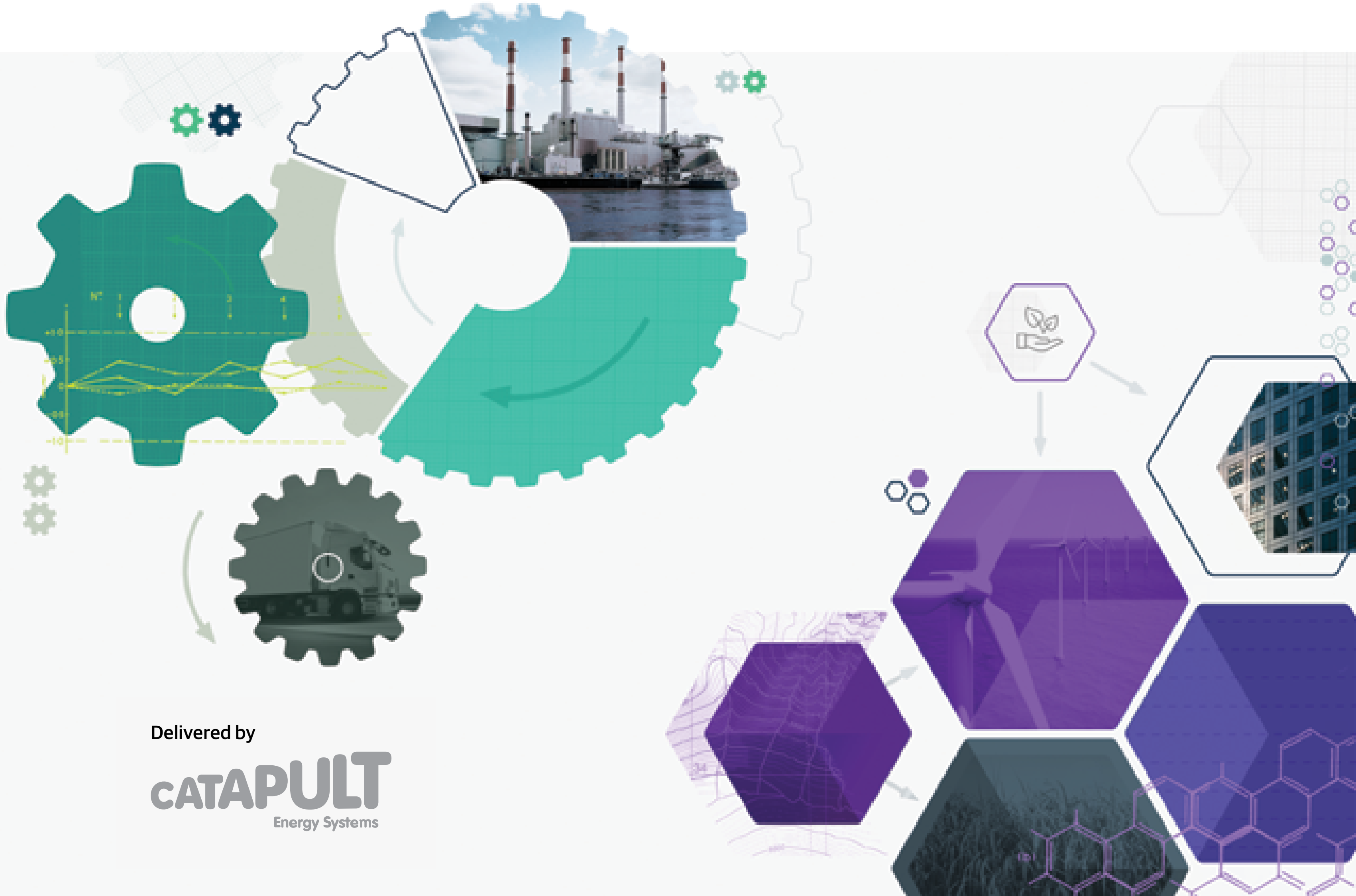
2018 Edition

energy technologies institute

Clockwork & Patchwork –
UK Energy System Scenarios

OPTIONS, CHOICES ACTIONS UPDATED



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CONTENTS

CLOCKWORK & PATCHWORK –

TWO PLAUSIBLE SCENARIOS FOR MEETING THE UK'S 2050 CLIMATE TARGETS

EXECUTIVE SUMMARY —

01 A balanced, multi-vector approach can deliver an affordable, low carbon UK energy transition, with costs rising to around 1% of GDP by 2050. Without certain key technologies, meeting carbon targets would be much harder, jeopardising industry and severely limiting lifestyle choices.

02 The potential for innovation across a range of technologies means we cannot be prescriptive about the precise mix over a 30-year period. Developing a basket of the most promising solutions offers strategic flexibility, as opportunities and barriers become clearer.

03 Sustainably grown biomass has the potential to become a critical resource for the UK energy system. It can be burned directly for heat and power, or converted into low carbon gases and liquid fuels to decarbonise hard-to-treat sectors.

04 Carbon Capture and Storage (CCS) offers a versatile solution with applications across power, industry and hydrogen production. Without CCS, UK carbon abatement costs could be double by 2050.

05 Bioenergy and CCS are especially valuable in combination. Together, they offer the potential for negative emissions to counterbalance the continued use of fossil fuels in difficult sectors like aviation. Without negative emissions generated in the UK, achieving a 'net zero' emissions target will require the prohibition of certain industrial activities and lifestyle choices or reliance on imported carbon credits from other countries.

06 System flexibility requirements will change, and new approaches will be needed. Storage of electricity, heat and gas (including hydrogen) will all have a role to play, along with backup generation in power and hybrid systems for heat.

07 Low carbon heat solutions exist but consumer experience is key. Most UK households have relied on gas boilers for more than a generation. Low carbon alternatives will require powerful consumer propositions that match, if not exceed, current experiences.

08 Electrification of transport can begin to deliver significant carbon reductions from 2020 onwards. The speed of transition remains uncertain, but whole system coordination can ensure we make best use of existing electricity system capacity, minimising the need for investment in upgrades to support mass adoption of plug-in electric vehicles.

> “ A BALANCED, MULTI-VECTOR APPROACH CAN DELIVER AN AFFORDABLE, LOW CARBON UK ENERGY TRANSITION, WITH COSTS RISING TO AROUND 1% OF GDP BY 2050

FOREWORD –

A MESSAGE FROM THE CHIEF EXECUTIVE OFFICER

JONATHAN WILLS

⟶ In 2015 when we first published Options, Choices, Actions we hoped that the presented scenarios of two plausible 2050 pathways to meeting UK climate targets would inform and provoke debate about how we would generate power and heat in the UK, as well as how we might move people and goods in the future.

A lot has happened since 2015 – not least the historic signing of the Paris Climate Agreement by over 200 countries. In the UK, the government has published its Industrial Strategy which highlights "Clean Growth" as one of the core challenges, and has made available Industrial Strategy Challenge Funds to stimulate private sector and academic innovation. The government has also published a Clean Growth Strategy and we are also seeing a number of sector deals being developed to add details onto how the government and industry intends to deliver this clean growth aspiration.

The core parameters of the low carbon transition facing the UK have not changed. The UK energy environment remains a complex web of needs, technologies and choices. There have been technology and commercial advancements as well as societal changes and modified assumptions over the last two or three years. For instance the pace of new-build nuclear capacity is slower than anticipated; the costs of renewables have dropped more quickly; there has been an increased focus on hydrogen pathways; the deployment of carbon capture and storage has slowed considerably; and new targets to remove or reduce petrol and diesel engines in vehicles have been announced, primarily in response to air quality concerns.

As the ETI comes to the end of its operational life (the end of 2019) we have worked with the Energy Systems Catapult, who have inherited our strategic analysis capability, to update our 2015 scenarios. This update examines the possible effects of some of these changes on the originally identified pathways which still leads to a position in 2050 that continues to meet climate targets.

These scenarios also call upon a decade of our work on accelerating low carbon technologies and providing strategic insight. It is our hope that these scenarios can help ensure the debate on how best to achieve the low carbon transition is based on informed evidence.

The work of the ETI to accelerate technologies is drawing to a close. Whole systems analysis and targeted demonstrations of breakthrough technologies, concepts and business models shaped by an evidenced approach have proven critical to the ETI's impact. Beyond 2019, this approach will need to be championed by others, including the Catapult network, the private sector and academia, if the UK is to progress through the low carbon transition at least cost and with the greatest economic and societal benefit.

> A LOT HAS HAPPENED SINCE 2015 – NOT LEAST THE HISTORIC SIGNING OF THE PARIS CLIMATE AGREEMENT BY OVER 200 COUNTRIES

SECTION ONE –

BACKGROUND

ABOUT THE ETI —

THE ETI IS A £400M INDUSTRY AND UK GOVERNMENT PARTNERSHIP IN LOW CARBON ENERGY SYSTEM PLANNING AND TECHNOLOGY DEVELOPMENT.

Its mission is to accelerate the development, demonstration and eventual commercial deployment of a focused portfolio of energy technologies, which will increase energy efficiency, reduce greenhouse gas emissions and help achieve energy and climate change goals.

Since 2007, the ETI has invested in research and development activity across heat, power, transport and the infrastructure that links them – delivering innovation from strategic thinking through to technology demonstration. It has created a project portfolio that has built knowledge and developed and demonstrated new technology alongside undertaking whole energy system strategic analysis and planning.

OUR MEMBERS

bp

CATERPILLAR

EDF ENERGY

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EPSRC
Pioneering research and skills

Department for Business, Energy & Industrial Strategy

Innovate UK

ETI PROGRAMME ASSOCIATE

HITACHI
Inspire the Next

WHOLE ENERGY SYSTEM MODELLING CAPABILITY —

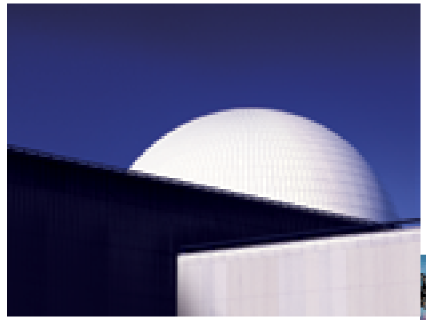
The ETI created a strategic analysis function, staffed by experts in engineering, economics and energy policy to provide whole energy system modelling and analysis alongside technology innovation management and road mapping at international, national and local levels.

Part of the legacy of the ETI which ends at the end of 2019 is to retain the team, the knowledge generated and their capability. At the end of 2017 the capability was transferred to the Energy Systems Catapult (ESC) to continue to identify and accelerate energy innovation to support the transition to a secure, affordable low carbon future.

The ESC now manages the system modelling suite developed by the ETI as well as providing consultancy services to the ETI as it completes its portfolio of energy innovation projects and analysis.

The ESC's whole energy system modelling and analysis team have managed this update to the Clockwork and Patchwork scenarios originally developed by the ETI in 2015.

CATAPULT
Energy Systems



> THE ETI WAS ESTABLISHED BECAUSE IT WAS RECOGNISED THAT THERE WAS AN URGENT NEED TO ACCELERATE THE PACE AND VOLUME OF INNOVATION ACTIVITY IN LOW CARBON ENERGY

ENERGY SYSTEM MODELLING –

> ESME HAS DEVELOPED INTO A CORE TOOL FOR THE IDENTIFICATION OF HIGH-LEVEL NATIONAL ENERGY STRATEGIES

ESME
Energy System
Modelling Environment

The ETI developed its Energy System Modelling Environment (ESME), early in the life of the organisation. ESME is a national whole energy system planning capability, helping to identify the lowest-cost decarbonisation pathways for the UK.

The model covers:

- energy use in transport[1], buildings and industry
- energy conversion steps including power, heat and hydrogen
- energy resources such as fossil fuels, biomass, nuclear and renewable energy, and
- infrastructure including transmission and distribution networks for electricity and gas, pipelines and storage for captured CO_2.

ESME is a least-cost optimisation model covering the period out to 2050, subject to additional constraints around energy security, peak energy demand and more.

Given the inherent uncertainty when operating over these timescales, ESME tests many thousands of simulations looking for robust strategies and technology choices under a wide range of assumptions. In this way, it has been able to identify the most promising technologies under different conditions, and focus ETI innovation projects accordingly.

ESME has drawn upon expert inputs from an advisory group of industrial and modelling experts. Since 2010, the model has been enhanced and peer reviewed, with its growing credibility evidenced by its use to inform a range of projects by ESC, the Department for Business, Energy and Industrial Strategy (BEIS), Committee on Climate Change (CCC), academia and industry. More detail on the modelling approach is available online[2].

ESME has developed into a core tool for the identification of high-level national energy strategies. At the same time, we recognise that many of the challenges and opportunities in the low carbon transition are not well represented in a techno-economic optimisation. For that reason, ESME analysis has always been part of a much wider programme of research including analysis of consumer needs, business models, land-use impacts and more.

SCENARIO APPROACH –

⟶ In 2015, the ETI published "Options, Choices, Actions: UK scenarios for a low carbon energy transition"[3]. This featured two scenarios (referred to here as Clockwork15 and Patchwork15). These illustrated different decarbonisation pathways for the UK energy system out to 2050. To define the scenario inputs, the scenarios team worked with experts from across the ETI membership (industry and government) and beyond. A high-level summary of those original scenarios is provided on the following pages.

