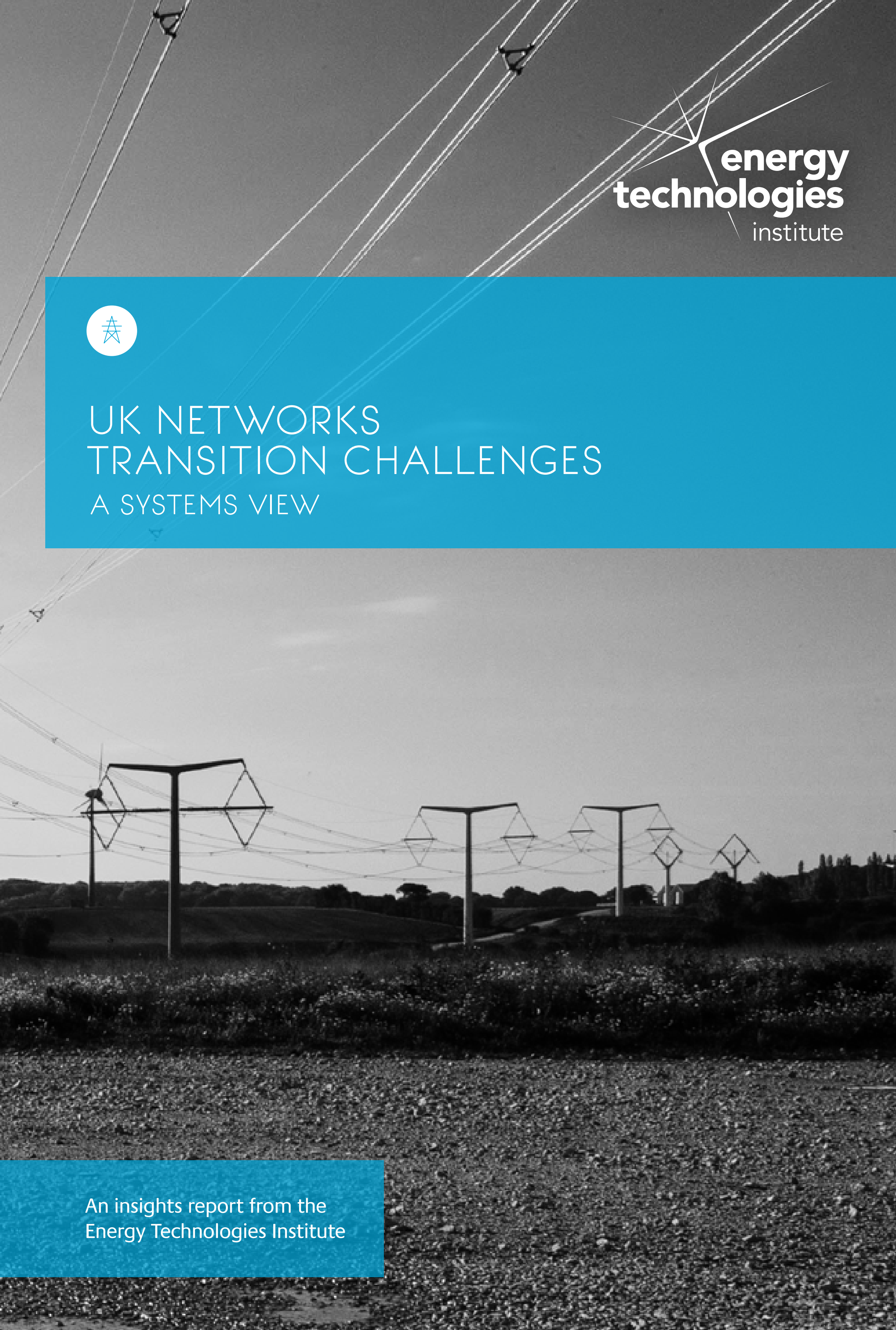

UK NETWORKS TRANSITION CHALLENGES

A SYSTEMS VIEW

An insights report from the Energy Technologies Institute

Contents

future networks

There are three challenges to transitioning UK networks...

1. Adapting and enhancing existing networks

2. Creating efficient and effective new networks

3. Integrating networks to optimise performance across energy vectors

UK NETWORKS TRANSITION CHALLENGES

A SYSTEMS OVERVIEW

ETI sees value in employing a multi-vector approach to energy supply

Decisions have to be made ahead of need and to be right for long-term solutions

Current governance and regulatory frameworks are simply not designed to enable and incentivise the radical transformation needed

Whole energy system thinking is critical – the challenge is one of knowing where, when and to what extent to enhance and adapt the UK's energy networks

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ETI recommends...

- Incentivisation and targeting investment to adapt and enhance existing networks
- Decide upon and invest in creating efficient and effective new networks
- Design network infrastructures that work together efficiently across multiple energy vectors in real time

INTRODUCTION

Over the coming decades the UK energy system will need to transition in order to meet challenging greenhouse gas emissions reductions targets. Population growth, changing demographics, and changing patterns of energy use will all affect how energy needs to be provided.

Equally, the availability of natural resources, the maturity of technologies, their relative costs and the various factors that influence their sustainability, will all affect the ways in which energy can be produced and supplied.

For a variety of practical and economic reasons, energy is rarely created in the location it is ultimately consumed. Networks perform the vital role of transporting energy from where it is produced to where it is required. They also perform a crucial role in helping to balance supply and demand, ensuring that energy is not only available in the right locations but also at the right time. This part of their role is likely to take on greater significance as the energy system evolves.

Currently, most of the UK's energy is moved around the country, and sometimes beyond, by electricity and gas networks, and the liquid fuel supply system (e.g. petrol and diesel). This is illustrated in Figure 1. The roles of these networks will inevitably change as the ways in which we provide and consume energy evolve and as other networks emerge, not least those carrying heat and hydrogen. It is imperative that all of these networks are fit for purpose and robust enough to respond to future uncertainties. Choices need to be made about which networks to build, develop, maintain or decommission, as well as where and when to do so. As networks can take years or even decades to build, the right decisions must be made ahead of need. Equally, once they are built networks cannot easily be moved or changed, so decisions need to be right for the long term.

It is also likely that there will need to be significantly more interaction between different parts of the energy system in the future, and therefore, by implication, there will need to be more interaction between the respective networks. Consequently, decisions about the future of networks should also consider how other energy networks are likely to evolve.

All of the above is in the context of significant uncertainty; any future network investments therefore need to be robust in the face of a range of possible transition pathway outcomes.

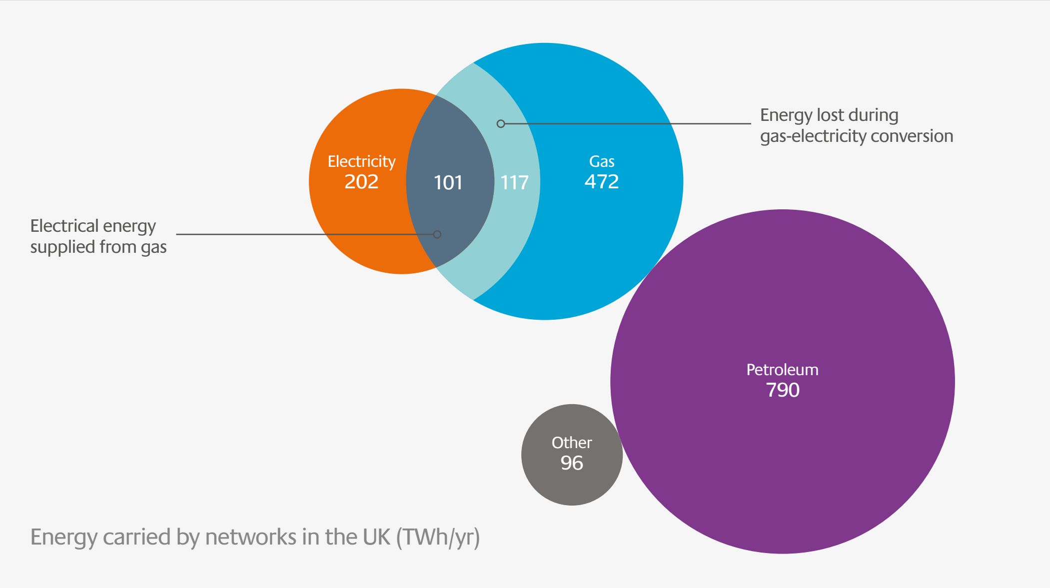
In this insight report we set out some of the key issues faced over the coming decades in pursuing different choices in relation to energy networks. We have focused on electricity, gas, heat and hydrogen networks, which we believe have vital roles to play over the period out to 2050. Our analysis also highlights the importance of CO_2 networks and transport fuel over that period. These have been discussed in earlier ETI publications[1 2 3 4] so are not discussed in detail here. Each of the networks we cover are expected to face a number of prominent challenges as part of their evolution in support of a wider energy system transition.

But how might the wider energy system change? In already published work, the ETI has outlined potential pathways and the challenges and opportunities for broader energy system transitions in its Options, Choices, Actions[5] and energy system transitions[6] insight reports, respectively. Whilst not being exhaustive, these offer a useful basis on which to explore how energy networks will need to evolve to enable an efficient broader transition in the energy system.

Not all of the networks mentioned will be affected in the same way or to the same degree. In fact the challenges they each face may be quite distinct. We explore some of the broader issues faced by energy networks as the overall energy system transitions, from how existing networks will need to adapt to how to create new energy networks. The challenges and potential opportunities associated with the likely increased interaction between different energy networks is also explored.

Accompanying ETI publications[7 8 9 10] explore each of the networks (electricity, gas, heat and hydrogen) individually, in terms of how their roles might change and the technical challenges that these changes are likely to bring as well as considering their likely interactions with each other.

