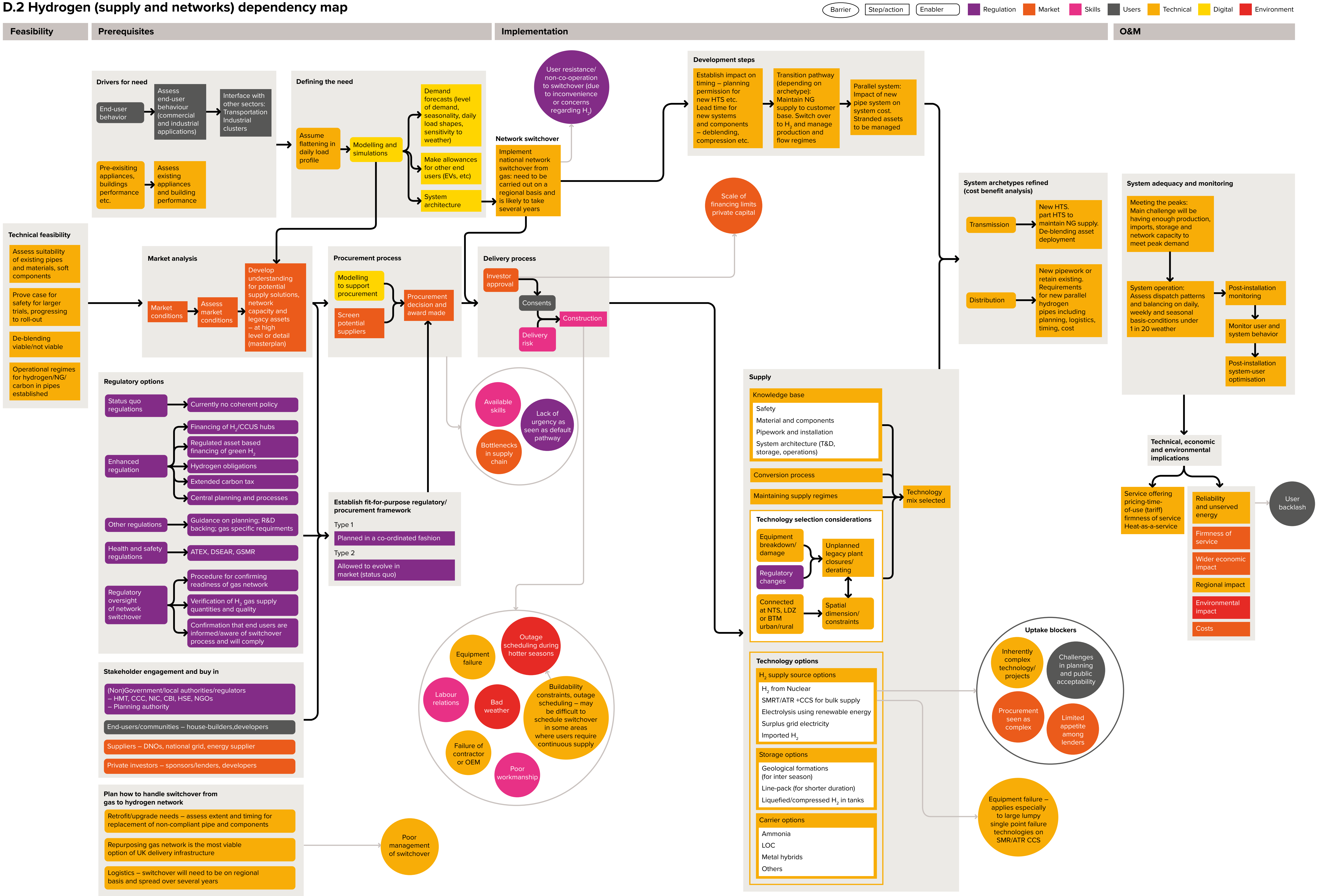
A number of issues were identified as central for the deployment of hydrogen heating:

- **Hydrogen feasibility:** The technical and commercial feasibility and safety case for hydrogen for end-users needs to be proven before the roll-out is implemented. This is currently being investigated under a number of projects including Hy4Heat and H100, with trials expected to be developed in the coming years. It is expected that a programme to establish the feasibility could last until 2025. After this assumed decision point, a number of years would be needed before conversion can be started for parts of the distribution systems and end-users.

- **Skills creation:** A national hydrogen conversion will require roll-out of training based on developed hydrogen standards and regulation, where many of the skills and competences from gas installers and heating engineers should be easily adapted. At the peak rate of conversion this will dictate a larger trained workforce than is currently available but, within a conversion strategy that aims for a decision in 2025 and starts in earnest in 2030, there is time to convert the skills of existing installers and engineers and increase the size of the workforce. However consideration is needed as to how the market will be stimulated to develop training materials and providers, and eventually deliver this increased and hydrogen-ready workforce. Developing Gas Safe conversion programmes and training installers to take part in large scale trials would be steps that would help bridge the installer numbers gap to the number required for a full roll-out.

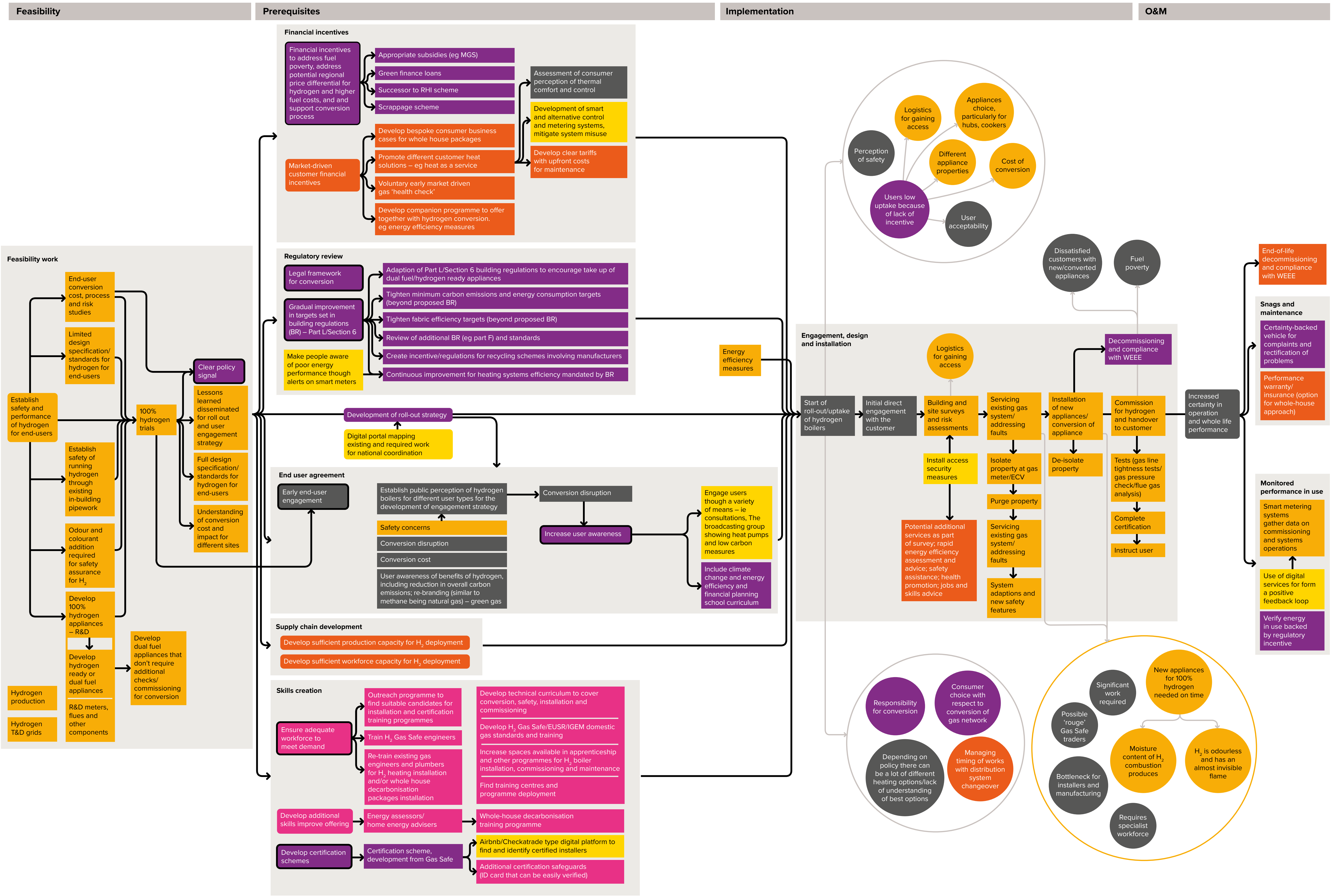
- **Roll-out strategy and co-ordination with supply side roll-out:** One of the key steps for the hydrogen heating deployment will be the development of the roll-out strategy. This will have to be in place well before the policy trigger and will align with the development of plans for the conversion of the distribution network and the development of the hydrogen transmission system. This is a very complex aspect of the hydrogen pathway in that the gas network and the end-users will have to be converted in parallel as the roll-out spreads geographically. Between 2025 and the eventual roll-out, low cost preparations could be made which would help minimise the risks at roll-out, for example using hydrogen-ready boilers, though the cost versus the benefit of some of these measures need to be understood in more detail. It is not clear whether such measures will make significant or marginal differences to the risks and costs of conversion and further work is needed to understand this.

D.2 Hydrogen (supply and networks) dependency map



D.3 Hydrogen systems dependency map

Barrier | Step/action | Enabler | Regulation | Market | Skills | Users | Technical | Digital | Environment



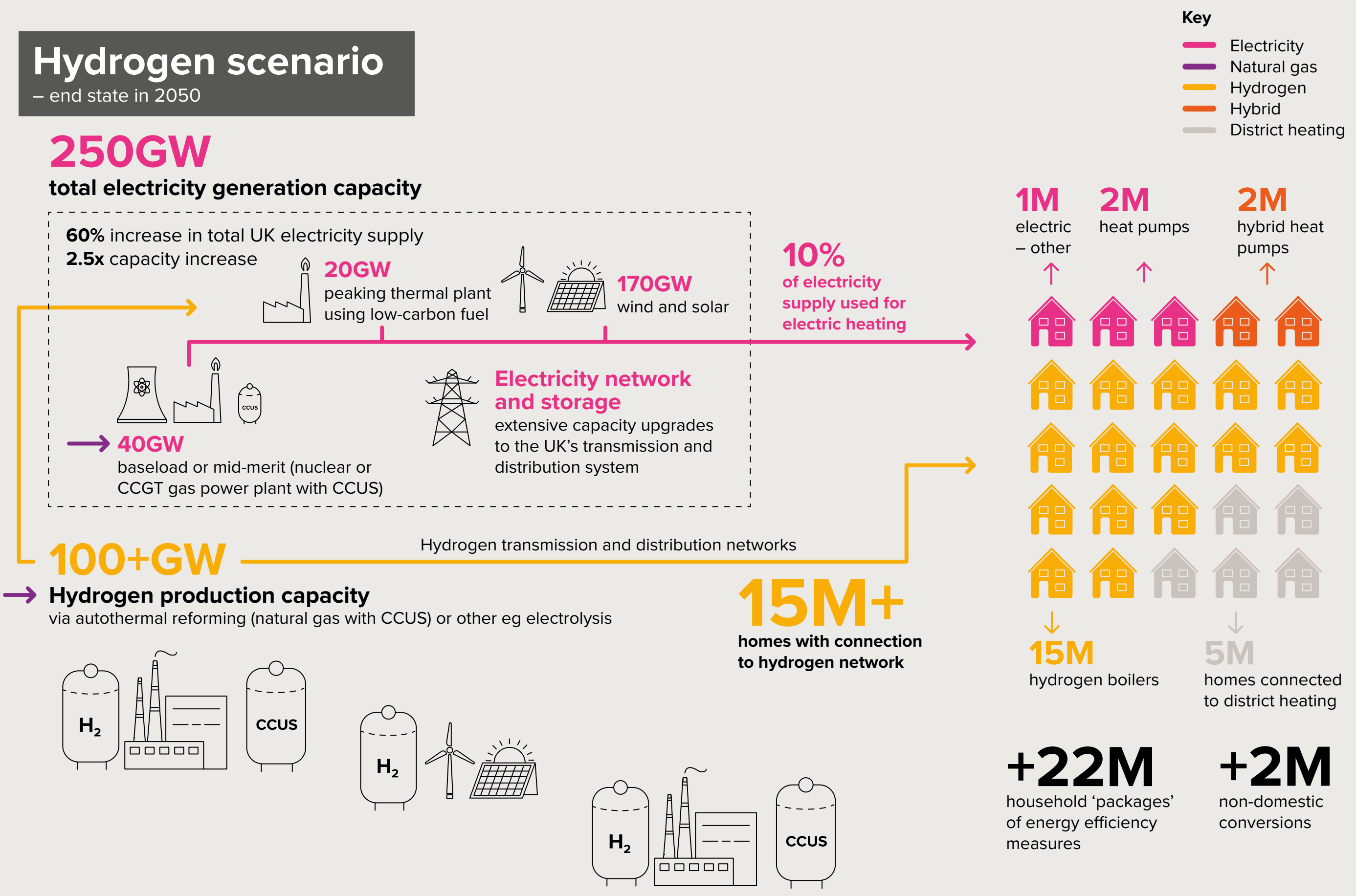
D.4 Hydrogen roadmap – discussion

D.4.1 The 2050 technology mix

The 2050 technology mix and capacities for the supply side part of the pathway were based on the hydrogen scenario with 10MtCO$_2$ residual emissions detailed in the ICL report (H$_2$[10]). This is due to the high additional cost calculated by ICL for achieving the H$_2$[0] pathway. Based on this end assumption, the main infrastructure requirements and the progression in the pathway were mapped to provide an indication of the timing of key activities. The assumption, as further discussed below, is that the work currently being done in the industrial clusters to trial and test production, CCUS and T&D/storage infrastructure will act as the precursor to wider scale roll-out during the transition.

The roadmaps themselves have been based on the H$_2$[10] technology mix figures for hydrogen production and electricity generation. These indicate that over 100GW of hydrogen production capacity is expected by 2050 in line with the H$_2$[10] pathway. This is initially assumed to be large-scale centralised production based on ATR of natural gas with CCUS, for which all technologies would need to be trialled and the supply chains readied for large scale roll-out. However, renewable hydrogen produced via electrolysis has the advantage of being able to respond to changes in electrical and gas demand. This could make it a long-term solution provided the supply chain is established, and the cost reductions are achieved through large-scale roll-out.

Figure 7: The 2050 technology mix – Hydrogen



The production of hydrogen will be as per the table below regarding technology and capacity:

Table 3: Hydrogen production

H_2 production capacity (GW)		
	ATR + CCUS	90
	Electrolyser	2
	Biomass + CCUS	12
H_2 production (TWh – HHV)		
	ATR + CCUS	661
	Electrolyser	2.8
	Biomass + CCUS	93.2
Total (TWh – HHV)		
	Total (Mt)	19.2
Biogas (TWh)		
	Biogas	21

The H_2[10] pathway limits the amount of hydrogen produced by electrolysis based on capital and lifecycle cost. It is likely that further cost reductions can be achieved for electrolysis based on further development and increased global deployment, which would mean more hydrogen via electrolysis and a lower future deployment of ATR and CCUS. As such, this technology and other green production systems should be retained as sustainable, viable alternatives.

End-users

The 2050 technology mix is based on the EE/UCL Hydrogen Further Ambition scenario. The ICL and EE/UCL studies have only domestic end-users within their scope, which is a reasonable simplification. However, the feasibility for other end-users (including non-domestic heating and industrial process heating) needs to be understood before a decision to convert to hydrogen is taken. We have therefore expanded our thinking to include non-domestic heat.

The mix of domestic end-user technologies by 2050 will be dominated by hydrogen boilers, with just over 15 million installed. There will also be around 1.8 million hydrogen boilers included as part of hybrid heat pump systems. Prototype domestic hydrogen boilers are already being developed as part of programmes such as Hy4Heat, but there is still work to be done to understand the overall safety, disruption and cost of domestic end user conversion, especially in more complex domestic buildings (eg multi-storey).

The number of ASHPs will be limited to around 2.3 million, with these potentially being deployed in areas off the gas grid. As with the other two roadmaps, around 5.3 million end-users will be connected to district heating networks.

Of the 2 million non-domestic users, those converted to hydrogen will have a much larger variety of hydrogen fired end uses, including air heaters, water heaters and radiant heaters. Non-domestic site conversion will be a much more complex undertaking than domestic for some sites, including large sites with a significant end-user gas system such as hospitals and larger industrial sites.

D.4.2 Assumptions for the roadmap

The roadmap was developed to achieve the ICL and EE/UCL 2050 technology mix. We have made assumptions regarding key mobilising actions and the deployment rates that are possible for various interventions. These have been captured below for the hydrogen infrastructure and hydrogen end-user heating systems, as these are the driving components for the hydrogen pathway. Assumptions made for energy efficiency measures and heat networks are presented in the cross-cutting section.

On the supply side, we assumed that the deployment and construction of the hydrogen production facilities will follow a phased approach:

1. Pilot testing and demonstration of SMR/ATR, plus CO_2 and hydrogen transport and storage facilities.
2. Detailed planning and design of full-scale CO_2 and hydrogen transport and storage facilities.
3. Large scale testing and initial commercial deployment at the industrial clusters of SMR/ATR facilities and associated CO_2 transport and storage.
4. Production capacity scale-up and supply chain development for larger scale deployment.
5. The build phase will commence with planning and pre-development phases whereby the locations are confirmed through an iterative modelling and optimisation approach that follows from the initiation phases.

Supply assumptions

- The work being done to establish the feasibility of converting the transmission and distribution system under the H21, H100, HyNTS and other programmes continues until 2025 and presents acceptable outcomes that are used to inform policy.
- The safety case for hydrogen is established and the required modifications to protocols, procedures and mechanisms, such as a requirement for additional safety valves, are developed and put in place to allow conversion to commence.