> TWO DIFFERENT DECARBONISATION PATHWAYS FOR THE UK ENERGY SYSTEM OUT TO 2050

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[1] The transport sector includes the UK share of international aviation and shipping

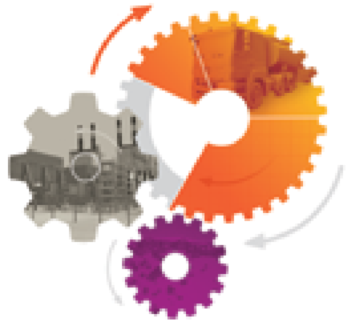
[2] http://www.eti.co.uk/wp-content/uploads/2014/04/ESME_Modelling_Paper.pdf

[3] ETI 2015 http://www.eti.co.uk/insights/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system

SCENARIO APPROACH

CLOCKWORK15 SUMMARY —

→ "Well-coordinated, long-term investments allow new energy infrastructure to be installed like clockwork. The regular build of new nuclear, CCS plants and renewables ensures a steady decarbonisation of the power sector. National-level planning enables the deployment of large-scale district heating networks, with the local gas distribution network retiring incrementally from 2040 onwards. By contrast, due to a strong role for emissions offsetting, the transportation system remains in the earlier stages of a transition and people and companies continue to buy and use vehicles in a similar way to today, albeit with regulation and innovation continuing to improve their efficiency."



POWER

The policy framework supports large-scale investments in CCS and nuclear. Clarity over the role of CCS enables early investment in "outsized" infrastructure and investor support for follow-on CCS projects

—

The current pipeline of renewables projects are delivered out to 2020 and capacity is maintained on a replacement basis until new capacity is added in the 2040s

—

Hydrogen for peaking plants is produced from biomass with CCS, providing system benefits including negative emissions

—

The capacity of nuclear, CCS and renewables is evenly balanced by 2050

HEAT

A national framework for large-scale district heating is introduced, enabled in part by waste heat from thermal power plants

—

A phased shutdown of the local gas distribution network from the 2040s encourages the uptake of district heating schemes

—

Subsidies are provided for heat pumps and efficiency improvements to speed up rural and suburban decarbonisation

TRANSPORT

A steady tightening of EU vehicle efficiency targets for new cars is met through the uptake of hybrid and plug-in hybrid vehicles

—

The introduction of "soft" incentives such as road tax or congestion charge concessions for low-carbon vehicles

—

Emissions reduction of freight is market-led, driven by cost of liquid fuels

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SCENARIO APPROACH

PATCHWORK15 SUMMARY —

→ "With central government taking less of a leading role, a patchwork of distinct energy strategies develops at a regional level. Society becomes more actively engaged in decarbonisation, partly by choice and partly in response to higher costs. Popular attention is paid to other social and environmental values, influencing decision-making. There is a more limited role for emissions offsetting, meaning more extensive decarbonisation across all sectors, including transport. Cities and regions compete for central support to meet energy needs which is tailored to local preferences and resources. Over time, central government begins to integrate the patchwork of networks to provide national solutions."

POWER

Renewables find support at all levels of society: central government backs large-scale projects such as offshore wind, while local authorities and communities support combined heat and power, onshore wind and solar

—

Initially, there is uncertainty over the role of nuclear and CCS due to a growing focus on renewables. This dampens investor appetite and limits the co-ordination of infrastructure planning

—

Later on, CCS deployment picks up, enabling clean hydrogen production from a mixture of biomass and coal, although biomass uptake is limited by societal concerns about land-use change and biodiversity as well as by market failures

HEAT

There is "grassroots" support for small and medium-scale district heating projects, coupled with private sector and local authority investment

—

A mixture of changing attitudes and high energy costs cause the growth in average indoor temperature to level off from 2030

—

There is improved efficiency of housing stock through selective retrofit of existing homes, and with apartments increasingly dominating the market for new builds

TRANSPORT

Greater urbanisation and modal shift means slower growth in new car sales, particularly for large cars

—

Some cities set more aggressive vehicle efficiency targets as part of their measures to improve urban air quality

—

Freight transport experiences a market-led reduction in emissions due to liquid fuel costs

SCENARIO APPROACH –

CONTINUED

These scenarios were not intended as a forecast of the most probable outcomes. Their purpose was to stand as illustrations of the key lessons learned as part of the ETI's whole systems analysis programme.

In the three years that have passed since their original publication, the ESME model has continued to be refined with the latest evidence from ETI projects and other industry data. We have taken the opportunity to update both scenarios to reflect these changes, the most important of which are detailed later.

> “
> IN THE THREE YEARS THAT HAVE PASSED SINCE THEIR ORIGINAL PUBLICATION, THE ESME MODEL HAS CONTINUED TO BE REFINED WITH THE LATEST EVIDENCE FROM ETI PROJECTS AND OTHER INDUSTRY DATA

UK CLIMATE AMBITION –

One important factor that has not changed is the legislated UK emissions reduction target. In our 2015 publication we explored the potential impact of the UK delaying action on emissions reduction, followed by an attempt to play catch-up later.

The result was a more costly transition with efforts to build up indigenous UK supply chains thwarted. Inward investment would then have to be coaxed back in under generous terms. Imported low carbon solutions would have to be fast-tracked into service, straining the ability of the UK workforce to develop the skills and know-how to ensure successful implementation. Consumers would be adversely impacted as heating, transport and other assets had to be scrapped midway through their anticipated technical life.

We concluded that the UK should continue the journey established by its world-leading climate legislation and has seen successful delivery of carbon budgets to date. Developments since 2015 have not changed this view. The UK is a signatory of the Paris Agreement. If anything, achieving a 1.5°C pathway would require even greater ambition from the UK, including a net zero emissions target well before the end of this century.

In the revised Clockwork and Patchwork scenarios, we continue to assume an emissions trajectory consistent with current legislation. Later in this document we consider the possible impact of a net zero emissions target for the UK.

> “
> THE UK IS A SIGNATORY OF THE PARIS AGREEMENT. IF ANYTHING, ACHIEVING A 1.5°C PATHWAY WOULD REQUIRE EVEN GREATER AMBITION FROM THE UK

SECTION TWO –

LATEST CONTEXT

UNDERLYING SOCIO-ECONOMIC ASSUMPTIONS –

Since the 2015 scenarios were published, the various government projections that inform these scenarios have been revised, sometimes significantly. Downward revisions in energy service demand tend to make carbon targets easier to meet. At the same time though, other revisions imply tighter constraints on the supply side, for example with lower levels of sustainable biomass resource assumed to be available for import to the UK in the longer term[4].

Such uncertainty about the future is precisely why we make different assumptions in our two scenarios in the first place.

We have chosen not to explicitly examine the potential ramifications of Brexit in these two scenarios because they are unknown at the point of writing. Clockwork and Patchwork have always followed distinct socio-economic pathways, allowing the reader to speculate on the role of different political drivers.

Our Clockwork scenario uses socio-economic assumptions based largely on central government projections, with the key exception that population is based on the Office for National Statistics ‘low migration’ projection. Patchwork represents a qualitatively different economy, with a higher population projection and GDP growth.

In Clockwork, energy service demands in buildings, transport and industry are also closely aligned with government projections. Despite a higher and wealthier population, Patchwork has lower aggregate energy service demand due to greater urbanisation, transport modal shift, and a more service-based economy.

Representative population and GDP growth

2050 POPULATION

CLOCKWORK 71.5M
PATCHWORK 75M

2050 GDP/PP

CLOCKWORK £48,000
PATCHWORK £50,000

(Given in 2010 GBP)

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[4] We have chosen to base biomass import assumptions on the most conservative scenario in: https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model

CARBON CAPTURE AND STORAGE –

One of the key messages conveyed through the 2015 scenarios was the critical role of CCS as part of an affordable transition towards our 2050 goals, with both scenarios featuring CCS to varying degrees.

In Clockwork15, a stronger role for CCS was based on early implementation (from 2020) rapidly gaining momentum as part of a commercially strategic plan. CCS risks and uncertainties were reflected in Patchwork15, with commercial deployment beginning later, from 2025.

At the time, it was considered that early implementation might have occurred through the government’s £1bn CCS competition to deliver commercial-scale projects by 2020, but support for this was withdrawn. The Government has since established the CCS Cost Reduction Task Force, while the CCC has also re-emphasised the importance of CCS, advising that the UK should not plan on meeting 2050 targets without it.

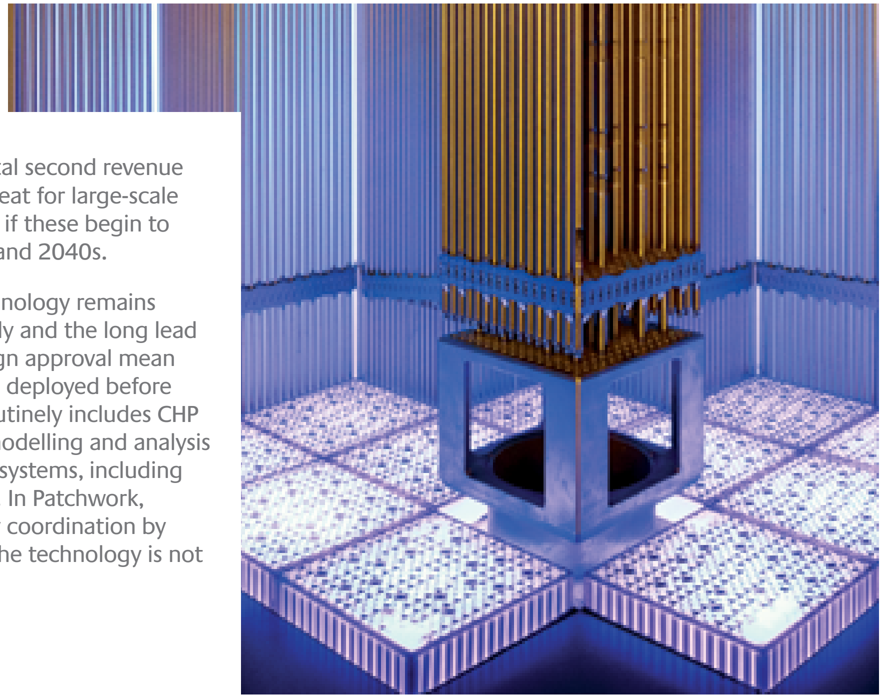
The updated Clockwork scenario reflects this renewed focus on the strategic value of CCS, with commercial deployment from 2025. The updated Patchwork scenario reflects continued challenges in identifying a route to CCS commercialisation, with the earliest deployment coming five years later and rolling out less rapidly.

NUCLEAR —

There were no new nuclear projects in construction in the UK when the 2015 scenarios were published; however, Clockwork15 included the steady deployment of new nuclear, reaching 35GW by 2050. Patchwork15 featured a more limited nuclear role, with replacement of historic capacity only, at 16GW by 2050. Since that time, EDF have started construction of Hinkley Point C, which is 3.2GW of capacity.

Since the original publication, nuclear small modular reactors (SMRs) have also received significant attention in the UK. The ETI contributed to a techno-economic assessment of nuclear SMRs commissioned by HM Government in 2015. Crucially, the economic case for this technology looks far more favourable when these are designed to deliver combined heat and power (CHP). This could unlock a vital second revenue stream by providing heat for large-scale district heat networks if these begin to emerge in the 2030s and 2040s.

Nevertheless, the technology remains unproven commercially and the long lead times for reactor design approval mean they are unlikely to be deployed before 2030. The ETI now routinely includes CHP nuclear SMRs in our modelling and analysis of low carbon energy systems, including in the new Clockwork. In Patchwork, without the necessary coordination by central government, the technology is not available.



SMR Deployment Enablers
This project provides a greater understanding of the necessary actions required over the next five years if a first of a kind small modular reactor plant is to be in operation in the UK by 2030

3.2GW

EDF have started construction of Hinkley Point C, which is 3.2GW of capacity

SOLAR PV —

> THE UK COULD ACCOMMODATE A LOT MORE SOLAR PV, ESPECIALLY OUT TO 2030 WHERE THIS WOULD REDUCE THE OPERATION OF GAS TURBINES

Global deployment of solar photovoltaics (PV) has more than doubled in three years, reaching 400GW by end of 2017. In the UK, capacity grew from 5.5GW to 12.8GW over the same time period, although growth has slowed just as dramatically after the withdrawal of support.

The UK could accommodate a lot more solar PV, especially out to 2030 where this would reduce the operation of gas turbines. However, beyond a certain capacity, PV begins to cannibalise its own market. Additional low carbon capacity would need to concentrate on supporting the UK's higher winter evening demand, for which PV is a poor fit. Monthly average PV capacity factors can reach 20% for the summer but drop to 3% in winter[5]. The emergence of cheaper batteries can support within-day smoothing, but they cannot transfer meaningful quantities of electricity across seasons.

Technology learning rates due to further global deployment will continue to bring down PV module costs over the long term. Our modelling assumptions for PV have been revised to follow a cost reduction profile based on analysis by the UK Solar Trade Association and Germany's Fraunhofer Institute[6].

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[5] The capacity factor describes the average power over a period divided by the rated peak power. E.g. if a 1kW PV system generated 876kWh over a year, this would imply an average power of 100W/h (over 8760 hours). 100W/1kW = a 10% annual capacity factor.

