Research Councils UK Energy Programme Strategy Fellowship

ENERGY RESEARCH AND TRAINING PROSPECTUS: REPORT NO 10

Energy Infrastructure

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Research Councils Energy Programme

The Research Councils UK (RCUK) Energy Programme aims to position the UK to meet its energy and environmental targets and policy goals through world-class research and training. The Energy Programme is investing more than £625 million in research and skills to pioneer a low carbon future. This builds on an investment of £839 million over the period 2004-11.

Led by the Engineering and Physical Sciences Research Council (EPSRC), the Energy Programme brings together the work of EPSRC and that of the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC), and the Science and Technology Facilities Council (STFC).

In 2010, the EPSRC organised a Review of Energy on behalf of RCUK in conjunction with the learned societies. The aim of the review, which was carried out by a panel of international experts, was to provide an independent assessment of the quality and impact of the UK programme. The Review Panel concluded that interesting, leading edge and world class research was being conducted in almost all areas while suggesting mechanisms for strengthening impact in terms of economic benefit, industry development and quality of life.

Energy Strategy Fellowship

The RCUK Energy Strategy Fellowship was established by EPSRC on behalf of RCUK in April 2012 in response to the international Review Panel's recommendation that a fully integrated 'roadmap' for UK research targets should be completed and maintained. The position is held by Jim Skea, Professor of Sustainable Energy in the Centre for Environmental Policy at Imperial College London. The main initial task is to synthesise an Energy Research and Training Prospectus to explore research, skills and training needs across the energy landscape. Professor Skea leads a small team at Imperial College London tasked with developing the Prospectus.

The Prospectus contributes to the evidence base upon which the RCUK Energy Programme can plan activities alongside Government, Research, Development and Demonstration (RD&D) funding bodies, the private sector and other stakeholders. The Prospectus highlights links along the innovation chain from basic science through to commercialisation. It is intended to be a flexible and adaptable tool that takes explicit account of uncertainties so that it can remain robust against emerging evidence about research achievements and policy priorities.

One of the main inputs to the Prospectus has been a series of four high-level strategic workshops and six in-depth expert workshops which took place between October 2012 and July 2013. The main report, *Investing in a brighter energy future: energy research and training prospectus*, was published in November 2013. This is one of nine topic-specific documents supporting the main report. All reports can be downloaded from www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports. This first version of the Prospectus will be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This report is the product of work conducted independently under EPSRC Grant EP/K00154X/1, RCUK Energy Programme: Energy Strategy Fellowship. The draft report was reviewed by Goran Andersson of ETH Zurich, Jeff Hardy of Ofgem and Nick Jenkins of Cardiff University. While the report draws on extensive consultations, the views expressed are those of the Fellowship team alone.

Contents

Executive Summary

This report covers energy infrastructure, i.e. the physical assets associated with transporting electricity, gas, heat, and hydrogen from suppliers to consumers, as well as the transport of CO_2 from capture processes to storage sites. The management and regulation of infrastructure is also in scope. The report also covers 'smart' grid technologies, i.e. the IT-based management of interactions between suppliers and consumers. The conclusions from a two-day, facilitated expert workshop attended by academics along with representatives from the private sector and public sector organisations has been one of the most important inputs to this report. The report sets these conclusions in the context of the UK's scientific and industrial capabilities, policy ambitions, global and UK developments and outputs from existing roadmaps and needs assessments.

The main findings are:

- Significant development in energy infrastructure is critical to the UK's energy future. Significant asset replacement and upgrades will be required even in the event of no significant decarbonisation of the energy system. The increasing quantities of intermittent low-carbon generation and distributed generation found in many decarbonisation scenarios will require a substantial reworking of the UK's infrastructure.

- Research in this sector, especially on power networks, is well-funded via a combination of research council grants, other public innovation bodies such as the Technology Strategy Board and the Energy Technologies Institute, industry programmes and the Low Carbon Network Fund administered by Ofgem. There are potential saturation issues arising from a lack of academic capacity in relation to the volume of work available, and efforts to retain and develop academic researchers in this sector are important.

- There are substantial global opportunities for UK academics in this sector in providing technology, expertise and consultancy services to other nations. Academics and the research councils should be open to international collaboration on a best-with-best basis, and ensure that UK research helps inform and define EU and global standardisation and interoperability efforts.

- The Low Carbon Network Fund has significantly expanded the funding available in this sector since its introduction. The Research Councils and Ofgem should work closely together to harmonise research directions and programmes, as well as to outline clear divisions of research areas and responsibilities along the innovation chain.

- Attention should be given to collecting and curating data from smart meter trials, as this will provide valuable research opportunities for social scientists, economists and engineers. This will require careful attention to issues such as data confidentiality and protection of intellectual property.

- Shared demonstration and testing facilities between industry and academia would allow greater sharing of expertise and working methods between industrial and academic researchers. Secondments of PhD students and early-career postdocs into industry and government should be supported.

Acronyms

AC	alternating current
AMI	Advanced Metering Infrastructure
BBSRC	Biotechnology and Biological Sciences Research Council
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CDT	Centre for Doctoral Training
CEGB	Central Electricity Generating Board
CHP	Combined heat and power
CHPA	Combined Heat and Power Association
CO_2	carbon dioxide
DECC	Department of Energy and Climate Change
DER	Distributed Energy Resources
DSM	Demand-side management
DNO	Distribution Network Operators
EC	European Commission
EERA	European Energy Research Alliance
EII	European Industrial Initiative
EMR	Energy Market Reform
ENA	Electricity Networks Association
ENSG	Electricity Networks Strategy Group
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
ETP	Energy Technology Perspectives
EV	electric vehicle
FACTS	Flexible AC Transmission System
FP7	Framework Programme 7
GB	Great Britain
GERG	European Gas Research Group
GHG	greenhouse gas
HNDU	Heat Networks Delivery Unit
HVDC	high-voltage direct current
ICT	Information and Communication Technology
IEA	International Energy Agency
IET	Institution of Engineering and Technology
IP	intellectual property
LCICG	Low Carbon Innovation Carbon Group
LCNF	Low Carbon Network Fund
LHNE	London Hydrogen Network Expansion
LVDC	low-voltage direct current
MARKAL	Market Allocation (Model)
NCIL	no clear international lead
NERC	Natural Environment Research Council
NIC	Network Innovation Competition
NTS	National Transmission System
Ofgem	Office of Gas and Electricity Markets

R&D	Research and development
RCUK	Research Councils UK
RD&D	Research, development & demonstration
RIIO	Revenue = Incentives + Innovation + Outputs (Ofgem)
SO	System Operator
STFC	Science and Technology Facilities Council
TINA	Technology Innovation Needs Assessment
TRL	Technology Readiness Level
TSB	Technology Strategy Board
TYS	Ten Year Statement
UKERC	UK Energy Research Centre

1 Introduction

This document is one of a series of reports that sets out conclusions about UK research and training needs in the energy area. The focus of this report is energy infrastructure systems and components. The primary audience is Research Councils UK (RCUK) which supports energy research in UK higher education institutions through the RCUK Energy Programme.[2] However, other bodies involved in funding energy research and innovation, notably those involved in the UK's Low Carbon Innovation Carbon Group (LCICG)[3] may also find the content useful. The report is also being disseminated widely throughout the UK energy research and innovation community to encourage debate and raise awareness of the work conducted under the Fellowship.