In order to shape the infrastructure delivery, our judgement and experience has informed the following:
- To reach the 90GW+ production capacity, we suggest that the ATR/CCUS be deployed in two build phases each lasting approximately 10 years. At the end of the first build phase, it is assumed that the first pilot scale facilities will reach end of life.
- Prior to the commencement of build phase 2, the technology roadmap will be reviewed and the potential of deploying more electrolysis or other technologies will be evaluated, with the phased approach reducing the limit of stranded assets.

CCUS assumptions
- The production, CCUS, storage and transmission infrastructure will be constructed in parallel and brought on-line sequentially as the demand transition takes place.

Transmission assumptions
- The NTS will continue to supply NG to heavy industry and large power producers in the short and medium term.
- The NTS will eventually transition from supplying natural gas to hydrogen.
- A new hydrogen transmission system (HTS) will be built to connect hydrogen bulk supply points, bulk demand points and storage.
- The NTS or large sections thereof can be repurposed for use with 100% hydrogen.
- Increased volumetric flow will need to be accommodated in the system if the same operating pressures are retained.
- Asset replacement, such as valves and compressors, is required.

Distribution assumptions
- The majority of the distribution system will be compatible with hydrogen, post completion of the iron mains replacement programme.
- Some asset and/or component replacement will need to take place to ensure safe operation, including pressure reducing stations.
- Increased volumetric flow will need to be accommodated in the system if the same operating pressures are retained.
- Changes to clearance distances can mostly be accommodated without drastically altering the system.
- Operational and maintenance procedures are developed and successfully implemented on the repurposed networks.

End-user assumptions
- The case for hydrogen recognises that there is a requirement for more work to properly understand the feasibility, safety and cost of conversion to hydrogen for end-users. It has yet to be demonstrated that hydrogen can be as safe and effective for end-users as natural gas. Like transmission and distribution, an end date of 2025 for the necessary research and trial activities is assumed. The demonstration of the commercial viability of hydrogen conversion is also needed.
- It is assumed that end-user natural gas piped systems and the features of the buildings (eg ventilation) in which they are housed will be easily adaptable to hydrogen (eg pipes are largely reused). This has yet to be demonstrated. The identification of a need for significant alteration and replacement in the feasibility stages could greatly increase the cost of the hydrogen pathway.
- Actual conversion of end-users can't start in earnest until around 2030, when the natural gas network begins to be converted.
- Approaching 17 million (if domestic sites only are considered and hybrid heat pumps are included) building conversions would be required, resulting in over 70,000 conversions each month on average over a 20-year period. Potentially some sites might only be tackled outside the heating season, so at certain times the rate of conversion could be even higher.
- Assuming an average of 3 person-days per conversion (and for some larger bespoke projects it may be very much greater than this), then this dictates over 210,000 person-days of installer time each month.
- Non-domestic conversions will be much lower in number but much more challenging, as individual projects with potentially significant risks of downtime and site disruption.
- Work on standards, regulation and training can be prepared for prior to 2025, but can only progress in earnest after this date, after a decision has been made.
- The requirement to undertake end-user conversion in tandem with distribution system conversion adds to the complexity of sequencing and managing hydrogen conversion.
- There is a further requirement to characterise and engage with hydrogen end-users. Some commercial and industrial users will need ample time to consider and prepare for the conversion to hydrogen.

D.4.3 Roadmap description

Hydrogen – feasibility
From 2020 until 2024, technical feasibility of pipes, components and applications need to be tested through the HyNTS, H21, H100 and other projects. This will lead to the establishment of a body of standards and codes of practice. It also leads to training of the workforce and further testing of hydrogen in commercial and industrial sectors, all between 2024 and 2028.

Between 2020 and 2023, techno-economic appraisal of development pathways into the end state needs to be undertaken. This is seen as critical for the viability of this roadmap.

Following the development of the safety case another critical action for the pathway, namely progressing with public trials, is assumed to go forward – from small scale, controlled environment to larger scale community trials. Trials of larger commercial and industrial sites will also be required. This leads to the public case for safety and consequently a major policy decision around hydrogen in 2025. From this we must establish the regulatory and procurement framework between 2026 and 2028.

Hydrogen – production
We mapped several key strands of work associated with the transition process itself, as our core understanding of the future grid and systems including the likely archetypes must be understood to allow for appropriate planning. These will all feed into policy decisions that are likely to take place between 2025 and 2027, and are required to provide market confidence in the likelihood of hydrogen vector transition over the next two decades.

The sequencing of the infrastructure development activities is vital, as production has to be brought on-line when transmission and distribution (T&D) assets, storage build-up and operational and safety requirements have been built and met. The transition pathway whereby end-users and other customers are sequentially converted from natural gas to hydrogen has to align with the availability of the new infrastructure and assets in order to protect the security of supply to customers.

The evolution of hydrogen production via ATR and electrolysis, including the interdependencies, were considered and the preparation, initial roll-out and eventual buildout phases were estimated based on likely scales and required timeframes to deliver these. Key aspects such as technology readiness, development of the supply chain and skills base as well as the requirements to meet planning and design/procurement were considered.

For gas reforming, pilot projects are underway to trial ATR and CCUS between 2020 and 2024. This will lead into supply chain development and scale-up of production capacity. In parallel, between 2022 and 2027, a scale-up of industrial production through industrial clusters is needed. This allows for a highly ambitious first build phase between 2027 and 2040, using an ATR single train capacity limit of 1.4GW. Phased procurement and construction is implemented while sequentially bringing production online with demand uptake.

For renewable electrolysis development, the roadmap assumes the scaling up of local production capacity (eg Gigastack) and the establishment of pilot projects to trial feasibility from 2020 to the end of 2022. From 2023, further production scale-up is required at very accelerated timescales and requires major development of the supply chain, using small scale roll-out to drive cost reduction. Between 2027 to 2030, planning for wider scale roll-out must be undertaken and market conditions established. This leads to build phase 1 (2030-2040) by delivering more than a GW of installed capacity, which will be distributed and co-located with renewables. Build phase 2 in 2040 to 2050 will follow. Depending on global market conditions and development of the technologies and supply chains, the deployment of 'green' hydrogen production systems can be increased and accelerated in the programme.

To test the case for an alternative 'green' hydrogen via nuclear hydrogen production, between 2020 and 2028 the industry needs technology development of higher performance electrolysers – solid oxide, high temperature systems – as well as direct coupling of steam cycles and hydrogen production using thermochemical splitting. From 2024 to 2030, further production scale up and supply chain development for electrolysis, thermochemical/electrochemical splitting coupled with modular nuclear and other systems will take place with initial small scale rollout. From 2030 this will lead to deployment at several selected sites to deliver the first larger scale systems by 2035.

Between 2020 and 2023, blending trials of up to 20% are required, using HyDeploy 2 as an example scheme. Further blending from 2023 at industrial clusters could also be trialled. Also, between 2020 and 2023, the feasibility of de-blending in the NTS must be established, with this action marked as critical and followed by trials for small scale de-blending between 2023 and 2026.

Biomass and gasification (pyrolysis) as a further form of low-carbon hydrogen production needs to have further proof of concept at higher capacities between 2020 and 2026.

Between 2020 and 2025, biomass gasification will focus on construction of a ~5MW plant and the FEED studies for a ~50MW plant. This ~50MW first-of-its-kind plant will be constructed by 2035, and thereafter these plants will be deployed at scale. This deployment at scale and the scaling up of biomass plants (which can begin now) are seen as the key challenges in hydrogen production. The Green Gas Levy is also utilised to support biomethane production.

CCUS
A policy and regulatory framework including financing and risk mechanism needs to be developed. From 2020, market signals for deployment (policy, financing, risk sharing, liabilities and cost reduction) are needed, and at a highly ambitious rate. In parallel, from 2021 to 2027, the first CCUS demonstration projects need to be deployed as part of industrial clusters, as well as the development of CO_2 transport networks and CO_2 storage. The storage in particular is seen as highly challenging and ambitious within this timeframe. This leads to scale-up throughout the 2030s and interdependencies with the gas networks and CCUS to manage flow regimes. By 2040, CO_2 transport and storage needs to be in place. The rates of CCUS deployment in parallel with the hydrogen production facilities 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).

Storage (hydrogen)
Much like the other pathways, in order to supply hydrogen to meet peak demands, storage is a vital element in order to provide the capacity for demand response. In the early 2020s, we must define storage requirements and geographical mapping. This must be closely followed by proof of concept at small scale between 2021 and 2025 and through industrial clusters between 2024 and 2030. Preparation of depleted gas fields and salt caverns is also needed in the period 2026 to 2030 to allow for development of storage infrastructure; this is critical for this pathway as the volumes of hydrogen storage are much more significant than in any other. Between 2030 and 2040, local and large-scale centralised storage is increasingly rolled out to balance demand and supply. Further storage is brought online from 2040, but in line with regional demands.

Transmission
From 2020 to 2023, we must prove the concept of hydrogen transmission via HyNTS and LTS futures, which leads to analysis and planning of a new HTS infrastructure in the 2023 to 2026 period. This includes consideration of whether a new HTS is needed or whether conversion of the existing network is viable. Between 2026 and 2029, planning permission and public consent should be sought for the HTS. This again is highly ambitious and on an accelerated timeframe, but is needed for the viability of hydrogen at such a scale. This enables the construction of a new HTS between 2029 and 2040. This is highly ambitious and challenging given the rates of pipeline deployment that this would entail.

In parallel, from 2021 to 2026, the development of new components/methods for operation for the existing national transmission system (NTS) is needed, and the scale of NTS replacement required must also be established by 2026. This leads to skills, workforce and equipment mobilisation in 2026 to 2029 for the conversion of the gas grid. From 2029, there will be replacement of components and compressors to run part of the existing NTS on hydrogen by 2034.

From 2040, it is anticipated that the HTS is operational, with focus on managing the flow regime as production scales up.

Distribution
The distribution grid's proof of concept is needed between 2020 and 2024 via the H21, H100, HyDeploy and other programmes. This leads to District Network Operator (DNO) trials between 2023 and 2028. In parallel, from 2021 to 2025, development of new components/methods for operation is required. Between 2025 and 2033, we must extend the Iron Mains Replacement Programme (IMRP). There is an ongoing conversion and regional switchover via industrial clusters as the gateway starting locations from 2030 to 2050.

Electric generation, storage, transmission and distribution
The issues for the electric components are largely similar to the electric pathway, but the challenge of delivery is much less due to the reduced absolute numbers of supply. See the electrification pathway section for more detail on these aspects. The key milestones that need to be reached are given below.

An outline detailed Regulatory Asset Base (RAB) model for GW nuclear scale is scheduled for 2022. The first RAB award for nuclear is assumed in 2024. The first GW-scale plant will be started in 2025 and commissioned in 2036. For thermal energy, the development of capacity market models to incentivise low utilisation thermal power plant are noted at the end of the 2020s, followed by the building of capacity.

For electrical storage, 2020/2021 are noted as milestones for the development of a clear and robust regulatory regime.

For electric distribution, establishing EV and HP growth projections for DNOs to use, and extending long term DNO planning are noted for 2024, along with establishing a flexibility market to give DNOs an option to manage peak demand on the network. In 2028, a different security of supply offer is scheduled for heating and EVs compared with other loads. A major difference to the electric pathway is that the widespread use of hydrogen boilers and hybrid heat pumps removes the additional network reinforcement beyond that required to support EVs.

Hydrogen heating – pre-decision
In 2025, the feasibility of the core selection of end-users needs to be established, leading to development of full regulation and policy framework. From 2020 to 2025, core safety case and technical knowledge development is required, leading to safety equivalence between hydrogen and natural gas. In addition, end-user conversion cost, implementation and risk studies as well as end-user financial proposition modelling is needed in the same time period. There is a strong interconnectivity with markets and policy here.

From 2020, there is a requirement to identify high-risk end-users, with end-user incentive scenario testing and solution optimisation in the 2022 to 2026 period.

Considerations will include:
- **Safety** – hydrogen has a much wider range of potentially explosive concentrations in comparison to methane and the ramifications for end-user systems have yet to be fully understood.
- **Technical** – hydrogen combustion will potentially generate a greater degree of NO_x than methane combustion, and the necessary adaptions to hydrogen equipment to mitigate this need to be understood.
- **Impact** – end-user sites could face costs and disruption for adaptions to equipment and piped systems, and there is a need to better understand these.

Work will proceed towards user trials, including the following typologies: simple domestic, complex domestic (eg multi-occupancy buildings), community, commercial and industrial. This is already reflected to some extent in existing programmes including Hy4heat and the Industrial Fuel Switching programme, and by DNOs, but is likely to need further expansion. In the early years of the programme, it will be critical to understand the coverage of the programme of research and trials – ie establishing how much work is required to establish the right level of confidence for end-users.

International developments in end-user feasibility could displace or complement parts of the UK's own programme.

Between 2020 and 2022, further characterisation of commercial and industrial users is needed, including identification of end-users who may have higher risk during the conversion process. Between 2026 and 2028, the government should issue detailed end-user proposals, leading to dependencies with hydrogen infrastructure preparation.

For the supply chain there will be a need for increasing engagement with suppliers and manufacturers throughout the 2020s, including manufacturer preparation and increasing levels of detail for conversion.

Hydrogen heating – delivery
From 2021, end-user workforce preparedness for trials (from existing trials) is needed. From 2023, a report on proposed structure and phasing for workforce development is proposed, while from 2026 to 2030 very ambitious workforce development is needed to reach >200,000 person days each month, not including non-domestic conversions and not accounting for the need for gas engineers to change over the distribution system at the same time.

Manufacturer engagement is already underway in programmes such as Hy4Heat, with the focus on engagement with individual manufacturers through competitions and public tenders. After 2025, it will be necessary to engage with the full set of existing natural gas equipment manufacturers, and in some cases this may include complex and bespoke equipment (eg regenerative thermal oxidisers), and here manufacturers will need time to consider changes to new equipment and the likely modifications to existing installed kit. Clear signals in terms of policy, regulation and end-user standards immediately after 2025 will be required.

Between 2030 and 2050, end-user conversion will be rolled out region-by-region, reaching almost 850,000 domestic conversions in each year at the peak in approximately 2038. Phasing out natural gas components begins in 2045.

D.4.4 Key risks and challenges

The following table summarises the key risks and issues of this pathway. This is not a comprehensive list of risks, but some of the main aspects that came out of the development of the roadmap. It is also of note that these risks relate to the specific pathway we have mapped, and different hydrogen pathways could have different risks.

We have categorised the risks under four categories – scale and delivery, technology, complexity and public acceptance – to help understand the differences between these pathways and the issues present.

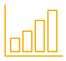
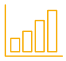
Key