Figure 1
How energy is delivered in the UK



Based on data in DECC's UK Energy Statistics 2015

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1 Ecofin Research Foundation. (2014). Developing a commercial and financial framework. [online] Available at: http://ow.ly/ygAD302IUBa

2 Day, G. (2014). Potential for CCS in the UK. [online]. Available at: http://ow.ly/Vl8x302IUCY

3 Day, G. (2015). Carbon capture and storage – Building the UK carbon capture and storage sector by 2030 – Scenarios and actions. [online]. Available at: http://ow.ly/hbTe302IUEE

4 Batterbee, J. (2013). An affordable transition to sustainable and secure energy from light vehicles in the UK. [online]. Available at: http://ow.ly/v0p7302IUMZ

5 Milne, S. (2015). Options, Choices, Actions - UK scenarios for a low carbon energy system transition. [online] Available at: http://ow.ly/oKYv302IUYJ

6 Coleman, J. (2015). Targets, technologies, infrastructure and investments - preparing the UK for the energy transition. [online] Available at: http://ow.ly/PEU8302IV9o

7 Lidstone, L. (2016). Electricity Network Transition Challenges. [online]

8 Lidstone, L. (2016). Gas Network Transition Challenges. [online]

9 Lidstone, L. (2016). Heat Network Transition Challenges. [online]

10 Lidstone, L. (2016). Hydrogen Network Transition Challenges. [online]

OVERVIEW OF ENERGY SYSTEM TRANSITION SCENARIOS

In this insight report we have used the ETI's published scenarios, which illustrate how the wider energy system might evolve, as a basis for exploring how we might need to adapt and invest in existing and new energy networks.

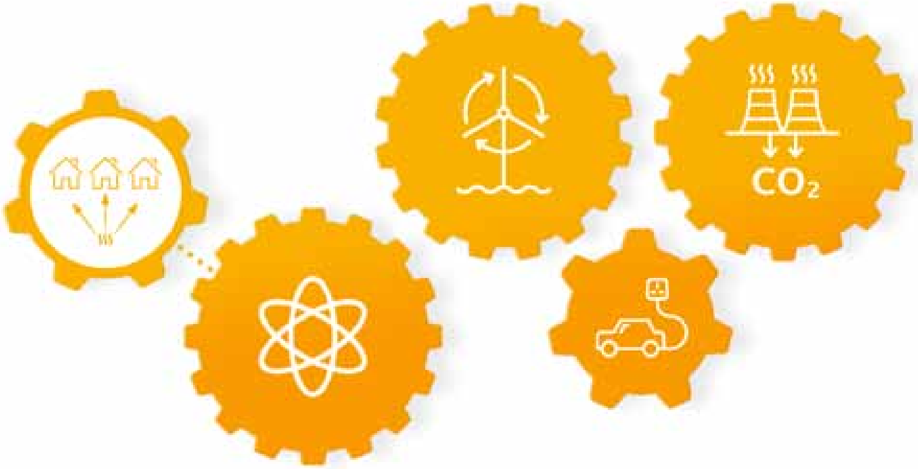
The scenarios themselves have been developed from extensive analysis of the overall energy system and how it might have to develop out to 2050 in order to meet the UK's greenhouse gas emissions targets. The underlying analysis covers, amongst other things: how technologies might develop; how they would need to interact with each other as part of an overall energy system; practical roll-out timeframes for those technologies; potential constraints on energy resources; operational constraints and, not least, changes in energy demands and customer expectations.

Two scenarios are depicted which offer contrasting pictures of the UK energy system evolution to 2050. These are referred to as **Clockwork** and **Patchwork** and are plausible and self-consistent examples of how the energy system might evolve to meet the UK's 2050 greenhouse gas emissions targets. They are not forecasts but portray distinct (yet not exhaustive) ways in which networks might need to evolve, offering a means to explore a range of challenges that networks might face.

The **Clockwork** scenario centres on the implementation of national level, coordinated planning for the energy system. This leads to large-scale investments in centralised thermal power generation – nuclear and Carbon Capture and Storage (CCS) – together with the networks. There is increased (but partial) electrification of both heat and transport. This scenario also sees significant deployment of large scale heat networks in tandem with a phased shut-down of the local gas distribution network. Hydrogen, meanwhile, becomes a major fuel for generating electricity at peak times. Industry continues to rely on gas for process heating but this is in conjunction with CCS.

In **Patchwork**, the development and implementation of energy strategies is led at a local level with strong societal engagement. This leads to a prominent role for renewable generation (large scale and distributed) and appreciably increased electrification of heat and transport. The gas distribution network is decommissioned in some areas and retained in others where gas boilers are used as backup to heat pumps or a partial decarbonisation of the gas supply takes place. Small and medium-scale heat networks are deployed in some towns and cities. Hydrogen is used for industry, in the transport sector and, in the longer term, to support peaking generation.

ELECTRICITY NETWORKS



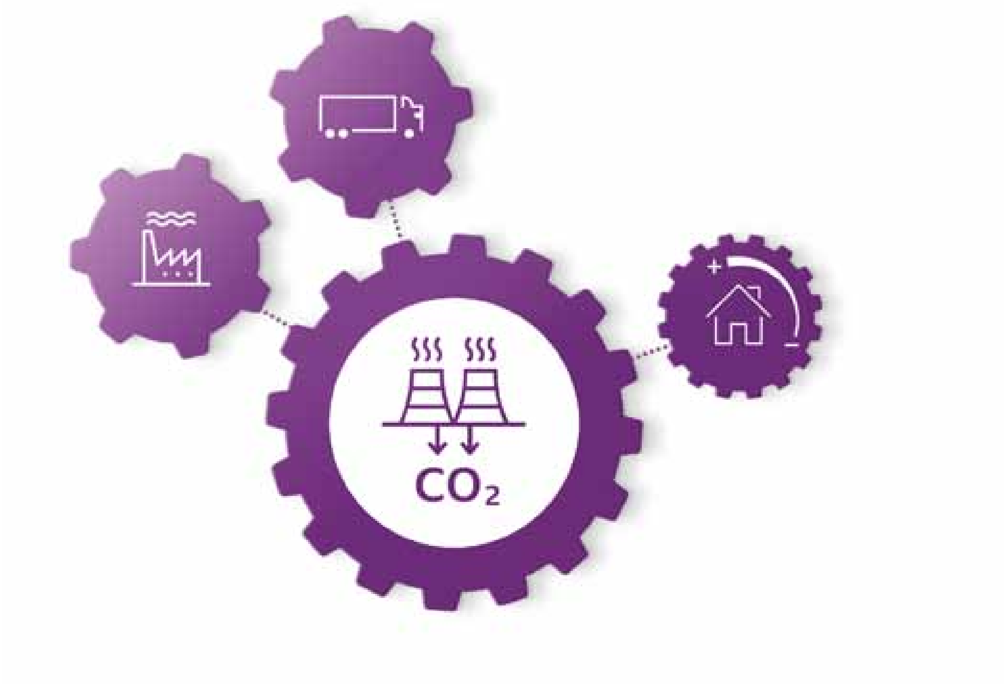
CLOCKWORK

- The electricity network increases in capacity to connect a steady but significant build-up of large scale thermal power generation and renewables at a mixture of established and new locations.
- Nuclear forms the bulk of this with coal plants nearly all shut down by the 2020s and unabated gas usage declining.
- Whilst the regional concentration of electricity generation into a small number of large-scale plants looks similar to today, some old sites are decommissioned in favour of new sites elsewhere, requiring both network expansion and decommissioning.
- From 2030 onwards, network expansion must also enable connection of other generation, including small modular reactors and hydrogen-fuelled generation; and by 2040 more renewable generation, including substantially more offshore wind.
- In addition to connecting new sites there is an overall growth in capacity requirements from 2030 onwards (with over 120GW of installed generation capacity by 2050) to allow the power sector to serve growing electrification of heat and transport.
- Electrification of heat occurs primarily in rural and some suburban areas, yet heat still becomes the largest consumer of electricity by 2050, with electricity networks having to carry three times as much electricity for home heating as today.
- Electrification of transport is spread more evenly geographically and by 2050 the growth in plug-in cars and vans requires electricity networks to carry eight times as much electricity as is currently used by the rail sector.
- These increases in energy demand require solutions for managing peak power demand in distribution networks.
- Upgrades to the distribution network are undertaken on a planned basis, including through the implementation of network operator instigated smart technologies and systems, with capacities increased to accommodate electrification of heat and transport.

PATCHWORK

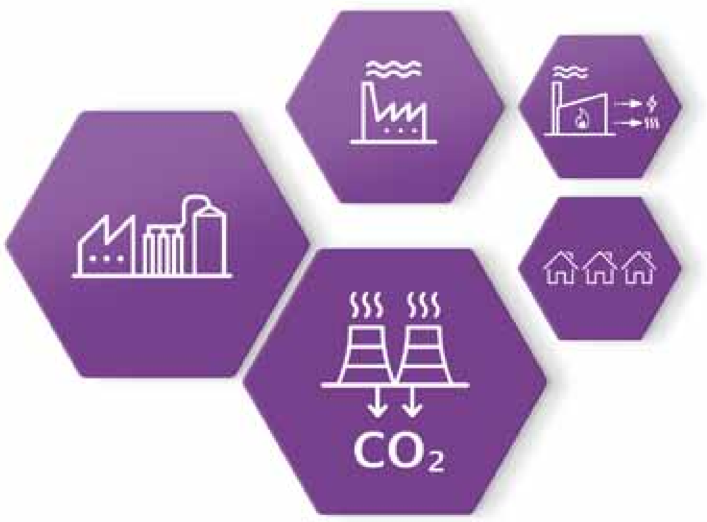
- The electricity network must expand over relatively short periods to connect renewable generation (especially offshore wind) at a far greater number of sites than today.
- Close to 200GW of generation capacity is connected by 2050 (more than double today's capacity).
- The growth in renewable generation (including rooftop and ground mounted solar PV and tidal) coincides with the closure of coal plants and some gas plants and the decommissioning of network connections to them.
- Wind is the dominant generation source by installed capacity; by 2050 75GW of wind capacity is connected, two-thirds of which is offshore, requiring significant grid reinforcement to allow transmission of power to centres of demand.
- The network expands to connect up to 2GW/yr of offshore wind alone by 2030 and up to 3GW/yr by 2050.
- In the 2040s renewables capacity expands at its greatest rate to meet increased electrification of heat and transport, placing greater onus on means of providing flexibility, including hydrogen peaking capacity (requiring further network expansion); interconnection; and integration with storage and smart energy systems.
- A mixture of measures to mitigate distribution network capacity constraints are adopted, from conventional reinforcement to smart energy solutions.
- The emergence of viable smart energy solutions and changes to network regulations in the 2020s and 2030s enables increased uptake of plug-in vehicles and alternative forms of heat supply, alongside greater integration between electricity, gas and heat networks.
- From the 2030s local electricity network capacity requirements are further affected by the deployment of large-scale heat pumps to supply heat networks. These both replace retiring gas combined heat and power (CHP) systems and allow further growth of heat networks.
- By 2050 the electricity network is carrying four times as much electricity for home heating as today.
- By the same point it is also supporting plug-in vehicles drawing on ten times as much electricity as the rail sector does today, on top of that needed to supply electrolysers in support of hydrogen vehicles.