The Fellowship team is using the EU/International Energy Agency (IEA) energy Research and Development (R&D) nomenclature[4] to map out the energy research landscape. This report covers sections within Group II **Fossil Fuels: Oil, Gas and Coal,** specifically sections II.1.2.4-2.10 **Gas storage and transport** and II.3.2 **CO_2 transport.** It also covers sections within Group V **Hydrogen and Fuel Cells,** specifically sections V.1.3 **Hydrogen Storage and Distribution** and V.1.4 **Hydrogen: Other Infrastructure and Systems R&D,** and Group VI **Other Power and Storage Technologies** specifically VI.2 **Electricity Transmission and Distribution.** Heat networks, represented under Group I.4 **Energy Efficiency - Other** are also covered by this report.

The conclusions respond to a recommendation of the 2010 International Panel for the RCUK Review of Energy[5] that the research supported by the Research Councils should be more aligned with the UK's long-term energy policy goals. The key criteria used in developing this report have been the three pillars of energy policy – environment, affordability and security – coupled with potential contributions to UK growth and competitiveness.

The most important input to this report has been a two-day, facilitated expert workshop held at the Institution of Engineering and Technology (IET) Austin Court, Birmingham on 17-18 April 2013. There were 23 participants at the workshop (excluding the Fellowship and facilitation team), most of whom were academics and researchers falling within the communities supported by the Engineering and Physical Sciences Research Council (EPSRC). In addition, a number of participants attended from private sector and government organisations. A full report of the workshop has previously been published as a working paper, which acted as a document of record and represents an intermediate step in the production of this report, which focuses on key messages and recommendations. The workshop also drew on the outcomes of a series of 'strategy' workshops which addressed: **energy strategies and energy research needs; the role of the environmental and social sciences;** and **the research councils and the energy innovation landscape.** Reports of these workshops are also available on the Fellowship website.[6]

This report is structured as follows. **Sections 2-4** provide the wider context within which research and training challenges are identified. Section 2 focuses on the possible role of energy infrastructure in future energy systems both globally and in the UK. Section 3 describes the current UK research landscape and capability levels. Section 4 reviews existing roadmaps and assessments of research and

[2] http://www.rcuk.ac.uk/research/xrcprogrammes/energy/Pages/home.aspx
[3] http://www.lowcarboninnovation.co.uk/
[4] http://ec.europa.eu/research/energy/pdf/statistics_en.pdf
[5] http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/ReviewOfEnergy2010PanelReportFinal.pdf
[6] http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports

innovation needs. **Sections 5-8** draw heavily on the Birmingham workshop. Section 5 sets out high-level research challenges in three broad application areas as well as a set of underpinning challenges. Annex B delves more deeply into these research challenges and identifies specific research questions that need to be addressed. Section 6 focuses on the ways in which the research councils operate, how the research they support is conducted and underlying needs for research infrastructure and data collection/curation. Many of the conclusions are generic in the sense that they may be applicable beyond the energy infrastructure area, across the energy domain or even more widely. Section 7 addresses training provision. Section 8 addresses generic issues about the role of the research councils within the wider UK energy innovation system and EU/international engagement. **Section 9** outlines the key conclusions and recommendations from the report.

2 Current and future roles of energy infrastructure

2.1 Global perspectives

Energy infrastructure is an essential part of any energy system given that energy is normally consumed some distance away from where it is generated. The four mature and widespread energy infrastructure systems globally are: 1) the electricity transmission and distribution networks, which transmit electricity from power stations to consumers; 2) the gas transmission and distribution networks, which deliver gas to consumers for heating and cooking; 3) the oil supply networks, which transfer crude oil to refineries and the refined products to end-users; and 4) the heat supply networks, which transfer generated heat to consumers. Of these, the electricity, gas and heat networks are in scope of this report, whilst the oil supply network was covered in Prospectus Report 5: **Fossil Fuels and Carbon Capture Storage.** There are also several types of emerging energy networks – hydrogen and carbon dioxide (CO_2) networks being the most prominent. Heat networks have been used successfully in many countries for over a century, but thus far have played a relatively small role in the UK.

Electricity transmission networks consist mainly of large capacity, high-voltage lines, which are designed to move electricity long distances from large generation plants to centres of demand. Electricity distribution networks take electricity from these high-voltage transmission networks and supply it to individual consumers through a system of lower-voltage lines.

Until the mid-2000s, electricity networks were considered to be a relatively mature sector considering that the basic concepts and technologies had not changed significantly since the post-war period and only incremental advances in efficiency and costs were being achieved. However, the rise of intermittent and inflexible low-carbon generation sources and distributed generation, along with new advances in information and communication technologies (ICT) enabling greater consumer tariff flexibility, demand-side participation and more flexible network management have spurred new interest in developing electricity network technologies.

Although district heating supplies only 1% of UK households, many other European countries use district heating extensively, including Denmark with 86% of homes heated and Sweden, Poland and Estonia with around 50%. District heat networks with heat supplied by combined heat and power (CHP) plants have been considered as a vector in decarbonising the heating system.

Hydrogen energy networks are still in an embryonic state internationally, with no large-scale networks for energy delivery yet rolled out worldwide, though several networks exist for chemical production purposes. There have been detailed studies and models of CO_2 pipeline networks to connect capture plants to storage sites across the UK and Europe.[7] Small-scale trial networks for hydrogen delivery have been built primarily in the US, Germany, Japan and Iceland, and the UK has built several hydrogen fuelling stations in and around London.

2.2 UK perspectives

2.2.1 Electricity

In 1926 the UK government passed the Electricity (Supply) Act which led to the establishment of the Central Electricity Board. It was mandated to set up a national alternating current AC electricity grid, running at 50Hz and 132kV. By 1938 a series of regional grids had been joined together into a single national electricity transmission system. From 1965, the transmission grid was partly upgraded to 400kV. Until 1989, this grid was nationalised and run by the Central Electricity Generating Board (CEGB), a vertically integrated organisation running the electricity system from generation to supply. In 1989, the CEGB was split up and privatised into separate generation, transmission and distribution companies.

The Great Britain (GB) transmission grid is privatised and run by three operators: 1) National Grid, which covers England and Wales; 2) SP Energy Networks, which covers the south of Scotland; and 3) Scottish and Southern Energy Power Distribution, which covers the north of Scotland. The electricity network is coordinated and operated by the System Operator (SO), which is the National Grid.

There are 14 electricity distribution network regions covering Great Britain. Each network region is run by a Distribution Network Operator (DNO), a private company with a mandate to operate and maintain the network in that region. Six groups in total own the 14 licenses. In some other countries, electricity is supplied to customers by a vertically-integrated company, which owns the networks and often generation plants. In Britain's liberalised system, electricity suppliers are separated from owners of the transmission and distribution networks, and pay to transfer energy across the networks to their customers.

The UK has set ambitious greenhouse gas (GHG) emission reduction targets, aiming to achieve an 80% reduction from 1990 levels by 2050. Multiple pathways have been proposed to reach this target from different government, academic and industry organisations. The majority of these pathways focus on decarbonising the electricity system relatively quickly and then supplying heating and transport needs with a mixture of greater electrification, biomass and fossil fuels. Current low-carbon generating technologies, such as nuclear and wind energy, are less flexible in generating output than conventional fossil-fuel power stations owing to the inherent characteristics of the energy source. There is also the issue of location; given that the majority of the most productive on- and off-shore wind farm sites are located in the North of England and in Scotland, significantly greater electricity transmission capacity will be required to carry the generated electricity to major demand centres in the South.