[6] UK STA (2015), http://www.solar-trade.org.uk/wp-content/uploads/2015/03/LCOE-report.pdf, Fraunhofer ISE (2015), https://www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf

WIND —

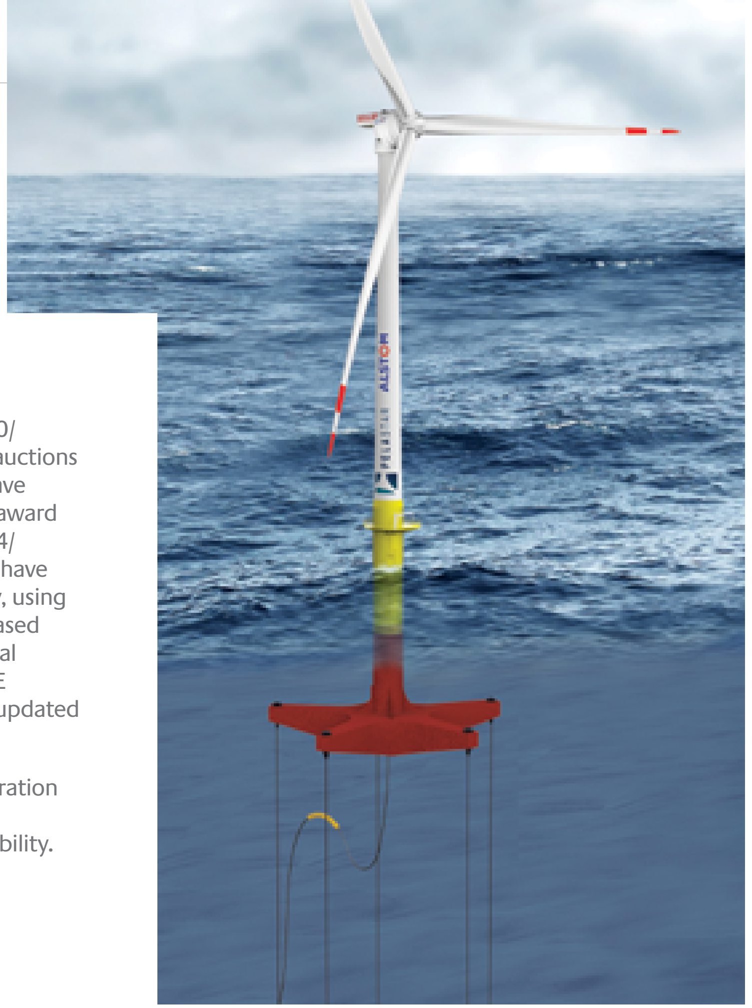
For onshore wind, it was announced that support would no longer be available beyond 2017, leading to a rush of construction activity in that year, bringing onshore wind capacity to 12GW. Our assumptions have been updated accordingly.

Offshore wind has gone from being viewed as an important hedge option to now being seen as a key component of a cost-effective decarbonisation pathway, with over 7GW currently installed and several large wind farms in or awaiting construction. The ETI has invested £60m+ over ten years to accelerate innovation in this technology. Our analysis and project data has consistently led us to describe some of the lowest available cost projections for UK offshore wind. This has been more than borne out by recent experience.

In 2014, the government awarded contracts for difference at £140-150/MWh. However, since competitive auctions were introduced these contracts have come down rapidly, with the 2017 award round seeing an average CfD of £64/MWh (for delivery in 2022/23). We have validated this recent cost trajectory, using a catalogued expenditure model based on completed projects and industrial knowledge and evidence. Our ESME modelling assumptions have been updated accordingly.

In the longer term, very high penetration rates will increasingly rely on other investments to provide system flexibility.

> THE ETI HAS INVESTED £60M+ OVER TEN YEARS TO ACCELERATE INNOVATION IN THIS TECHNOLOGY



Floating Platform System
The Glosten Associates designed a tension leg platform floating system demonstrator through a FEED study

LOW CARBON VEHICLES —

Since the 2015 scenarios we have seen an increase in alternatives to the traditional internal combustion engine (ICE) vehicle on UK roads. The most popular alternative has been (non-plug-in) hybrid ICEs, but the provision of a grant towards the cost of a new plug-in electric vehicle has helped spur the adoption of plug-in hybrid electric vehicles (PHEVs), and pure battery electric vehicles (BEVs). PHEV and BEVs currently equate to 2% of new vehicle sales and 0.4% of the existing fleet.

Real world learning from the proliferation of EV models on the market has allowed us to better represent (i.e. reduce) the cost profile for electric vehicles in our modelling.

In the Patchwork15 narrative, societal pressure to improve urban air quality resulted in strict efficiency targets for new vehicles. In the last three years, concerns over air quality have come into stronger focus, and the government has recently published its Clean Air Strategy. Local authorities are actively investigating the possibility of low or zero emissions zones to discourage the most polluting vehicles from travelling within air quality hotspots. This might include the use of geofencing technology to automatically signal to PHEVs where an electric driving mode is mandatory.

While we do not capture air quality in our energy models, we have a proxy in the form of fleet average CO_2/km emissions targets for new vehicles. In both scenarios these targets tighten over time. Although ongoing improvements to ICE performance are assumed in our model, the targets in our scenarios are sufficiently strict that they can only be met through the increased uptake of alternative vehicles (hybrid ICE, PHEV, BEV).

Over the longer term, our scenarios address the recent announcement from the government of a ban on new sales of traditional ICE vehicles from 2040. This ban may or may not apply to (non-plug-in) hybrid ICEs. We have reflected this uncertainty in the new scenarios.

> IN THE LAST THREE YEARS, CONCERNS OVER AIR QUALITY HAVE COME INTO STRONGER FOCUS, AND THE GOVERNMENT HAS RECENTLY PUBLISHED ITS CLEAN AIR STRATEGY

Consumers, Vehicles and Energy Integration
A project to understand the required changes to market structures and energy supply systems in order to encourage wider adoption of plug-in vehicles and their integration into the energy system

HYDROGEN FOR HEAT —

The idea of using hydrogen for heat in buildings has gained traction in the last couple of years[7]. To make a meaningful contribution to long-term emissions reduction, this would involve complete transition from natural gas to hydrogen (in strategically appropriate regions), as opposed to blending a small proportion of hydrogen within existing natural gas networks. This conversion would involve the construction of a new gas transmission network, the conversion of existing gas distribution networks to carry hydrogen and upgrading of household heating and cooking appliances.

The hydrogen required for this would need to be produced by low carbon means, and while the likely production and storage technologies to do this are largely understood, the extent of the requirement would present a hugely significant scaling challenge if this solution is to fulfil anything like the role played by natural gas today.

Our model has been modified to include hydrogen transmission, distribution and domestic end-use technologies and has been used to extensively study hydrogen for heat strategies. The Clockwork scenario has been informed by this work and might be viewed as being based on optimistic but plausible assumptions. The degree of coordination required to implement hydrogen for heating at scale by 2050 is inconsistent with a Patchwork scenario.

> THE IDEA OF USING HYDROGEN FOR HEAT IN BUILDINGS HAS GAINED TRACTION IN THE LAST COUPLE OF YEARS

> TO MAKE A MEANINGFUL CONTRIBUTION TO LONG-TERM EMISSIONS REDUCTION THIS WOULD INVOLVE COMPLETE TRANSITION FROM NATURAL GAS TO HYDROGEN

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[7] See for example the H21 Leeds City Gate report: https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf

SECTION THREE –

THE SCENARIOS

CLOCKWORK

UK SOCIETY AND ECONOMY —

⟶ In Clockwork, the UK population grows by around five million from today, reaching 71.5 million by 2050. This growth is concentrated in London and surrounding regions, but urbanisation is balanced against a continuing aspiration towards suburban living.

Economic growth is powered by services and increasing industrial output from value-added sectors. Energy-intensive industry sectors (e.g. Iron, Steel and Other Metals; Refining; Cement) continue to decline, albeit slowly.

People are accepting of the need to reduce carbon emissions, but generally expect to leave this to other agents (government, utilities, manufacturers of goods and services) rather than to undergo significant behavioural change.

Decarbonisation efforts by the government and companies are therefore concentrated on those actions that cause least disruption to existing lifestyles, and other environmental issues receive less attention.

CLOCKWORK

CLOCKWORK

ENERGY SYSTEM OVERVIEW —

⟶ In Clockwork, coordination by central government means long-term investment in strategic energy infrastructure.

The power sector sees retirement of all coal plant in the early 2020s and reliance on unabated gas is reduced through the 2030s, ensuring emissions reduction can be achieved through electrification of heat and transport.

The first CCS projects come online by 2025 with commercial deployment thereafter, focusing on large-scale hydrogen production but also deployed directly in power and industry. Some regions of the gas distribution network undergo full conversion to carry hydrogen to buildings for heating and cooking.

Negative emissions from bioenergy with CCS allow the 2050 target to be met as part of a cost-effective pathway, even though unabated fossil fuel use persists in hard-to-treat sectors.

CLOCKWORK

BUILDINGS AND HEAT —

In Clockwork, over eight million new homes are built by 2050 to meet total demand of 34 million (with an average 38m^2 per person), and these are constructed to a good thermal standard, minimising additional space heat demand.

Another ten million existing homes undergo whole-house retrofits to improve thermal performance by 20-30%.

With occupants expecting increasing levels of comfort in the home, indoor average temperatures continue to rise slowly through to 2050, as they have done historically.

Despite the increase in numbers of homes and comfort levels, the higher efficiency of new builds, combined with retrofits means total space heat demand in 2050 is similar to today.

10m

Another ten million existing homes undergo whole-house retrofits to improve thermal performance by 20-30%.

FIGURE 1 — Clockwork Buildings Space Heat Capacity (GW)

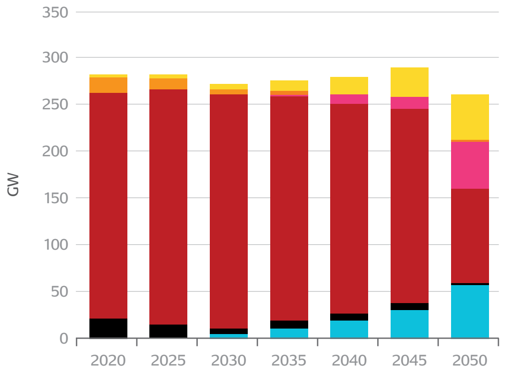
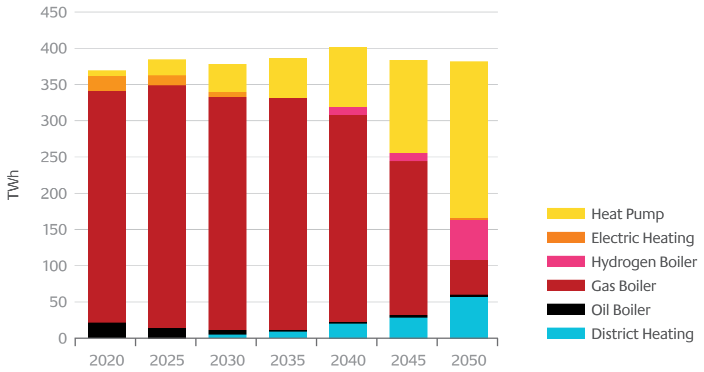


FIGURE 2 — Clockwork Buildings Space Heat Production (TWh)



CLOCKWORK

BUILDINGS AND HEAT –

CONTINUED

Electrification

Adoption of electric heat pumps begins in the 2020s, although deployment at scale only begins in the 2030s as consumers begin to feel the effects of carbon prices on gas boiler operation.

Heat pumps are typically deployed as part of a hybrid solution with gas boilers. In this way, progressively decarbonised electricity can provide most of the base heat requirement throughout the year, while gas boilers provide a supplementary heat source on cold days. This allows heat pumps to be modestly sized, and operate almost as ‘baseload’, rather than having to be oversized (at great expense) to meet occasional peak demand.

This configuration means that by 2050, heat pumps account for a modest 20% of all building heating capacity, but over 50% of annual space heat production across the UK.

Space heat storage (in hot water tanks) plays an important role in many of these homes, ensuring that the heat pump production overnight or in the middle of the day can be stored up and released when needed.

District heat networks

In major population centres around the UK, large district heat networks are rolled out from 2030 onwards. Since high take-up rates are essential to the economics of heat networks, local strategic planning is required to identify those areas where heat networks offer customers the best, most cost-effective solution.

A range of technologies are deployed to supply the heat to these networks, beginning with smaller gas CHP plants. In the medium term, low carbon sources include heat recovery from large-scale thermal electricity generation. In the longer term, new and extended networks are fed by heat offtake from small modular CHP nuclear reactors. Commercial scale marine heat pumps also make a sizable contribution by 2050.

As these low carbon alternatives scale up, the gas CHP plants remain in service to provide flexibility and resilience to the networks. This means district heat networks can be sized to provide the necessary flow of heat to cope with extreme cold events, minimising the need for secondary heating systems within homes. For this reason, gas distribution networks in these areas begin to be decommissioned.

Gas networks

In those areas where heat networks are not economic, there is a recognition that full electrification – to the extent required to cope with extreme cold weather – would place undue stress on electricity networks. For this reason, existing gas networks in these areas are maintained but energy throughput is much reduced, with gas boilers now playing a supplementary role in support of electric heat pumps, as part of a hybrid solution.

Some areas undergo conversion of the gas distribution network to deliver hydrogen to buildings. In areas anticipating hydrogen conversion, advanced notice ensures end-of-life gas boilers are replaced with hydrogen-ready models, minimising the risk of stranded assets.

Thanks to a concerted effort by government and gas network operators, around one third of the remaining gas network in 2050 is fully converted to hydrogen distribution, delivering over 55TWh of hydrogen annually.

The other two thirds of the remaining distribution network continue to supply natural gas, but reduced gas boiler operation means that annual delivered energy is actually lower than from hydrogen.

Buildings and Heat – Challenges and Implications

- The majority of UK households have relied on gas boilers for more than a generation. Transitioning to any of the alternatives portrayed here will require powerful consumer propositions to be developed that match, if not exceed, current experiences of energy provision in the home. This includes cost-effectiveness and convenience, but also space requirements for systems comprising multiple components (e.g. heat pump, backup boiler, heat storage).
- The idea of hydrogen conversion of the gas grid is gaining traction, but there is still a limited understanding of the technical constraints and costs. The conversion seen in Clockwork relies on the most optimistic assumptions in the current literature, but test and demonstration projects now being funded by BEIS will deliver more robust evidence in due course.
- Where Clockwork assumes a transition to hybrid systems (heat pumps with backup boilers), the optimal sizing of heat pumps will depend on the timing of any hydrogen conversion in a given local area. Eventually, with effective carbon pricing as in Clockwork, it will be more expensive to run natural gas boilers than hydrogen boilers. For those areas expecting to rely on natural gas distribution out to 2050, heat pump sizing (and electricity network reinforcement) will need to take account of this. For those areas anticipating earlier hydrogen conversion, heat pumps may be more modestly sized.
- Although our analysis only goes as far as 2050, in Clockwork, utilisation of the gas grid has declined considerably by that point. If carbon emissions are to decline further in line with net zero targets, there may be no room for natural gas distribution much beyond 2050.
- Retrofitting of homes will be a high priority across rural and suburban areas where heat networks are unavailable and gas networks are decommissioned. Doing so will minimise the scale of the necessary electricity network upgrades required in support of heat pump deployment.