GAS NETWORKS



CLOCKWORK

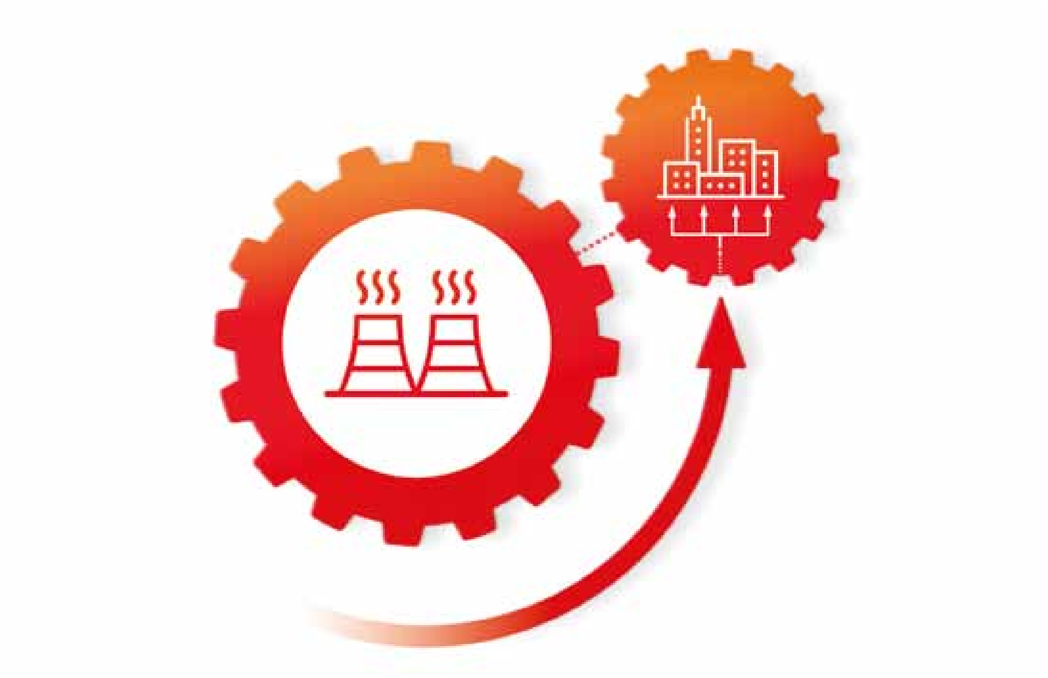
- From the mid-2020s onwards, a planned, phased shutdown of the gas distribution network takes place as home heating transfers to other fuel sources.
- This starts both at the extremities of the gas network in the most expensive to supply rural areas and in those urban areas that are first to adopt heat networks.
- Over the course of the next few decades decommissioning of the gas distribution network accelerates in line with the adoption of heat pumps and heat networks.
- The gas transmission system, meanwhile, is retained to supply both the power and industry sectors.
- The availability of CCS allows over 300TWh of gas a year to be used for power generation in the mid-2020s but restricts where new power stations can be sited and thus where the gas transmission network must serve.
- Over subsequent decades, gas usage in the power sector declines as older gas plants close and those that remain need to operate at lower utilisation, for example, with large seasonal variations – with less than 200TWh a year of gas used in the sector by 2050.
- Overall gas use in industry stays relatively flat out to 2050 as efficiency improvements and the availability of CCS offset growth in the sector. Some sites switch from gas to hydrogen.
- A growing use of gas in the heavy duty transport sector from the 2030s onwards has the gas network adapting to supply refuelling facilities at depots and eventually along major highways nationwide.



PATCHWORK

- In the 2020s and 2030s the emergence of viable smart energy solutions and changes to regulation accelerates heat pump and district heating network (DHN) uptake affecting the gas distribution network in multiple ways.
- In some locations, the gas distribution network is decommissioned. In some other areas it is retained, but at much lower utilisation.
- In some urban areas where heat networks are deployed the gas network is partially retained to fuel CHP systems, until the gas CHP systems are eventually replaced by lower carbon alternatives.
- In some locations local efforts drive a switch to alternative types of gas (such as bio-SNG and hydrogen) allowing the network itself to be operated in a similar fashion to today.
- In the power sector, with CCS unavailable until the 2030s, short-term growth in gas use is mainly limited to supplanting retiring coal stations – with the gas network delivering over 200TWh by the mid-2020s.
- The eventual emergence of CCS allows gas to remain in the power sector, with it taking on more of a peaking role and seeing a steady decline to 150TWh a year. Overall gas use in the industry sector halves between now and 2050 as the sector shrinks and emissions constraints take effect, alongside the availability from 2040 of hydrogen as an alternative fuel for the sector.

HEAT NETWORKS



CLOCKWORK

- Large scale heat networks are deployed across urban and suburban areas, in line with a national strategic plan to transition the heating sector.
- From 2020 heat network deployment more than doubles every decade.
- These networks connect to both centralised and distributed power stations for heat supply.
- Heat offtake from some large-scale power stations is transmitted over long distances (up to 30km) to reach demand centres.
- Small modular reactors may offer an alternative heat source in other locations, particularly where heat demand is lower[11].
- Heat network and power station deployment is coordinated to meet investment requirements (power station deployment in turn aligns with wider growth in electricity demand).
- By 2050 about one-third of all heat in the UK (over 110TWh) is delivered by heat networks.

PATCHWORK

- Local schemes drive the deployment of small and medium-scale heat networks in urban areas on an ad-hoc basis. Some adjacent networks merge.
- Over time, heat networks adapt to accommodate changes to heat supply type and, in some instances, location.
- Gas-fuelled CHP is the initial heat source of choice alongside biomass for commercial applications.
- The emergence of viable smart energy solutions and changes to network regulations in the 2020s and 2030s allow excess electricity from these CHP systems to indirectly support heat pump deployment in rural areas.
- The evolution of this to optimise energy supply across networks accelerates the deployment of heat networks.
- By 2040 efforts to decarbonise further lead to the integration of lower carbon forms of heat supply appropriate to each local area, including large-scale marine heat pumps (powered by a now even more decarbonised electricity network) and advanced geothermal systems.
- Heat networks continue to grow and by 2050 over 50TWh of heat is delivered by heat networks a year.

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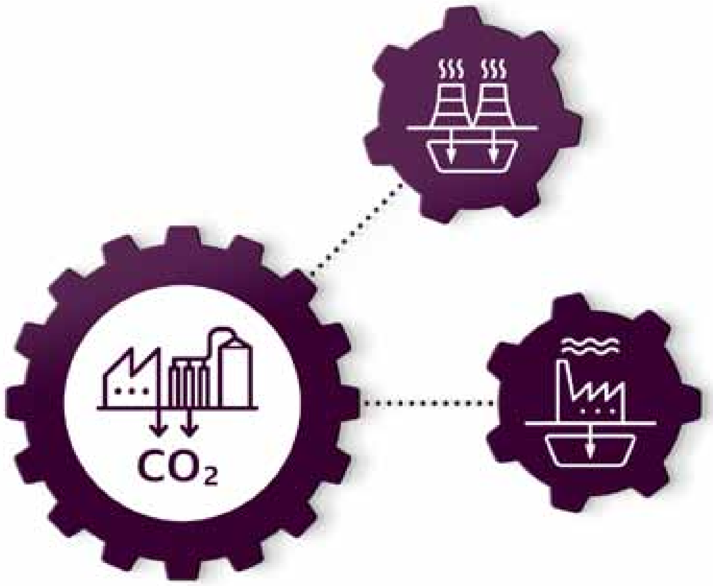
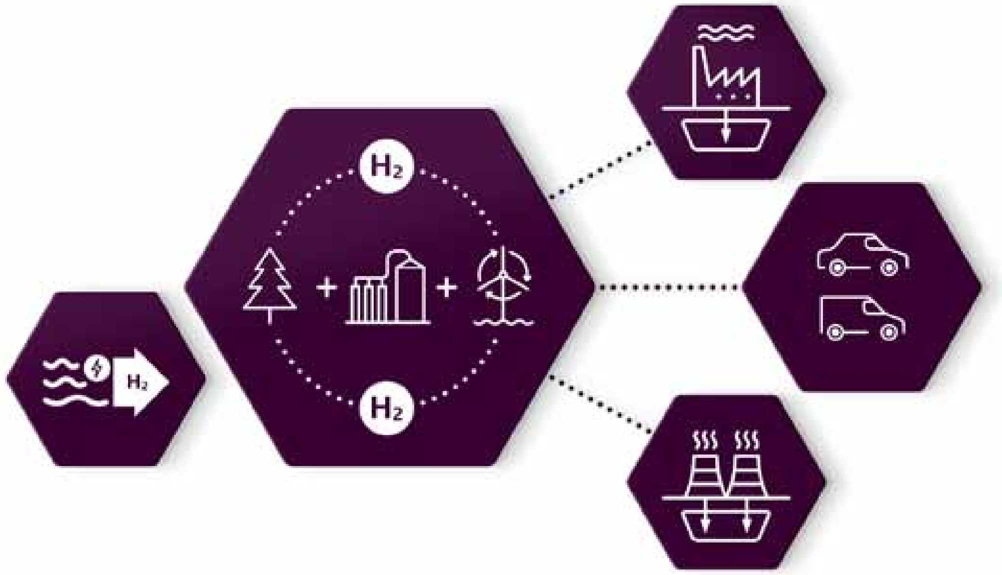
[11] Middleton, M. (2015). The role for nuclear within a low carbon energy system. [online]. Available at: http://ow.ly/cJsF302IVna

HYDROGEN NETWORKS



CLOCKWORK

- From the mid-2030s hydrogen networks are steadily developed to serve both the power and industry sectors.
- For the power sector, the onus is on hydrogen storage infrastructure with the hydrogen fuelling flexible power generation[12].
- The predominant source of hydrogen is CCS equipped plants located in the north-east and north-west of England[13].
- As well as access to CCS these regions also offer geology well suited to large-scale hydrogen storage – with over 30GWh built by 2050.
- By 2050, this enables over 40TWh a year of hydrogen to be used by 4GW of power generation, primarily for mid-merit, seasonal and peak generation, where there is sufficient shorter duration flexibility elsewhere in the system.
- For the industry sector, the earliest opportunities lie in the north-east of England. Subsequently, a means of moving hydrogen from points of production to industry sites further afield is put in place.
- Annual consumption of hydrogen by industry reaches more than 80TWh by 2050.