National Grid produces forecasts for electricity demand and supply, as well as the transmission grid requirements needed to service these needs. Ten Year Statements (TYS) (until recently Seven Year Statements) are published annually for both the electricity and gas networks,[8] and incorporate a range of scenarios for the development of the transmission and distribution system that take into account the uncertainty of the future energy generation mix into account.

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[7] **Europe-wide CO_2 Infrastructures**, European Commission, 2010, http://ec.europa.eu/energy/coal/studies/coal_en.htm

[8] National Grid: **Ten Year Statement**: http://www.nationalgrid.com/uk/Electricity/ten-year-statement/current-elec-tys/

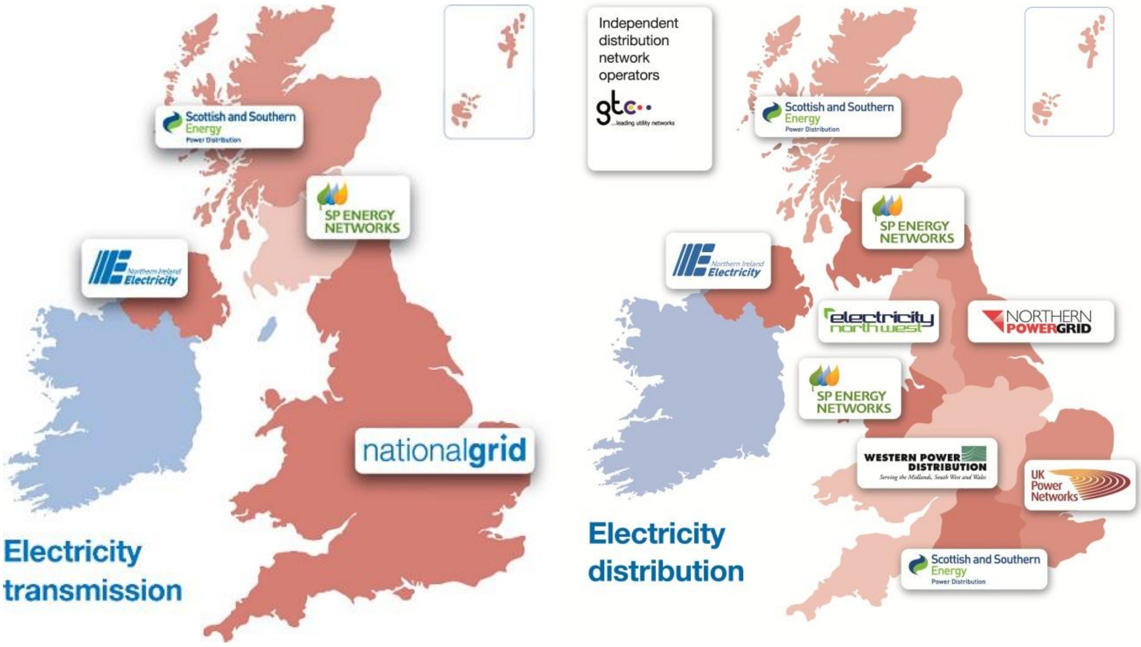

Figure 1: Maps of the UK electricity transmission and distribution networks by owner © Electricity Networks Association

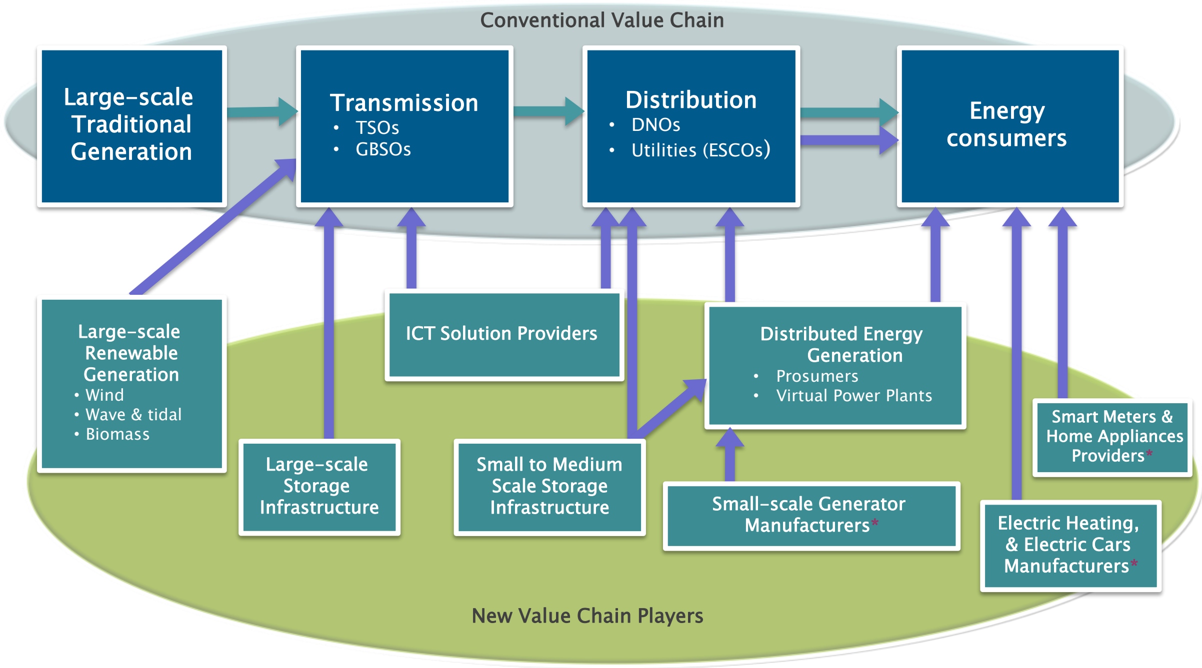

Figure 2: Potential new technologies and services for electricity networks (© 2011 EG&S KTN[9])

[9] **UK Smart Grid Capabilities Development Programme,** Energy Generation and Supply Knowledge Transfer Network, 2011, https://connect.innovateuk.org/web/energyktn/publications

It is foreseen that very significant investment will be required over the next decade in the UK's energy networks. In 2010, Ofgem, the UK's energy regulator, forecast that £32 billion worth of investments in the electricity and gas networks in the UK will be required over the next decade to incorporate new generation and patterns of demand, as well as to replace and update aging infrastructure. Figure 2, below, shows the new vectors and players that could enter the electricity industry value chain.

Ofgem also perceived that the RPI-X price control mechanism, used to regulate the regional monopolies of the electricity networks, was not stimulating sufficient investment efforts by the operating companies in their assets. The RPI-X mechanism, which caps prices at the rate of inflation minus an efficiency constant, was viewed to have driven down costs at the expense of investment in assets and innovation. In 2010 Ofgem unveiled a successor to RPI-X named RIIO (Revenue = Incentives + Innovation + Outputs). This scheme is designed to move to output-based incentives, to incentivise greater spending on innovative technology and business models, as well as encouraging greater investment in physical assets on the networks.[10] The RIIO mechanism is currently running for electricity transmission and gas transmission and distribution, and will be adopted for electricity distribution in 2015.