55TWh

Thanks to a concerted effort by government and gas network operators, around one third of the remaining gas network in 2050 is fully converted to hydrogen distribution, delivering over 55TWh of hydrogen annually.

CLOCKWORK
TRANSPORT –

Fletttner Rotor Sails
The first installation of wind-powered energy technology on a product tanker vessel

Aviation and Shipping

Passenger aviation demand continues to grow out to 2050 in line with government forecasts. No radical alternative to conventional kerosene-fuelled aircraft are assumed to be commercially available in the period to 2050, but advances in aeroplane efficiency and aviation operations mean that overall emissions from this sector remain on a par with 2010 levels.

Shipping demand also sees some growth in Clockwork, but emissions are again held steady, this time thanks to alternative technologies in the form of dual-fuel ships burning a combination of liquid fuel and natural gas.

Road transport

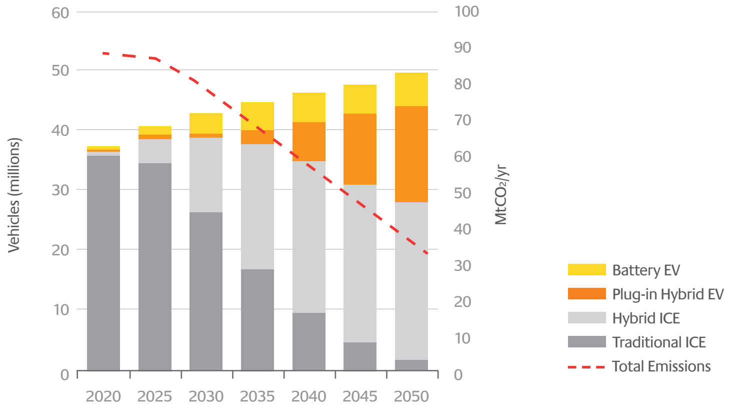
For light vehicles, manufacturers respond to fleet average CO_2 targets by developing a wider range of (non-plug-in) hybrid ICE models. Over time these become mainstream and traditional ICE sales fall away.

Battery-only electric vehicles (BEVs) appeal to some consumer segments as a low carbon lifestyle choice, but play a more modest role than some anticipated, with plug-in hybrid electric vehicles (PHEVs) emerging as the preferred low carbon alternative.

Hydrogen fuel cells fail to take off due to lack of any widespread investment in refuelling infrastructure and lack of consumer appetite for these more expensive models.

Overall, across all road transport (cars, vans, buses and other medium and heavy-duty vehicles), Clockwork sees a significant reduction and diversification in final energy consumption.

FIGURE 3 – Clockwork Fleet of Cars and Vans (million vehicles, left; $MtCO_2$/yr, right)



Liquid fuel declines from a peak of 430TWh in 2020 to 150TWh in 2050, (from 95% down to 60% of all road transport energy). Natural gas is rapidly adopted as a transitional fuel in heavy-duty road transport, before more comprehensive low carbon alternatives are adopted.

Electrification makes up 20% of all road transport energy consumption by 2050.

Transport – Challenges and Implications

- Electrification of light transport is less comprehensive here than in some scenarios we (and others) have explored. The level of EV adoption seen here might be supported largely via off-street private charging, with less need for extensive public charging infrastructure.
- A key challenge will be ensuring the continuing viability of refuelling stations in the UK, particularly in more remote areas, as the volume of liquid fuel consumption declines.
- Any carbon taxes on fuels could fall disproportionately on the least affluent households who cannot afford to purchase new vehicles and so tend to run older, less efficient models (and incidentally may not have the option of off-street private charging).
- For heavy transport, the rapid deployment of gas fuelling infrastructure may prove challenging in an industry where the customer appetite for risk is low.
- In aviation the development of hybrid electric/fuel aircraft could improve overall efficiency but aviation will remain a key source of emissions out to 2050.

CLOCKWORK

INDUSTRY —

The Clockwork scenario sees overall industrial growth to 2050 with a continuing but gradual shift away from more energy intensive activities. Combined with a drive towards greater energy efficiency generally, this results in a 12% reduction in total industrial energy demand by 2035[8].

After this, efficiency gains are less pronounced but manage to counterbalance growth, resulting in a levelling out of total energy demand.

CCS is deployed to capture emissions from industrial activity. By 2040, around 7 $MtCO_2$ of industrial emissions are being captured and stored annually. An even higher volume of CO_2 is captured upstream during production of hydrogen for industrial use.

Natural gas remains a major fuel for industrial energy use (34% of the 2050 total), but the emergence of hydrogen as a significant low carbon energy carrier helps to displace the higher carbon fossil fuels. By 2050, hydrogen accounts for 15% of all industrial energy consumption, ahead of liquid fuel (14%) and coal (3%).

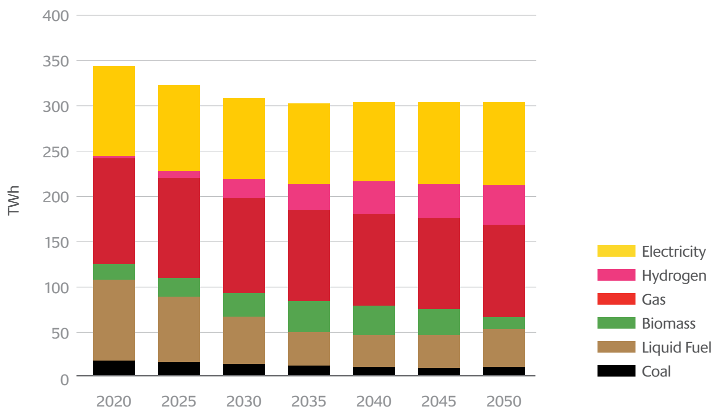
Since the production of low carbon hydrogen in Clockwork relies on CCS, this takes some time to scale up. As an interim measure, an increasing volume of biomass is used for combustion in industry.

Through displacement of fossil fuels or direct CO_2 capture, emissions from industry fall from around 60 $MtCO_2$ in 2015 to 33 $MtCO_2$ in 2050.

Industry – Challenges and Implications

- If energy-intensive industries undergo a slow decline as represented here, this may involve some activity simply being moved offshore rather than truly displaced by other UK activity.
- Biomass imports are relied upon to deliver industrial emissions reduction in the medium term, before global competition and associated higher costs limit the amount economically available to the UK. Industries without a viable transition plan towards more indigenous low carbon alternatives may struggle with stranded assets as a result.

FIGURE 4 — Clockwork industry energy consumption (TWh)



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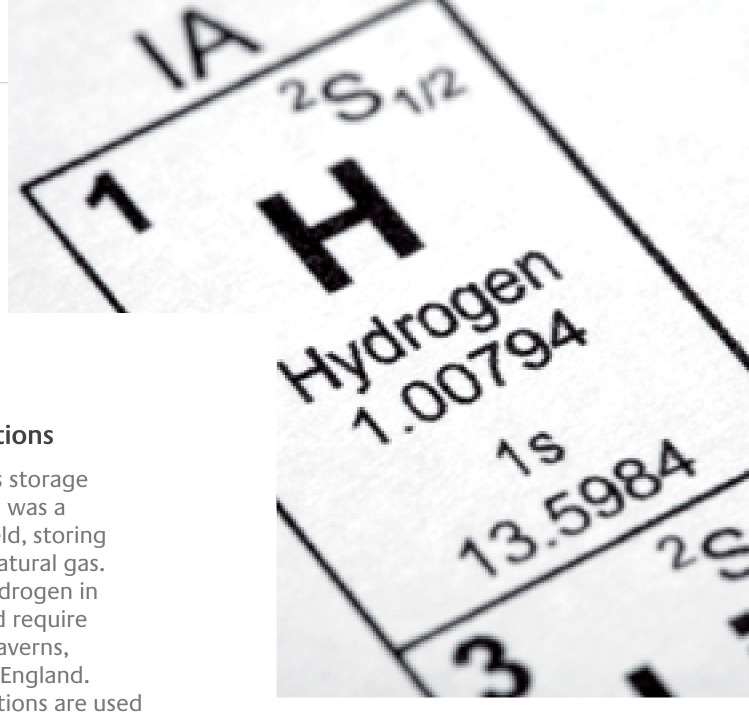
[8] Clockwork industry assumptions based largely on government projections (BEIS, EEP 2016).

CLOCKWORK

HYDROGEN —



Hydrogen production of 160TWh by 2050 is delivered through a combination of coal and biomass gasification, both with CCS.

Industry and power are the early adopters of hydrogen in Clockwork, eventually overtaken by demand from the converted gas distribution networks.

As an interim measure until a CCS infrastructure is built out, some unabated Steam Methane Reforming is used in the 2020s to build a runway for hydrogen adoption across industry.

Geological storage facilities for over 2,000GWh of hydrogen are required in Clockwork by 2050 to ensure hydrogen boilers in homes can be supplied with sufficient fuel during a peak cold weather event.

Hydrogen – Challenges and Implications

- The largest historical gas storage facility in the UK (Rough) was a partially depleted gas field, storing around 35,000GWh of natural gas. Geological storage of hydrogen in Clockwork would instead require the preparation of salt caverns, primarily in the north of England. Similar geological formations are used today to store natural gas, although differences in energy density mean you require three times the volume of storage per GWh for hydrogen as you do for natural gas. The UK currently stores around 10,000GWh of natural gas in these formations[9], greater than the hydrogen storage requirement in Clockwork, even allowing for energy density.
- Electrolysis offers a potential route to low carbon hydrogen (assuming low carbon electricity generation), but based on current engineering evidence we do not foresee this playing a role in high volume production (see Hydrogen section). Rather, it may provide small-scale production for those parts of the UK where pipeline distribution would remain uneconomic for some time.

160TWh

Hydrogen production of 160TWh by 2050 is delivered through a combination of coal and biomass gasification, both with CCS.

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[9] "The role of hydrogen storage in a clean responsive power system", ETI, 2015, http://www.eti.co.uk/insights/carbon-capture-and-storage-the-role-of-hydrogen-storage-in-a-clean-responsive-power-system/

CLOCKWORK

ELECTRICITY GENERATION —

In Clockwork, partial electrification of the transport and heat sectors leads to annual electricity consumption in 2050 of 440TWh (up from ~300TWh today). The majority share of electricity is delivered through a combination of wind and nuclear.

A combination of fixed and floating offshore wind turbines provides 40GW of capacity and 40% of total electricity generation in 2050, while onshore wind contributes a further 14GW and 10% of generation.

A new fleet of large nuclear plants with a capacity of 16GW provides baseload generation (with an average annual capacity factor of 90%), accounting for 30% of electricity in 2050.

Flexibility

With intermittent wind and baseload nuclear providing 80% of annual generation, there is a considerable need for flexibility in the system to deal with daily and seasonal variations in demand.

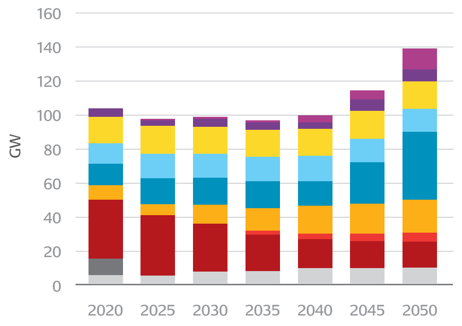
Around 6GW of Combined Cycle Gas Turbines (CCGT) with CCS is deployed by 2050. This is used to boost generation in the winter months (to support demand from electric heating) but experiences low load factors through the summer, with an average capacity factor of 43% delivering 5% of total annual electricity.

Hydrogen turbines emerge as a low carbon peak generation technology, with 13GW installed by 2050. Notably, this is a significant step up from 5GW in 2045, while annual generation from hydrogen turbines actually falls over this period.

This reflects the increasing capacity of offshore wind, providing a cheaper low carbon generation option, with H2 turbines shifting to more of a backup role. At the same time, from a whole-system perspective, use of hydrogen is prioritised for heat production in buildings.

Around 8GW of electricity storage (not shown in these charts) and 10GW of interconnectors provide further day-to-day flexibility. Finally, a total of 16GW of unabated gas is maintained as backup (of which 9GW is CHP capacity supporting district heat networks). This reflects a merit order ultimately relying on technologies with increasing carbon intensity (but lower capital cost) to deal with exceptional conditions.