PATCHWORK

- Hydrogen networks, led by smaller initiatives, are developed to supply the transport, industry and power sectors.
- Hydrogen use in the domestic sector is an option explored in certain regions as a means of utilising the existing gas network once a cost-effective hydrogen supply emerges.
- Supply to the transport sector begins in the mid-2020s initially serving back-to-base fleets of cars and vans.
- As confidence in the technology grows, a nationwide refuelling infrastructure is developed with annual hydrogen consumption in the transport sector reaching 40TWh by 2050.
- Once the availability of CCS enables sufficiently low-cost hydrogen to be produced in the 2040s, the industry and power sectors become major markets.
- By 2050 industry demand reaches over 50TWh a year requiring the infrastructure to rapidly increase both its capacity and the number of locations it serves.
- In the power sector hydrogen is used as fuel for peaking generation with 3TWh consumed annually by 2050 in 17GW of power plants, utilising over 25GWh of storage capacity.
- The power sector also delivers an alternative source of hydrogen with excess renewable output converted to hydrogen via electrolysis.

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[12] Gammer, D. (2015). The role of hydrogen storage in a clean responsive power system. [online]. Available at: http://ow.ly/euuq302IVsO

[13] Day, G. (2014). Potential for CCS in the UK. [online]. Available at: http://ow.ly/VI8x302IUCY

ENERGY NETWORK TRANSITION CHALLENGES

As is clear from the changes highlighted by the scenarios, the challenges that networks face as the energy system transitions are diverse. Across all of these, however, certain themes repeatedly emerge. Firstly, there is the need for existing, established networks to adapt to both accommodate and enable changing production and consumption of energy. Secondly, there is a need to grow new networks from virtually nothing to the point where they perform a pivotal role in the delivery of energy. Finally, it is necessary to understand how to integrate networks, both new and old, to deliver maximum value.

The themes are summarised on the following page:

Challenge one

Adapting and enhancing existing network infrastructures

Challenge two

Enabling creation of efficient and effective new network infrastructures

Challenge three

Integrating new and existing networks to enable optimisation across vectors

ADAPTING AND ENHANCING EXISTING NETWORK INFRASTRUCTURES

The UK's electricity and gas networks are both well established, with the former providing the most extensive coverage of any UK network and the latter currently carrying more energy than all of the other networks discussed here combined. Despite this significant presence and enormous sunk cost, both will need to adapt if the UK is to meet its greenhouse gas emissions targets.

Electricity networks

With efforts to decarbonise leading to increased electrification of heat and transport, the role of electricity networks will grow in prominence. They will need to adapt to carry far more electricity, manage higher peak loads and connect new generation sites.

ETI Project
Pre-saturated core fault current limiter

Development and demonstration of a pre-saturated core fault current limiter.

The fault current limiter, developed during this project by GridON, was commissioned into service in May 2013 at a UK Power Networks main substation in Newhaven. It has successfully suppressed multiple faults during its service.

Product design offers advantages of a non-superconducting pre-saturated core fault current limiter with instant response and recovery, a small footprint and can utilise established transformer design and build processes.

Increased capacity

Whilst there are multiple options for enhancing the network to carry greater loads – from smart grid solutions, to fault current limiters, to energy storage and conventional reinforcement – not all will be suitable for all parts of the network. Some parts of the network are closer to their existing capacity limits than others, whilst growth in loads will not be equally spread across the existing parts of the network. Added to this variation in capacity growth requirements are factors such as available physical space or land value, which are specific to local areas and will differentially affect the viability of the enhancement options in those locations.

There is a major challenge in knowing where, when, and to what extent to enhance the network. This will be particularly acute for the distribution network, where information on the existing state of the network is not as widely available, an issue further exacerbated by the growth in distributed energy.

The industry will need to have sufficient confidence to deploy any new options. This will require continued advances in the technologies, understanding of their application and a clear view of the market for the service(s) being provided.

ETI Project
Offshore Connection

This project examined the specific challenges and opportunities arising from the connection of offshore energy to the UK grid system and considered the impact of large-scale offshore development.

It also looked into the novel electrical system designs and control strategies that could be developed to collect, manage and transmit energy back to shore and identified and assessed innovative technology solutions to these issues and quantified their benefits.

ADAPTING AND ENHANCING EXISTING NETWORK INFRASTRUCTURES

Continued ›

New connections

Increased electrification requires the network to be adapted. New sites will need to be connected to add more power generation capacity and to replace retiring power stations, the sites of which will not all be suitable for the generation that replaces them. The decarbonisation of electricity will alter the generation mix, placing different requirements on sites. Whilst most obvious for offshore renewables, this is also true for CCS-connected and nuclear generation, the former needing appropriate access to a CCS pipeline[14] and sites for the latter having their own particular set of requirements. This means some connections will be decommissioned as the network as a whole needs to expand, both of which will incur costs.

The network solutions for connecting fewer large-scale power plants are very different to those for connecting many more renewable sites, particularly when such a high proportion are offshore. For example, overall network length will be far greater for connecting the requisite amount of offshore renewables, whilst higher capacity connections will be necessary for large-scale CCS-connected and nuclear generation. Less conventional solutions, such as High Voltage Direct Current (HVDC), may prove the most cost-effective in certain circumstances.

Trade-offs also exist when only considering a single type of generation. For example, offshore wind might have lower electricity production costs when sited off the coast of Scotland but once network costs are included it may be less expensive if it is spread around the UK so that it is closer to demand[15]. Understanding which are the most cost-effective solutions requires an overall system view. However, network expansion and adaptation will need to respond to changes in supply and demand, no matter which approach is adopted.

Gas networks

Whilst gas is an effective means for providing heat to over 80% of homes in the UK, for the greenhouse gas emissions targets to be met there will need to be significant decarbonisation of heat supply, which has implications for the entire gas distribution grid.

There are three main options:

- Decommission
- Operate at much lower utilisation
- Integrate low carbon fuels at a significant level (close to 100%)

ETI Project

Transition Analysis

Techno-economic analysis of the lowest cost pathways to reach particular future network structures. This project will:

- Define overall network structures that would enable wider energy system transition to be realised
- Analyse the costs of different routes for delivering those network structures
- Account for the risk inherent in these approaches and develop robust routes to pursue
- Consider the market, policy and regulatory implications and requirements of the transitions

Decommission

Where alternative heating supply systems are able to fully supplant gas supply to homes it will likely be necessary to decommission all or relevant parts of the gas distribution system.

What this would actually entail needs to be fully ascertained but is expected to require purging of the pipelines and may involve infill or removal of the pipeline infrastructure.

Given the extent of the gas distribution network and the decades it took to construct, it is anticipated that the resources needed to undertake this would be substantial. There may well be opportunities for technology advances to reduce the labour and financial cost of doing so, however any decommissioning would need to address the logistical issues of managing the switch-over to the replacement heating supply system. This would need to account for changes to the in-home heating (and cooking) systems and the upstream supply, in addition to the installation or adaptation of the "new" network alongside the decommissioning of the gas network, all whilst maintaining service provision of heating and cooking.

In the case where the "new" network requires groundworks (e.g. for the installation of a heat network), the situation may arise where it is more cost-effective to decommission the gas network at the same time as installing the heat network than to dig up the ground twice. In this case it may be necessary to do so at a time of year where it is feasible to (for example) provide bottled gas during the switch-over to maintain supply.

Where gas CHP systems are used to supply heat networks, a gas connection to the CHP system will still be needed. Here it will be necessary to decommission the "last mile" that connects to homes whilst retaining "trunk" lines to serve the CHP plant. It will be necessary to then decommission these trunk lines by the mid-2040s, as the gas CHP systems will need to be replaced with lower carbon alternatives to meet decarbonisation targets.

Operate at much lower utilisation

An alternative to full replacement of gas for heating is to retain the gas distribution network (or large parts of it) for use when there is insufficient capacity in the replacement heating system. This, for example, would allow a heat pump to deliver the bulk of the heating within a dwelling throughout the year and the gas boiler (or gas part of a hybrid heat pump) to provide additional heating at the coldest times of the year, when demand is at its highest and heat pumps are at their least efficient. This means the vast majority of the heat supplied is low or zero carbon, providing the electricity supply is sufficiently decarbonised.

Whilst this has the potential to save money by reducing the size of the heat pump, the amount of in-home storage, the level of electricity network reinforcement and the amount of electricity generation capacity, it does incur the cost of maintaining and operating two separate networks, one of which is under-utilised.

There are efficiency, safety and reliability impacts for use of the gas distribution network at low levels of utilisation that all need to be properly examined. These will all affect the operating approach and level of maintenance that is required and consequently the cost of operation.

In this context sustainable operation will continue to require the costs of infrastructure operation and maintenance to be recouped.