- Scale and delivery
- Complexity
- Technology
- Public acceptance

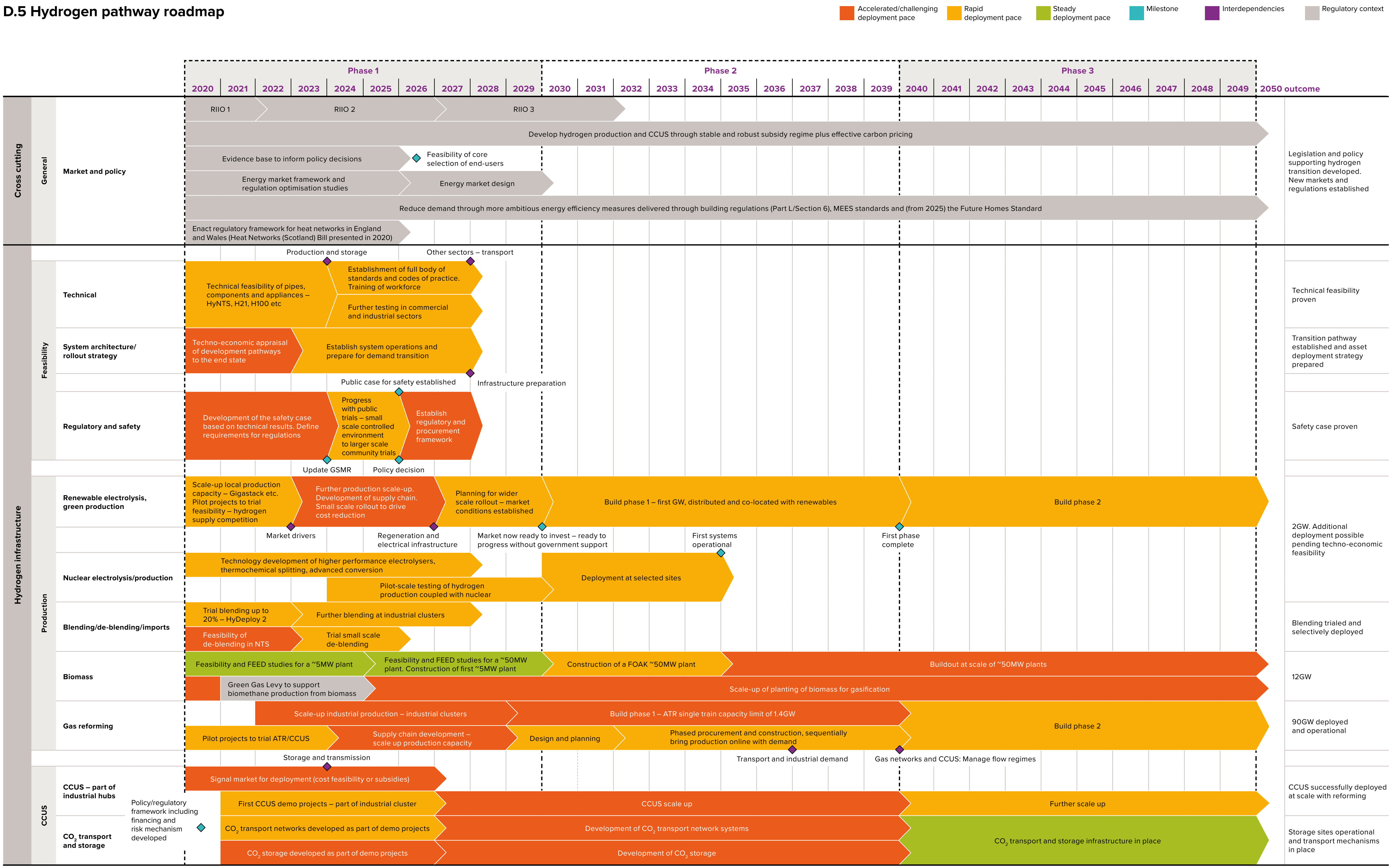
Table 4: Risks and challenges

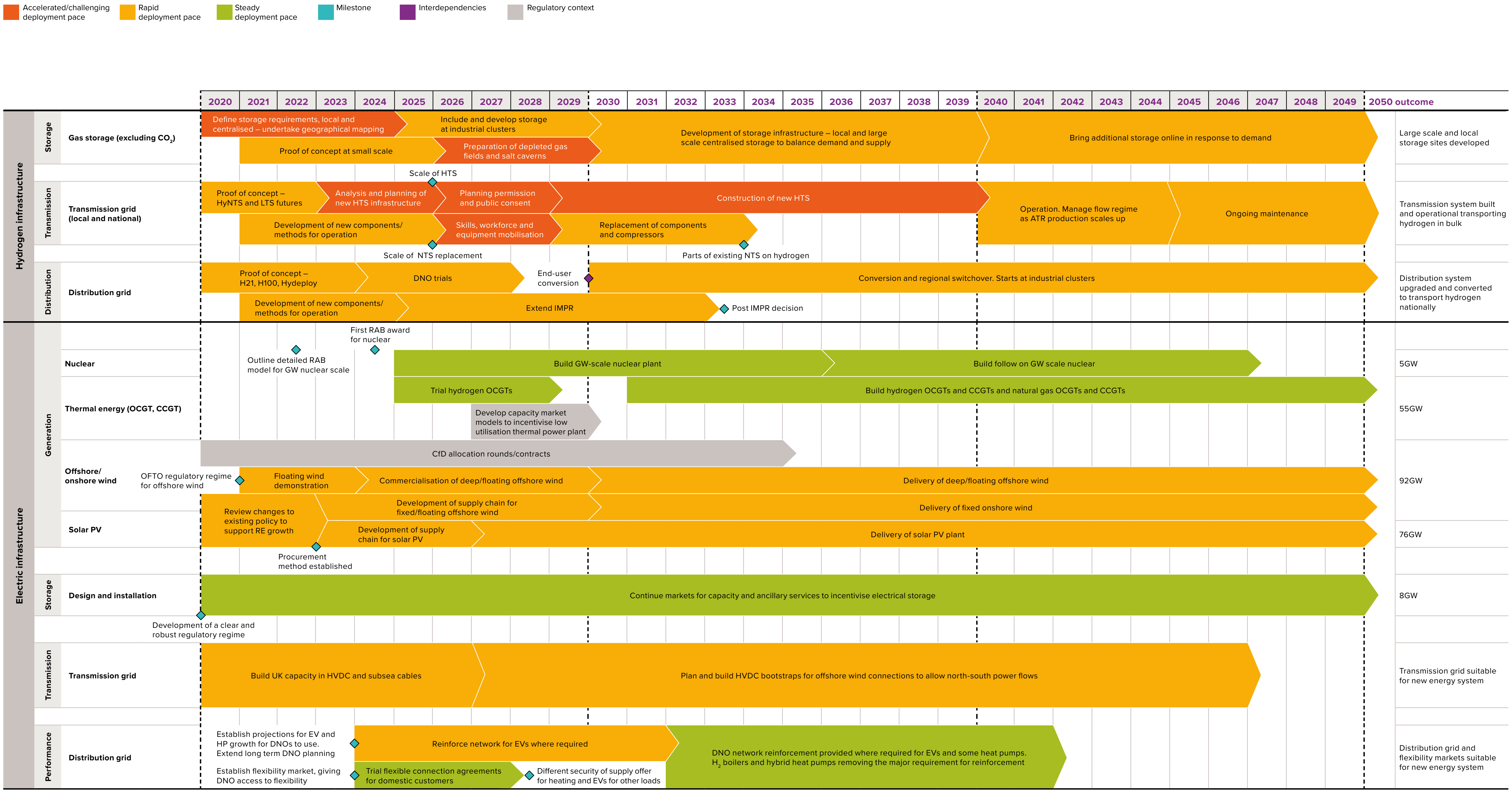
Risk/challenge	Type		Solution
The technical feasibility and safety case must be proven for most of the system by latest 2025 in order to not prohibit or delay roll-out.	Technology		Continue and expand existing programmes of research
ATR and CCUS have not been tested at scale	Scale and delivery		To meet the target capacities the supply chains must be developed early in the programme and the pilot projects progressed at the industrial clusters. The role of the market and associated policy decisions must be made by the late 2020s to allow the supply chain time to prepare.
The scale of the roll-out will be significant for ATR and CCUS, especially given CCUS is currently only in an early phase of deployment.	Scale and delivery		The supply chains must be developed early in the programme. The timing of the infrastructure deployment must also be carefully managed.
The rates of CCUS deployment implied by this scenario push up against the limits of what is realistically achievable from an infrastructure delivery perspective.	Scale and delivery	Technology	Further develop projects and scale of CCUS to continue the development of the supply chains. Should the required rates not be feasible, a shift over time from ATR to alternative green production methods should be considered.
Reliance on biomass gasification as part of this pathway, but not currently proven at scale.	Technology		Biomass gasification will require further initial investment and development to achieve the targets set.
Having adjacent hydrogen generation and CO_2 storage systems that need to be brought online and the volume of storage closely tracking the demand from generation volumes. Creating stranded assets if timing not planned or co-ordinated.	Scale and delivery		The construction of the new hydrogen production, carbon capture and storage (gas and carbon) should follow a sequenced approach with several review phases to avoid stranded assets. As electrolysis and other green hydrogen production technologies are further developed and deployed globally, the cost reduction should allow for more green production to be constructed at the end of the first build phase.
Planning and co-ordination risk of constructing a new hydrogen transmission system (HTS), which will be a significant national infrastructure development project.	Scale and delivery	Public acceptance	The project will require careful planning and coordination.
Market not behind the infrastructure investment and roll-out, leading to slower delivery rates than required, and/or increased costs.	Scale and delivery		Market framework required – the role of the market in the roll-out of the system must be established early in the programme.
Lack of required co-ordination between local and national storage of hydrogen.	Technology		High capacity local and national storage for hydrogen must be developed.

Risk/challenge	Type	Solution
Components and materials for the NG pipe infrastructure must be tested and standards adapted to meet safety and operability requirements. For example, existing pipe materials may not be compatible with hydrogen, and existing safety features including explosion ignition clearances may need to be revised.		Continue and expand existing programmes of research.
Balancing the supply, demand and storage associated with biogas, CO_2 and hydrogen in the system will be challenging.		Capacities and flow regimes must be established and quantified to develop operational and control philosophies and procedures.
CO_2 network risks due to the 'natural monopoly' nature of this type of infrastructure.		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 Based model or equivalent approaches.
The rate of end-user conversion is seen as a significant challenge (~1 million conversions/year), especially considering the lack of historic precedent for this type of conversion.		Recognise this through government planning, supply chain development and skills creation. The roll-out of end-user conversion will need to be carefully co-ordinated with the changeover of the network and distribution systems. The planning and co-ordination of these two elements will be a huge undertaking.
Insufficient number of trained engineers and installers, creating skills gaps to deliver the scale of end-user conversion required. The workforce required to deliver this can largely be adapted from existing skill sets (eg Gas Safe engineers), but there will need to be a steep increase in the training of workers to deliver conversion. As with gas, some installers will need to be highly qualified eg for large industrial sites.		The workforce needed to convert end-users can be adapted from existing gas engineers, installers and heating engineers but there is a significant scale-up required and again clear signals to the market will be required as soon as a decision is made to drive this.
The fundamental safety and technical feasibility of hydrogen end-user appliances has yet to be established.		The case for basic domestic and commercial scale appliances is developing but there are still technical problems to overcome and in some cases hydrogen heating may require, for example, additional or markedly different safety features – the extent of these need to be understood. The existing programmes of end-user research will need to be continued and expanded.

Risk/challenge	Type	Solution
The convertibility of buildings, ancillary devices and piped systems for end-users is also yet to be established. If in-building piped systems need to be substantially altered the cost of the overall hydrogen conversion could alter significantly.	 	In addition to the current technical research and trial activities, there needs to be an assessment of end-user impact. What are the benefits for end-users, what disruption will conversion entail, what changes to existing natural gas piped systems will be required, what capital and operating costs will end-users need to consider? It is suggested that a sample of individual site feasibility studies may help to improve understanding of impacts.
There is a need to develop viable end-user appliances in short order, and at present the favoured option is through tendered award of contracts for individual manufacturers to develop appliances and end-user equipment. However, as the hydrogen programme expands there will be a need to share developed knowledge more widely and to prompt manufacturers to prepare for roll-out.		Beyond the current individual appointments through competitions, a wider range of manufacturers/installers and their representative groups need to be engaged as 2025 approaches. Beyond 2025 there will be a need to share knowledge derived from prototypes and to clearly signal intentions through policy, regulation and equipment standards.
Complexity of some site conversions will be significant engineering projects in their own right (eg large industrial sites with space and process heating requirements). There will be many of these across the country; they will be very tough and costly carbon sources to abate but will be required to fully decarbonise.	 	Work is needed to understand the sequences and risks of conversion on different types of large sites, and to develop a better understanding of the cost of conversion and how this can be borne by different types of end-users. Feasibility and trial activity can feed into best practice case studies and proforma approaches to site conversion.

D.5 Hydrogen pathway roadmap




Accelerated/challenging deployment pace
Rapid deployment pace
Steady deployment pace
Milestone
Interdependencies
Regulatory context
2020
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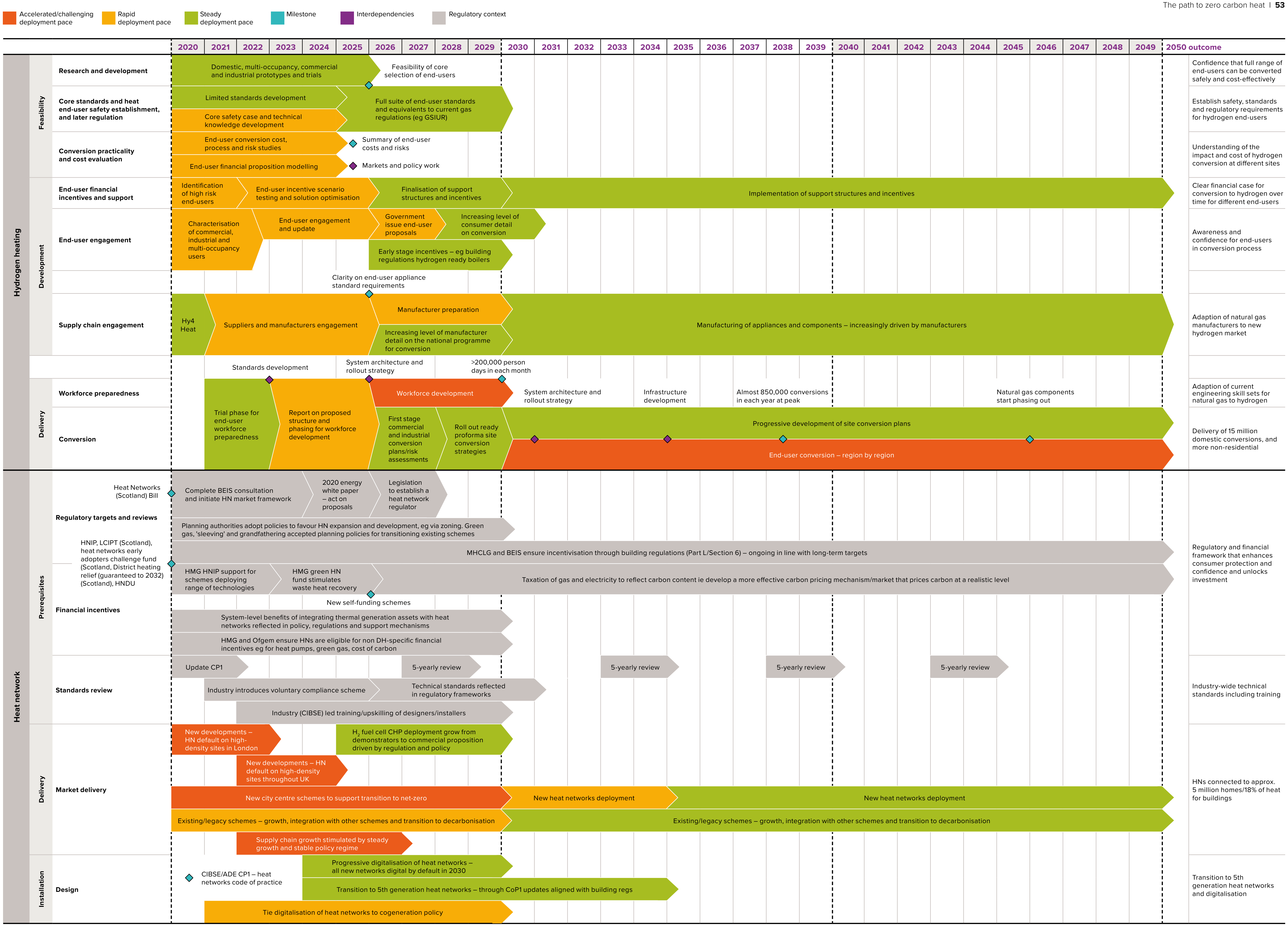
2049
2050 outcome
Hydrogen infrastructure
Storage
Gas storage (excluding CO_2)
Define storage requirements, local and centralised – undertake geographical mapping
Include and develop storage at industrial clusters
Development of storage infrastructure – local and large scale centralised storage to balance demand and supply
Bring additional storage online in response to demand
Proof of concept at small scale
Preparation of depleted gas fields and salt caverns
Large scale and local storage sites developed
Scale of HTS
Transmission
Transmission grid (local and national)
Proof of concept – HyNTS and LTS futures
Analysis and planning of new HTS infrastructure
Planning permission and public consent
Construction of new HTS
Operation. Manage flow regime as ATR production scales up
Ongoing maintenance
Development of new components/ methods for operation
Skills, workforce and equipment mobilisation
Replacement of components and compressors
Transmission system built and operational transporting hydrogen in bulk
Scale of NTS replacement
Parts of existing NTS on hydrogen
Distribution
Distribution grid
Proof of concept – H21, H100, Hydeploy
DNO trials
End-user conversion
Conversion and regional switchover. Starts at industrial clusters
Development of new components/ methods for operation
Extend IMPR
Post IMPR decision
Distribution system upgraded and converted to transport hydrogen nationally
Electric infrastructure
Generation
First RAB award for nuclear
Nuclear
Outline detailed RAB model for GW nuclear scale
Build GW-scale nuclear plant
Build follow on GW scale nuclear
5GW
Thermal energy (OCGT, CCGT)
Trial hydrogen OCGTs
Build hydrogen OCGTs and CCGTs and natural gas OCGTs and CCGTs
Develop capacity market models to incentivise low utilisation thermal power plant
55GW
CfD allocation rounds/contracts
Offshore/ onshore wind
OFTO regulatory regime for offshore wind
Floating wind demonstration
Commercialisation of deep/floating offshore wind
Delivery of deep/floating offshore wind
92GW
Development of supply chain for fixed/floating offshore wind
Delivery of fixed onshore wind
Solar PV
Review changes to existing policy to support RE growth
Development of supply chain for solar PV
Delivery of solar PV plant
76GW
Procurement method established
Storage
Design and installation
Continue markets for capacity and ancillary services to incentivise electrical storage
8GW
Development of a clear and robust regulatory regime
Transmission
Transmission grid
Build UK capacity in HVDC and subsea cables
Plan and build HVDC bootstraps for offshore wind connections to allow north-south power flows
Transmission grid suitable for new energy system
Performance
Distribution grid
Establish projections for EV and HP growth for DNOs to use. Extend long term DNO planning
Reinforce network for EVs where required
DNO network reinforcement provided where required for EVs and some heat pumps. H_2 boilers and hybrid heat pumps removing the major requirement for reinforcement
Establish flexibility market, giving DNO access to flexibility
Trial flexible connection agreements for domestic customers
Different security of supply offer for heating and EVs for other loads
Distribution grid and flexibility markets suitable for new energy system