Smart metering technologies, distributed generation, flexible time-of-use tariffs and increased quantities of electric vehicles and heating require advances in system operation and flexibility. This will require significant innovation investments in the transmission and distribution networks. In order to cover this 'gap' in innovation funding Ofgem launched the Low Carbon Network Fund (LCNF), providing £500 million funding to develop and demonstrate innovative technologies and business models on the distribution networks in the 2010-2015 period.

Estimates from the completed electricity transmission and gas transmission and distribution RIIO price controls, as well as the currently running LCNF, put the resource earmarked for innovative projects as approximately £158 million per annum, with £100 million of this from the LCNF, £19 million from electricity transmission and £39 million from the gas networks. From 2015, there will be a Network Innovation Competition (NIC) for the electricity networks, and one for the gas networks. The exact value of this competition is still to be confirmed.

2.2.2 Gas

The gas transmission and distribution networks in the UK are privatised in a similar manner to the electricity networks – National Grid owns and operates the GB gas transmission system, known at the National Transmission System (NTS) and the gas distribution systems are divided into eight regions, which are owned by separate gas DNO companies. The networks are regulated by Ofgem, and were moved to the RIIO price control method as of 1 April 2013. The gas networks in the UK are not expected to change, via the integration of 'smart' technology, to the same degree as electricity networks, though the advent of smart metering and monitoring systems should increase the efficiency and controllability of the system.

2.2.3 District heating

District heating schemes in the UK mostly date from the post-war period, in which large housing estates were designed with heating systems in place. However, heat networks never gained the momentum in the UK that they have in other countries, and today heat networks supply around only 1% of UK domestic heating needs (approximately 210,000 dwellings) with somewhat higher but still small

[10] **RIIO – A New Way to Regulate Energy Networks**, Ofgem, 2010, http://www.ofgem.gov.uk/Media/FactSheets/Documents1/re-wiringbritainfs.pdf

penetrations in the commercial and industrial sectors. Recently, district heating has climbed up the Government agenda as a means of enabling low-carbon domestic heating.

2.2.4 Carbon dioxide

There currently exist no large-scale CO_2 transport pipelines in the UK, though these will form an integral part of any future carbon capture and storage (CCS) system. CO_2 transportation technology is similar in many ways to natural gas transportation, and there exist proposals to adapt the NTS to carry CO_2 from CCS power plants to North Sea storage facilities.

2.2.5 Hydrogen

Hydrogen pipelines and distribution network facilities do not exist on a commercial scale in the UK, though hydrogen fuelling stations exist at Heathrow Airport and in Stratford to refuel test and demonstration vehicles, including London's small fleet of hydrogen buses. In January 2013, a consortium backed by the Technology Strategy Board (TSB) launched a programme called the London Hydrogen Network Expansion (LHNE) to provide additional fuelling stations in and around London, as well as upgrading the existing Heathrow station.

2.3 Conclusions

Energy infrastructure technologies, especially electricity network technologies, will have a large role to play in the future of energy in the UK. There are significant challenges to integrate large quantities of new generation technologies and the electrification of heat and transport, together with the promise of ICT to revolutionise consumer engagement, network monitoring and demand-side participation models. Other network types such as heat, hydrogen and CO_2 will potentially play important roles in the future, depending on the development of the UK's energy system.

3 Current UK research capabilities

3.1 Overview

This section is based on two sources of evidence: a) subjective judgements made at the first strategic workshop about UK research and industrial capabilities in relation to energy infrastructure as well other energy areas; and b) peer-reviewed assessments of UK R&D capabilities documented through the UK Energy Research Centre (UKERC) Energy Research Atlas 'landscape' documents.[11] The UKERC Energy Research Atlas contains one landscape document specific to electricity transmission and distribution, which falls wholly within the scope of this prospectus. Additionally, the landscape documents on hydrogen and CCS have portions relevant to the scope of this prospectus.

3.2 Strategy workshop

At the strategy workshop **Energy strategies and energy research needs**, participants were invited to consider various key features of a future UK energy system and specify what technology mix they **wanted** to see in 2050 (aspiration) and what they **expected** to happen, given their knowledge of barriers, policy directions, technology limitations and other factors. In general, people's aspirations were aligned with a world in which a great deal of progress was made towards reaching climate goals. However, they 'expected' much slower progress to be made in deploying low carbon technologies in practice.

[11] http://ukerc.rl.ac.uk/ERL001.html

Energy infrastructure technologies were considered mostly under the 'disruptive technologies and scenarios' section due to advances in infrastructure technologies potentially enabling disruptive business models and services. Examples of disruptive technologies and scenarios relating to energy infrastructure include:

- the role of heat networks in system balancing;
- localised energy system optimisation and control;
- 'smart' business models and market models;
- supergrids, high-voltage direct current lines (HVDC);
- 'smart' technology needed to manage centralised, decentralised and small-scale energy systems;
- explosion of available data and analytics creates disruptive new services;
- smart load shifting;
- dynamic system monitoring to drive infrastructure harder; and
- smart meters.

There is a high level of emphasis on ICT, data analysis and business models, showcasing the interplay between these factors and conventional infrastructure technologies. In general, participants rated 'smart grid' innovations as having a high level of potential to enable new models and positively disrupt current UK energy systems and markets, though consumer acceptance and regulatory change would both be required.

Figure 3 was the major output of the strategic workshop on UK research and industrial capabilities. This plots subjective judgments as to how the UK's industrial capabilities in specific areas of energy research are mapped against 'relevance to UK energy futures' (environment, affordability, security, economic opportunity). The size of the coloured circles represents a subjective judgment about the level of scientific capability in the UK. Research areas to the left of the vertical axis represent areas where there is thought to be no clear international lead or a clear lead has yet to be established.