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[14] Day, G. (2014). Potential for CCS in the UK. [online]. Available at: http://ow.ly/Vl8x302IUCY

[15] Bradley, S. (2015). Floating Wind Technology. [online]. Available at: http://ow.ly/jFSd302IVGf

ADAPTING AND ENHANCING EXISTING NETWORK INFRASTRUCTURES

Continued ›

Options for this include:

- An increase to the unit price of the gas – consumers would thus pay high costs for usage. Given that this would be to meet needs at the coldest times of the year this heavily penalises necessary usage and would disproportionately affect those least able to afford it.
- Pay for access rather than usage – this limits the opportunity for consumers to save money by reducing consumption as well as reducing the incentive not to use too much gas, which could be detrimental to efforts to decarbonise.
- A combination of price change and usage cap measures – as with any option but particularly so when combining measures it is important that tariffs and mechanisms are effective and not too complicated, to avoid unintended consequences and allow consumers to affordably access the utility they require. There will need to be enough interest from service providers to ensure there is a competitive market.
- Greater management of overall energy usage by suppliers or third parties – this would require effective regulation and market structures to ensure operation for the benefit of consumers and the wider environment as well as effective integration across networks. Utilising the gas network in this way lends itself well to the adoption of a more integrated service provision model between gas and electricity which will require system control across the two networks.

Integrate low carbon fuels

Reducing the carbon intensity of the gas carried in the gas grid is a third option for decarbonising heat supply and would allow retention of the gas network infrastructure. There are two main options:

- Hydrogen
- Lower carbon methane replacement

Whilst small percentages of hydrogen can be blended into the gas grid with little effect, more meaningful amounts would require changes to both the infrastructure and, for example, heating systems. Estimates vary but it is expected that issues would start to arise once blends exceed around 5-20%[16] [17] [18]. Blends would need to be substantially greater than this, however, for CO_2 emissions to meaningfully reduce. Hydrogen has a (volumetric) energy density around a third that of natural gas. This means that even if blends were to reach 50%, emissions (for the same level of output) would only be reduced by around 25%.

At higher blends hydrogen's properties affect how it can be used. Hydrogen causes embrittlement of the steel grades commonly used in gas pipelines. This is not an issue for those pipelines in the distribution network that have been replaced with polyethylene in recent years. Further work is needed to assess the impact on gas network components, such as compressors. The small molecular size of hydrogen means that it is more prone to leakage than natural gas, which is an issue both in terms of lost energy and safety.

The aforementioned also apply if hydrogen were to fully replace natural gas in the gas network. For the same level of energy delivery to be maintained, the lower energy density of hydrogen means that flow rates would need to be tripled. How much of an effect this would have on operating pressures, components, leakage rates, etc. needs to be more fully established and there are several projects[19] [20], that have been commissioned to look at issues with repurposing the gas grid.

How appropriate it is to adapt the gas grid to carry larger amounts of hydrogen will depend on the degree of physical adaptation needed and public acceptance, as well as the availability of a sustainable source of hydrogen and how much of the network to adapt. For example, a regional rather than national conversion would not require adaptation of the transmission network other than for those distribution networks that are converted to be disconnected from it.

Using a replacement gas more similar to natural gas, such as bio-SNG (biomass-derived substitute or synthetic natural gas), reduces the level of adaptation needed, both for the network and boilers, etc. in the home. Adaptations could be limited to expanding the network to connect new sources and/or integrate injection points. With any substitute gas of this nature, however, CO_2 is still emitted at the point of consumption (e.g. the boiler). So to deliver a net reduction in CO_2 emissions, sufficient CO_2 consumption needs to happen elsewhere in the lifecycle, e.g. in the growth of the bioenergy used to produce the bio-SNG. Assessment of the overall lifecycle emissions is critical.

A sustainable source of the substitute gas would be needed to make this viable. Inevitably, and as with hydrogen, constrained resources and the ability for these to be used in other sectors will mean there is competition for its use. Full system level analysis offers the best opportunity to decide where to deploy constrained resources. For example, ETI analysis[21] has concluded that with limited biomass resource, what is available is most effectively utilised in the power sector and industry in conjunction with CCS.

The gas grid

The above focuses on how the gas distribution grid would need to adapt to decarbonise heat supply. The gas grid as a whole also serves the power and industry sectors, predominantly via the gas transmission system, which also links to each of the gas distribution networks. There is the prospect that gas consumption in non-heat sectors would grow in the 2020s and 2030s, as consumption in the domestic sector, and overall, declines.

The long term viability of gas consumption in these sectors is dependent on the availability of CCS. With CCS it can continue to be used in meaningful quantities into the 2040s (roughly half the total level used today by 2050) but without CCS it would be relegated to a marginal peaking role in the power sector and the impact for the industrial sector could be more far-reaching.

Adapting the network to meet these differing requirements poses investment challenges, not least will be understanding how to maintain investment in the gas network as a whole when there is declining overall usage and so a reduction in its main means of generating revenue. The lack of certainty about the future role of the network adds to the investment risk, increasing the cost of capital. Apportioning the cost of adaptations also presents challenges, for example, whether for those who are disconnected, those who remain or some other means is found to pay for any decommissioning of the network. The remaining life of assets will also influence decisions taken.

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ENABLING EFFECTIVE NEW NETWORK INFRASTRUCTURES

The transformation of the energy system will also rely on the successful emergence of new ways of conveying energy. Examples of these networks already exist in the UK, but they need to grow significantly to become a core part of the energy system.

The principal networks amongst these are heat and hydrogen.

Heat networks

Heat networks are well suited to delivering large quantities of heat in denser areas, such as towns and cities. Traditionally, heat networks have been built to serve new developments but there will need to be a shift to also connect existing properties (which are less efficient than new-build housing and for which there are few alternative low carbon heating solutions) and to do so on a large scale, to enable the widespread decarbonisation of heating.

This presents challenges in terms of delivering solutions suited to this market:

- Cost reduction and technology advancement
- Supply chain scale-up
- Adoption

ETI Project

Heat Infrastructure Development

This project is seeking to identify the innovative solutions needed to deliver major reductions in the capital cost of retrofitting heat network infrastructure and accelerate its deployment

It is examining the technical, process and system developments needed to deliver a step change reduction in the capital costs, along with cost estimates and timeframes for undertaking these developments

Cost reduction and technology advancement

A major reduction in heat network costs and advances in installation processes will be needed if they are to be commercially viable for retrofits. Serving existing properties requires negotiating already crowded and heavily populated areas and managing the logistics of switching over heating supply systems. Technology and process advances can facilitate cost reduction and minimise disruption. Advances made in these areas will need to be compatible with the qualities of heat networks, notably the ability to deliver large quantities of heat, long asset life and fuel source flexibility, that contribute to making them a compelling proposition.

Supply chain scale-up

Supply chain scale-up would need to enable growth in heat networks from serving less than 2% to as much as 40% of home heating needs by 2050. This increased level of deployment would need to be delivered in roughly the same amount of time that existing heat network deployment was reached (i.e. greater than 50 years[22]).

Technology and process advances should help but will also require the industrial supply chain to be proficient with the advances that are made and at a sufficient level of maturity to deliver this reliably. Early experiences will shape the perception and future potential market share of heat networks.

Adoption

Successful deployment will depend on a sufficiently high adoption in the areas where heat networks are deployed. How this is achieved will in part depend on the reasoning behind the deployment of the heat network and the alternative options (if any) available to those who live within the area. Whether heat networks are suitable for a given area, for example, will depend on the make-up of the properties in the local area, local geography, the ability to connect low carbon heat supply sources, the state and availability of other means of meeting heating needs and customer acceptance. These may have an impact on the mechanisms chosen to achieve sufficiently high adoption, which could range from incentive-based schemes through to legislated measures.

Developments elsewhere in the energy system play a part here. The future of the gas distribution network is an obvious one but there are also links, for example, to the uptake of electrified heating in other areas. This electricity demand for heating individual households would be able to utilise excess electricity produced by the CHP systems (local gas CHP and/or power stations) that would supply the heat networks, lowering costs and increasing energy security.

Hydrogen networks

Hydrogen use today in the UK is almost exclusively for the chemical industry. It has the potential, though, to play a major role as an energy carrier. It can be produced from a variety of sources and offers flexibility in terms of the end uses it can serve. Crucially it is also a low carbon energy carrier, so does not emit CO_2 when it is used.

The level of hydrogen use in the chemical industry is small in comparison to the volumes that would be required for it to operate as an energy carrier. The needs of the sectors it would serve as an energy carrier also differ from the chemical industry. To enable the effective creation of a hydrogen supply infrastructure, both of these factors will need to be addressed.

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ENABLING EFFECTIVE NEW NETWORK INFRASTRUCTURES

Continued ›

ETI Project

Infrastructure Cost Calculator

This tool provides data on costs of key types of fixed energy infrastructure and can be used to assess the relevant merits of different infrastructure options given different energy generation and demand scenarios

Scale-up

The ETI scenarios do not depict hydrogen being used in significant quantities until the 2030s. In the Patchwork scenario, where hydrogen starts to be used in the transport sector prior to this, this is to serve back-to-base fleets and in sufficiently small quantities that it places less emphasis on a hydrogen supply infrastructure.

To achieve the longer term scale-up of hydrogen supply, decisions need to be made around the role of hydrogen and initial steps taken (such as the development of hydrogen turbines and implementing back-to-base hydrogen vehicle refuelling) by the mid-2020s to demonstrate and prove these options.

In terms of the infrastructure itself there is the potential that road tanker transportation, new pipelines, repurposed natural gas pipelines, hydrogen storage and electrolysis could all play a part. There are both practical and economic reasons for the use, or not, of each of these:

- New pipelines are generally the cheapest long-term option (where demands are high enough and routes are consistent) but are capital intensive, so there needs to be confidence that both the supply and demand for the hydrogen are there in sufficient quantities and for the long term, to make them viable.
- Repurposing existing gas pipelines to carry hydrogen may be less expensive, if the degree of physical adaptation required is not too great and the existing routes and capacities are appropriate.
- Road tanker transportation, carrying either compressed or liquefied hydrogen, offers more flexibility in terms of routes but is more appropriate for lower quantities of hydrogen than pipelines. It may also have a role in facilitating scale-up of a hydrogen supply or as a means of distribution alongside a dedicated pipeline system.
- Hydrogen storage options are varied, from large-scale salt cavern storage to smaller tank-based storage. Salt cavern storage, whilst cost effective, does have high upfront costs and can be time consuming to construct, so like pipelines, require sufficient confidence that they will be needed for the long term to be viable[23]. They can also only be deployed where there is the appropriate geology, though the UK is fortunate in this instance. Tank-based storage can be deployed in many more locations although it is more expensive per unit of hydrogen stored than large-scale storage.
- Electrolysis, whilst a means of producing hydrogen, affects the electricity network more than a hydrogen network[24]. It could be used to support a hydrogen supply infrastructure although its long-term cost effectiveness is unclear.