FIGURE 5 — Clockwork electricity capacity (GW)



* Other renewables include Biomass, Energy from Waste, Hydro and Tidal

FIGURE 6 — Clockwork electricity generation (TWh)

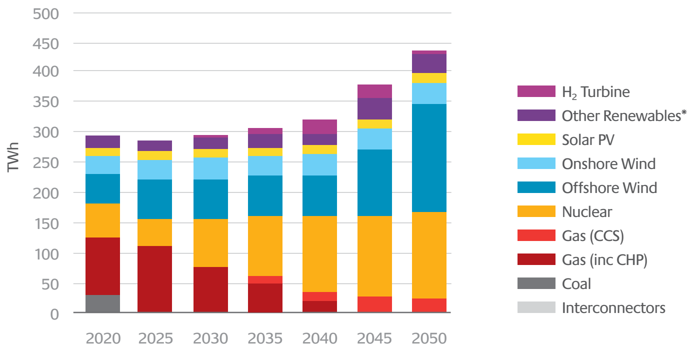
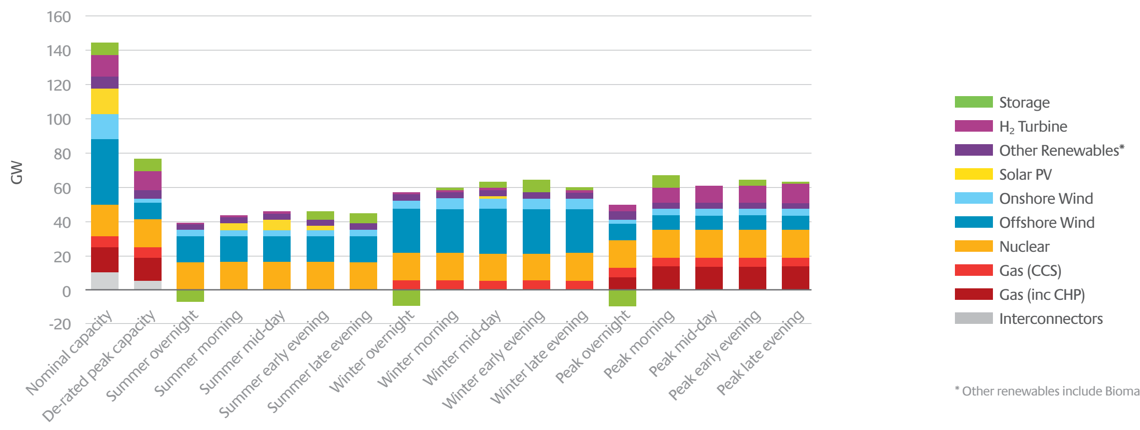


FIGURE 7 — Clockwork 2050 electricity supply by timeslice (for the average summer and winter days and a notional peak day)



* Other renewables include Biomass, Energy from Waste, Hydro and Tidal

Typical days in summer and winter may enjoy significant volumes of electricity from the large capacity of wind. This will mean there are many hours of the year where surplus generation can be used to boost hot water or space heat storage to support system balancing. On a peak day though, for security of supply reasons, the system must be resilient against de-rated capacity of renewables (shown as De-rated Peak Capacity). At these times, the various storage and backup technologies described above come into operation.

Around 16GW of solar PV is installed by 2020. Since Clockwork follows a strategic pathway in support of higher winter demand, the resulting capacity of wind and nuclear generation with low or zero marginal cost of production means any further PV capacity would begin to cannibalise its own market.

Electricity – Challenges and Implications

- 16GW of new Gen III nuclear is built by 2040 in this scenario. This is broadly equivalent to the collection of projects earmarked for Hinkley, Sizewell, Moorside, Wylfa Newydd, Oldbury and Bradwell.
- Assuming commercial CCS deployment is delayed until post-2025, there is a limited window of opportunity for this to support early decarbonisation of the power sector (i.e. to achieve near-zero emissions by the early 2030s).
- In this scenario, fossil-fuel power stations with CCS only emerge later, to play a seasonal balancing role with a low annual capacity factor.
- With declining electricity demand in the near term, the power sector sees aggregate build rates of 2GW/yr through the 2020s, sufficient to counter the retirement of coal and rolling replacement of other capacity.
- This rises to an average 5GW/yr from 2030-2050 to support increasing electricity demand for heating and transport.
- Reliance on 10GW of power from neighbouring electricity systems to help balance the UK electricity grid may present a risk to security of supply, if the generation mix in those other systems is not complementary to our own or there are political and commercial barriers to access.

PATCHWORK

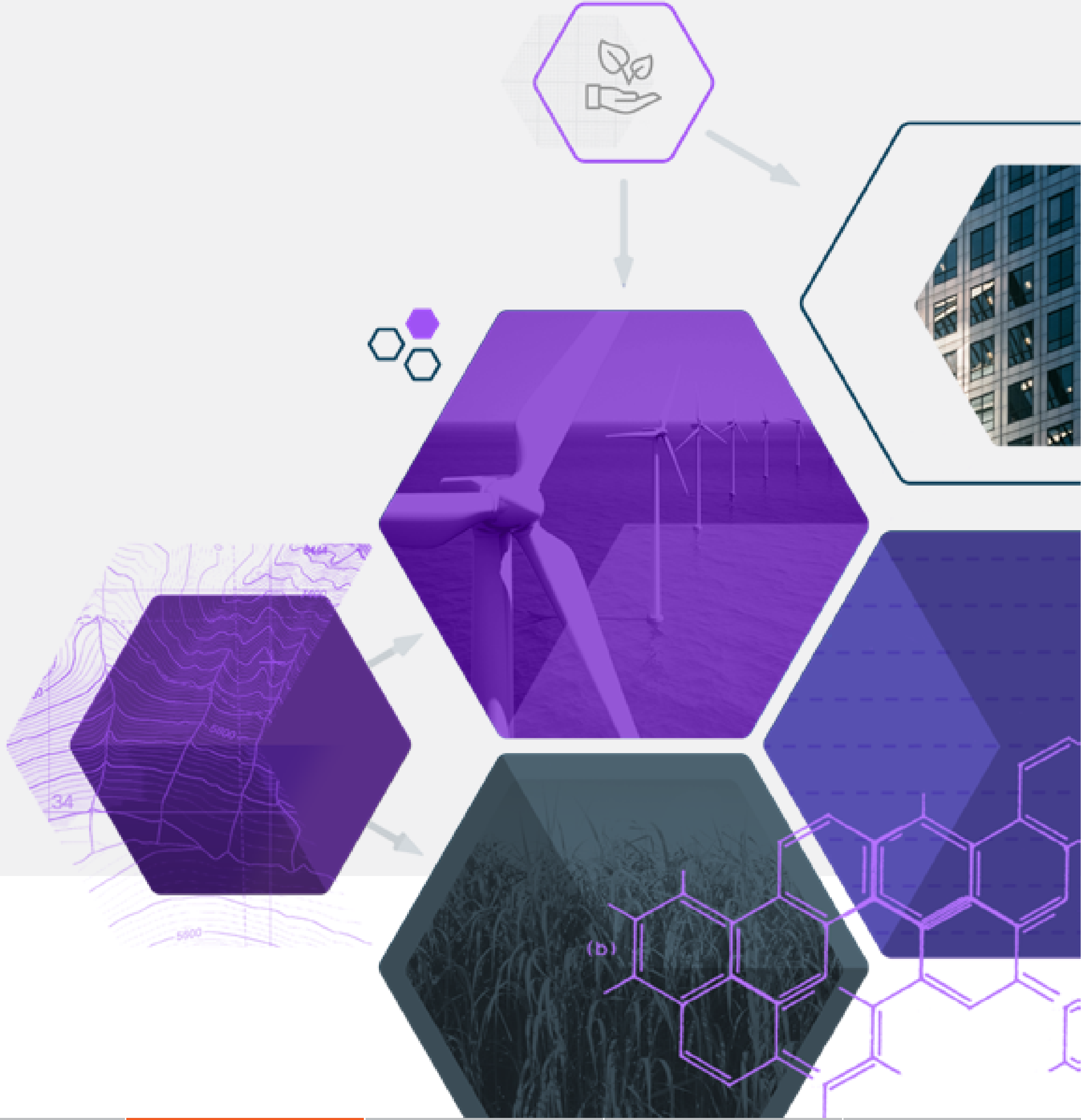
UK SOCIETY AND ECONOMY —

⟶ In the Patchwork scenario, the UK population grows by 8.5 million to reach 75 million by 2050, with cities outpacing the national average. This brings a shift towards higher density built environments and lower growth in private car ownership in favour of public transport. Urbanisation also ensures a sustained focus on local air quality.

Economic growth is fuelled by innovation. Energy-intensive heavy industry continues in a few areas but declines overall. Advanced manufacturing processes ensure that more value-added activities (high-tech, automotive) remain firmly established in the UK. New opportunities emerge in rapidly growing service-based sectors.

Opportunities for asset-sharing fit well with a more urbanised society and support a general dematerialisation of the economy. At the same time, a growing population with increasing household incomes and a thirst for new experiences drives growth in international travel.

PATCHWORK



PATCHWORK

ENERGY SYSTEM OVERVIEW —

⟶ With central government providing less strategic coordination, a patchwork of distinct energy strategies develops at a regional/sectoral level.

A new nuclear programme fails to materialise beyond an initial two facilities. Deployment of CCS infrastructure is held back, with the first demonstration projects delayed until 2030, and subsequent growth is constrained by lack of a coherent national plan. Lack of coordination also results in slower growth of a domestic bioenergy sector and more limited investment in port facilities for imported biomass resources.

Taken together, constrained bioenergy and CCS programmes limit the potential for negative emissions, meaning more comprehensive reduction of gross emissions is required across the energy system to meet legally binding targets.

PATCHWORK

BUILDINGS AND HEAT —

In Patchwork, a growing urban population leads to a significant shift in housing needs. By 2050 there are 34 million homes (with an average 35m^2 per person). New homes are predominantly apartments and terraced/semi-detached houses.

Out of today's 27 million homes, ten million undergo extensive retrofits.

Historical increases in indoor average temperatures level out from 2030, with higher energy prices curbing further growth.

This combination of lower demand, retrofits and a focus on higher density new housing leads to a reduction in energy for space heat by 2050.

Electrification

Electric heat pumps prove popular as consumers face increasing carbon prices. Electric storage heaters provide a complementary boost, harnessing electricity when it is more plentiful and cheap, to be released during periods of peak demand.

Where local electricity network capacity permits, electric resistive radiators can provide further peak capacity during cold weather events. For other areas, this is heavily discouraged due to stresses on the network, and secondary gas systems must be maintained here.

As electric systems gain consumer trust these grow to provide over 70% of space heat by 2050.

FIGURE 8 — Patchwork buildings space heat capacity (GW)

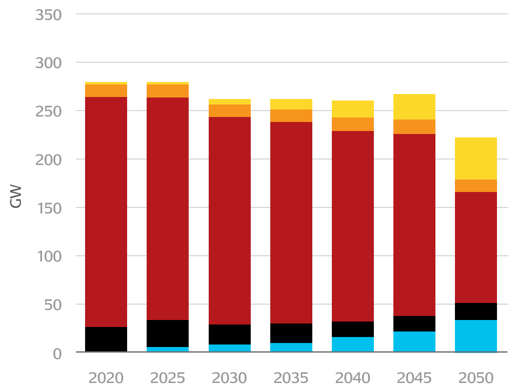
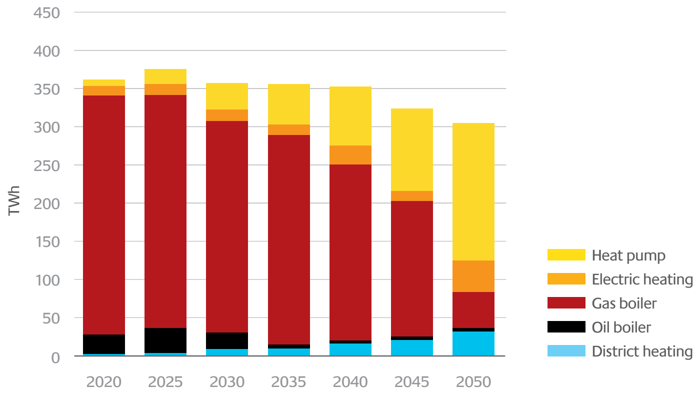


FIGURE 9 — Patchwork buildings space heat production (TWh)



PATCHWORK

BUILDINGS AND HEAT —

CONTINUED

District Heat networks

In many urban areas there is strong public engagement and support for community-scale district heat networks. Due to the initial small scale of these schemes, an eclectic mix of technologies is deployed to provide network heat. This includes different varieties of CHP fuelled by gas, biomass or waste.

Commercial heat pumps also play an important role. Since these can be expensive to run during periods of already high electricity demand (and/or low supply, given the high renewable mix) schemes with commercial heat pumps rely on significant heat storage facilities.

Over time, as these local schemes expand, they are gradually connected into larger networks to enhance their resilience against variations in supply and demand.

As scale and local strategy permits, recovered heat from Gas CCGT power plants with CCS provides a steady source of dispatchable heat from the 2040s.

Gas networks

Local strategies in many urban areas focus on district heat networks (and electrification of cooking appliances), with gas networks in those areas being largely decommissioned.

Other areas focus on electricity network reinforcement, motivated by support for electric vehicle charging but resulting in sufficient capacity to transition most home heating away from gas.

In areas where gas networks persist, these continue to carry natural gas. Hydrogen conversion fails to materialise without a national programme to drive investment in the necessary production, storage and transportation infrastructure. In a world of high carbon prices, natural gas boilers become expensive to operate and are reduced to the role of secondary systems for peak heating during cold winter days, with annual energy production in 2050 less than 50TWh.

Buildings and Heat – Challenges and Implications

- With much lower gas usage through distribution networks, standing charges will need to be increased to pay for ongoing maintenance if these are to provide reliable peak capacity. Below a certain threshold, the economics of network maintenance may suggest a gradual decommissioning in some areas and a shift towards bottled propane gas.
- Decarbonisation presents both risks and opportunities for tackling fuel poverty[10]. While Patchwork describes a more affluent society in general terms, the lower heat demand assumed here may result from poorer households being unable to afford the higher energy bills resulting from less strategic decision making.

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[10] "How Can People Get The Heat They Want At Home, Without The Carbon?", ESC, 2018, https://es.catapult.org.uk/publications/how-can-people-get-the-heat-they-want-at-home-without-the-carbon/

PATCHWORK

TRANSPORT —

Aviation and Shipping

In Patchwork, increasing household incomes lead to continued growth in passenger aviation demand.