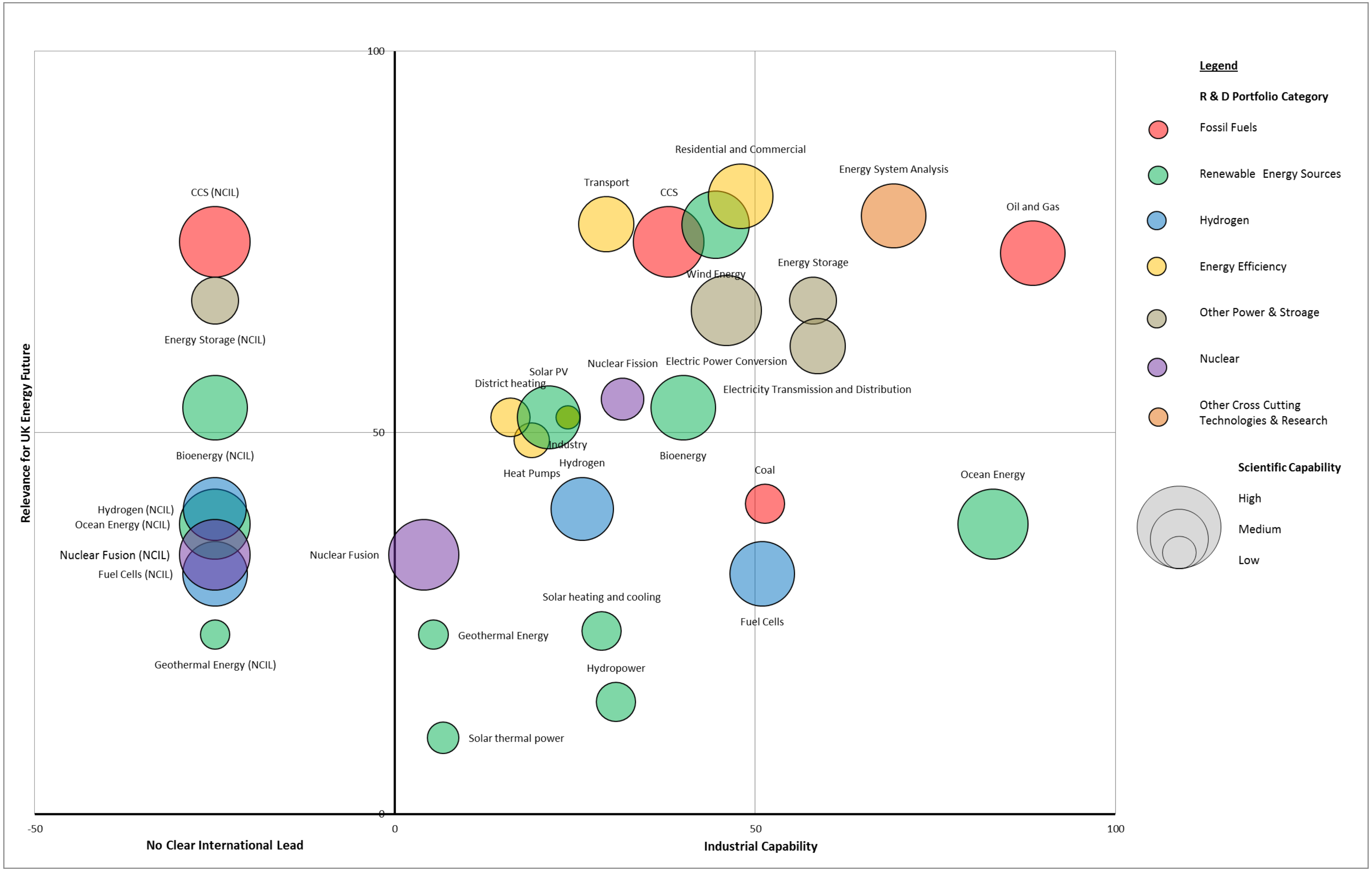

Figure 3: The UK's current and future energy R&D portfolio

3.2.1 Electricity transmission and distribution

At the first Fellowship strategy workshop, the electricity transmission and distribution area was rated highly, both in terms of the criticality of the sector to the UK's energy system policy needs and the UK's industrial capacity in the area. Academic research capability was rated as 'medium' for the UK, though this was a somewhat contentious point with several workshop participants rating it as 'high'. This analysis suggests that electricity networks will be a crucial part of UK energy futures, and that the nation's capabilities in this area are strong.

The UKERC Research Landscape **Electricity Transmission and Distribution** ranks the UK's strengths as extensive in the fields of network operation, network stewardship, consultancy and R&D, with the UK being perceived internationally as very strong in the design of incentives to encourage the uptake of clean fuels and technologies for power generation. Industrial research capability built up under the days of nationalisation under the CEGB reduced significantly after privatisation. However academic capabilities in this area remain strong and recent changes to regulation are incentivising network companies to rebuild capacity and form collaborative efforts with other organisations. The breakdown of capabilities is as follows:

Table 1: UK's research capabilities in electricity transmission and distribution

High Capability	• Transmission and Distribution plant design and development (cables and lines, transformers, transmission towers and accessories etc.); • Technical consultancy; • Transmission and Distribution network planning; • Transmission and Distribution network protection, operation and control; • Power electronics and HVDC; and • Materials science.
Medium Capability	• Plant installation and commissioning; • Test and assessment facilities; and • Education and Training.
Low Capability	None identified

There are significant RCUK research programmes in electricity transmission and distribution, mainly funded by EPSRC. These fall into several 'clusters' including: materials science and component design; protection, communication and control systems; active distribution network management; regulation; and commercial prospects. The £4.7 million SUPERGEN HubNet programme is designed to provide a central core, providing research funding and outreach and communication activities in smart and mega grid, future asset, power electronics and multi-energy themes.

Significant other funding comes from the Ofgem LCNF programmes, which are undertaken by DNO-led consortia including academic researchers. These projects are worth up to £500m in the period 2010-15, at which point they will be replaced by the NIC, part of the new RIIO price control mechanism. There are also substantial EU Framework Programme 7 (FP7) programmes in this area, which investigate, among other subjects, balancing large percentages of intermittent generation, market and regulatory design and islanded grid networks. Views were expressed at the expert workshop that UK academics working in the electricity networks sector were 'saturated', meaning that there is little to no spare academic capacity available in this area at present. Overall, electricity networks are a strongly-funded sector of research in the UK at present, with a vibrant and internationally-renowned academic research community.

3.2.2 Gas

Gas transmission and distribution infrastructure was not covered directly by the strategic workshop participants, though as a whole the UK's oil and gas industrial and research capabilities were rated extremely highly by the participants, as well as being very important to UK energy futures. The UKERC Research Landscape document **Oil and Gas** rates UK capabilities in both onshore and offshore pipelines as very high, with strengths in materials, flow control, corrosion studies and non-destructive evaluation.

3.2.3 District heating

District heating was concluded by the strategic workshop participants to be moderately important to the UK's energy futures. However, the research and industrial capabilities in this area were thought to be low compared to others and were rated poorly in terms of industrial strength and moderately in terms of academic research capabilities. This can be seen as a consequence of the UK's low level of adoption of district heating and it is likely that greater investments in research and industrial capability or collaborations with nations with greater capabilities in this area (e.g. Denmark) will be necessary before district heating is deployed at scale in the UK.

There is currently no UKERC Research Landscape document covering district heating.

3.2.4 Carbon dioxide

CO_2 transportation was not assessed as a separate topic by strategic workshop participants as it fell under the banner of carbon capture and storage, which was rated highly in terms of academic capability and medium to low in industrial capability. CCS was rated highly in terms of relevance to the UK's energy futures, and CO_2 transportation will be essential as an enabler. The UKERC Landscape document on **CCS** mentions research priorities in the evaluation of pipeline re-use availability, staged entry opportunities and optimisation of shared facilities as important to enable economic business cases for new CCS plant. CCS is discussed in greater detail in **Prospectus Report 5: Fossil Fuels and CCS.**

3.2.5 Hydrogen

The UKERC Research Landscape document **Hydrogen** covers the UK's research programmes in hydrogen production, delivery and use. **Prospectus Report 6: Electrochemical Energy Technologies and Energy Storage** covers hydrogen production, storage and use in detail. Hydrogen will need to be transported in pipelines at bulk, which require corrosion-resistant composite materials to prevent damage. Much of the research done in the UK on hydrogen transport relates to storage, which is covered in **Prospectus Report 6.**

3.3 Expert workshop

Participants at the expert workshop were asked to score on a scale of 0-10 how well they thought the UK was now in terms of research capabilities for tackling future challenges in energy infrastructure. The average score of the participants was 4.9 (±1.7), with 20% of participants giving the UK a high score (7-10), 60% giving a medium score (4-6) and 20% giving a low score (0-3).