Accelerated/challenging deployment pace
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Steady deployment pace
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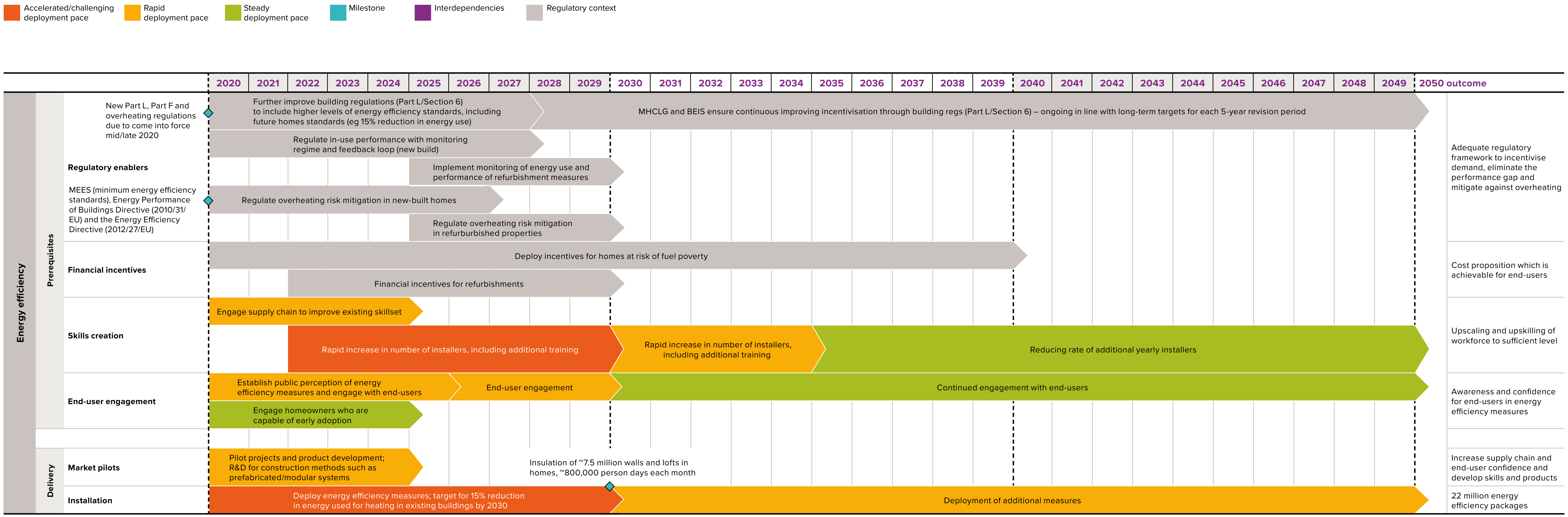
Interdependencies
Regulatory context
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049
2050 outcome
Hydrogen heating
Feasibility
Research and development
Domestic, multi-occupancy, commercial and industrial prototypes and trials
Feasibility of core selection of end-users
Confidence that full range of end-users can be converted safely and cost-effectively
Core standards and heat end-user safety establishment, and later regulation
Limited standards development
Core safety case and technical knowledge development
Full suite of end-user standards and equivalents to current gas regulations (eg GSIUR)
Establish safety, standards and regulatory requirements for hydrogen end-users
Conversion practicality and cost evaluation
End-user conversion cost, process and risk studies
Summary of end-user costs and risks
End-user financial proposition modelling
Markets and policy work
Understanding of the impact and cost of hydrogen conversion at different sites
Development
End-user financial incentives and support
Identification of high risk end-users
End-user incentive scenario testing and solution optimisation
Finalisation of support structures and incentives
Implementation of support structures and incentives
Clear financial case for conversion to hydrogen over time for different end-users
End-user engagement
Characterisation of commercial, industrial and multi-occupancy users
End-user engagement and update
Government issue end-user proposals
Increasing level of consumer detail on conversion
Early stage incentives – eg building regulations hydrogen ready boilers
Clarity on end-user appliance standard requirements
Awareness and confidence for end-users in conversion process
Supply chain engagement
Hy4 Heat
Suppliers and manufacturers engagement
Manufacturer preparation
Increasing level of manufacturer detail on the national programme for conversion
Manufacturing of appliances and components – increasingly driven by manufacturers
Adaption of natural gas manufacturers to new hydrogen market
Delivery
Standards development
System architecture and rollout strategy
>200,000 person days in each month
Workforce preparedness
Trial phase for end-user workforce preparedness
Report on proposed structure and phasing for workforce development
Workforce development
System architecture and rollout strategy
Infrastructure development
Almost 850,000 conversions in each year at peak
Natural gas components start phasing out
Adaption of current engineering skill sets for natural gas to hydrogen
Conversion
First stage commercial and industrial conversion plans/risk assessments
Roll out ready proforma site conversion strategies
Progressive development of site conversion plans
End-user conversion – region by region
Delivery of 15 million domestic conversions, and more non-residential
Heat network
Prerequisites
Heat Networks (Scotland) Bill
Complete BEIS consultation and initiate HN market framework
2020 energy white paper – act on proposals
Legislation to establish a heat network regulator
Regulatory targets and reviews
Planning authorities adopt policies to favour HN expansion and development, eg via zoning. Green gas, 'sleeving' and grandfathering accepted planning policies for transitioning existing schemes
HNIP, LCIPT (Scotland), heat networks early adopters challenge fund (Scotland, District heating relief (guaranteed to 2032) (Scotland), HNDU
MHCLG and BEIS ensure incentivisation through building regulations (Part L/Section 6) – ongoing in line with long-term targets
HMG HNIP support for schemes deploying range of technologies
HMG green HN fund stimulates waste heat recovery
Taxation of gas and electricity to reflect carbon content ie develop a more effective carbon pricing mechanism/market that prices carbon at a realistic level
New self-funding schemes
Financial incentives
System-level benefits of integrating thermal generation assets with heat networks reflected in policy, regulations and support mechanisms
HMG and Ofgem ensure HNs are eligible for non DH-specific financial incentives eg for heat pumps, green gas, cost of carbon
Regulatory and financial framework that enhances consumer protection and confidence and unlocks investment
Standards review
Update CP1
5-yearly review
5-yearly review
5-yearly review
5-yearly review
Industry introduces voluntary compliance scheme
Technical standards reflected in regulatory frameworks
Industry (CIBSE) led training/upskilling of designers/installers
Industry-wide technical standards including training
Delivery
Market delivery
New developments – HN default on high-density sites in London
H2 fuel cell CHP deployment grow from demonstrators to commercial proposition driven by regulation and policy
New developments – HN default on high-density sites throughout UK
New city centre schemes to support transition to net-zero
New heat networks deployment
New heat networks deployment
Existing/legacy schemes – growth, integration with other schemes and transition to decarbonisation
Existing/legacy schemes – growth, integration with other schemes and transition to decarbonisation
Supply chain growth stimulated by steady growth and stable policy regime
HNs connected to approx. 5 million homes/18% of heat for buildings
Installation
Design
CIBSE/ADE CP1 – heat networks code of practice
Progressive digitalisation of heat networks – all new networks digital by default in 2030
Transition to 5th generation heat networks – through CoP1 updates aligned with building regs
Tie digitalisation of heat networks to cogeneration policy
Transition to 5th generation heat networks and digitalisation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2048
2049
2050 outcome
Energy efficiency
Prerequisites
Regulatory enablers
New Part L, Part F and overheating regulations due to come into force mid/late 2020
MEES (minimum energy efficiency standards), Energy Performance of Buildings Directive (2010/31/EU) and the Energy Efficiency Directive (2012/27/EU)
Further improve building regulations (Part L/Section 6) to include higher levels of energy efficiency standards, including future homes standards (eg 15% reduction in energy use)
MHCLG and BEIS ensure continuous improving incentivisation through building regs (Part L/Section 6) – ongoing in line with long-term targets for each 5-year revision period
Regulate in-use performance with monitoring regime and feedback loop (new build)
Implement monitoring of energy use and performance of refurbishment measures
Regulate overheating risk mitigation in new-built homes
Regulate overheating risk mitigation in refurbished properties
Adequate regulatory framework to incentivise demand, eliminate the performance gap and mitigate against overheating
Financial incentives
Deploy incentives for homes at risk of fuel poverty
Financial incentives for refurbishments
Cost proposition which is achievable for end-users
Skills creation
Engage supply chain to improve existing skillset
Rapid increase in number of installers, including additional training
Rapid increase in number of installers, including additional training
Reducing rate of additional yearly installers
Upscaling and upskilling of workforce to sufficient level
End-user engagement
Establish public perception of energy efficiency measures and engage with end-users
End-user engagement
Continued engagement with end-users
Engage homeowners who are capable of early adoption
Awareness and confidence for end-users in energy efficiency measures
Delivery
Market pilots
Pilot projects and product development; R&D for construction methods such as prefabricated/modular systems
Insulation of ~7.5 million walls and lofts in homes, ~800,000 person days each month
Increase supply chain and end-user confidence and develop skills and products
Installation
Deploy energy efficiency measures; target for 15% reduction in energy used for heating in existing buildings by 2030
Deployment of additional measures
22 million energy efficiency packages

E. Hybrid pathway

E. Hybrid pathway

E.1 Introduction to the scenario

There is a wide range of potential hybrid pathways between the full-electric and hydrogen pathways. It could be the case that the approach allows for regional variation, where different parts of the UK de-carbonise their heat in different ways depending on their specific circumstances. Our pathway does not focus on the possibility of different approaches for different regions but rather considers the overall composition of end-user systems with the hybrid pathway being characterised by the application of hybrid heat pumps among other end-user systems. Hybrid heat pumps comprise an electrically-driven heat pump used in combination with another heat source. Very often this additional heat source is a boiler, but other types such as resistive electric heating can be applied. In a hybrid system both items of heating plant feed into a wet heating distribution system. Although there are a variety of potential control configurations, the systems are usually configured to maximise the utilisation of the heat pump rather than the other heating plant.

Hybrid heat pumps, and hybrid pathways generally, have the potential to downsize the electrical generation infrastructure needed and for some end-users it may allow a better match between the specific circumstances of a building and the appropriate heating solution. Further, for many reasons, hybrid heat pumps could facilitate a faster uptake of low-carbon heat in the short term, not least by building user confidence in the principle of heat delivered through heat pump technology.

The actual number of hybrid heat pumps versus other end-user technologies could vary enormously in different hybrid pathways. Even in the source material we used as our set of starting assumptions there are differences in relation to the actual numbers of systems to be deployed. The ICL study (which considers the overall energy system) envisages that the bulk of heat in 2050 would be provided by hybrid heat pumps whereas the EE/UCL study (which solely considers the end-users) portrays a hybrid pathway where conventional heat pumps are still the predominant end-user technology and where hybrid heat pumps play more of a supporting role (serving only 21% of domestic end-users). We have embraced this variation and have welcomed the discussion that these different interpretations have generated, but clearly this underlines that there is work to do to understand and optimise the use of hybrid heat pumps in a hybrid pathway.

E.1.1 Pathway components

No specific dependency map was developed for the hybrid pathway, either for energy generation and distribution, or for end-user systems. The hybrid pathway is expected to incorporate elements of most of the generated dependency maps, but with many of the hydrogen-specific requirements removed, including the need to:

- demonstrate the safety and development of a wide range of 100% hydrogen appliances;
- significantly adapt both the natural gas transmission and distribution systems to 100% hydrogen;
- develop renewable and nuclear electrolysis, and ATR technology

Hydrogen will, however, still have a role as a blended component of decarbonised natural gas and in a thermal generation capacity.

The hybrid pathway provides a portfolio of solutions for end-users and requires the development of infrastructure for electrification (but on a slightly smaller scale than for the full electrification pathway) and some (much more limited than in the hydrogen pathway) alteration to the natural gas infrastructure. The real complexity comes though the integration of the multi vector solutions for supply and end-users in an effective way.

The roadmap focuses on both the gas and electric infrastructure as well as the pathway-specific type of end-user systems that will be required for a hybrid solution.

E.2 Discussion on differences for the hybrid pathway

E.2.1 Electrical infrastructure

The key difference between the supply side of the hybrid pathway and the electrification pathway is the reduction in peaking thermal plant. In the electrification pathway 139GW of peaking thermal plant is required (with approximately a 5% capacity factor). In the hybrid pathway this decreases to 36GW, with approximately a 10% capacity factor. The role of the peaking plant is predominantly replaced by the gas component of the hybrid heat pumps to manage the peak electrical loads and intermittency of wind. See section C.4 for further details.

E.2.2 Decarbonised gas

In contrast to the hydrogen pathway, the retained gas infrastructure will only deliver a relatively small amount of the overall heat delivered. This will contain natural gas blended with hydrogen (up to 20%) and potentially biomethane; this blend being compatible with existing transmission, distribution and end-user systems. The use of this gas means that much of the work for the conversion of natural gas systems to 100% hydrogen will be avoided.

We also perceive that some industrial end-users in proximity to a limited number of industrial clusters may utilise 100% hydrogen.

Again, there is ample opportunity for variation in this aspect for other hybrid pathways, but if the blend of hydrogen increases above 20% (by volume) then a greater degree of change to natural gas infrastructure will be required at a much greater cost. Other options could include the use of 100% hydrogen for hybrid heat pumps.

E.2.3 Hybrid heat pumps

Hybrid heat pumps displace a large number of the conventional heat pumps seen in the electrification pathway. The extent to which this occurs could vary significantly and it is suggested that some form of end-user heat model (potentially a digital heat map informed by national and regional heat strategy) is needed to optimise end-user heat requirements with overall infrastructure requirements.

Regulating or incentivising the correct proportions of hybrid and conventional systems will in itself be a challenge and will potentially be more complex than the other pathways.

E.3 Hybrid roadmap – discussion

E.3.1 The 2050 technology mix

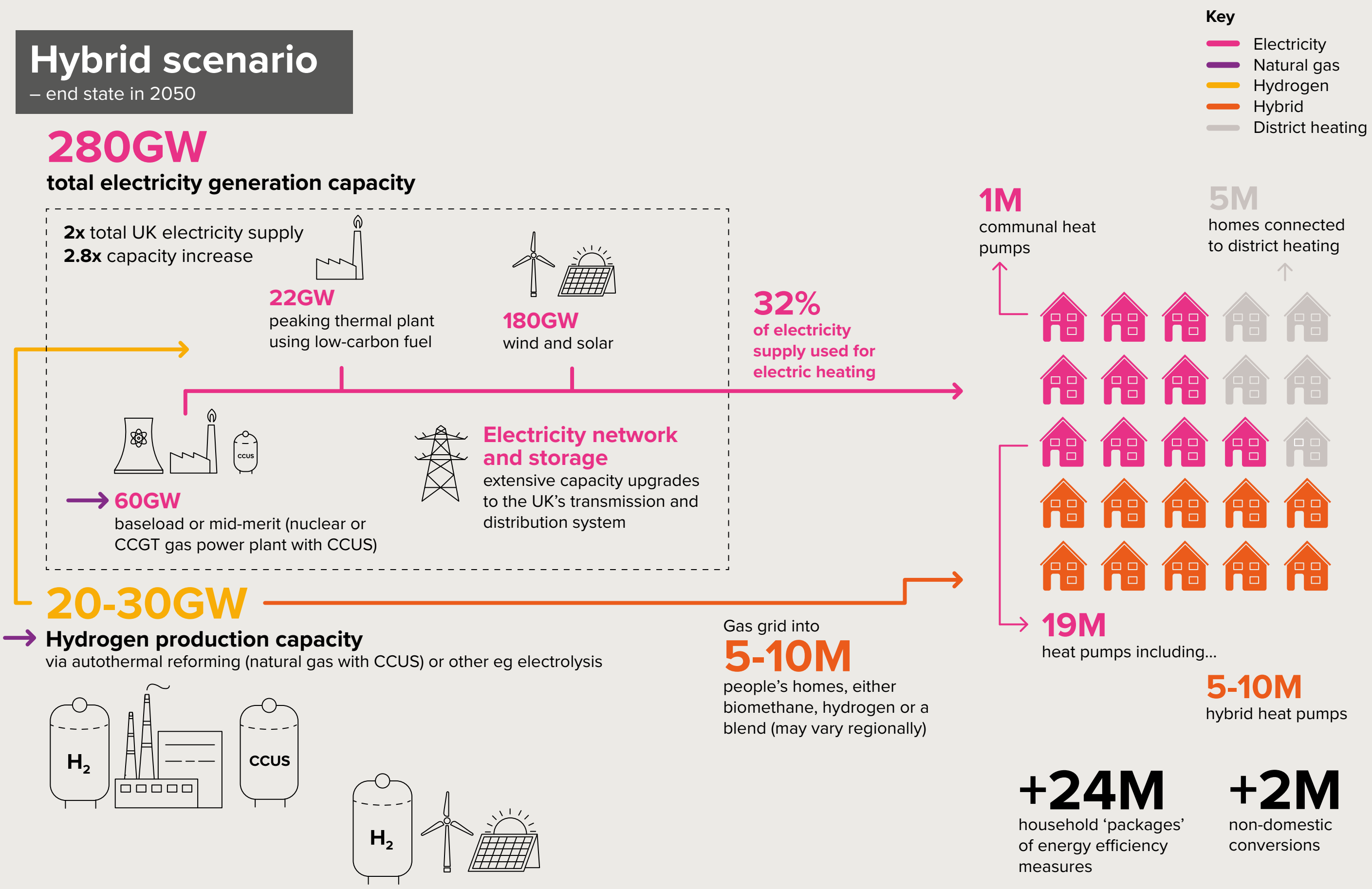
Data has been derived from the ICL Analysis of alternative UK heat decarbonisation pathways, Scenario: Hybrid [0] and the EE/UCL report.

The pathway requires a total electricity generation capacity of 282GW, less than Electric[0]. It has an increased production capacity of hydrogen at 25GW compared to the 15GW of the electric pathway, but significantly lower than the hydrogen pathway. It is of note here that depending on the end use for hydrogen, other hybrid pathways have hydrogen production at a capacity closer to 40GW.

In our pathway there is a mixture of hydrogen production through 'green' hydrogen and biomass coupled with CCUS. Depending on global market conditions, technology development and roll-out, increased 'green' hydrogen production might be deployed.

The Hybrid[0] pathway technology mix for the supply of electricity is similar to the Electric[0] one as it is based on similar assumptions.

Figure 8: The 2050 technology mix – Hybrid



The defining end-user feature of our hybrid pathway is the application of hybrid heat pumps (it is worth noting that hybrid heat pumps do feature in the other pathways, albeit in smaller numbers) to reduce the required electrical capacity of the overall system. Hybrid heat pump systems will eventually depend upon a decarbonised gas supply being available for the boiler component; here it is assumed that the gas boiler element transitions over time to use biomethane, or potentially small quantities of natural gas blended with hydrogen.

In the EE/UCL 2050 systems mix, the majority of end-user systems will be converted to heat pumps rather than hybrid heat pumps, with hybrid systems only accounting for 5-6 million properties and conventional heat pumps comprising around 2.5 times as many installations. However, it should be noted that the composition of end-user technologies within a hybrid pathway could vary enormously. For example, the sensitivity analyses within the EE/UCL report indicate that the number of hybrid heat pumps could be over 50% of the 2050 end-user systems. Although much good research work has been done on hybrid heat pumps, this variation underlines the limitations of current understanding of what systems would be best for end-users in each specific circumstance and how this would fit with the optimum infrastructure arrangements, potentially with these being different regionally.

As noted above, this EE/UCL composition was used as a starting point for the study, but it could easily be the case that hybrid heat pumps come to dominate among end-users in this scenario, and they may play a more prominent role as a bridging technology.

E.3.2 Assumptions for the roadmap

As noted, the roadmap was developed to achieve the ICL and EE/UCL 2050 technology mix. We have made assumptions regarding key mobilising actions and the deployment rates that are possible for various interventions. The hybrid pathway has a number of overlapping assumptions with the electrification pathway, and only the ones that are different have been noted below.

Hydrogen supply assumptions

- Hydrogen production will be through electrolysis and BECCs.

Gas transmission grid assumptions

- The NTS is retained in its current form with possible blending with hydrogen up to 20% by volume.