With no fundamental breakthroughs in aviation technology, the sector must rely on operational efficiencies to mitigate against excessive emissions growth. By 2050 international aviation emissions are 10% higher than today.

Demand for shipping sees some modest growth in Patchwork, but a switch to dual-fuel (diesel and natural gas) engines ensures emissions are marginally lower than today.

Road Transport

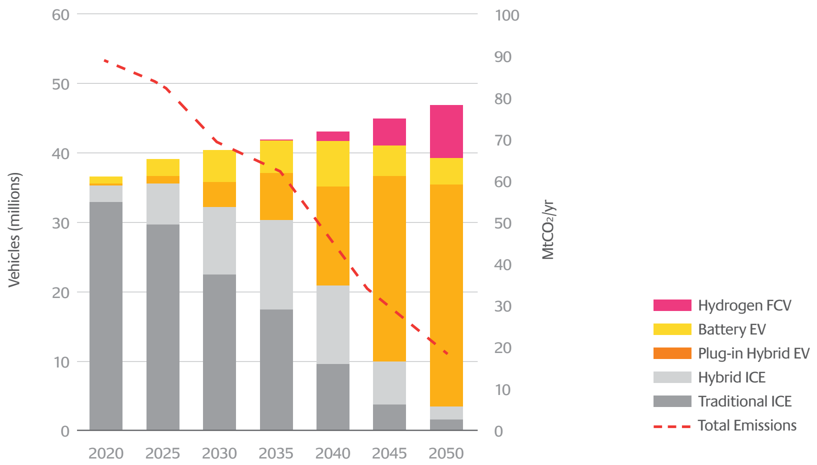
For light vehicles, sales of traditional ICE peak in 2020 as stringent fleet efficiency targets are imposed and local authorities adopt emissions controls in air quality hotspots. The light vehicle market quickly diversifies, with non-plug hybrid ICEs appealing to many as a familiar alternative.

With a ban on sales of new ICEs and hybrid ICEs from 2040, the market shifts towards PHEVs and pure BEVs.

With the rapid expansion of EVs, increasing stress is placed on the electricity distribution networks at times of peak demand. Pricing mechanisms are brought in to mitigate against this, including premium rates for convenience charging, meaning further growth in electric vehicles is concentrated on more flexible PHEV models.

Elsewhere, commercial fleet operators begin switching to hydrogen fuel cell vehicles (FCV) where the longer range and fast refuelling are especially important. Gradually, hydrogen refuelling is rolled out around major cities and motorways as more affluent consumers make the switch.

FIGURE 10 — Patchwork fleet of cars and vans (million vehicles, left; MtCO$_2$/yr, right)



PATCHWORK

TRANSPORT –

CONTINUED

In Patchwork, across all road transport (cars, vans, trucks, buses) final energy consumption peaks in 2020, as efficiency improvements – including substantial electrification – drive reductions year after year.

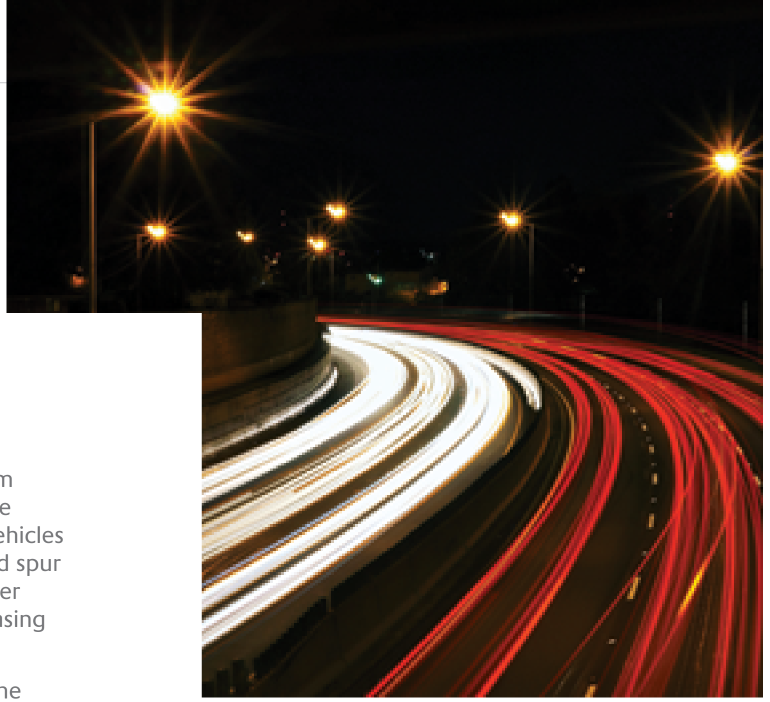
By 2050, electricity accounts for 70TWh of road transport energy use. Meanwhile liquid fuel use falls away dramatically from a peak of 430TWh to just 80TWh in 2050.

Natural gas acts as a lower carbon alternative to diesel in heavy-duty vehicles, with natural gas (and diesel/gas hybrid) vehicles making up 75% of all HDVs in 2040.

Hydrogen also emerges as an important energy vector in transport, accounting for 10% of final energy consumption by 2050.

Transport – Challenges and Implications

- As the market shifts away from traditional and hybrid ICEs, the second-hand value of these vehicles may rapidly decline. This could spur many consumers towards lower commitment asset-sharing/leasing models.
- For less affluent car owners, the diminishing value of their cars could impede the switch to lower carbon models, leaving them stranded and facing higher penalties in low emissions zones.
- Patchwork will require more substantial upgrades to electricity networks, with charging points off street, on street and at workplaces.
- Conventional refuelling stations may require financial support to meet the high upfront investment required for new hydrogen infrastructure and rapid electric charging points just as cashflow is declining from liquid fuel sales.
- UK refineries will struggle to survive in a Patchwork world, meaning residual demand for liquid fuels (including for aviation and shipping) may have to be met through imports.



> “AS THE MARKET SHIFTS AWAY FROM TRADITIONAL AND HYBRID ICEs, THE SECOND-HAND VALUE OF THESE VEHICLES MAY RAPIDLY DECLINE. THIS COULD SPUR MANY CONSUMERS TOWARDS LOWER COMMITMENT ASSET-SHARING/LEASING MODELS

PATCHWORK

INDUSTRY –

Traditional industries decline overall in Patchwork, as activity shifts into high-value design and manufacturing, and into a thriving services sector. Combined with efficiency improvements, by 2035 overall energy use for industry has declined 23% from current levels. By 2050 this has fallen 30% relative to today.

Natural gas continues to play an important part in industry, accounting for 33% of all energy use in the sector by 2050, while electrification accounts for another 33%. While these shares are fairly similar to today, the major difference is in the remaining shares, where liquid fuels decline from today’s 25% share to just 13% in 2050, a contribution eventually matched by hydrogen. Biomass and coal play a marginal role with 5% and 3% of energy respectively.

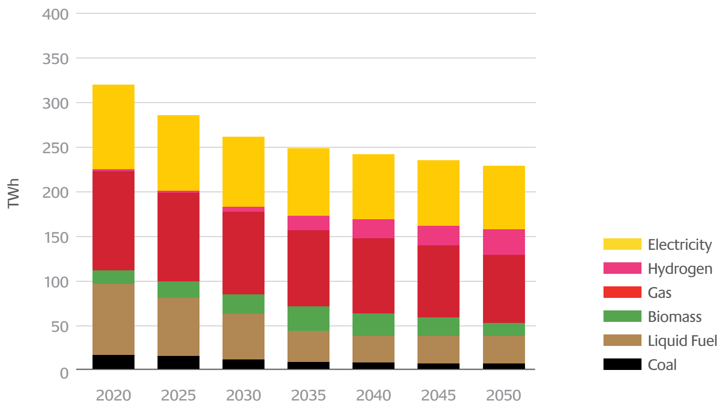
Given the lack of a national strategy on CCS, industry decarbonisation is carried forward more by the shift in industry composition than by technological change. Nevertheless, as a CCS programme eventually emerges, industry applications are rolled out resulting in 5MtCO_2 being captured annually by 2050.

Overall, industry emissions fall from around 60MtCO_2 today to 26MtCO_2 in 2050.

Industry – Challenges and Implications

- While Patchwork assumes lower industrial energy demand *a priori*, the lack of commitment to hydrogen and CCS hubs is likely to contribute to this by reinforcing a view that UK is unable to support a competitive and heavy industry sector in a low carbon economy.
- As part of this, some of the more energy-intensive activities may be moved offshore rather than displaced entirely. This may increase embedded emissions in imported goods and services.

FIGURE 11 — Patchwork industry energy consumption (TWh)



23%

Combined with efficiency improvements, by 2035 overall energy use for industry has declined 23% from current levels.

PATCHWORK

HYDROGEN –

Hydrogen production reaches almost 90TWh by 2050, being limited to this level by a slow roll-out of CCS, resistance to coal use and limits on UK and imported biomass.

Industry adopts hydrogen early on, relying on unabated Steam Methane Reforming to begin with, and later dedicated facilities for methane reforming with CCS. By 2050 industry accounts for 30TWh of hydrogen consumption. Another 23TWh is consumed in transport, while hydrogen turbines in the power sector consume 32TWh.

Geological storage requirements in Patchwork are modest, since consumption in industry and transport is fairly evenly distributed across the year, allowing production capacity to be sized according to need with only limited storage. Hydrogen use in the power sector is peakier, so 35GWh of hydrogen storage is deployed to smooth out daily fluctuations.

Hydrogen – Challenges and Implications

- The negative emissions resulting from bio-CCS hydrogen production are highly valuable when viewed in a whole systems context. In a Patchwork world with less coordination, there is a risk of failing to establish confidence in the accounting rules that reflect this value, which could create a barrier to investment.
- Steam methane reforming with CCS may encounter less resistance, while electrolysis will be championed by many as a cleaner alternative, but is a more expensive option for national-scale production.
- With the emergence of hydrogen fuel cell vehicles in transport, a high grade of hydrogen purity will be required, and this varies across methods of production and distribution. Centralised hydrogen production with transmission by trunk pipelines, delivery by tanker to more remote areas, and local production via distributed electrolysis may all have a role to play, with different implications for purification requirements.

> “WITH THE EMERGENCE OF HYDROGEN FUEL CELL VEHICLES IN TRANSPORT, A HIGH GRADE OF HYDROGEN PURITY WILL BE REQUIRED, AND THIS VARIES ACROSS METHODS OF PRODUCTION AND DISTRIBUTION.

PATCHWORK

ELECTRICITY GENERATION –

In Patchwork, electrification of heat and especially transport means annual electricity demand in 2050 rises to 520TWh (from around 300TWh today). Wind energy is the largest source of electricity by that point, providing 54% of annual generation.

Lack of a national programme to bring forward investment in new nuclear plants means only two projects are completed. Combined with legacy capacity still operating in 2050, these provide 8GW capacity and 12% of total annual generation.

Solar PV enjoys steady growth over the period, with over 40GW capacity providing 7% of electricity in 2050. Although the total annual contribution is fairly modest, there are many periods during summer days when solar provides a high share of electricity supply.

54%

Wind energy is the largest source of electricity by 2050, providing 54% of annual generation.

FIGURE 12 – Patchwork electricity capacity (GW)

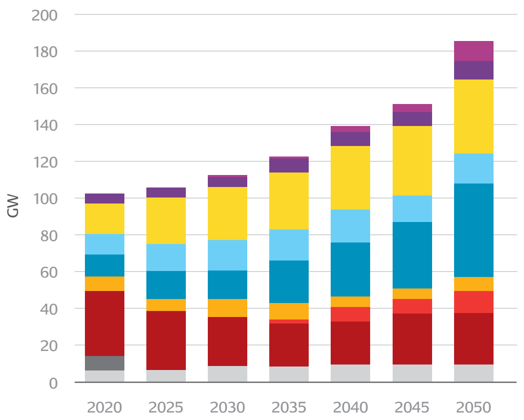
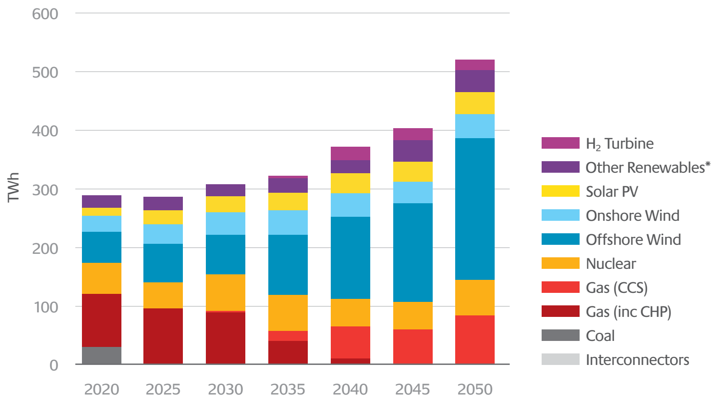


FIGURE 13 – Patchwork electricity generation (TWh)



* Other renewables include Biomass, Energy from Waste, Hydro and Tidal

PATCHWORK

ELECTRICITY GENERATION –

CONTINUED

Flexibility

As CCS infrastructure begins to emerge in Patchwork, this is quickly adopted for new gas-fired generation capacity to provide much needed dispatchable low carbon generation. By 2050, Gas CCS capacity reaches 13GW (waste gasification with CCS provides an additional 2GW). Since Patchwork is characterised by high electrification of transport, demand for which is broadly the same across the year, these CCS plants enjoy an average capacity factor of 75% and provide 20% of total electricity generation.