For any of these options there would need to be a sufficient scale-up of an industry supply chain to deliver the roll-out required. Many of the above are at a level of maturity where it would be expected that cost improvements would predominantly arise from economies of scale and continued advances in manufacture and installation. For electrolysis there is still the opportunity to further reduce the cost and improve the performance and reliability of the technology itself as well.

Further analysis is needed to understand the cost points that these individual infrastructure elements need to reach and by when. This will be influenced by the extent to which each is required.

Meeting the demands of different sectors

Hydrogen has the capability to serve the power, industry, transport and heating sectors. The needs of each place varying requirements on the infrastructure.

Use in the power sector would require the ability to move hydrogen between fixed locations in large quantities throughout the day and year, as well as to store it in large quantities for use across the day and between seasons. This would be well suited to dedicated pipeline systems and salt cavern storage. The north-east and north-west of England provide a good opportunity for both CCS-connected production of hydrogen (from gas, coal or biomass) and large-scale salt cavern storage and means pipelines would be limited in length[25 26].

Industry process heat demand also lends itself well to the use of pipelines, with the need to move large quantities of hydrogen. In this case, with this demand currently being met by natural gas there may be the opportunity to utilise repurposed natural gas pipelines. The presumptions here are that industry demand does not alter significantly (in terms of output or locations), that hydrogen can be cost-effectively supplied to the pipelines and that the pipelines can be cost-effectively repurposed.

For hydrogen vehicles to become mainstream, nationwide refuelling will need to be available, requiring any network(s) supplying hydrogen to serve a dispersed set of locations. Pipelines, road tankers and local electrolysis could all play a part, and which of these are most appropriate will depend on both the volumes of hydrogen that need delivering and how enduring the supply and demand locations are. The need for very high purity hydrogen, for use in fuel cells, and the ability to cater to varying demand levels (particularly throughout the day) may also influence which are most suitable. For hydrogen vehicles to become mainstream, a period of transition, likely to take several decades, will be needed. This places a great deal of emphasis on the establishment and growth of the hydrogen infrastructure. It may be that multiple infrastructure types, both during the transition and once it reaches maturity, represent the most effective way of delivering hydrogen to the transport sector.

The development of a viable hydrogen network would need to consider the implications for potentially serving all of these sectors and the domestic sector covered in the earlier section on adaptation of the gas system, and how their various requirements would evolve over time, as well as how the supply of hydrogen can be scaled up and how developments elsewhere in the energy system (e.g. CCS, low carbon electricity) affect both.

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INTEGRATING ACROSS NETWORKS

ETI Project
EnergyPath Networks

- A software tool to design cost-effective local energy systems for the UK
- Designed in partnership with local authorities
- Demonstrating the capability to create future-proof and economic local heating solutions for the UK

ETI Project
EnergyPath Operations

- EnergyPath Operations will enable an expert user to dynamically simulate the operation of energy system assets within the context of various business models / value propositions and specify potential control architecture
- EnergyPath Operations will be capable of representing a wide range of potential policy, regulatory and business models
- EnergyPath Operations will provide additional confidence in the delivery of value propositions to support business models which may enable an SSH type market roll-out

EnergyPath Networks

EnergyPath Operations

Future energy system development raises the prospect of increased interdependence between the different energy networks that supply the nation's energy, now and in the future. This can arise both in terms of how networks develop and how they are operated.

Network development interactions

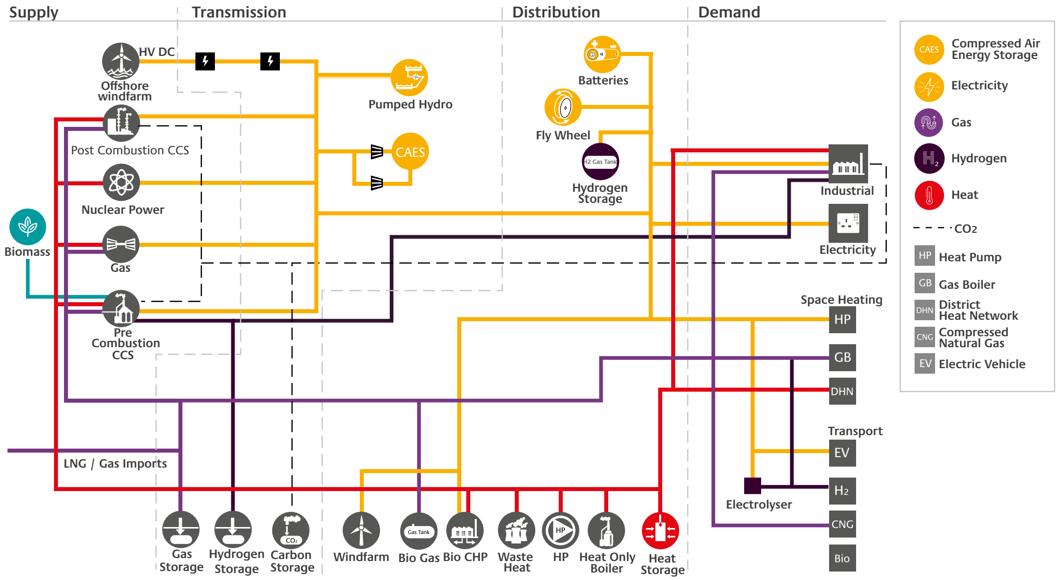
A case in point is the transition to decarbonised heat supply for buildings. As outlined in the scenarios, achieving this places significant emphasis on electrification, the roll-out of district heat networks and the future role of the gas network.

Clearly the future role of the gas distribution network will depend upon the success or otherwise of the roll-out of heat networks and the development of the electricity network to support electrified heat. The reverse is also true, since the ability for electricity and heat networks to take on a significant amount of heat supply for buildings depends on a viable plan for the changeover of the heat supply from gas to these alternatives.

There are also interactions between the roll-out of heat networks and the transition to electrification of heat in other areas. Where CHP systems serve heat networks there is a significant amount of electricity produced; in many cases this will be much more than is needed by the area being served by the heat network. This points to the excess electricity being exported to other areas, with highest exports when heating demand is high and consequently affecting the electricity network.

So the deployment of one set of heating solutions affects the viability of deploying others, both locally and more broadly. The above is just one example of the interdependence in relation to the development of networks.

Figure 2
Illustrative interactions between different networks



Network operation interactions

Currently electricity and gas networks are regulated in such a way that they have to be operated independently. However, with their role in the future energy system expected to evolve, alongside a greater role for heat and hydrogen networks, closer and more complex interactions between networks are set to emerge.

Types of interactions might include: a shortfall in energy available via one network being met by energy supplied by a second network; one network providing additional energy when a primary network reaches the limit of its capacity; or two (or more) networks permanently working in tandem with one another. These types of network integration represent a distinct opportunity. There is a developing body of evidence, both within the ETI and from other research[27] [28], that there is value in employing a multi-vector approach to energy supply.

There will be specific challenges and limitations to employing a multi-vector infrastructure approach. For such an approach to be realised it will be important to understand what those restrictions are and to what extent they can be overcome. This will also help to establish what the full potential for multi-vector energy supply is and to what extent it can deliver system-wide benefits. Addressing this question will help to inform what is the best way to deploy new networks alongside existing networks; how best to transition from existing to new networks; and what opportunity there is to make continued use of existing assets.

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INTEGRATING ACROSS NETWORKS

Continued ›

ETI Project

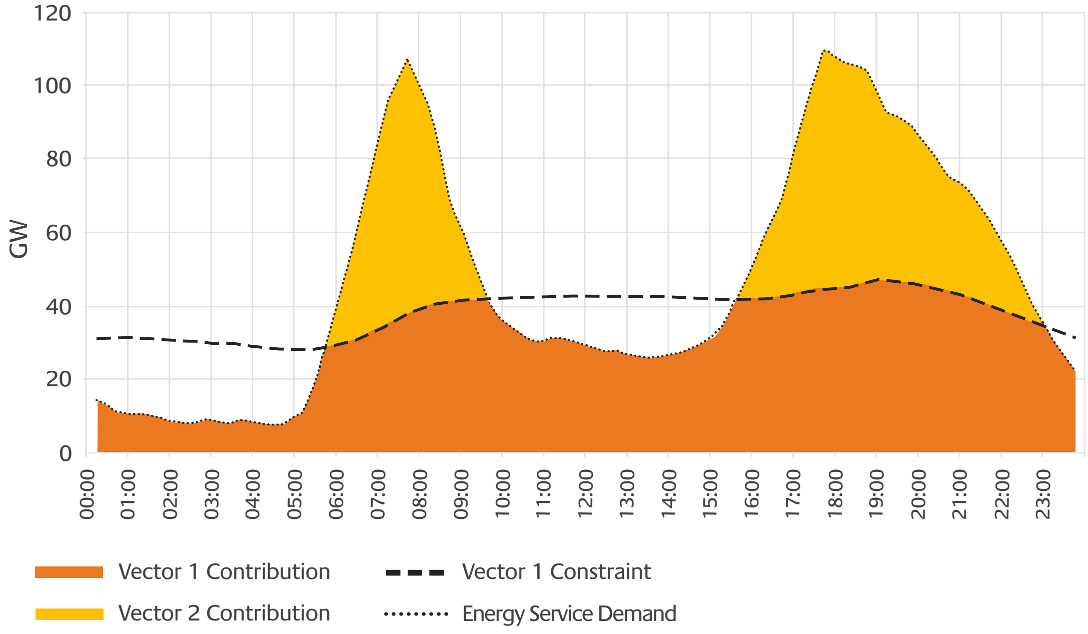
Multi-Vector Integration

This project aims to understand the opportunity for, and implications of moving to, more integrated multi-vector networks. This will include:

- Identifying the ways in which different networks could interact, e.g. one network providing peak capacity support for another
- Determining how prominent these interdependencies could be
- Examining what the effects on each of the networks would be and
- Identifying any technology and/or operational opportunities that would facilitate any increased integration between vectors that may emerge

Figure 3

Illustrative example of two vectors operating in an integrated way to meet an end user service demand



BALANCING SUPPLY AND DEMAND

A crucial facet of a functional energy system is ensuring the right amount of energy is delivered when it is needed. This is about ensuring energy supply is in balance with energy demand. An energy system needs to have sufficient operational flexibility to allow this to happen and energy networks have an important role within this.