Broadly, the group believed that the UK is well placed to address emerging research challenges around electricity infrastructure but is less well placed to address challenges posed by other infrastructures and the integration of different infrastructures. The group also highlighted the need for: 1) further inter-disciplinary research to be conducted into energy infrastructure; 2) more energy infrastructure-focused engineers to be trained; and 3) improved levels of integration across the energy infrastructure research landscape.

4 Existing roadmaps and innovation needs assessments

Roadmaps and needs assessments in this sector have focused mostly on electricity transmission and distribution, which due to concerns about integrating intermittent generation and the nature of integrating future, 'smarter' network technologies have received a lot of attention. Both public and private sectors have attempted to lay out broad visions for their definitions of a 'smart grid', with significant work done in the UK by Ofgem, the Electricity Networks Strategy Group (ENSG), the Electricity Networks Association (ENA), SmartGrid GB, the industry trade association and recently the Smart Grid Forum, a joint Department of Energy and Climate Change (DECC)/Ofgem-chaired grouping of industrial, commercial and regulatory stakeholders.

Unlike many energy technologies, networks evolve in place, with newer, more advanced component technologies gradually replacing older assets. This means that a roadmap towards a network with certain capabilities depends on the deployment of many separate individual components, each with its own R&D challenges and deployment costs.

4.1 Electricity networks

UK

The ENSG, a high-level forum bringing together government, regulatory and industrial stakeholders in UK networks, published a vision for UK smart grids in 2009,[12] followed by a more detailed route map in 2010.[13] This route map focuses on three critical smart grid roles to help enable the UK's low carbon transition:

- integration of inflexible generation;
- electrification of transport and heating; and
- integration of distributed energy resources (DER).

This routemap calls for a range of well-targeted pilot programmes and integrated end-to-end scale trials to be delivered by 2015, alongside the beginnings of the UK smart meter rollout. These projects run alongside the development of common standards for interoperability and regulatory and commercial changes to stimulate smart technology deployment, before full integrated smart grid systems begin to be deployed towards the end of this decade. A high-level routemap plots out potential activities beyond 2020, including integrating transport and heating electrification, microgrids and coordination of different energy networks and vectors. The DECC/Ofgem Smart Grid Forum is currently preparing as one of its work streams a smart grid vision and roadmap, which will supersede these earlier documents from the ENSG.

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12 ENSG, **A Smart Grid Vision**, 2009, http://webarchive.nationalarchives.gov.uk/20100919181607/http:/www.ensg.gov.uk/assets/ensg_smart_grid_wg_smart_grid_vision_final_issue_1.pdf

13 ENSG, **A Smart Grid Routemap**, 2010, http://webarchive.nationalarchives.gov.uk/20100919181607/http:/www.ensg.gov.uk/assets/ensg_routemap_final.pdf

The summary report of the Technology Innovation Needs Assessment (TINA) on electricity networks and storage,[14] prepared by the LCICG, predicts innovating in these technologies could save the UK between £4-19bn in deployment costs to 2050, provide UK-based business opportunities worth £6-34bn, and could act as enablers for the deployment of other key technologies, providing significant added value. This innovation is expected to be driven largely by the private sector, with public sector support made available to support underpinning research challenges and to help overcome market and regulatory failures. Due to the globally tradable nature of many of these technologies, the UK can benefit from other countries' innovation and development efforts, making UK-specific adaptations when required.

The exact future level of deployment of energy network and storage technologies is uncertain, according to the TINA report, and reliant on changes in the energy generation mix and demand patterns. The report considers six major high-level technology areas:

- advanced transmission;
- smart distribution;
- storage;
- home hub;
- demand response; and
- electric vehicle integration.

Key uncertainties identified include the role and share of storage in future electricity systems, as well as the unproven market for domestic energy management and demand-side management systems. Vehicle-to-grid technologies, where electric vehicles provide demand response by feeding power from their batteries back into the grid, also face significant uncertainties due to battery technology limitations and the need to deploy specialised distribution control systems. Many network technologies, such as smart distribution, electric vehicle (EV) integration and demand response technologies, are mutually-reinforcing and dependant on one another, requiring coordinated effort from multiple stakeholders in order to deploy successfully.

EU

Many EU member states' electricity networks are highly integrated there are several European research programmes in this sector. These include the Smart Grid Joint Programme of the European Energy Research Alliance (EERA) and the European Industrial Initiative (EII) on grid technologies. In addition, the European Commission (EC) has created a Smart Grid Task Force with a mission to oversee coordinated EU standardisation and implementation of Smart Grids under the EU's Third Energy Package. This Task Force has produced several recommendations on smart grid pilot projects, standardisation and interoperability. As part of their work, in 2011 they produced a Communication setting out the major challenges for EU smart grid deployment.[15] These were:

- developing technical standards;
- ensuring data protection for consumers;

[14] LCICG, **TINA: Electricity Networks and Storage,** http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/electricity_networks_storage

[15] **EC Smart Grids Task Force** (2011-13), http://ec.europa.eu/energy/gas_electricity/smartgrids/smartgrids_en.htm

- establishing a regulatory framework to provide incentives for smart grid deployment;
- guaranteeing an open and competitive retail market in the interest of consumers;
- providing continued support to innovation for technology and systems; and
- developing common European smart grids standards.

The Communication forecasts a high level of future grid investments, suggesting that cumulative investments in the electricity network between 2011-50 could reach €1.5- 2.2 trillion. The uncertainties in the future generation mix and demand requirements mean that longer-term roadmaps need to be flexible towards a wide range of outcomes.

The Smart Grids European Technology Platform has produced a Strategic Research Agenda looking out to 2035,[16] which set out a detailed list of core challenges and technological priorities that need to be addressed to push the research agenda forward. These include power electronics, ICT modelling and grid protection technologies, with substantial legal challenges and market structure innovation identified. European-wide standardisation and integration of systems is a major future challenge and one of the priorities for the EC in this sector.

Global

The International Energy Agency (IEA) produced a Smart Grids technology roadmap in 2011,[17] focusing on the need to deploy smart technologies in order to meet the challenges of balancing supply and demand along with increased electrification of transportation and heating. The roadmap identifies eight technology areas in this sector, covering networks from generation to consumer, along with their development maturity levels. These are as follows:

- wide-area monitoring and control (developing);
- ICT integration (mature);
- renewable and distributed generation integration (developing);
- transmission enhancement applications (mature);
- distribution grid management (developing);
- advanced metering infrastructure (AMI) (mature);
- EV charging infrastructure (developing); and
- customer-side systems (developing).

The report notes that, with the exception of distribution management technologies, all of the 'developing' technologies are moving at a fast rate. The roadmap utilises the Energy Technology Perspectives (ETP) 2010 BLUE Map scenario to calculate global and regional generation and demand, with both minimum and maximum deployment scenarios for smart grids. This shows that deploying smart grid technologies even to a minimum level will keep peak demand below demand growth in all regions apart from China, and will enable substantial CO_2 reductions of between 0.7 gtonnes and 2.1gtonnes annually by 2050, with the greatest potential in North America.