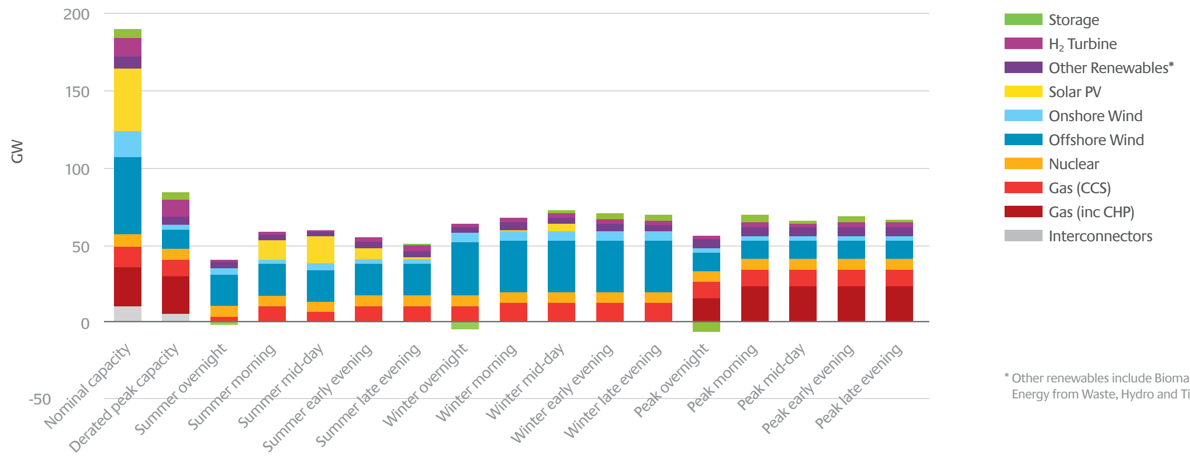
Day-to-day flexibility is provided by 5GW of electricity storage and 10GW interconnectors, with 12GW of hydrogen turbines providing further resilience on days when renewable output is low, storage is depleted and continental conditions mean interconnectors cannot be relied upon.

Since the design condition of the whole energy system is driven by winter peak heating demand, and since the system must be ready to meet this in the absence of any solar output and potential low wind conditions, a further 26GW of unabated gas backup is also kept in reserve, although rarely utilised, with annual load factors as low as 2% in some years.

Electricity – Challenges and Implications

- Despite the high deployment of wind and solar, without substantial deployment of either nuclear or CCS the Patchwork electricity system cannot be fully decarbonised until after 2040.
- Patchwork relies on historically unprecedented rates of annual capacity build. Aggregate build rates across this sector rise to 8GW/yr through the 2030s and 2040s.

FIGURE 14 – Patchwork 2050 electricity supply by timeslice (for the average summer and winter days and a notional peak day)



* Other renewables include Biomass, Energy from Waste, Hydro and Tidal

> AS CCS INFRASTRUCTURE BEGINS TO EMERGE IN PATCHWORK, THIS IS QUICKLY ADOPTED FOR NEW GAS-FIRED GENERATION CAPACITY TO PROVIDE MUCH NEEDED DISPATCHABLE LOW-CARBON GENERATION.

SECTION FOUR –

COMMENTARY

VERSATILITY OF HYDROGEN —

Hydrogen has the potential to play a highly versatile role in low carbon energy systems of the future. It can be produced in a variety of ways, it can be stored in vast quantities to mitigate peaks and troughs in demand, and it can be used in many different applications including industry high-temperature heat, peak power generation, fuel cell vehicles and potentially for heating buildings.

This versatility makes investment in de-risking hydrogen a low regrets option, despite uncertainty over the exact share of hydrogen consumption across each of these different markets.

Hydrogen production

Today, hydrogen is mostly used as a high-value feedstock in the chemical and refining industries, and most production is via Steam Methane Reforming, resulting in a sizeable carbon footprint.

For hydrogen to make sense in an energy context, it must be produced using low carbon methods. From our assessment of the full range of technology options, the most cost-effective solutions for large-scale production involve the use of carbon-based feedstocks (gas, coal, biomass) and so rely on CCS technology[11]. In the case of biomass gasification this results in negative emissions as valuable to the wider system as the hydrogen product itself.

Electrolysis is an alternative, using electricity to release hydrogen by cracking water molecules, with oxygen as the only by-product. This technology is sometimes promoted as a means of converting excess renewable generation to hydrogen, but the technology is capital intensive and low load factors would make investment unattractive.

On a smaller scale, distributed electrolysis (using low carbon electricity) could complement large-scale methods as part of a national hydrogen roll-out, particularly in remote areas with insufficient demand to justify the investment in dedicated hydrogen pipelines or delivery by truck[12].

Hydrogen consumption

Industry appears to be an obvious first choice for a nascent hydrogen market. This sector is already familiar with handling hydrogen as a process feedstock. Additionally, there are relatively few alternatives for industry carbon abatement, making hydrogen use almost inevitable in the longer term. Finally, where hydrogen is produced in large centralised CCS facilities, these are likely to be near existing centres of heavy industry (by serendipity, the best CO_2 storage sites lie in UK waters off some of our major industrial regions). This would minimise the need for immediate investment in long distance transmission infrastructure. As the market develops, dedicated pipelines could then be built out to support other sectors across the UK.

In the power sector, gas turbines are often used to provide occasional peak generation, but even with low average load factors the cost of carbon will start to challenge their economics of operation. By using hydrogen in place of natural gas, these peaking plants can continue to support the power system, especially as increasing amounts of intermittent renewables are deployed.

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[11] "Multi Vector Integration Study (Assessment of Local Cases)", ETI: http://www.eti.co.uk/programmes/energy-storage-distribution/multi-vector-integration

[12] "The importance of economies of scale, transport costs and demand patterns in optimising hydrogen fuelling infrastructure: An exploration with SHIPMod (Spatial hydrogen infrastructure planning model)" Agnolucci et al, 2013, https://doi.org/10.1016/j.ijhydene.2013.06.071

These would be part of a package of system flexibility solutions including demand side response, energy storage, and – in exceptional circumstances – open cycle (natural) gas turbines. Infrastructure needs can be kept to a minimum by siting hydrogen turbines close to centres of hydrogen production.

In transport, much depends on consumer attitudes and behaviours. In the consumer market, people may become relatively comfortable with the range and charging times associated with electric vehicles, meaning limited opportunity remains for hydrogen fuel cell vehicles once these are eventually ready for large-scale deployment. In the market for commercial vehicles (especially heavy-duty vehicles) the energy density of hydrogen over batteries may tip the scales. The economics of infrastructure roll-out would also favour the latter market, minimising the need for initial hydrogen refuelling facilities to a small number of commercial depots. Hydrogen for transport would likely be delivered through a combination of pipelines to major refuelling centres, along with truck deliveries to smaller facilities in the further reaches of the country.

Hydrogen for heat in buildings is just beginning to be explored seriously, with test and demonstration required before an accurate cost assessment can be made. In principle though, this could enable (parts of) the extensive UK gas distribution network (estimated at 275,000km in length[13]) to continue to provide a highly responsive means of heating homes. Inevitably though, the unit cost of hydrogen will be higher than for gas today, with resource extraction costs compounded by conversion costs (including losses) and CCS costs. As a result, it is highly unlikely that hydrogen for heat can avoid the need for (perhaps disruptive) interventions such as deep household retrofits and installation of electric heat pumps. If these measures are to be adopted anyway, then on a regional basis there will need to be strategic decisions as to whether it makes better sense to take these measures far enough that the gas network can be decommissioned altogether.

Hydrogen Transmission and Storage

A future hydrogen economy will require strategic investment in transmission and storage capacity. In the Clockwork scenario for example, most hydrogen production takes place in the East of England (in close proximity to CO_2 stores in the Southern North Sea). A hydrogen transmission network is deployed to meet demand across the country.

For industry, power and transport applications, this demand is reasonably well balanced across the year, meaning hydrogen production can be 'right-sized' with only a modest requirement for storage (e.g. to support bursts of a few hours for peak power generation).

Use of hydrogen for heating buildings implies a much more significant role for geological storage. To ensure sufficient hydrogen is available to cope with a 1-in-20-year cold weather event, many days' worth of hydrogen production would have to be stored. This is achieved in Clockwork by producing a surplus of hydrogen over the summer months, injecting this gradually into salt caverns. The most suitable geological formations for this are in the north of England.

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[13] "UK Network Transition Challenges – Gas", ETI, http://www.eti.co.uk/insights/uk-network-transition-challenges-gas

VERSATILITY OF HYDROGEN –

Since our population (and heat demand) is centred around London, the South East and West Midlands, this requires significant investment in hydrogen transmission capacity to ensure the necessary volume of hydrogen can be delivered southwards during these events.

High Hydrogen Pathway

In light of the current interest in hydrogen for heat, and with the inclusion of a hydrogen pathway in the Clean Growth Strategy (CGS)[14], we recently devised a pathway which assumes maximal use of hydrogen by energy consumers across heat, transport and industry: by 2050 all cars and vans on the road are hydrogen models, the gas distribution network is fully converted, and 20% of industrial energy use is from hydrogen. Also, consistent with the CGS, we prevented the use of bioenergy with CCS.

The production of hydrogen is consequently very high at over 530TWh in 2050 (vs ~160TWh for Clockwork, ~90TWh in Patchwork). This would require a huge investment to build the production, transmission and distribution infrastructure for an entire new energy sector, overtaking electricity generation in the space of 20 years. The pathway also hinges on the successful roll-out of CCS infrastructure from around 2030 (primarily applied to methane reforming).

The overall cost of meeting our targets in this way is discussed later.

> HYDROGEN HAS THE POTENTIAL TO PLAY A HIGHLY VERSATILE ROLE IN LOW CARBON ENERGY SYSTEMS OF THE FUTURE.

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[14] BEIS 2017 https://www.gov.uk/government/publications/clean-growth-strategy

OPTIMAL ELECTRIFICATION –

Whereas hydrogen requires the emergence of a new energy conversion sector, we can already see electricity used in buildings, transport and industry. In that sense, a low carbon electrification strategy would only require the expansion of a well understood and widely applied energy vector to displace the use of fossil fuels.

Indeed, some electrification of heat, transport and (to a limited extent) industry, will feature in any balanced, cost-effective low carbon pathways, as illustrated by Clockwork and Patchwork.

A general finding from our analysis is that electrification can always extend a bit further if other (more cost-effective) system-wide measures such as CCS or biomass are prohibited. However, there comes a point in each sector where the marginal cost of electrification gets very steep, for example in hard-to-treat buildings or in heavy-duty vehicles.

Electrification of light vehicles occupies an interesting middle ground at present. Set in the context of a system-wide decarbonisation, there appear to be more cost-effective ways of reaching our targets than pushing for early and complete electrification of cars and vans. In modelling terms, partial electrification via plug-in hybrids tends to be the optimal response to any pressure for further decarbonisation.

When modelling a highly electrified energy system pathway, we typically see significant deployment of nuclear power due to its low system cost (including the value of having dispatchable generation). To ensure that nuclear remains a viable option to support high electrification, the relevant actors in this industry must work together to deliver an integrated cost reduction programme[15].

High Electrification Pathway

For a recent high electrification pathway, we took a lead from the CGS electricity pathway where possible, ensuring that by 2050 all cars and vans on the road are battery electric; four out of five buildings use electric heat; one third of industry energy is electricity. In addition, this scenario does not permit CCS.

With 100% electric cars, and 80% of heat, total electricity generation in 2050 is over 630TWh (more than double from today). This would require around 35GW of new nuclear (the upper limit given siting constraints) and 64GW of wind. Although these are significant levels of deployment, it is not uncommon to see such high capacity of one or the other technology in some scenarios (e.g. 67GW Wind in Patchwork18, or 35GW Nuclear in Clockwork15).

The lessons from this run are as much about the prohibition on CCS as they are about the push for electrification.

Without negative emissions being generated from biomass with CCS, more comprehensive decarbonisation measures must be deployed across all sectors of the energy system. Heat and light transport have essentially been instructed to fully decarbonise anyway, but industry remains a challenge, given hard limits on the electrification potential of industrial processes and upper limits also on the availability of biomass to displace fossil fuel.

In a typical model run, CCS would allow direct abatement for any fossil fuel use in industry, but in this case the only remaining option is to use hydrogen. In the absence of CCS to support cost-effective hydrogen production from carbon-based feedstocks, this pathway sees electrolysis deployed at very high levels.

The cost implications of this and other runs are discussed overleaf.

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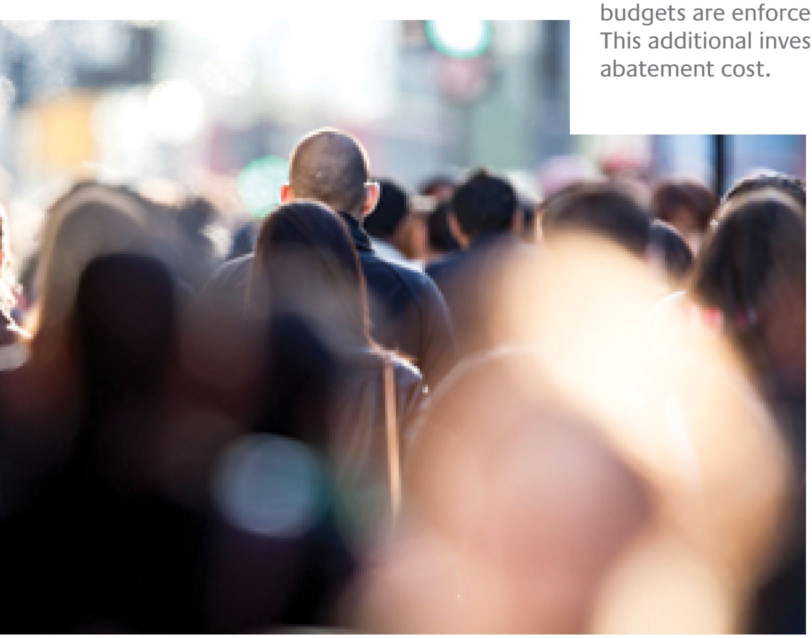
[15] ETI, 2018, http://www.eti.co.uk/news/cost-drivers-identified-to-support-investment-in-new-nuclear-power-and-its-role-in-the-uks-future-low-carbon-energy-system

INVESTING IN THE TRANSITION –

Due to the anticipated impact of climate change, failure to meet the Paris Agreement target could cost the global economy many times more than the estimated cost of mitigation[16].