Much of the operational flexibility that is currently provided is done so through varying supply, i.e. increasing or decreasing generation of energy to meet changes in demand (see figures 4 and 5). One alternative is to shift demand to better meet available supply and some demands have the potential to be shifted in time, either partially or fully. Another alternative is for the networks to provide the flexibility through some means of storage.

Storage is not a new part of the energy system. There are numerous ways in which fossil fuels, for example, already provide storage – be that in the power sector through the storage of gas or coal before it is converted to electricity; in home heating using the capacity of the gas network; in transport it is the liquid fuels in refuelling stations and the tanks of vehicles. Other ways in which storage is already used include: storage heaters in some electrically heated homes, hot water tanks in homes and other buildings and accumulators in heat networks.

The ability to provide storage varies amongst the network types. For gas and hydrogen, large-scale storage (such as in salt caverns) is very feasible. Whilst the scale of these storage options can represent a large capital cost, the cost per unit of energy is relatively low. Gaseous energy vectors also benefit from the ability of the pipeline network itself to act as storage, which is achieved by increasing the pressure in the pipeline (referred to as line-packing).

Similarly, heat networks also have a level of inherent storage, with this realised by exploiting the heat capacity of the water in the pipework, and to some extent the pipework itself and surrounding ground in which it is buried. Dedicated storage can be provided through large water tanks, which can be heated up and cooled as required. Again these have a relatively low cost per unit of energy stored.

Electricity supply needs to be in real-time balance and whilst there are a wide variety of technologies able to provide storage for electricity networks, most currently available options are either expensive (e.g. batteries) when compared to other means of providing system flexibility or constrained in terms of where they can be deployed (e.g. pumped hydro).

ETI Project

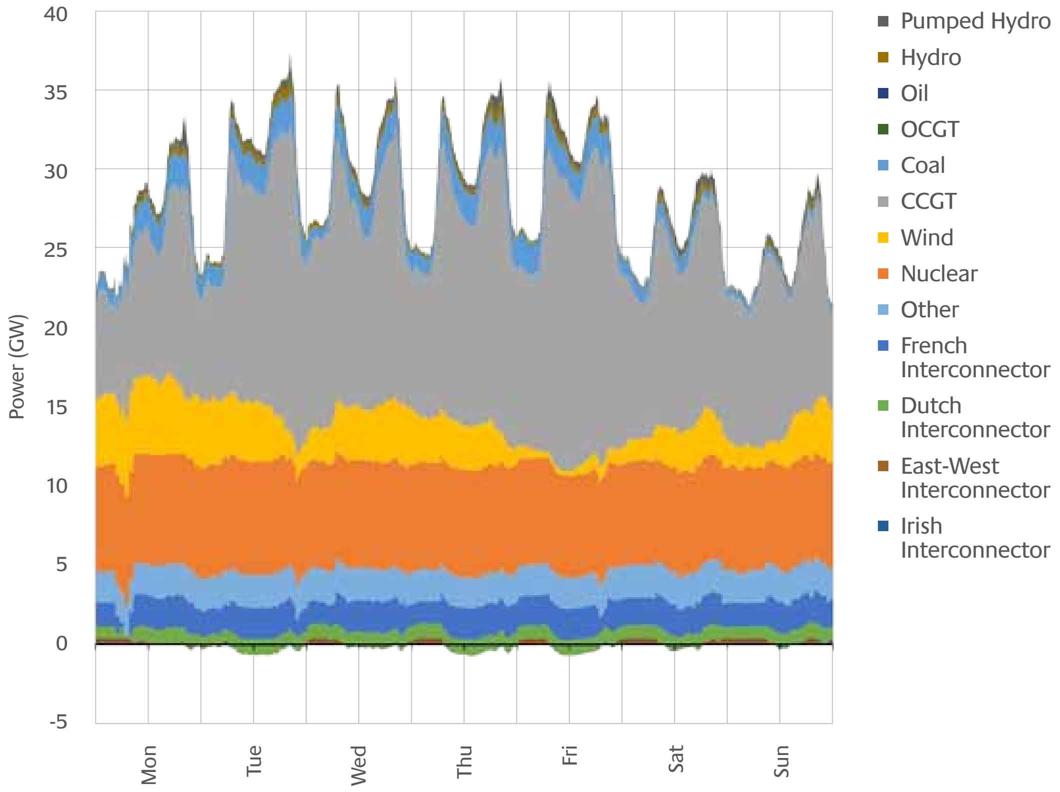
Salt Cavern Appraisal for Hydrogen and Gas Storage

This project will:

- Develop an understanding of salt cavern flexibility to support ETI system level modelling, for 100% hydrogen and hydrogen-methane mixtures that focus on flexibility and cost
- Characterise key constraints and their causes when operating fast churn storage at selected sites, including those caused by integration with the hydrogen supply and the gas turbines
- Identify a range of gas turbine offerings which match cavern capability or market needs

Figure 4

Example of how supply is varied to meet changes in demand in the electricity system, using different generation assets across the week

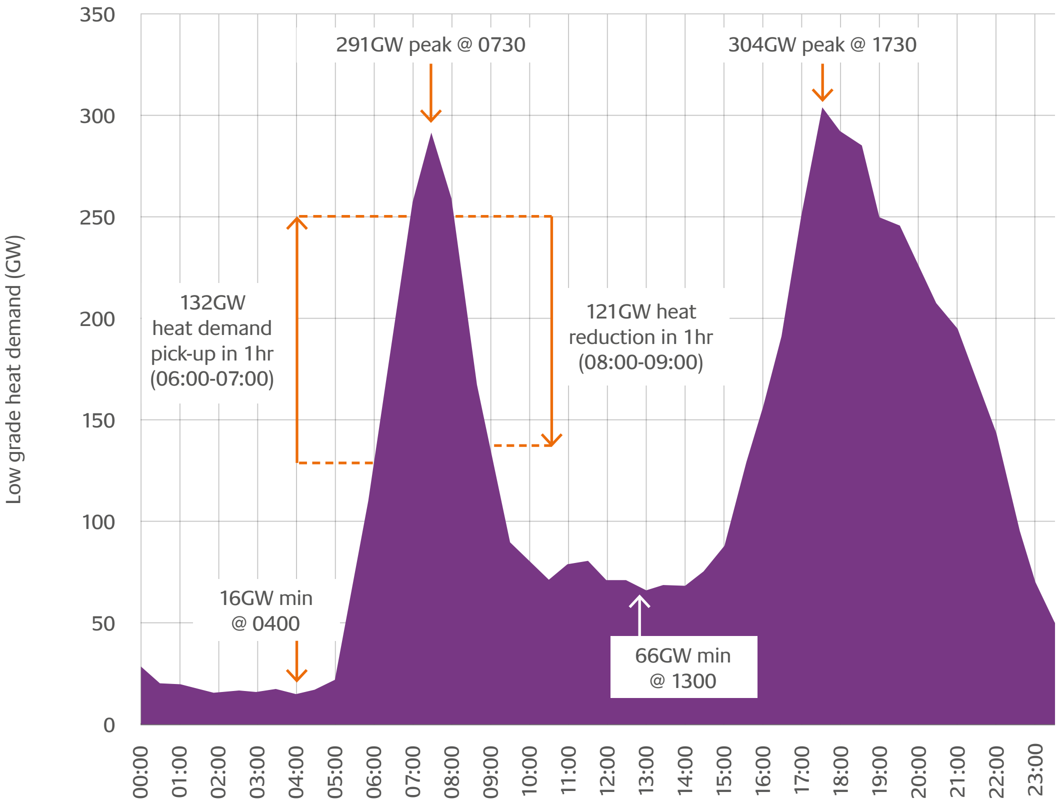


Based on data from Gridwatch (2016)

BALANCING SUPPLY AND DEMAND

Continued ›

Figure 5
Example of how supply is varied to meet changes in demand in the gas system by varying gas supply across the peak demand day in 2010



Based on data from Robert Sansom (2011)

Networks help to deliver flexibility through other means as well: having sufficient capacity to take full advantage of variable supplies; bringing in energy from other sources (including through interconnection); operating above normal limits for short periods of time; and use of multiple vectors to cater to particular demands.

As the energy system evolves, the ability for each part of the energy system to provide flexibility will also evolve. Whilst the issues around flexibility are most acute for electricity networks there are ways in which each of the networks discussed can contribute to balancing supply and demand across the whole energy system.

ETI Project

Storage and Flexibility Modelling

This project will assess the role of energy storage and other key means of providing energy system flexibility in the context of the overall energy system

Analysis by the ETI has identified a number of means of providing operational flexibility, which could be critical to the future energy system. Some of those which will have specific implications for energy networks include: gas and hydrogen storage to enable peaking power plant to help balance electricity supply; heat storage in homes allowing the load on electricity networks to be reduced at peak times; gas providing peak support for heat pumps; managed charging of plug-in vehicles; heat-led CHP systems managing variability of electricity output over the year by serving both heat networks and heat pumps, small modular reactors operated flexibly, pre-combustion CCS with the flexibility to produce power or hydrogen.

Some of the above represent opportunities to manage flexibility requirements through system design, the full benefits of which would not be apparent if only considering a part of the energy system or just one of the energy networks. The current focus on electricity system flexibility, for example, is understandable but there is a danger in ignoring the flexibility opportunity from other networks. Taking a complete system perspective helps to recognise these opportunities and establish which offer the most economic solutions.