The report does not provide a quantitative analysis of investment costs and operating savings, but makes the point that clever market design and regulation will be required to ensure that the costs and benefits are spread appropriately amongst the stakeholders in the system. Although component R&D efforts are proceeding in this sector at a significant rate, large scale commercial demonstrations are

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[16] Smart Grids European Technology Platform, **Strategic Research Agenda out to 2035**, http://www.smartgrids.eu/documents/sra2035.pdf

[17] IEA: **Technology Roadmap: Smart Grids.** http://www.iea.org/publications/freepublications/publication/name,3972,en.html

required in order to trial these new components in a real-world system, as well as to integrate them into regulatory structures and commercial models.

There is substantial work in developing 'smart' network technologies taking place in South Korea,[18] Japan[19] and the USA.[20]

4.2 Gas

UK

No TINA document has been produced in this area. The Energy Networks Association in 2010 produced the Gas Futures Scenarios Project[21] looking at the landscape for gas in Great Britain out to 2050. This report finds a 'compelling economic rationale' for operating the GB gas transmission and distribution networks for the foreseeable future considering these networks are low-cost in comparison to low-carbon system costs. The report foresees continuing roles for gas in CCS power stations, as well as unabated gas plant for balancing purposes, both of which require the transmission network. The role of the gas distribution networks remains less certain and will largely be dependent on the success of transport and heating electrification. The report makes no specific research recommendations, but makes the case that gas infrastructure technologies will remain important to the UK's energy future for many years.

The DECC strategic framework for heat indicates a potential long-term role for gas networks in providing peak heating, with hybrid gas/electric heating systems becoming widespread. The role of these hybrid technologies in system balancing is an important research challenge.

EU

The European Gas Research Group (GERG) has produced a Research Roadmap outlining the major challenges for European gas infrastructure out to 2030.[22] It outlines negative funding trends in European gas research, including falling funding volumes and a reduced interest in new gas and gas utilisation technologies. It recommends four research priorities to improve this situation up to 2030:

- securing the European gas supply by diversifying gas supply sources and routes and improving interoperability of European gas networks;
- improving the safety and integrity of gas networks by increasing the European gas network's integrity, durability, robustness of management, and developing simulation tools;
- developing smart gas uses and managing energy demand for the three energy markets, residential and commercial, industrial and transportation; and
- improving the sustainability of natural gas supply and use by:
    - reducing the GHG emissions of the gas industry, assessing CO_2 capture and storage technologies, and developing life cycle analysis of natural gas alternative solutions.
    - studying and validating future energy by assessing, for example, the feasibility and impact of large scale injection of biogas into existing natural gas networks and, in the longer term, hydrogen.

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18 Korea Smart Grid Institute, http://www.smartgrid.or.kr/eng.htm
19 Japan Smart Community Alliance, https://www.smart-japan.org/english/
20 US Department of Energy, http://www.smartgrid.gov/
21 'Gas Futures Scenarios Project', ENA, 2010, http://www.energynetworks.org/modx/assets/files/news/publications/ena_gas_future_scenarios_report.pdf
22 **Research Roadmap 2030**, GERG, 2008, http://www.gerg.eu/publications/GERG_ResearchRmap.pdf

The report specifically mentions the development and deployment of simulation tools for gas network management and control, as well as a more interconnected, robust gas network. The report also emphasises the need for gas networks in the future to be environmentally aware and to possess a smaller environmental footprint.

4.3 District heating

Roadmaps for district heating research and deployment are fewer and further between than those for electricity networks, and necessarily have to be UK-specific, due to inherent differences in building design and conventional heating technology. Heat networks are also currently not covered by a regulatory body in the UK. The government's 2011 **Carbon Plan** estimated that heat networks will provide between 10-38 TWh of heat in the UK by 2030.[23] In March 2013, DECC published a policy paper **The future of heating: meeting the challenge**[24] which outlined its policies to encourage heating networks. The building of heat networks are considered to be under the remit of local authorities, and DECC is establishing a Heat Networks Delivery Unit (HNDU) to work with local authority teams, as well as providing two years' funding to contribute to early stage heat network development and modelling.

In 2010, the Combined Heat and Power Association (CHPA) published a report outlining potential 2050 heat scenarios for the UK.[25] This report investigated the potential to provide CCS-CHP gas plants and large CHP biomass-fired plants, surrounded by district heating networks to a maximum radius of 30km. This scenario, based on the Committee on Climate Change (CCC) 80% GHG reduction scenario, provides 92 TWh of district heating and reduces electricity demand by 13% compared to the base scenario, which envisages a large penetration of electric heat-pump systems.

4.4 Carbon dioxide

The potential in deployment of CCS plant in the UK is covered in **Prospectus Report 5: Fossil Fuels and CCS.** There is considerable divergence in predictions for the deployment of CCS in the UK, with Market Allocation MARKAL (Model) models predicting around 10GW of CCS development, and the DECC Pathways Calculator varies widely based on the assumptions selected, with deployment efforts ranging from 0-60 GW by 2050.

The location and scale of CO_2 transport networks in the UK is currently uncertain, as they will depend on the location and number of CCS plants, as well as industrial sites that have been fitted with carbon capture technology. One developed concept is that of 'hubs' or 'clusters' of CCS power plants and industrial users, with a CO_2 transport network connected with offshore storage sites. One major site being investigated for this potential is the Yorkshire Humber region, which has several large industrial facilities and potential CCS power plants.[26]

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23 **The Carbon Plan**, 2011, HM Government, https://www.gov.uk/government/publications/the-carbon-plan-reducing-greenhouse-gas-emissions--2

24 **The Future of Heating: Meeting the Challenge**, 2013, DECC, https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge

25 CHPA: **'Building a Roadmap for Heat: 2050 scenarios and heat delivery in the UK'.** 2010, http://www.chpa.co.uk/medialibrary/2011/04/07/e9a9f61d/Building_a_roadmap_for_heat_Full.pdf

26 **The National, Regional and Local Economic Benefits of the Yorkshire and Humber Carbon Capture and Storage Cluster**, CO_2Sense, www.Co2Sense.co.uk

5 High-level research challenges

The research challenges identified in the Energy Infrastructure expert workshop fall into three broad application areas:

1. systems planning and operation;
2. policy design and market design; and
3. component technologies.

There are underpinning challenges in environmental, economic and public engagement and acceptance processes which cut across these three application areas.

Table 2: Research challenges in the area of systems planning and operation

Challenge	Notes
Future of the gas system and its interaction with the electricity system.	Can the gas networks be used for other purposes in a low-carbon energy system, and over what timescales?
Reliability of supply and robustness of the energy system.	Resilience to external events.
Challenges in upgrading and changing a system while maintaining continuous operation.	
Coordination of actors to maximise collective benefits.	
Natural capital protection: Ensuring infrastructure is environmentally benign.	
Balancing electricity supply/demand.	Complexities introduced by storage, smart demand management
Interconnection expansion and its role in future systems.	
Developing energy system and network models.	
System control and coordination.	
ICT integration into monitoring and coordination.	
Cyber-security: characterising risks and mitigation efforts.	
Integration of different energy vectors and networks: a 'system of systems' approach.	

Table 3: Research challenges in the area of policy design and market design

Challenge	Notes
Incentivising innovation in a conservative sector.	
Defining policy and market drivers.	Decarbonisation/equity/affordability/security.
Appropriate, sustainable business models.	
Market, governance and regulatory frameworks through energy supply chain.	
The role of the user in future energy systems.	
Investment and decision-making under uncertainty.	
Demand-side response in heat networks	
Strategies for developing heat-supplying infrastructure.	Huge uncertainties around heat networks to be resolved.