With such a clear net benefit, it can seem incongruous to even talk about the 'cost' of transition. Nevertheless, we should aim to be efficient in the way we invest to achieve our emissions reduction targets, given the ongoing need for spending on other social goals such as education and healthcare. This efficiency will also free up capital for further investment in deeper reduction measures if we choose to adopt them.



A cost-effective transition would protect consumer welfare by achieving climate goals without undue pressure on household budgets. It would also leave room in national budgets to mitigate against any adverse distributional impacts on the most vulnerable in society (such as those in fuel poverty).

Acknowledging the clear net benefits then, it is important to have some basis for comparing the economic efficiency of alternative pathways for delivering these. To do this, we create a notional benchmark pathway in our model, where all our energy demands must be met but no carbon targets are applied. We can then assess the additional investment required when a series of carbon budgets are enforced out to 2050. This additional investment we call the abatement cost.

Cost comparison

Since Clockwork and Patchwork use different demand (and GDP) trajectories, strict comparison of the abatement cost is problematic. On the one hand, the lower energy service demand assumed in Patchwork makes this inherently easier to decarbonise (other things being equal). But once we apply the wider assumptions associated with each scenario narrative, where Clockwork enjoys a comparative advantage in technology options, the abatement cost of each run is very similar, reaching around 1% of GDP by 2050:

Clockwork
2050 annual abatement cost:
£36.4bn (1.06% of 2050 GDP)

Patchwork
2050 annual abatement cost:
£37.3bn (0.99% of 2050 GDP)

Meanwhile, our two illustrative pathways with high hydrogen and electrification (both using the same demands as Clockwork) see considerably higher costs in 2050:

High Electric
2050 annual abatement cost:
£78.5bn (2.28% of 2050 GDP)

High Hydrogen
2050 annual abatement cost:
£121bn (3.51% of 2050 GDP)

It is worth noting the High Electric run includes a prohibition on CCS, which accounts for a sizeable portion of the added cost of this scenario (in a standard 'no CCS' ESME pathway we see the 2050 annual abatement cost double to around 2% of GDP).

For the hydrogen pathway, the cost implications seem clear: a strategy to enforce comprehensive adoption of hydrogen across the economy looks grossly inefficient based on current understanding of the relevant technologies.

Capital spend

The capital spend shown below provides a summary of where upfront investments would be required across the energy system in each decade. In terms of total cumulative investment, Patchwork is higher at £2.39tn, compared to Clockwork at £2.26tn.

Transport accounts for the bulk of this investment in both cases and is higher in Patchwork due to the higher upfront cost of ultra-low carbon vehicles, this is despite having fewer light vehicles overall compared to Clockwork.

In buildings, Patchwork benefits from an assumption of heat demand levelling out from 2030 whereas investment climbs in Clockwork to support increased comfort levels in larger homes, despite a lower population.

Capital Spend (£bn 2010 GBP)

Clockwork	2020s	2030s	2040s	Patchwork	2020s	2030s	2040s
Industry	6	10	7	Industry	4	10	7
Power & conversion	35	74	92	Power & conversion	42	82	88
Buildings & heat	172	192	250	Buildings & heat	177	208	211
Transport	418	470	441	Transport	497	471	493
Infrastructure	7	24	64	Infrastructure	9	31	61

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[16] Burke et al (2018) "Large potential reduction in economic damages under UN mitigation targets" https://www.nature.com/articles/s41586-018-0071-9

NEGATIVE EMISSIONS —

Clear strategies for bioenergy and for CCS are critical to delivering an affordable energy system transition in the UK. With both solutions available, we see a role for ‘negative emissions’ by combining atmospheric removal of carbon through biomass growth with permanent removal through CCS. Out to 2050, these negative emissions create headroom for continued fossil fuel use in hard-to-treat sectors (like aviation and shipping) as well as hard-to-treat non-CO_2 emissions outside of the energy system.

Pathways without one of these core solutions require more expensive alternative measures. By 2050, we estimate that annual abatement costs would be roughly 50% higher without bioenergy, or 100% higher without CCS. Without either of these solutions, achieving 2050 targets would require carbon prices that would push industry offshore and put international air travel out of reach for most people.

As part of the Paris Agreement ambition to limit the rise in global temperature to within 1.5°C, it is widely recognised that the world will need to achieve ‘net zero’ annual emissions sometime this century. On a country-by-country basis, target dates for net zero will vary according to ability and ambition. The UK Government has already requested advice from the CCC on the implications for the UK of aligning carbon targets with a 1.5°C ambition.

If the UK is to achieve net zero emissions early in the second half of the century, it is difficult to imagine how this can be achieved without use of negative emissions from bioenergy and CCS (BECCS).

Globally, the Intergovernmental Panel on Climate Change (IPCC) emissions pathways that meet the 1.5°C target typically rely on extensive use of negative emissions[17]. Recently, a collection of alternative studies have explored pathways that meet the targets with less or no reliance on negative emissions[18], by combining low assumptions for a range of other drivers including population growth, lifestyle change, international aviation growth and (non-CCS) low carbon technology costs.

Such low demand scenarios are part of the envelope of possible futures, but the reliance on multiple factors in combination puts these at one end of a spectrum of plausible outcomes. Furthermore, in many pathways featuring low demand, this would occur precisely because of limited optionality on the supply side, with higher carbon prices beginning to constrain lifestyle choices. This implicitly assumes the political will would exist to continue pushing for further emissions reductions despite these socio-economic impacts.

Continued investment in a range of supply-side options – including BECCS – mitigates against the risk of under-delivery from proactive demand side measures, limiting the need for reactive and unpopular measures that might threaten progress entirely. Current increasing interest in technologies for capturing CO_2 directly from the atmosphere and storing this securely for many hundreds of thousands of years in geological formations reflects concerns that the world will exceed the allowable total greenhouse gas emissions by around 2050, requiring more significant negative emissions than BECCS alone can provide[19].

> IF THE UK IS TO ACHIEVE NET ZERO EMISSIONS EARLY IN THE SECOND HALF OF THE CENTURY, IT IS DIFFICULT TO IMAGINE HOW THIS CAN BE ACHIEVED WITHOUT USE OF NEGATIVE EMISSIONS FROM BIOENERGY AND CCS (BECCS).

1.5°C

The UK Government has already requested advice from the CCC on the implications for the UK of aligning carbon targets with a 1.5°C ambition.

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[17] IPCC 2014, Summary for Policymakers https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf

[18] e.g.: Grubler et al, 2018, “A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies” https://www.nature.com/articles/s41560-018-0172-6 Van Vuuren, D. et al. (2018) Alternative pathways to the 1.5C target reduce the need for negative emission technologies, Nature Climate Change https://www.nature.com/articles/s41558-018-0119-8

[19] “Lowest Cost Decarbonisation for the UK: The Critical Role of CCS”, 2016, http://www.ccsassociation.org/news-and-events/reports-and-publications/parliamentary-advisory-group-on-ccs-report/

SECTION FIVE –

SUMMARY

SUMMARY –

In our 2015 scenarios publication, we emphasised that it was not possible to advocate for a single energy system blueprint out to 2050. Instead we recommended the UK focused on developing a basket of options from among the most promising supply and demand technologies. That message has not changed.

Clockwork and Patchwork are not forecasts, but rather two plausible scenarios. Our analysis shows that there are many pathways to a low carbon UK energy system within a wide range of variation.

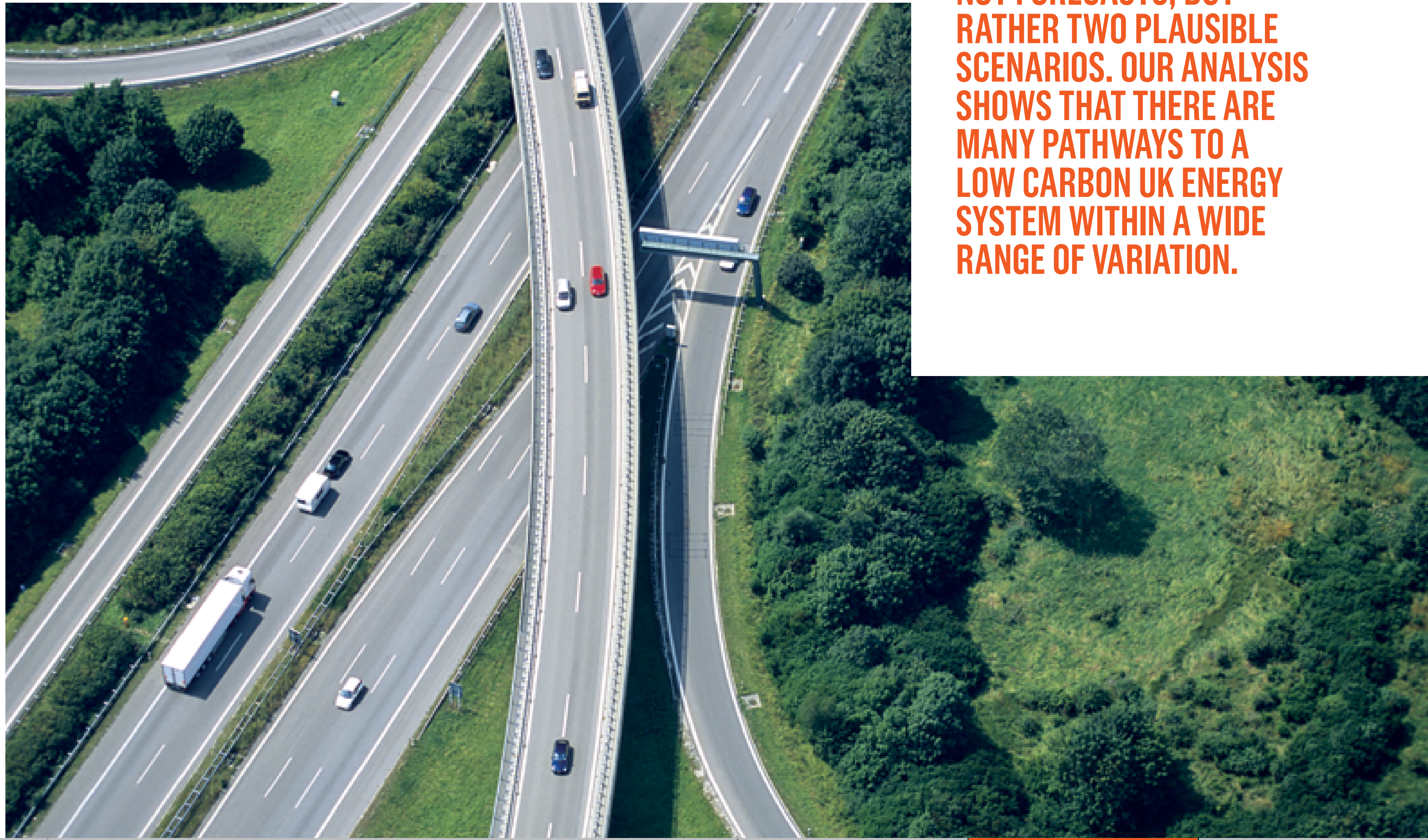
We know that in scenarios featuring a balanced, multi-vector approach it is possible to achieve long-term emissions targets while keeping costs to around 1% of GDP in 2050. If key technologies are taken off the table, these costs will inevitably rise, jeopardising UK industrial competitiveness and limiting lifestyle choices.

At a whole system level, bioenergy and CCS have consistently come out as the highest value options in our modelling and analysis. The prospect of net zero emissions targets has given new urgency to the development of a clear strategy for these technologies.

Although there are many possible future UK energy systems, and we cannot be certain which combination of technologies will best meet our 2050 needs, this update has left our recommended priorities for commercial development as bioenergy, CCS, offshore wind, new nuclear, gaseous systems, efficiency of vehicles and efficiency of heat provision for buildings.

The ETI has always taken its analysis down to practical detail, to avoid high level recommendations that cannot be made to work in practice. Our priority for further development of analysis by others is granularity: in electric vehicle charging and in retrofitting the fabric and heating systems of buildings. Although drivers and building occupants will fit within a wider energy system, that system needs to be designed and operate to meet their needs within their specific circumstances. Each of us needs cleanliness, comfort and mobility that is affordable, reliable and sustainable and the provision must be on an equitable basis.

We have refreshed Clockwork and Patchwork as part of the ETI's legacy of insights and evidence. The scenario team now takes this work forward within the Energy Systems Catapult. We hope that this publication will once again stimulate discussion with stakeholders across the energy system as we continue to learn together about the key options and choices facing decision-makers across the UK.



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ETI Scenarios 2015
www.eti.co.uk/insights/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system

> WE HAVE REFRESHED CLOCKWORK AND PATCHWORK AS PART OF THE ETI'S LEGACY OF INSIGHTS AND EVIDENCE. THE SCENARIO TEAM NOW TAKES THIS WORK FORWARD WITHIN THE ENERGY SYSTEMS CATAPULT. WE HOPE THAT THIS PUBLICATION WILL ONCE AGAIN STIMULATE DISCUSSION WITH STAKEHOLDERS ACROSS THE ENERGY SYSTEM AS WE CONTINUE TO LEARN TOGETHER ABOUT THE KEY OPTIONS AND CHOICES FACING DECISION-MAKERS ACROSS THE UK.

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