Hydrogen distribution grid assumptions

- It is assumed that the decarbonised gas network will not require significant conversion given the gas used. This features as a major cost-saving versus the hydrogen pathway, where significant changes will be needed to the overall natural gas system.

Electric distribution network assumptions

- We assume that rather than wholesale upgrading of the LV networks to accommodate additional load, existing cables are used with circuits divided into smaller groups. We note this may not be possible where tapered circuits have been used.
- There will be a major roll-out of EVs from 2025. However, we assume that smart charging, fuel switching (using hybrid heat pumps) and time-of-use tariffs limit the impact on peak load, with mitigation measures only required post-2030.

End-user assumptions

- It is assumed that the hybrid heat pump deployment will happen in three phases:
  - Early adopters pre-2025 (prior to decarbonisation decision being made)
  - 1st phase roll-out in first five years to 2030 (as production and skills scale up)
  - Larger scale roll-out beyond 2030 (for full roll-out)
- The hybrid pathway relies on the proliferation of optimally controlled hybrid heat pumps.
- Industrial space heating will also be through predominately electric end-user technologies (eg heat pumps or hybrid heat pumps). It is noted that that converting to heat pumps or hybrid heat pumps in some industrial sites could be a complex and costly undertaking (eg where existing space heating is provided by steam systems).
- We also assume that some industrial process heat requirements will have to be met by hydrogen or other decarbonised gas, purely given the difficulty of converting some processes to electricity.
- Gas heating uses biomethane or, potentially, small quantities of natural gas blended with hydrogen.
- It is acknowledged that hybrid heat pumps could also play a role in achieving medium-term goals for the decarbonisation of heat – the management of this has not been considered in detail in this pathway.

E.3.3 Roadmap description

Gas/hydrogen infrastructure
Up to 2030, the focus for hydrogen electrolysis production technologies (nuclear and renewables) will be on feasibility, pilots and early stage projects. After 2030, deployment and build will begin, with 10GW or more being achieved by 2050.

Between 2020 and 2025, biomass gasification will focus on construction of a ~5MW plant and the FEED studies for a ~50MW plant. This ~50MW first of its kind plant will be constructed by 2035, and thereafter these plants will be deployed at scale. This deployment at scale and the scaling up of biomass plant (which can begin now) are seen as key components. Reforming technologies do not form a critical part of this pathway.

CCUS will be demonstrated and trialled up to the end of 2026; key risks here include the need to give the right market signals to potential technology providers (eg subsidies may be necessary) and the successful demonstration of storage. After this, the CCUS transport and storage infrastructure will be developed up to 2050.

Hydrogen storage will focus on planning, demonstration and preparation in the 2020s. In the early 2030s, the development of storage infrastructure (local and large-scale centralised storage) is seen as requiring an accelerated pace. Thereafter additional storage can be brought online as required.

Work on the existing gas distribution grid is seen as much less challenging than in the hydrogen pathway. The Iron Mains Replacement Programme will continue and some proof of concept, trials and the development of specially adapted components will continue up to the late 2020s. It is thought that blending in the network with up to 20% hydrogen could start even before 2030.

Electric infrastructure
The overall scale of the electric infrastructure needed in the hybrid pathway is reduced in comparison to the full electrification pathway. This is certainly a benefit, but it does not eliminate all of the challenges with electric infrastructure.

In terms of generation, only 282GW of generation capacity is required in contrast to 399GW in the full electrification pathway, though there is an increase in both nuclear (from 42GW to 45GW) and wind (from 72GW to 82GW capacity) in the hybrid pathway. Again, solar PV has the largest installed capacity (103GW). OCGT and CCGT generation is greatly reduced in the hybrid pathway (from 139GW to 36GW), with most of the systems being hydrogen rather than natural gas.

The nuclear generation scale up and build programme remains a key challenge in this pathway, with work in the 2020s needing to demonstrate the economic case and reliability for both large-scale plant and small modular reactors. The first schemes need to be in place by the late 2020s, with the standardisation of design and supply chain for further expansion being in place very quickly afterwards.

Some work is needed to trial hydrogen thermal generation but given the reduction in scale from the electrification pathway, this is not seen as being as critical.

The wind and solar PV elements of the pathway remain similar to the electric pathway. The focus for electrical storage remains the development of a regulatory regime and incentives that will prompt the market to develop capacity.

For transmission, there is still a short-term challenge to build the UK's capacity in HVDC and subsea cables in the early 2020s. For the distribution grid, work on reinforcement of the DNO networks will still begin in the early 2030s but, given the much smaller scale of reinforcement required, this will be much less challenging than in the electrification pathway.

End-users
The hybrid pathway is characterised by the flexible approach to end-user heating technologies. In the early years of this pathway (up to 2025), it will be possible to implement the defining end-user technology (hybrid heat pumps) in a low regret manner, particularly for properties off the gas network. The same will be true of conventional heat pumps. There will be a limit to the number and type of such installations that can truly be considered low regret without a clear understanding of the final pathway to decarbonising heat. However, hybrid heat systems are notable for their flexibility and potential for further adaption.

Hybrid heat pump systems are not an entirely new technology, but confidence in their performance and understanding of their application is not uniformly high. Their role in the hybrid pathway is to balance the delivery of electrical and other heat in the overall energy system, increase end-user acceptability of heat pump solutions, and potentially in the short-term to reduce CO_2 emissions. However, they can only do so if there is continued confidence in their performance. Of all the end-user technologies considered, hybrid heat pumps have the greatest potential to fail to deliver their intended results if they are not well commissioned, controlled and maintained over time. It is very easy for the balance of heat delivered in an individual hybrid heat pump system to lean more heavily than intended on the boiler output rather than maximising heat pump output. In an individual heat pump system this could go largely unnoticed for extended periods. If this is scaled up to many hybrid heat pump systems then it could prove problematic in terms of gas capacity and/or electric capacity for the overall energy system.

There is therefore a requirement to focus on the quality of installations in this pathway. Early stage implementation in the years up to 2025 will allow:

- Increased capacity for delivering quality design and installation of retrofit hybrid heat pump systems.
- Improved understanding of the factors which dictate hybrid heat pump performance (eg continuous heating versus distinct heating periods) to build upon the outputs of recent research reports.
- Improvements to the manufacturer's overall hybrid system package, in particular improvements to packaged system controllers.
- Better understanding of what demand side and digital technology will be needed to ensure that hybrid systems continue to perform as intended.

These early year installations are considered critical to the programme as they could identify that hybrid heat pump installation (particularly in more complex buildings) is more problematic than originally hoped.

Between 2025 and 2030, 100,000 hybrid heat pump installations could be expected per annum. After 2030, as the workforce becomes more mature and confidence in the deployment of systems in various building types and regions is achieved, it is envisaged that around 300,000 would be installed each year up to 2045 (by which point hybrid heat pumps will be 2050 ready) but there is reasonable flexibility within this programme and the numbers and stages of deployment could change. It is noted that hybrid systems could be used as a bridging technology but the sequence of this has not been considered in detail.

Conventional heat pumps still form a very large portion of end-user systems in this pathway; it is thought that their development will follow that outlined in the electrification pathway and indeed much of the work on hybrid and conventional systems can happen in tandem. Again energy efficiency improvements will form an important element of this pathway along with heat networks (here accounting for as many end-users as hybrid heat pumps, but ultimately dependent on the model considered). More detail on the heat network element is provided in section F.

The pathway differs from the others in terms of the wide variations possible in end-user technology. More so than in the other pathways, those planning and developing the electric and decarbonised gas infrastructure could face uncertainty over actual end-user demand.

Work is needed to understand how this will be managed. For example, if it is left solely to end-users to decide whether their favoured heating system is a hybrid or conventional heat pump then the planning of electric and other infrastructure could prove extremely difficult in the longer term. Both aspects have to be considered. Eventually, an end-user plan or end-user technology heat map would be advisable, guiding and monitoring what end-user technology should be applied in which type of building and in which location. This end-user plan needs to take shape between now and 2025. In truth such a tool is needed for all of the pathways, but especially for the hybrid pathway.

Finally the enablers (the mixture of legislation, regulation, policy and incentives needed) will be more complex, here noting that the goal will not be to promote the use of a particular end use technology but rather a specific mixture of technologies, possibly with regional and local variation and even variation between building types. This will include a mixture of:

- Progressive amendments to building regulations (which can start with low regrets options now).
- Incentives such as successors to the Renewable Heat Incentive (RHI).
- Local planning and policy, if the application of heat pumps, hybrid heat pumps and other systems are to vary regionally.

E.3.4 Key risks and challenges

The following table summarises the key risks and issues of this pathway. This is not a comprehensive list of risks, but some of the main aspects that came out of the development of the roadmap. It is also of note that these risks relate to the specific pathway we have mapped, and different hybrid pathways could have different risks.

We have categorised the risks under four categories – scale and delivery, technology, complexity and public acceptance – to help understand the differences between these pathways and the issues they present.

Key

- Scale and delivery
- Complexity
- Technology
- Public acceptance

Table 5: Risks and challenges

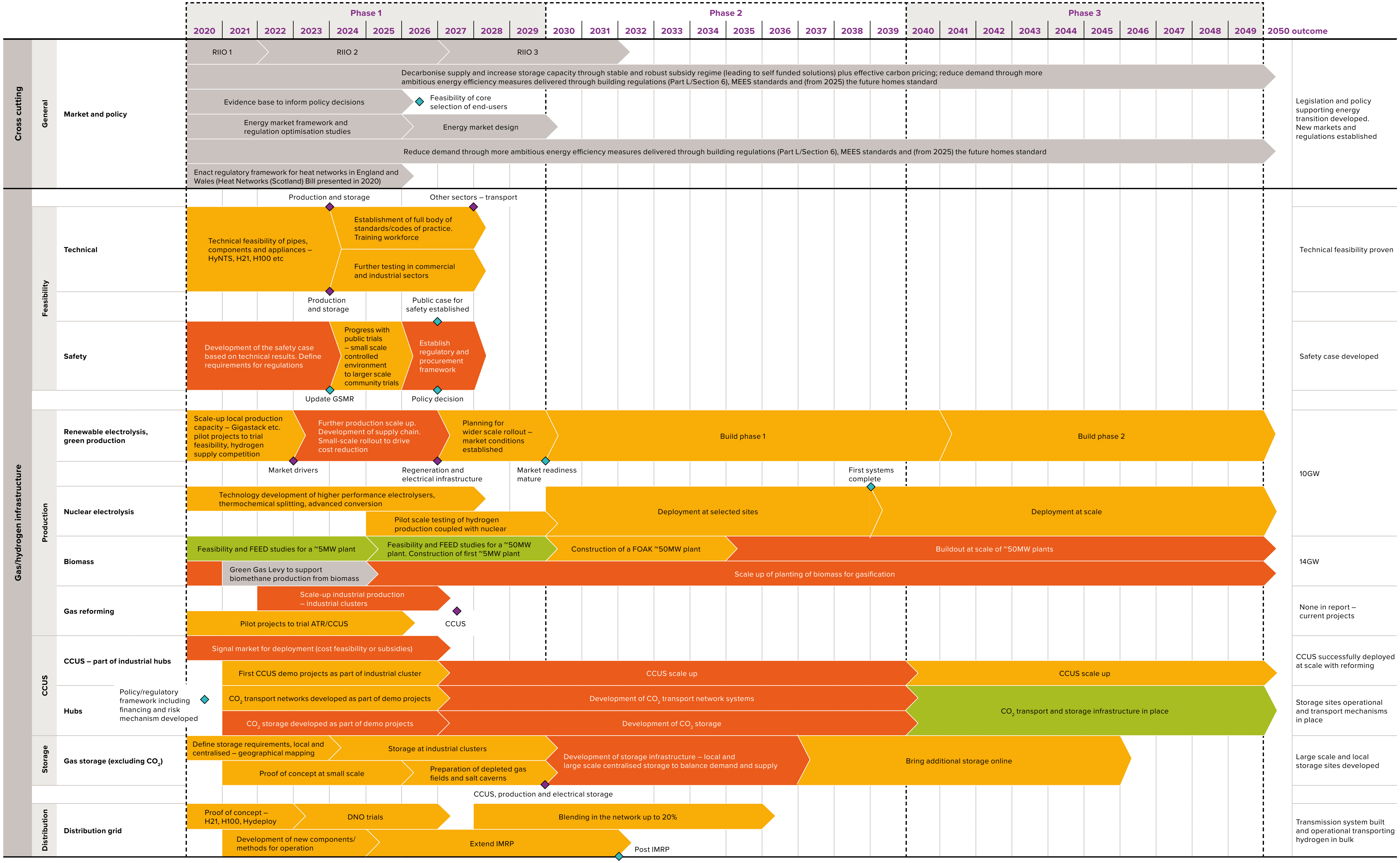
Risk/challenge	Type	Solution
To achieve nuclear roll-out at both GW scale and by using small modular reactors, technologies must be proven to deliver economically and reliably Small modular reactors need to be demonstrated by early 2030s. If this is not completed, alternative investments in more renewables and storage may be required.	Technology	GW scale nuclear power needs to deliver first schemes by late 2020s (~2027) and agree standard designs for wider implementation shortly afterwards. Industry commitment is needed for technology investment in R&D, deployment and scale-up. Planning for future scenarios needs to be undertaken, to bring online alternative solutions if some technologies are not realised at scale.
Negative societal perception of major infrastructure projects, especially transmission lines and substations, may slow the planning and consent process. Similar issues apply to new nuclear projects, both GW scale and small modular reactors, given the perceived risks associated with nuclear.	Scale and delivery, Complexity, Public acceptance	Use planning phases to begin stakeholder engagement. National scale communications regarding future rolls of technology to deliver net-zero. For small-scale nuclear seek to develop reduced exclusion zones.
Floating and deep-water offshore wind needs to be proven to allow the scalability and financial feasibility of wind power; without this it will be difficult to deploy the targeted wind capacity.	Technology	Industry needs government commitment to such technology and incentives to invest and scale up R&D and deployment.
Impacts on distribution networks past 2030, driven by accelerated uptake of heat pumps and EVs. This is not thought to be as challenging as in the electrification pathway but is still considered a risk.	Scale and delivery	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. Focus upgrades – which could be extensive – on low voltage parts of the system which are closer to end-users and where no redundancy exists. Minimise disruption to communities from local network upgrades. Co-ordinate physical works between geographical areas. Use 2020s to plan and prepare for these changes. Particularly key will be enabling DNOs to take advantage of smart systems and demand-side management at the end-user level. This could be via flexibility markets and end-user financial incentives.

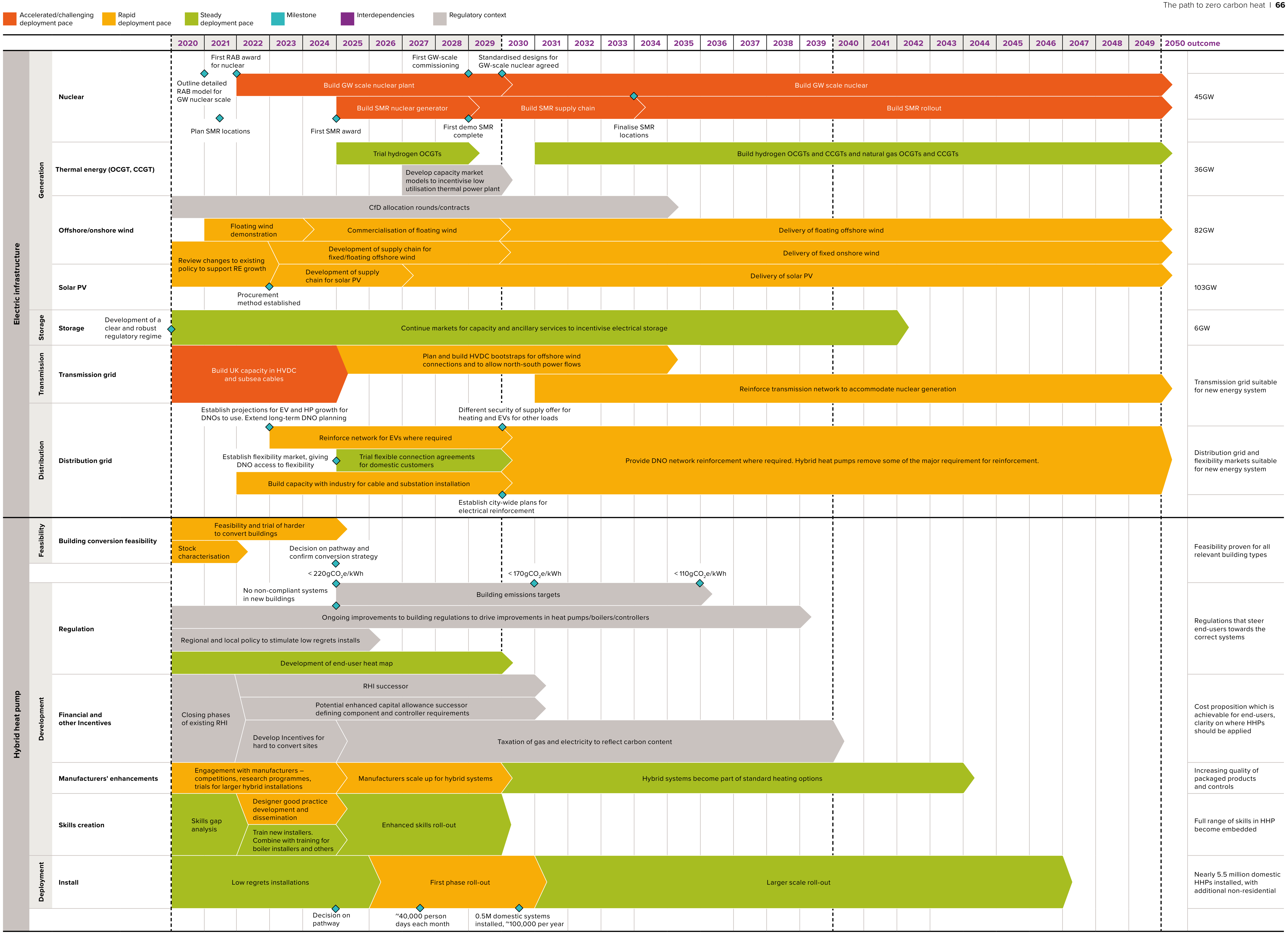
Risk/challenge	Type	Solution
Supply chains for wind and solar energy will require substantial build up.		Historic production indicates that this is possible. However this is likely to require a UK industrial strategy. This will include early promoting of key technologies such as HVDC stations, subsea cables and offshore wind turbines (either deep or floating). Suggested that this is developed as an imminent priority.
Consumer uptake of hybrid and conventional heat pumps.		It is anticipated that enablers for end-users will include incremental improvements in regulation (eg oversizing of system emitters in new buildings) but also successor programmes to the RHI will need to be in place by 2022. There may need to be a shift towards upfront grants rather than in usage payment methods.
Improvement in the design and application (to include control system design and set-up) of hybrid heat pumps is needed in the coming years, especially for more complex non-domestic buildings and especially for retrofit.		Implement measures such as: • Low regrets roll-out (eg off natural gas network properties) up to 2025, with careful monitoring of outcomes. • Enhanced metering and monitoring technology to allow users and others to understand operation in use. Expand DNO control of heat users. • Further characterisation of stock and targeted low regret installs to understand commercial and industrial applications and conversions • Acceptance of hybrid heat pumps as a user package, thus avoiding client complexity in terms of procurement, installation and ongoing maintenance.
Risk that hybrid heat pump systems are poorly installed, do not actually achieve desired energy balance (eg over-reliance on boilers) or function well for end-users.		Actions needed: • Improvements to control packages for hybrid heat pump systems – easier adaption, established good practice and development of specific control packages. • Engineering bodies to lead improvements to design and conversion practice. • Installers to develop and reskill for hybrid systems. • Manufacturers to develop packages. • Government to signal clear intention that hybrid heat pumps are part of long-term solution. • Eventual co-ordination with energy efficiency improvements (potentially combined installations to minimise disruption).
Complexity for end-users and potential for perceived choice as well as numerous system changes between now and 2050 from need for bridging technologies or systems.		Government and local councils need to play an active role in communicating choices and potential financial incentives for different systems. Their advice should be based on the end-user heat model.