POLICY AND ECONOMIC FACTORS

The ETI's work on energy system scenarios and market design raise a number of key challenges around the policy and regulatory frameworks for investment in the network infrastructure assets required to enable the transition to low carbon energy. By way of illustration, the aforementioned Clockwork and Patchwork scenarios envisage:

- Major shifts in the volume and patterns of usage of existing energy distribution networks (e.g. substantially different demands placed on electricity transmission and distribution assets, and impacts on gas distribution assets arising from emerging heat transitions).
- Substantial investment in new energy generation, conversion and storage facilities (e.g. new nuclear, CCS and renewable electricity generation, gasification plants, biomass handling infrastructure, etc.), with a need for economic signals to drive efficient choices and location decisions in relation to network capacity and new connections.
- Greater interaction (and potentially competition) between a range of energy vectors for power, heat and transport, entailing more complex trade-offs in investment choices and greater flexibility in the operation and balancing of different infrastructure networks (e.g. interacting heat and power networks, gaseous vectors, transport fuelling from both electricity and liquid fuels).
- The potential break up of some aspects of national energy network provision, with for example a variety of choices for heat provision reflecting local characteristics, as well as the development of new consumer propositions for home energy services.
- The efficient creation, location and establishment of new energy network infrastructures at varying scales (e.g. new local and city-scale heat networks, hydrogen storage and distribution infrastructure, CO_2 transport and storage infrastructure).

The ETI's contention is that an economically efficient transition to low carbon energy in the UK (i.e. one which contains overall costs to consumers and the wider economy) will require substantial reform of existing approaches to the governance, regulation and incentives for investment in network infrastructures. The ETI's techno-economic analysis and scenarios point to the potential for a broader mix of energy vectors, using flexibility to optimise supply and demand across heat, power and gaseous fuels. But this analysis does not take account of the incentives and signals which drive investment decisions, and there is a real risk that market failures and misaligned economic signals will drive investment choices that ultimately increase costs for consumers. For example, choices may be influenced by how costs are socialised across users of networks - heat network investments which may be 'optimal' could look expensive on a localised basis by comparison with alternatives simply due to the absence of a large charge base across which the costs of new heat network infrastructure can be socialised.

ETI Project

Enabling efficient low carbon networks

This project will build an understanding of options for reforming governance, market and regulatory arrangements to enable efficient investment in low carbon energy network infrastructures

This report is available online as a downloadable PDF:
http://www.eti.co.uk/library/enabling-efficient-networks-for-low-carbon-futures

Enabling an efficient transition to a new low carbon energy mix raises new and different issues for the regulation and governance of energy network infrastructure, which both challenge and go beyond the current essentially 'vector-specific' statutory regimes (e.g. electricity and gas acts).

Current governance and regulatory frameworks, and the structure of economic signals for investment, are simply not designed to enable and incentivise radical transformation.

Fresh thinking in governance, market and regulatory arrangements is needed in:

Adapting and enhancing existing network infrastructures

Incentivise and target investment in substantially adapting and enhancing existing network infrastructures (e.g. efficient configuration of electricity networks to meet needs of low carbon generation)

Enabling creation of efficient and effective new network infrastructures

Enable clear decision making and incentivise investment in creating efficiently configured new network infrastructures (e.g. new heat networks and/or heat-based energy storage)

Integrating new and existing networks to enable optimisation across vectors

Ensure that network infrastructures are designed and work together efficiently across vectors in real time (e.g. enabling efficient interplay of power, heat and gaseous energy vectors)

CONCLUSIONS

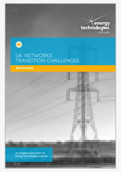
It is clear there are a number of overarching challenges facing the energy system and energy networks specifically. Greater electrification of energy and more renewable generation are already having an impact but both have the potential to increase significantly. The mix of energy sources, both in terms of type and location, will change dramatically. New technologies and propositions will invoke radical changes to how energy is used. The ability to meet peak energy requirements remains critical to the effective operation of the system and low carbon heat delivery to homes is probably the greatest challenge and spans multiple energy vectors.

Energy networks are a vital part of the energy system. Over the next decade, decisions will be needed about which existing networks to enhance or adapt, which new networks to create and how new and existing networks can be integrated to optimise across the whole energy system. Systems thinking is critical which means across vectors and up and down the energy supply chain.

Decisions need to be made in a timely manner but also be robust to a range of possible futures. For networks it is essential to invest ahead of need. Long construction and planning timeframes prevent major changes taking place overnight. If the networks are not ready, the energy supply cannot be utilised and the energy demand cannot be met.

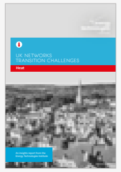
All of the above rely on the ability to make informed decisions, based on well-evidenced data and analysis. This needs to take account of future changes to how energy may be generated and consumed and is relevant to both a planned approach and when adopting an emergent strategy. Given the rate at which networks can be transitioned, and the need for many key decisions in the mid-2020s, the next decade will be a critical time in which to develop the evidence, through ongoing research and demonstrations at increasing scale.

ACCOMPANYING MATERIAL



UK Networks Transition Challenges – Electricity

http://www.eti.co.uk/insights/network-electricity



UK Networks Transition Challenges – Heat

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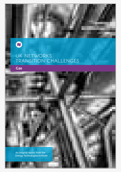
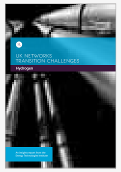


UK Networks Transition Challenges – Gas

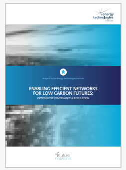
http://www.eti.co.uk/insights/network-gas



UK Networks Transition Challenges – Hydrogen

http://www.eti.co.uk/insights/network-hydrogen

FURTHER READING FROM THE ETI



Enabling Efficient Networks

http://www.eti.co.uk/library/enabling-efficient-networks-for-low-carbon-futures

ABOUT THE AUTHOR

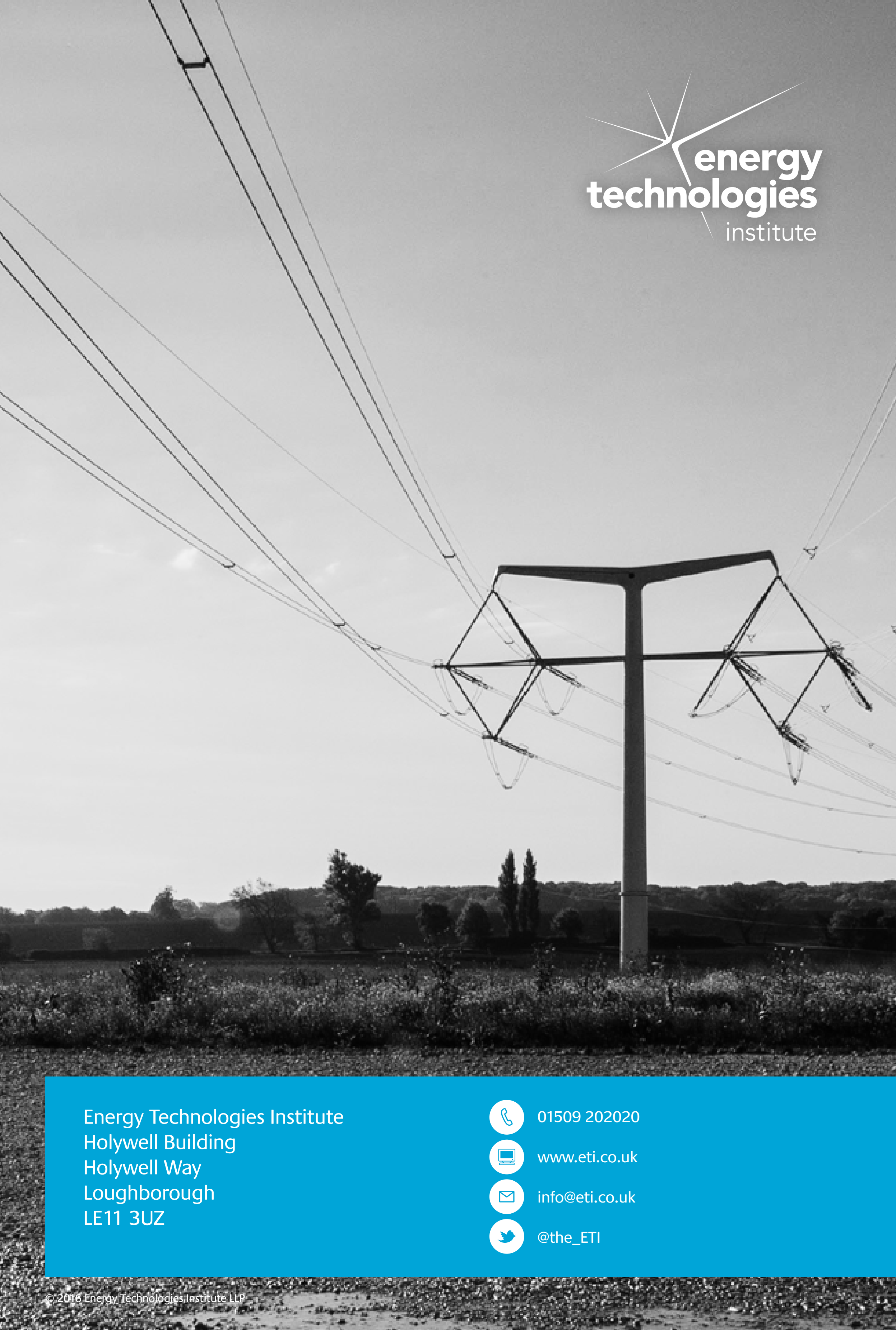
Liam Lidstone

BEng, EngD, MIMechE, CEng

Strategy Manager – Energy Storage and Distribution

Liam Lidstone joined the ETI in 2009 and has worked as Strategy Manager across the Smart Systems and Heat, Buildings, Distributed Energy and Marine programmes. He now has responsibility for Energy Storage and Distribution and Light Vehicle Integration.

☎ 01509 202055
✉ liam.lidstone@eti.co.uk



Energy Technologies Institute
Holywell Building
Holywell Way
Loughborough
LE11 3UZ

01509 202020
www.eti.co.uk
info@eti.co.uk
@the_ETI