Risk/challenge	Type	Solution
The actual uptake of different end-user systems will have to be controlled. More than the other pathways, the hybrid pathway will depend on the right types of technology being deployed in the right location. There may also be a dual role for hybrid heat pumps here (and elsewhere) as a transition technology to meet medium term goals prior to 2050.		A co-ordinated end-user heat model (eg digital heat map) needs to be developed to consider end-user requirements alongside the potential regional variations to infrastructure – to understand what technologies should be deployed in which location. Some form of end-user heat model will be required in all of the pathways, so work on this can begin now in a low regrets manner. This needs to be co-ordinated with regulation, policy and incentives (to include regional planning and other policy), to ensure that end-users are driven to install the correct systems at the correct times in the correct locations.
A development and ramping up of specialist skills is needed, building upon existing HVAC skill sets to deliver the quality of installation needed for hybrid heat pumps in particular. Without this the emission reductions will not be met. This includes: • Installers: domestic and other • Maintenance providers • Designers • Facilities managers		In the near term, carry out a gap analysis to understand how the skills of existing providers could be adapted. Up to 2025, this can focus on improving the quality of skills and training, after this the skills development should begin the scale-up. Particular focus is needed on conversion of existing buildings and especially those which are deemed most difficult to convert. At present the focus has been on the simple domestic typology, but complex domestic, commercial and industrial building types need consideration too.
Potential to overlook the bridging role that hybrid heat pumps may play in meeting pre-2050 targets.		Detailed development of the end-user heat model discussed in this pathway will help policymakers and others understand how hybrid heat pumps and more generally a hybrid pathway could help meet pre-2050 targets. Further to this, regardless of the targets considered (long-term or near-term), the principles for successful delivery remain the same, with focus on low regrets roll-out and trial of these systems in the early 2020s (to develop good installation, manufacture and design and to understand the strengths and weaknesses of hybrid heat pumps versus other systems) and to regulate (eg near term changes to building regulations) and provide incentives (RHI successor, capital grants).

E.4 Hybrid pathway roadmap

Accelerated/challenging deployment pace | Rapid deployment pace | Steady deployment pace | Milestone | Interdependencies | Regulatory context




Accelerated/challenging deployment pace
Rapid deployment pace
Steady deployment pace
Milestone
Interdependencies
Regulatory context
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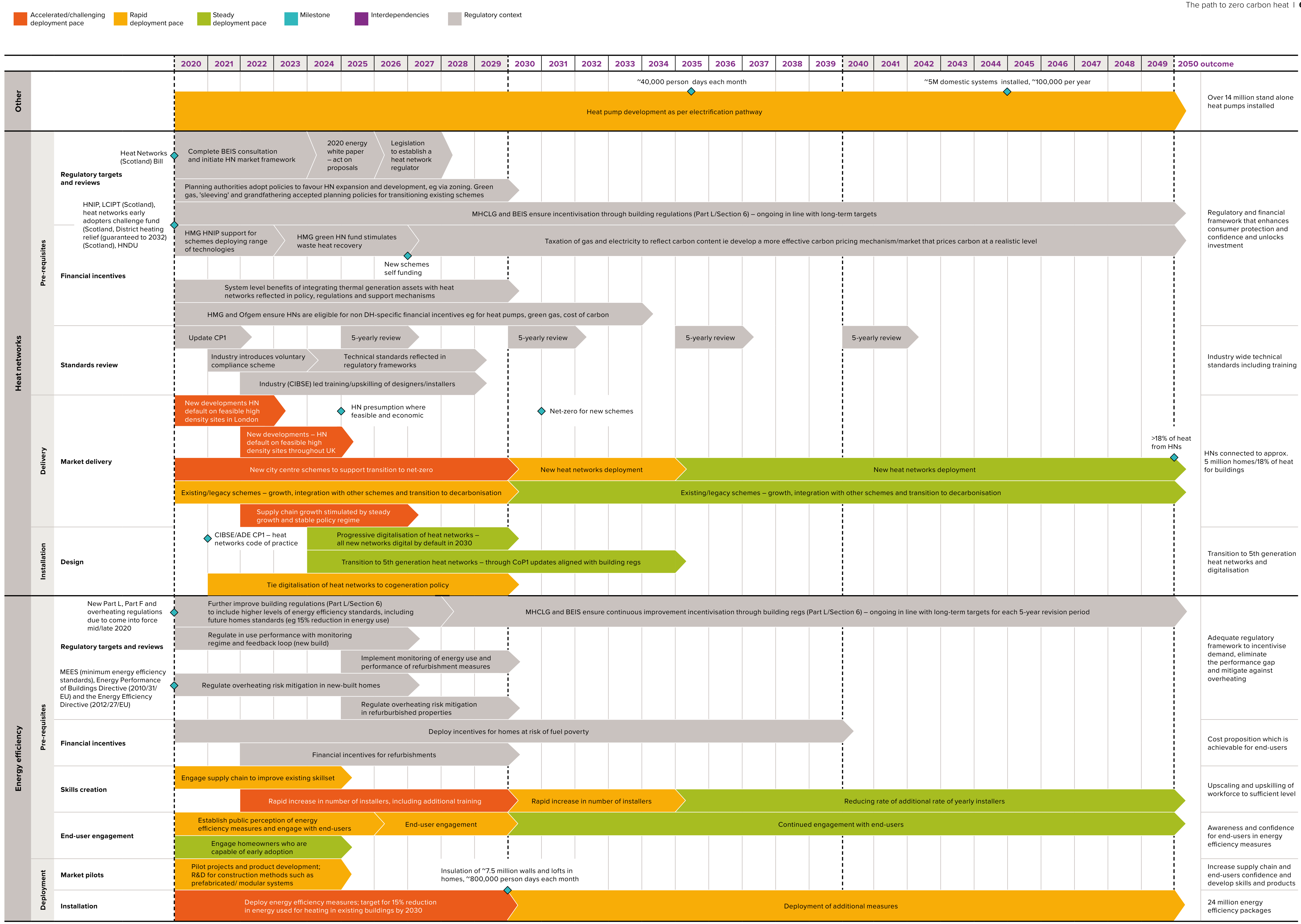
2050 outcome
Electric infrastructure
Generation
Nuclear
First RAB award for nuclear
Outline detailed RAB model for GW nuclear scale
First GW-scale commissioning
Standardised designs for GW-scale nuclear agreed
Build GW scale nuclear plant
Build GW scale nuclear
Build SMR nuclear generator
Build SMR supply chain
Build SMR rollout
Plan SMR locations
First SMR award
First demo SMR complete
Finalise SMR locations
45GW
Thermal energy (OCGT, CCGT)
Trial hydrogen OCGTs
Build hydrogen OCGTs and CCGTs and natural gas OCGTs and CCGTs
Develop capacity market models to incentivise low utilisation thermal power plant
36GW
Offshore/onshore wind
CfD allocation rounds/contracts
Floating wind demonstration
Commercialisation of floating wind
Delivery of floating offshore wind
Review changes to existing policy to support RE growth
Development of supply chain for fixed/floating offshore wind
Delivery of fixed onshore wind
82GW
Solar PV
Development of supply chain for solar PV
Delivery of solar PV
Procurement method established
103GW
Storage
Storage
Development of a clear and robust regulatory regime
Continue markets for capacity and ancillary services to incentivise electrical storage
6GW
Transmission
Transmission grid
Build UK capacity in HVDC and subsea cables
Plan and build HVDC bootstraps for offshore wind connections and to allow north-south power flows
Reinforce transmission network to accommodate nuclear generation
Transmission grid suitable for new energy system
Distribution
Distribution grid
Establish projections for EV and HP growth for DNOs to use. Extend long-term DNO planning
Different security of supply offer for heating and EVs for other loads
Reinforce network for EVs where required
Establish flexibility market, giving DNO access to flexibility
Trial flexible connection agreements for domestic customers
Provide DNO network reinforcement where required. Hybrid heat pumps remove some of the major requirement for reinforcement.
Build capacity with industry for cable and substation installation
Establish city-wide plans for electrical reinforcement
Distribution grid and flexibility markets suitable for new energy system
Hybrid heat pump
Feasibility
Building conversion feasibility
Feasibility and trial of harder to convert buildings
Stock characterisation
Decision on pathway and confirm conversion strategy
Feasibility proven for all relevant building types
Development
Regulation
< 220gCO$_2$e/kWh
< 170gCO$_2$e/kWh
< 110gCO$_2$e/kWh
No non-compliant systems in new buildings
Building emissions targets
Ongoing improvements to building regulations to drive improvements in heat pumps/boilers/controllers
Regional and local policy to stimulate low regrets installs
Development of end-user heat map
Regulations that steer end-users towards the correct systems
Financial and other Incentives
Closing phases of existing RHI
RHI successor
Potential enhanced capital allowance successor defining component and controller requirements
Develop Incentives for hard to convert sites
Taxation of gas and electricity to reflect carbon content
Cost proposition which is achievable for end-users, clarity on where HHPs should be applied
Manufacturers' enhancements
Engagement with manufacturers – competitions, research programmes, trials for larger hybrid installations
Manufacturers scale up for hybrid systems
Hybrid systems become part of standard heating options
Increasing quality of packaged products and controls
Skills creation
Skills gap analysis
Designer good practice development and dissemination
Train new installers. Combine with training for boiler installers and others
Enhanced skills roll-out
Full range of skills in HHP become embedded
Deployment
Install
Low regrets installations
First phase roll-out
Larger scale roll-out
Decision on pathway
~40,000 person days each month
0.5M domestic systems installed, ~100,000 per year
Nearly 5.5 million domestic HHPs installed, with additional non-residential


Accelerated/challenging deployment pace
Rapid deployment pace
Steady deployment pace
Milestone
Interdependencies
Regulatory context
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049
2050 outcome
Other
~40,000 person days each month
~5M domestic systems installed, ~100,000 per year
Heat pump development as per electrification pathway
Over 14 million stand alone heat pumps installed
Heat networks
Pre-requisites
Heat Networks (Scotland) Bill
Regulatory targets and reviews
Complete BEIS consultation and initiate HN market framework
2020 energy white paper – act on proposals
Legislation to establish a heat network regulator
Planning authorities adopt policies to favour HN expansion and development, eg via zoning. Green gas, 'sleeving' and grandfathering accepted planning policies for transitioning existing schemes
HNIP, LCIPT (Scotland), heat networks early adopters challenge fund (Scotland, District heating relief (guaranteed to 2032) (Scotland), HNDU
MHCLG and BEIS ensure incentivisation through building regulations (Part L/Section 6) – ongoing in line with long-term targets
HMG HNIP support for schemes deploying range of technologies
HMG green HN fund stimulates waste heat recovery
Taxation of gas and electricity to reflect carbon content ie develop a more effective carbon pricing mechanism/market that prices carbon at a realistic level
Regulatory and financial framework that enhances consumer protection and confidence and unlocks investment
New schemes self funding
Financial incentives
System level benefits of integrating thermal generation assets with heat networks reflected in policy, regulations and support mechanisms
HMG and Ofgem ensure HNs are eligible for non DH-specific financial incentives eg for heat pumps, green gas, cost of carbon
Standards review
Update CP1
5-yearly review
5-yearly review
5-yearly review
5-yearly review
Industry introduces voluntary compliance scheme
Technical standards reflected in regulatory frameworks
Industry (CIBSE) led training/upskilling of designers/installers
Industry wide technical standards including training
Delivery
Market delivery
New developments HN default on feasible high density sites in London
HN presumption where feasible and economic
Net-zero for new schemes
New developments – HN default on feasible high density sites throughout UK
>18% of heat from HNs
New city centre schemes to support transition to net-zero
New heat networks deployment
New heat networks deployment
HNs connected to approx. 5 million homes/18% of heat for buildings
Existing/legacy schemes – growth, integration with other schemes and transition to decarbonisation
Existing/legacy schemes – growth, integration with other schemes and transition to decarbonisation
Supply chain growth stimulated by steady growth and stable policy regime
Installation
Design
CIBSE/ADE CP1 – heat networks code of practice
Progressive digitalisation of heat networks – all new networks digital by default in 2030
Transition to 5th generation heat networks – through CoP1 updates aligned with building regs
Transition to 5th generation heat networks and digitalisation
Tie digitalisation of heat networks to cogeneration policy
Energy efficiency
Pre-requisites
New Part L, Part F and overheating regulations due to come into force mid/late 2020
Further improve building regulations (Part L/Section 6) to include higher levels of energy efficiency standards, including future homes standards (eg 15% reduction in energy use)
MHCLG and BEIS ensure continuous improvement incentivisation through building regs (Part L/Section 6) – ongoing in line with long-term targets for each 5-year revision period
Regulatory targets and reviews
Regulate in use performance with monitoring regime and feedback loop (new build)
Implement monitoring of energy use and performance of refurbishment measures
Adequate regulatory framework to incentivise demand, eliminate the performance gap and mitigate against overheating
MEES (minimum energy efficiency standards), Energy Performance of Buildings Directive (2010/31/EU) and the Energy Efficiency Directive (2012/27/EU)
Regulate overheating risk mitigation in new-built homes
Regulate overheating risk mitigation in refurbished properties
Financial incentives
Deploy incentives for homes at risk of fuel poverty
Financial incentives for refurbishments
Cost proposition which is achievable for end-users
Skills creation
Engage supply chain to improve existing skillset
Rapid increase in number of installers, including additional training
Rapid increase in number of installers
Reducing rate of additional rate of yearly installers
Upscaling and upskilling of workforce to sufficient level
End-user engagement
Establish public perception of energy efficiency measures and engage with end-users
End-user engagement
Continued engagement with end-users
Engage homeowners who are capable of early adoption
Awareness and confidence for end-users in energy efficiency measures
Deployment
Market pilots
Pilot projects and product development; R&D for construction methods such as prefabricated/ modular systems
Insulation of ~7.5 million walls and lofts in homes, ~800,000 person days each month
Increase supply chain and end-users confidence and develop skills and products
Installation
Deploy energy efficiency measures; target for 15% reduction in energy used for heating in existing buildings by 2030
Deployment of additional measures
24 million energy efficiency packages

F. Cross-cutting components

F. Cross-cutting components

The regulatory context, energy efficiency measures and heat networks are presented as cross-cutting components for the three roadmaps.

While the regulatory framework will be key for each pathway, and is expected to differ depending on the pathway selected, this aspect was not at the core of the roadmaps and is included in the cross-cutting section to offer a general context for all pathways.

The energy efficiency and heat networks components for the roadmaps are considered critical infrastructure for all three pathways, and should be delivered at a similar pace across the three pathways. As such, they are presented under the cross-cutting section.

F.1 Regulatory context

Regulatory decisions will determine the direction for each pathway. While the focus of the roadmaps was not on these regulatory decisions, we considered it important to provide the regulatory context for the roadmaps and highlight possible impacts for each pathway. Each roadmap has a cross-cutting section that includes some of the main policies that will impact all components of the roadmap; these are also explained below.

F.1.1 Overarching regulatory context – supply

We consider that the following are the key policies on the supply side that drive the decarbonisation of heat:

- **The RIIO framework.** RIIO stands for setting Revenue using Incentives to deliver Innovation and Outputs. This is a price control framework that operators of gas and electricity networks in the UK must adhere to. It caps the amount of revenue network companies can make from use of network charges. The current RIIO price control period is eight years and ends in 2021. The next RIIO price control (RIIO-2) period runs for five years from 2021 to 2026 for gas distribution and electricity and gas transmission, and from 2023 to 2028 for electricity distribution.

  It would be expected that key policy decisions on the decarbonisation of heat would be aligned with the RIIO periods to allow key investment decisions to be made prior to the start of a price control period. However, Ofgem has noted that key decisions on the decarbonisation of heat will be required in the 2020s, and that RIIO-2 needs to be capable of responding flexibly to actions related to decarbonisation and allow such actions to be taken during the RIIO price control period and not just at the start of each period. This means that RIIO-2 could be more flexible than the current RIIO price control period, and could be designed to be capable of responding to policy decisions taken during the price control period. This would enable more flexibility for all pathways.

- **The Renewable Heat Incentive (RHI).** The RHI directly incentivises the uptake of heat from renewable sources, such as biomass, biomethane and the electrification of heat through heat pumps, by paying a tariff per unit of heat energy supplied. The Domestic RHI was recently extended in the 2020 budget to 31 March 2022. It is due to be followed by a new 'low-carbon heat support scheme' from April 2022, backed by £100m of new exchequer funding. This is yet to be consulted on. The future shape of RHI (whether it will be a grant or tariff-based) will impact on the uptake of the different end-user systems.
- **Contracts for Difference (CfD).** This is the government's main mechanism for supporting low-carbon electricity generation. Developers compete against each other for a contract in an auction or 'allocation round'. Successful developers enter into a 15-year contract that provides price certainty through the provision of a flat (indexed) rate for electricity produced. Among other technologies, offshore wind, and, from the next allocation round, onshore wind and solar are eligible for this mechanism.
- **Electricity storage.** This falls within the existing regulatory regime for electricity generation, and is licensed by Ofgem, unless exempt. A clear and robust regulatory regime around storage needs to be developed as this becomes an essential part of a decarbonised energy/heat system.
- **Carbon capture, utilisation and storage (CCUS).** The regulatory regime for CCUS is as yet undeveloped.

F.1.2 Overarching regulatory context – demand

There are two key elements to the regulatory framework on the demand or end-user side. The first is the reduction of energy demand for heating, primarily via the installation of energy efficiency measures. The second is the regulation of centralised heat networks to provide greater consumer protection and rights. Both are of relevance to all heat decarbonisation pathways.

Energy efficiency: Buildings policy has been the predominant regulatory framework for introducing energy efficiency measures in the UK. Although a number of recent programmes aimed at strengthening energy efficiency requirements in buildings policy have been wound down or had their funding reduced, a strengthened Part L of the Building Regulations is due to be enacted in mid/late 2020, and a new Future Homes Standard is due to come into force by 2025. These policies would need to be strengthened and extended to existing buildings to achieve energy efficiency, not only for new build but to also stimulate the retrofit market. Minimum Energy Efficiency Standards (MEES) standards provide minimum energy efficiency standards for rented buildings. A key challenge remains in the governance of policy on energy efficiency, which is unco-ordinated between a national level (eg through building regulations) and a local and regional level (eg through local and regional energy planning and implementation). Decisions on how planning regulations are reviewed and relaxed to enable the required interventions will also be important – for example, in the implementation of essential energy efficiency measures such as external wall insulation.

Heat networks: BEIS is currently consulting on building a market framework for heat networks that sets out its preferred approach for regulating district heat networks and the supply of heat in the UK. This consultation ended in early June 2020, with feedback now being analysed. The government's energy white paper is due to be published later in 2020. Following these, a legislative process will be required in order to empower a regulator for heat (which will most likely be Ofgem) and bring forward the legislation required to regulate the heat market. In Scotland, the Heat Networks (Scotland) Bill was introduced on 2 March 2020, but is yet to come into force. These actions should be done in parallel with policies on the incentivisation of connections to district heating networks, and maintaining cost competitiveness compared to other heating solutions.

End-user systems regulation: Each pathway will have specific requirements in terms of regulation and incentives to drive the adoption of the correct end-user systems at the right time. It is not possible to be prescriptive about the shape of this regulation now, but it is possible to consider the likely common and pathway specific features. In all instances understanding how the allocation of end-user technology needs to vary geographically and for different end-user circumstances (through development of an end-user heat model) will be critical to development of enablers.

F.1.2.1 Differences in regulatory context for individual pathways

Electrification pathway

The regulatory framework for electrification is arguably the most developed, as it would fall within the already established regulatory framework for electricity generation, transmission and distribution, and would be within Ofgem's mandate. A key challenge here is to facilitate a 'least cost' upgrade of the distribution network (particularly at lower voltages); this may require involving more stakeholders in network planning and having city/region heating plans. It may also require investing ahead of demand to allow for the expected rapid changes required for the network.

The enablers for the electrification pathway, where the onus is on driving the majority of end-users over time to heat pumps, can begin to be shaped now. A potential timeline for key end-user enablers might be as follows:

- **2020:** Building Regulations (Part L and Section 6) amended to reflect greater energy efficiency and adaptability of user for heat pumps.
- **2022:** Successor to RHI for domestic and non-domestic users. Alternatives could include a grant rather than tariff-based approach. Mechanisms for installer training programmes and certification schemes.
- **2025:** Phase out of gas boilers in new build, and enhanced Building Regulations for energy and ventilation through adoption of the standards such as the Future Homes Energy Standard.
- **2030:** Phase out of retrofit boilers.
- **2040:** End of subsidy for boiler scrappage scheme.

The pre-2025 measures will result in low regrets install of heat pumps in new developments and buildings off the gas grid. It may also be the case that in the early years regional variations in planning and policy are needed to drive the adoption of systems in the correct locations (eg off gas network buildings).

Hydrogen pathway

The regulatory framework for hydrogen is currently the least developed of the three pathways. Significant regulatory development would be required in terms of network development, gas safety regulation, hydrogen production and CCUS, alongside a programme of changing appliances in properties currently connected to the gas grid. There is currently no clear regulator for hydrogen development: Ofgem considers that its responsibilities extend to customers on hydrogen gas networks, but not to hydrogen production or CCUS.

The regulations and incentives for the hydrogen pathway will hinge upon the decision date, when it is envisaged that there will be a sufficient understanding of the safety, practicality and cost of hydrogen conversion for end-users (and more generally). Up until this point work will be directed towards identifying the likely changes in regulation (e.g. Gas Safety (Installation and Use) Regulations) and end-user standards (e.g. IGEM standards) for hydrogen end-user systems to operate safely and understanding what these differences entail in terms of cost and disruption. Thereafter these will drive and enable a change of end-user systems to hydrogen. Other medium-term regulation could include the stipulation of hydrogen-ready boiler systems and appliances. Other enablers, to include incentives, will be dependent on the actual cost of conversion, and how these can be distributed across the actual years of conversion.

Hybrid pathway

To the extent that the hybrid pathway relies on hydrogen gas, the regulatory challenges facing any hydrogen pathway will apply. The regulatory framework is otherwise well developed and, as for electrification, would fall within the already established regulatory framework for electricity and gas generation, transmission and distribution, and would be within Ofgem's mandate. Again, the challenges around developing a clear and robust regulatory regime for electricity storage, and a consistent policy framework to provide market and investor confidence apply.

The hybrid pathway may utilise some of the same elements of the electrification approach (not including boiler scrappage), but driving the adoption of hybrid heat pumps as opposed to standard heat pumps will necessarily mean that the enablers will become more complex. As well as driving down the carbon intensity of the end-user system (building and heating system), the hybrid pathway will need consideration of how the quantity of hybrid versus standard heat pump systems (and others) can be managed such that the hybrid pathway's benefits in terms of downsizing electrical capacity can be realised. Again, regional policy and regulatory variations may form part of this process.

F.1.3 Takeaways and recommendations from a regulatory perspective

We have identified four key takeaways in relation to the decarbonisation of heat from a regulatory perspective:

There is no 'silver bullet'. A range of technical and policy solutions and a combination of the three pathways identified will be required in order to effectively decarbonise heat. For example, for customers that are currently off the gas grid, hydrogen is unlikely to be a viable solution and electrification may be the most cost-effective route to decarbonisation. However, hydrogen (in combination with CCUS/storage) may be the most effective pathway for customers who are currently connected to the gas grid as households could retain existing appliances and technologies.

Reducing energy demand is key. Policy to date in the UK has tended to focus on supply-side options rather than prioritising energy demand solutions. The low- or zero-carbon heating systems considered in the three pathways are all more expensive than incumbent technologies. In order to make their adoption viable, it will be necessary to reduce demand for heating and hot water. The policy approach needs to change, and demand-side solutions need to be considered equally as, if not more, important than decarbonising supply if the UK is to effectively decarbonise heat.

A systemic, 'whole systems' approach is required, both in terms of the energy system and the delivery of the decarbonisation of heat. For example, consideration needs to be given to interaction between the timing of policy decisions and frameworks, such as RIIO, which govern timeframes for investment. These need to align, or otherwise be sufficiently flexible to adapt to new policy decisions, in order for effective investment decisions to be made. The decarbonisation of heat requires a transformation in the way that heat is used and supplied. This needs to be led by government, but delivered by a range of stakeholders across the business community and civil society who need to be better engaged and empowered at an early stage in the decarbonisation process.

Greater consistency in policymaking for the decarbonisation of heat is required. There have been multiple policy changes in recent years on both the energy supply side and the energy demand side. Well-designed, effective policies have in some cases been scaled back or changed. This is confusing for the market, and does not create a conducive policy environment for investment.

F.2 Heat networks

F.2.1 Role of heat networks in the pathway

Heat networks are an important component across all three scenarios and are expected to provide multiple opportunities for both the transition to net-zero and for the 2050 endpoint.

For both the transition and 2050 endpoint, heat networks in dense urban environments will be able to connect diverse loads, including buildings difficult to decarbonise, provide energy storage and grid services, and enable access at scale to point sources of low-carbon renewable heat (such as energy from waste). In addition to this, when combined with cooling loads, further cost and carbon savings can be achieved through capturing the heat rejected from chillers and/or using absorption chillers to avoid peak electricity charges.

We based the roadmap 2050 target on the EE/UCL report, which is in line with the CCC recommendations. The report assumed that within the three decarbonisation pathways, by 2050 heat networks will be deployed for up to 19% of the domestic stock (approximatively 5 million homes).

Heat networks can access and distribute heat from a diverse range of low-carbon energy sources, such as large-scale heat pumps, waste heat, large-scale biomass plants, energy from waste plants and efficient gas CHP. This also means that they are able to provide flexibility and accommodate energy sources depending on the selected pathway. The EE/UCL report assumes that for the hydrogen-led and hybrid (central) pathways, hydrogen and peaking hydrogen is used for district heating networks heat plant. For the electric pathway, it was assumed that electricity-driven systems such as heat pumps generate the heat for the heat network and no hydrogen boilers are used.

F.2.2 Key aspects and assumptions

Energy systems modelling completed for the European Commission shows heat networks could cost-effectively supply 27-72% of heat in UK buildings by 2050. This is above the pathway 2050 19% target, and represents a 1-2% year-on -year growth in connections for the next 30 years, similar to the CCC's analysis.

Delivering the physical infrastructure at this scale over the next 30 years is seen as achievable with a continuous growth rate. However, this level of growth requires a step change in approaches to unlock the barriers that the industry has been struggling with for a decade: level-playing field (compliance burden in building regulations and costs faced by other utilities), demand assurance, technology costs and supply-chain capacity.

Achieving this in the next decade assumes the continuation of government support for heat network development and market interventions (tax or grant) to make low-carbon heat cost competitive against natural gas. Alongside this, regulatory frameworks will need to incentivise building connections, the integration of heat and power networks and appropriate technical standards, stimulate the deployment of large-scale heat pumps, green gas cogeneration and utilisation of waste heat.

Assumptions are that newly built schemes are designed to be low temperature ('5th generation'), while existing schemes are progressively decarbonised through asset replacement cycles and fuel substitution. As the regulatory framework matures and the external costs of carbon are reflected in the cost of energy and infrastructure, the 2030s sees a self-sustaining industry no longer dependent upon government grants or subsidies.

F.2.3 Description of heat network roadmap

The heat networks roadmap was developed based on the assumptions noted above and incorporates examples of regulatory items that can achieve the required increase in the deployment rate.

Following the 2020 BEIS consultation for the introduction of the Heat Network Market Framework, 2020-2023 is marked for the implementation of the agreed regulatory framework, aligning with other utilities and guaranteed standards of performance, including the establishment of a heat regulator. The Heat Networks Market Regulatory Framework role will be implemented to provide the consumer and investment confidence, transparency and market certainty needed to stimulate new entrants and existing operators and their supply-chains to scale-up. From 2020-2030, it is also expected that planning authorities adopt policies to favour heat network expansion and development for example via zoning, green gas and "sleeving" for transitioning existing schemes.

Current financial incentives and programmes are noted for 2020, such as: Heat Networks Investment Project (HNIP), Low Carbon Infrastructure Transition Programme (LCITP – Scotland), Heat Networks Early Adopters Challenge Fund (Scotland, District heating relief guaranteed to 2032 – Scotland), and the Heat Networks Delivery Unit (HNDU). From 2023 the HMG Green HN Fund is expected to stimulate waste heat recovery. A milestone of new schemes being self-funding is placed in 2027. Past this point, a taxation of gas and electricity to reflect carbon content more accurately is expected so that a more effective carbon pricing mechanism is developed.

From 2020-2030, it is expected that policy will reflect system level benefits of integrating thermal generation assets with heat networks. In parallel to these items, from 2020 to 2034 it is proposed that HNs are eligible for non district-heat specific financial incentives, eg for heat pumps, green gas, and the cost of carbon.

With regard to reviews of standards, in 2021-2024 the industry is expected to introduce a voluntary compliance scheme, and that from 2024 to 2029 technical standards are reflected in regulatory frameworks. This is followed in parallel from 2022 to 2029 by industry (CIBSE) led training/upskilling of designers and installers.

In terms of delivery, it is expected that district heat networks will become the default for high density sites (where feasible and economic) between 2020 and 2025, with an initial emphasis on very large schemes and very high density sites. This transition is seen as ambitious.

The implementation of HN new city centre schemes and the transformation of existing/legacy schemes runs from 2020 to 2050. Because of the step change required to stimulate the initial growth of the supply chain, the first 10 years to 2030 are seen as the most ambitious and difficult period. As the deployment rate increases, and the regulatory and market framework gets established, the delivery process is noted as less difficult.

From 2024, there needs to be progressive digitisation of heat networks – with all new networks to be digital by default by 2030. From 2025, a transition to 5th generation heat networks, assumed through Heat Networks Code of Practice (CoP) updates, will be mirrored with building regulations.

F.2.4 Takeaways and recommendations

In order to deliver net-zero carbon targets, it is essential that energy and heat are treated equitably to deliver co-ordinated infrastructure planning, strong investment signals, strengthened competition and, critically, consistent consumer protection.

Accelerating the growth of district heat networks is a key recommendation as a low regrets action in the next five years.

To achieve this, large-scale heat networks need to be facilitated for in densely populated areas. All scenarios require the connection of over 5 million 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. To achieve this, the 2020s must be used to remove barriers and develop supportive policy, regulatory and financial frameworks. Critical near-term actions include the finalisation of policy/regulatory frameworks to improve consumer protection and confidence, such as establishing a heat network regulator, levelling the playing field between heat supply and gas/electricity supply in terms of issues like rights of access, and achieving policy clarity and consistency to sustain investor confidence in district heating as a long-term infrastructure asset investment.

The roadmap also illustrates a number of more detailed prerequisites to achieve this growth:

Regulation and policy – alignment with other utilities and guaranteed standards of performance.

- Complete consultation and initiate HN Market Framework Regulation as the basis for putting heat networks on a level-playing field with other utilities.
- Ensure incentivisation of heat networks through Building Regulations Part L and Section 6, with on-going review in line with long-term targets for heat network growth. At present, there is inconsistency and this can disincentivise heat network connections to new buildings from new and existing networks.
- Improve consumer protection and confidence through measures, such as the establishment of a heat network regulator.
- Align planning policy in the UK to support heat network expansion and development, such that it becomes the default option in dense urban areas. Potential action to achieve this could include:
  - An obligation to connect to heat networks within pre-determined 'zoned' areas
  - Prioritisation of heat networks as the presumed heat source for new build developments
  - Concession areas or clear strategic development goals for defined zones to provide clear investment signals
  - Requirements that renovation to existing buildings should include 'future proofing' to enable later connection to heat networks within zones

Financial incentives – to address funding gaps in the build up to market maturity.

- Availability of grants and soft loans for the transition away from natural gas through an evolution of the renewable heat incentive, appropriate eligibility rules for the government's proposed Green Heat Networks grant scheme and ongoing development of the Heat Networks Investment Programme.
- Longer term financial incentives and policy to provide transitional support for existing/legacy schemes to decarbonise; including flexibility to 'sleeve' low carbon heat through a heat network to specific end-users.
- Eligibility for non DH-specific financial incentives (eg for heat pumps, green gas, cost of carbon) to ensure consistency across heat options.

Standards – to ensure the application of industry wide standards (design and consumer protection) to deliver common standards and lower capital costs.

- Update of the existing Heat Networks Code of Practice (CoP) and regular review and updating to incorporate best practice and technology advances.
- Introduction of a compliance scheme for operators to demonstrate alignment with CoP and eligibility for incentive schemes.
- Associated training/upskilling of designers/ installers to ensure application of CoP.

F.3 Role of energy efficiency measures in the pathways

Energy efficiency measures for both new and existing stock are considered vital for all pathways. Reducing heating demand is not only a prerequisite for the effective implementation of systems such as heat pumps, but will also be required to minimise the scale of the infrastructure that will have to be built.

Energy efficiency measures are seen as an important low regret action across all three pathways for both new and existing building stock. It is important that intensive energy efficiency deployment is achieved imminently, to reduce the total energy demand and thus increase the likelihood that the decarbonisation target is achievable. An early deployment and successful installation of energy efficiency measures will also help stimulate the supply chain, build consumer confidence and help increase the installation rate. Raising awareness to encourage uptake on the side of the end-user is crucial, as is developing the financial strategy and upskilling the industry.

The assumptions for energy efficiency for 2050 were based on the EE/UCL report. In this report, three packages of energy efficiency measures were developed (low, medium and high), each with a different combination of measures from a range, including loft insulation, wall insulation, double glazing and floor insulation. Under the hybrid and the hydrogen-led scenarios, the energy efficiency measures are expected to deliver up to 25% and 24% reduction in heat demand respectively, compared to 2017 data. For this to happen at least one measure is installed in 85% of the UK stock.

Under the electrification, the EE/UCL report expected energy demand reduction through energy efficiency measures to be up to 30% compared to 2017.

However, for our roadmaps, we have assumed the higher level of deployment of energy efficiency measures across all pathways because the implementation of these measures will be key in reducing the energy generation capacity.

F.3.1 Key aspects and assumptions

The roll-out assumptions made in the roadmap and shown below are in line with the CCC target of achieving a 15% reduction in heating energy demand in existing buildings by 2030 through energy efficiency measures or over 7 million energy efficiency measures by 2030. The final 2050 number of measures that need to be deployed are assumed in line with the Analysis on abating direct emissions from 'hard-to-decarbonise' homes' (EE/UCL):

- 2.5 million cavity wall insulation installations by 2030, 2.8 million between 2025 and 2050
- 0.5 million solid wall insulation installations by 2030, 5 million between 2025 and 2050
- 3.5 million loft insulation installations by 2030, 15.9 million between 2025 and 2050
- 0.75 million floor insulation installations by 2030, 1.5 million between 2025 and 2050

The current market capacity was not assessed for this work, but drawing from past data[14] and estimated time required for delivery it is expected that the supply chain will need to achieve a 20-40% year-on-year increase in deployment rate reaching a value twice the peak energy efficiency installation rate from the last 10 years. Past trends indicate that with appropriate policy incentives such dramatic increases can be achieved for some types of energy efficiency measures for a limited number of years, but delivering this rate of increase over a period of more than 10 years is considered to be incredibly challenging.

The target to install 7 million measures by 2030 is estimated to require approximately 800,000 person-days time equivalent each month by 2030. The number of person-days and the increase in deployment rate are estimated assuming:

- A constant year-on-year percentage increase in deployed rate
- An average duration of work ranging from 1-2 person-days for cavity wall insulation to 10-20 person-days for solid wall insulation

It is of note that automation and prefabrication techniques, which are being developed for refurbishment projects under programmes such as the Energiesprong,[15] could significantly reduce the time required for the installation of energy efficiency measures. The implementation of these techniques has not been accounted for in the assumptions made for the roadmap in the short term (2020s), but have been referenced in the roadmap though the proposal for pilot projects.

14. See: Committee on Climate Change (2019) UK housing: Fit for the future?
15. Energiesprog is a whole house refurbishment and funding approach first developed in the Netherlands. It is a self-financing model that is solution agnostic and is based on short delivery times and guaranteed performance in use for a range of measures such as fabric and heating systems improvements.

Setting up pilot programmes is seen as an effective way of promoting the development of new fabrication and installation techniques. It can also encourage uptake on the side of the end-user, by increasing consumer confidence in the effectiveness of measures and building the capacity of the supply chain, through supporting innovation and building up demand. In the Scaling up retrofit 2050 report,[16] the IET and Nottingham Trent University reference an Energiesprong study estimating that 25,000 pilots need to be completed in a five-year period to make energy efficiency measures installations market ready. This is considered challenging to achieve, as such pilots are largely yet to be initiated. In line with this recommendation, it also assumed that 3500 pilot projects will be initiated within the next five years.

The successful deployment of these measures assumes that the blockers identified in the dependency maps, such as planning restrictions, low consumer confidence, lack of skills in the supply chain, are addressed. Examples of policies that could tackle these blockers have been included as examples in the roadmap.

Occupant behaviour can significantly impact what is achievable through energy demand reduction, therefore, it was also assumed that raising awareness on energy efficient ways of controlling indoor environments will be an important factor alongside the physical deployment of energy efficiency measures.

F.3.2 Description of the energy efficiency roadmap

The energy efficiency roadmap was developed based on the assumptions noted above and incorporates examples of regulatory items that can achieve the required increase in the deployment rate.

Standards: MEEES (Minimum Energy Efficiency Standards), Energy Performance of Buildings Directive (2010/31/EU) and the Energy Efficiency Directive (2012/27/EU) along with the national implementation equivalents are some of the current key standards and regulations for energy efficiency noted in the roadmap. Building on the current building regulations review, the roadmap assumes there will be an improvement in the levels of energy efficiency and regulation of in use performance for new build. Examples of such required milestones are Energy Building Regulations (Part L and Section 6) amendments for tighter fabric energy efficiency standards both for new build and retrofit ahead of 2025 Future Homes Standard, and the standard itself defining high levels of energy efficiency standard for new homes, with space heating demand below 15 kWh/m^2 per annum.

From 2025, linked with the next round of updates to building regulations, it is assumed that the same regulation to optimise building performance as for new buildings will be implemented for refurbishments. To incentivise high quality design solutions and reduce the performance gap, these will include a monitoring regime and feedback loop, as well as mitigation for overheating risk.

Incentives: Financial incentives are critical throughout the energy efficiency implementation period, particularly for homes at risk of fuel poverty. Suitable financing mechanisms and incentives for energy efficiency measures are noted up to 2030. At this point, the market is assumed to have matured, and measures optimised from a cost and delivery point of view, leading to significantly reduced payback times.

Skills and training: The availability of skills is a critical aspect in the delivery of energy efficiency measures and is likely to involve significant effort to upskill and increase the size of the existing workforce. From 2022 until 2030, there needs to be a significant increase in the training of installers. This is will require priming as, at this point and particularly at the early phases, there may be limited regulatory or market support for this. This period also allows a couple of years in which pilot projects can develop and small scale regional upskilling can happen. From 2030 until 2035, installer numbers also need to increase. By the end of the 2030s, we will need enough installers to meet a monthly rate of approximatively additional 800,000 person-days to ensure a sufficient workforce for the number of retrofits required.

End-user engagement: Engagement with potential early adopters should be pursued as early as possible. Local authorities and housing associations are seen as an example of such early adopters because of their long-term view and interest in the quality and performance of the building stock.[17] Engagement with installers is also present at this stage to help upskill the workforce and build confidence in energy efficiency measures in the supply chain and end-users, as well as a long term end-user engagement strategy that runs up to 2050 but is focused on the 2020s.

Delivery: Achieving a 15% reduction in energy used for heating existing buildings by 2030 through efficiency improvements is very ambitious. This peaks at ~7 million domestic wall and loft insulations by 2030. Pilot projects will be critical in 2020-2025, particularly for hard to retrofit domestic and non-domestic properties, to see what kind of energy efficiency improvements are achievable for different typologies.

16. See: IET and Nottingham Trent University (2020) Scaling up retrofit 2050
17. See: IET and Nottingham Trent University (2020) Scaling up retrofit 2050

F.3.3 Takeaways/recommendations

In order to upgrade the energy efficiency of the vast majority of the building stock it is essential to engage the end-user, to incentivise the uptake of energy efficiency measures, both from a regulatory and from a financial point of view, and crucially to ensure that there is an adequate, fully skilled workforce to deliver the task at the required scale. The key points below are significant in all three pathways, but critical for the electrification pathway, as heat pumps can be ineffective in poorly insulated buildings.

The key recommendation for the energy efficiency measures is the need for national programmes to reduce heat demand. All of the 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 25 million 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.

The roadmap and dependency maps also illustrate a number of more detailed prerequisites to achieve this goal:

Regulation and policy – to tighten efficiency targets and safeguard performance in use and timely uptake of measures.

- Tighten fabric efficiency targets, as well as minimum carbon emissions and energy consumption targets, beyond current building regulations, and extend to refurbishment projects.
- Review planning restrictions that might hinder the uptake of energy efficiency measures.
- Reinvigorate building control officers to a more advisory role that can help local construction firms develop and deliver better design solutions.
- Develop end-user engagement strategy to incentivise end-users' uptake of energy efficiency measures, both at local and at national level.

Financial Incentives – to address fuel poverty and to ensure a successful full roll-out.

- Develop appropriate subsidies to help the industry to grow in terms of skills and workforce size.
- Develop green finance loans with measurable benefits to make the investment affordable and appealing to the end-user, accounting for and leveraging the fact that the energy efficiency measures can increase the value of a property.
- Develop market driven financial incentives and financing programmes for energy efficiency packages.

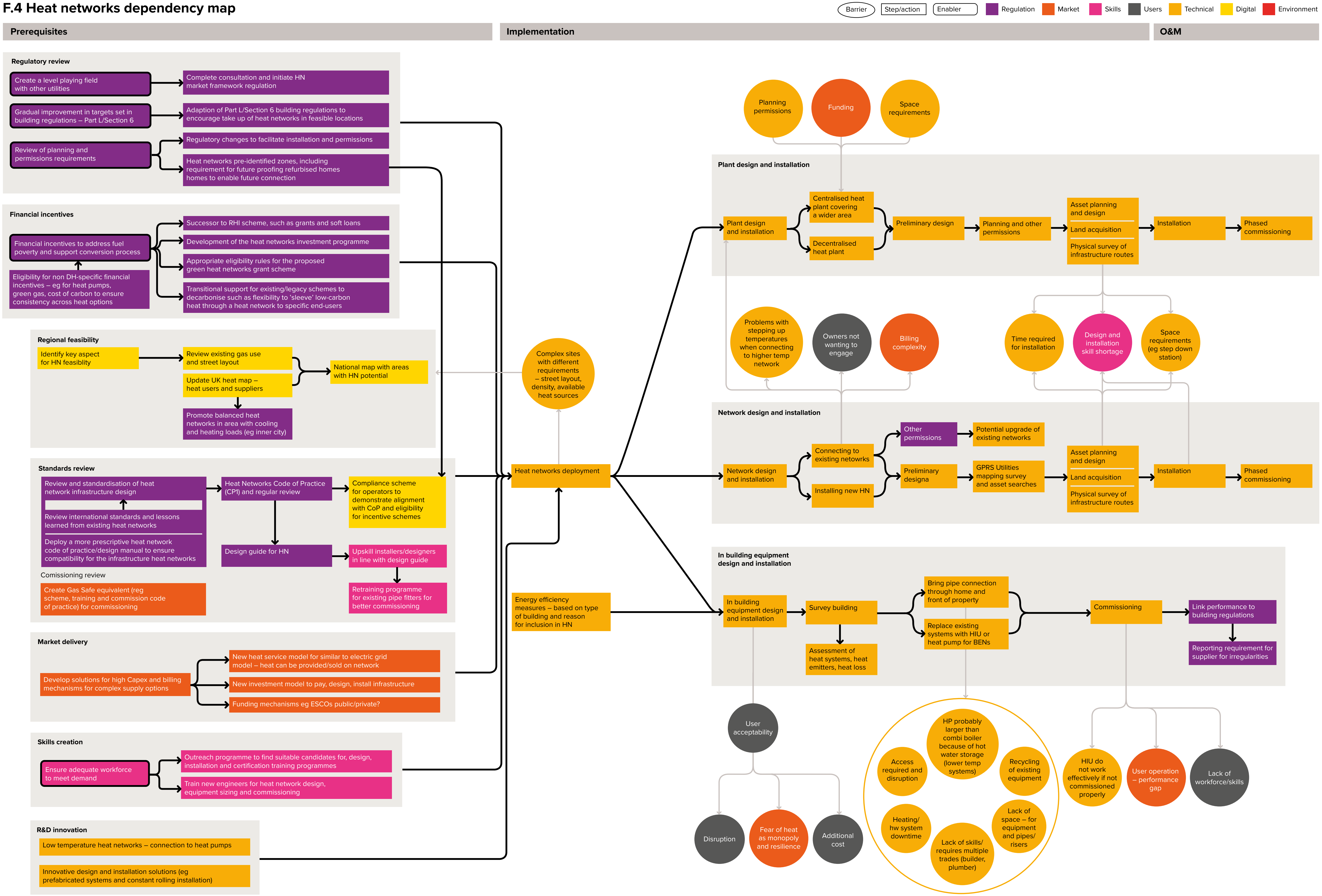
Skills – to increase delivery capacity and upskill the industry.

- Develop training programmes to upskill the existing workforce and deliver early successful installations to build confidence during initial stages.
- Develop certification scheme for installers linked to a digital platform to enable consumers to easily find qualified installers, and help help build consumer confidence.
- Create outreach programme to attract more to the workforce.
- Develop strategies for local deployment, based on locally suitable solutions and building expertise.

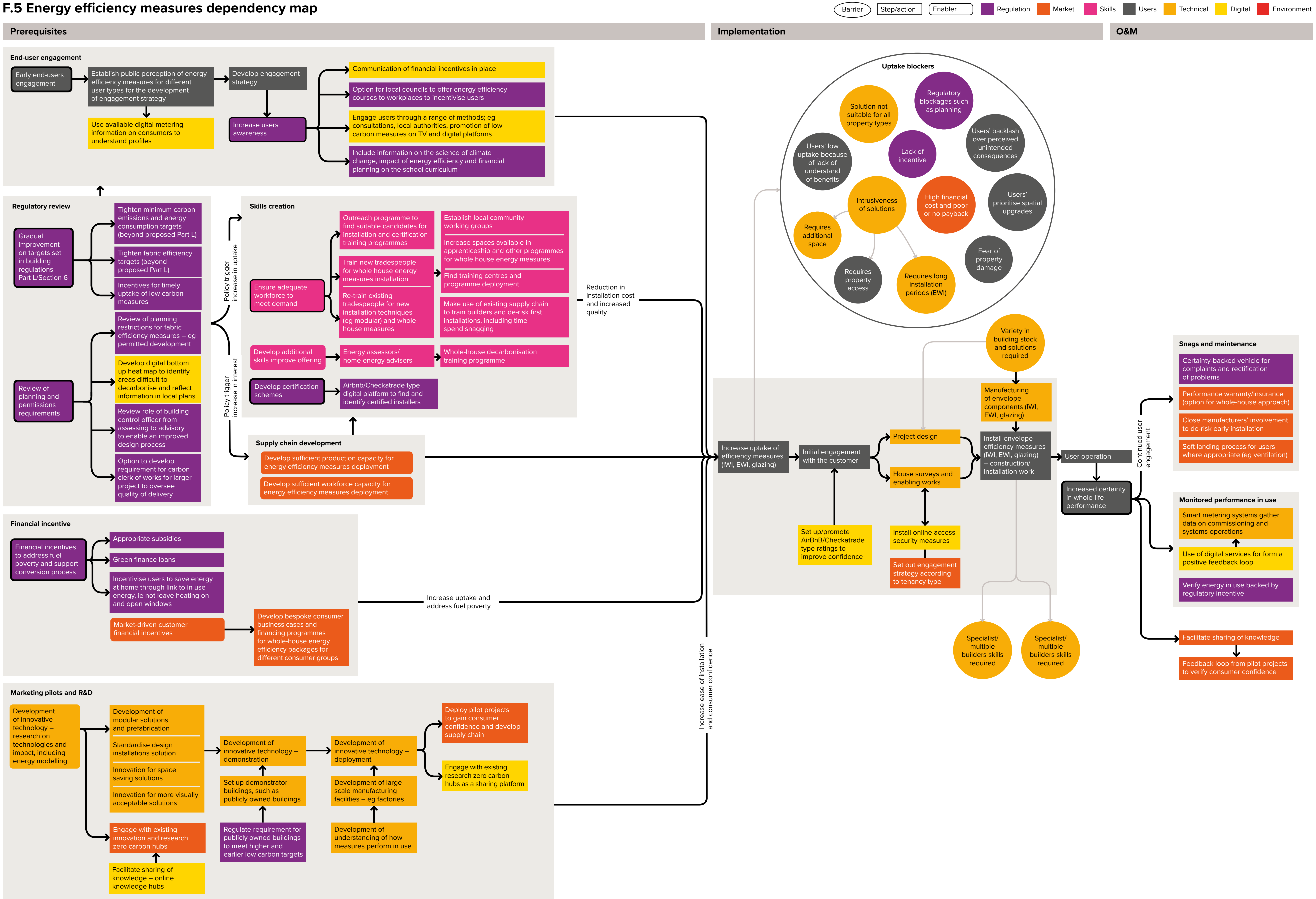
Innovation and marketing – to help standardise solutions to address the diverse building stock and ensure a timely roll-out of energy efficiency measures and to communicate success of retrofits to increase uptake.

- Develop whole house solutions to improve performance, and decrease installation times and cost by reducing number of separate installations required.
- Develop and implement easy to use digital solutions for energy consumption monitoring and installation quality assurance.
- Develop solutions based on prefabricated modular systems linked with 3D building surveys for all wall insulation energy efficiency measures, aiming to increase installation quality and decrease space requirements, particularly for internal wall insulation.

F.4 Heat networks dependency map



F.5 Energy efficiency measures dependency map



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Terminology and acronyms

Key terms

ADE	Association for Decentralised Energy
ATR	Autothermal Reforming Plant
BEIS	Department for Business, Energy and Industrial Strategy
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon capture, utilisation and storage
CIBSE	Chartered Institution of Building Services Engineers
CfD	Contracts for Difference
CP1	Heat Networks: Code of Practice for the UK
DNO	Distribution Network Operators
EV	Electric Vehicle
FEED	Front End Engineering Design
FOAK	First of a Kind
GSIUR	Gas Safety (Installation and Use) Regulations 1998
GSMR	Gas Safety (Management) Regulations 1996
GW	Gigawatt
H21	DNO led suite of gas industry projects designed to look at 100% hydrogen use
H100	DNO led suite of projects looking at network conversion to 100% hydrogen
HMG	Government of the United Kingdom
HNIP	Heat Networks Investment Project
IMRP	Iron Mains Replacement Programme
HP	Heat Pump
HHP	Hybrid Heat Pump
HN	Heat Network
HVDC	High-voltage Direct Current
HTS	Hydrogen Transmission System
Hy4Heat	Project on use of 100% hydrogen for end-users
HyDeploy	DNO led suite of projects on use of a 20% hydrogen blend
HyNTS	National Grid set of programmes on feasibility of hydrogen in the NTS
Part L	Building Regulations Conservation of fuel and power: Approved Document L (England and Wales)
MEES	Minimum Energy Efficiency Standards
MHCLG	Ministry of Housing, Communities and Local Government
MW	Megawatt
NTS	National Transmission System, the high pressure gas network which transports natural gas in the UK
OCGT	Open Cycle Gas Turbine
PV	Photovoltaic systems
R&D	Research and Development
RE	Renewable energy technology
RHI	Renewable Heat Incentive
RIIO	Revenue using Incentives to deliver Innovation and Outputs, OFGEM's framework for network price controls
RAB	Regulatory Asset Base
Section 6	Building Standards Section 6 Energy (Scotland)
SMR	Small Modular Reactors (nuclear section)

Opening opportunities with connected thinking.