Table 4: Research challenges in the area of component technologies

Challenge	Notes
Accelerating development and deployment of new component technologies.	
The role of HDVC in electricity networks.	
Technical aspects of network control.	
Technical aspects of integrating energy storage technologies.	
Flexibility in cable ratings.	
Offshore transmission components.	
The role of DC networks, including low-voltage direct current (LVDC) distribution.	
Power line communication technologies.	

Table 5: Underpinning challenges

Challenge	Notes
Ensuring that customer usage and network performance data is acquired and stored successfully, and is able to be accessed by researchers when appropriate.	The Data Protection Act, as well as the fragmented nature of the commercial system, provides challenges in ensuring that data can be accessed.
Analysis of customer behaviour including usage patterns, across a wide variety of social groups and different household compositions.	Overlaps with energy demand research, covered in **Prospectus Report 3: Energy in the Home and Workplace.**
Understanding barriers to acceptance of new network technologies, including smart meters and demand-side management (DSM) technologies.	

6 Research support

6.1 Ways of working

Integrate the innovation chain. There is a need to improve integration of key processes along the energy infrastructure innovation chain. For example, it is important not only that various themes within the RCUK's research funding programme are fully integrated, but their funding programmes should be linked with those of other key funding organisations across the innovation chain. The chain, from theoretical to practical energy infrastructure research, should be well understood and managed. For example the evidence flow between RCUK funded research and research funded by the Energy Technologies Institute (ETI).

Truly interdisciplinary research. High quality energy infrastructure research will rely on input from various disciplines including engineers, mathematicians, social scientists, psychologists and economists. Truly inter-disciplinary working would be help produce holistic research outputs in this area. This can be fostered in a variety of ways, including the design of truly inter-disciplinary research methodologies and PhD training, as well as restructuring the research proposal process to factor inter-disciplinarily from the outset.

Resolve policy and research timeframes. The policy landscape is moving much more quickly than the research landscape, meaning that valuable evidence generated by academia may not be ready in time to inform policy. Fast tracking certain funding calls may help this. There is a similar issue between power engineering and ICT communities, which operate on different timescales. ICT is a fast-moving sector, with innovations occurring on a yearly timescale. In comparison, power engineering is a more conservative sector with a slower pace of innovation and deployment.

Reconsidering the UK's innovation system. The technology-specific Technology Readiness Level (TRL) level system works for some areas of energy infrastructure research but not all. The overarching innovation framework needs to reflect the reality of the changing infrastructure system, and should be considered as a whole, including policy and market models and not just as a series of technologies.

New/different incentives for academics. Non-journal paper outputs from academia (e.g. reports, consultancy, providing evidence to committee reports) should be suitably rewarded in the academic system. These outputs are valuable, particularly in this field.

Danger of focusing research agenda on commercial value. The number one rationale for innovation in energy research should be to develop an appropriate infrastructure to underpin a low carbon and secure energy system. The extent to which particular technologies and solutions could be marketed abroad, while still important, should be secondary to this goal.

Support for interdisciplinary coordination bodies. A need was identified for flagship interdisciplinary energy coordinating centres to bring together researchers from across the energy programme. UKERC was mentioned as having been very successful in this area. This is important for energy infrastructure researchers, as centres like these help identify and analyse future scenarios for energy supply and demand.

6.2 Long-term perspectives

Longer-term funding perspectives. Longer-term funding could be advantageous in this sector, as in other areas of energy, especially for field trials and pilot studies where it may take some years for investments to yield their full scientific benefit. At the same time, effective reporting and monitoring processes would be required to ensure that investments stay on track.

6.3 Data

Large publicly available data sets of UK energy consumer behaviour. It would be particularly useful if these data sets were anonymised and live so that researchers could track and understand demand variations 'in the moment', instead of after it. Competitions could be established to encourage the innovative design of technologies or software such as mobile apps to best use this data resource.

Data quality and storage. The quality of data curation is important, not just the raw quantity of data acquired. A centralised data storage repository, managed by the Research Councils, would be extremely useful to researchers. Centralising data protection and legal issues would also reduce the time taken by individual research institutions to address these.

6.4 Infrastructure and facilities

National Energy Demand Emulator. A national demand emulator, which could receive high temporal resolution of energy/power data from a spatially and demographically diverse range of housing, commercial and industrial loads, would be an important addition to the UK's infrastructure research capabilities. It would be fully anonymised but would be available in real time. This could serve as a national reference dataset for the development of DSM technologies and models.

Test facilities to test energy infrastructure. Energy network components need to be tested in 'real environments' with 'real consumers'. The necessary test facilities and regulatory frameworks should be in place to enable these. There is a need for a test city or region, a test 'campus' approved by the regulator. The LCNF is helping to provide these testbeds. However such efforts are very expensive. Researchers should be able to collaborate with industry to build and utilise these facilities.

7 Training

Secondment schemes. Secondment schemes to policy and industry, including Ofgem and utility companies, would be an excellent way for PhD students and post-docs to gain valuable skills and experience and to gain an understanding of industry culture and drivers. This experience would be very valuable for research programmes in this area.

Academic 'retreats'. Several areas of research have schemes for senior academics to 'retreat' to interdisciplinary centres for a few weeks to a month, utilising the time to work in depth and flesh out ideas away from the distractions of their day jobs. This could be a successful way of revitalising the thinking and research priorities of senior academics.

Creating and retaining expertise in academia and industry. It is common in this sector for more experienced staff to take up consultancy roles, which gives them flexibility but can lead to a lack of experienced staff available both to train junior members and to respond to immediate and unforeseen problems. More efforts should be made to retain senior staff and ensure that there are options for both management and technical career paths in the organisation.

PhD training. More interdisciplinary grants in the energy infrastructure area, specific PhD grants to train students in modelling the energy system, and a specific Centre for Doctoral Training (CDT) for energy infrastructure research would all assist the training of new researchers in this sector.

8 Connections

8.1 Connections across research areas

As might be expected, this area has numerous connections with other research areas:

- **Industrial energy demand (Prospectus Report 2)** in respect of load balancing and industrial demand response;
- **Energy in the home and workplace (Prospectus Report 3)** in respect of consumer participation, demand-side management and distributed generation;
- **Transport energy (Prospectus Report 4)** in respect of vehicle-to-grid technologies and transport energy demand;
- **Fossil fuels and CCS (Prospectus Report 5)** in respect of CO_2 transportation;
- **Electrochemical energy technologies and storage (Prospectus Report 6)** in respect of energy storage and distributed generation technologies and their effect on the system;
- **Wind, wave and tidal (Prospectus Report 7)** in respect of offshore transmission and the integration of distributed generation;
- The IEA energy research area **Energy Systems Analysis** (VII.1.1/VII.1.2)in respect of: systems level analysis and modelling of the energy networks.

8.2 Linkages outside the research council sphere

Combination of Ofgem and RCUK funding. It is important that RCUK funding is available to drive forward theoretical research into energy infrastructure, whilst Ofgem-managed funding such as the LCNF and Network Innovation Competition is available to support more applied/practical development and to undertake large-scale infrastructure demonstrations.

Academia-industry collaboration. There is a need for greater collaboration between academic institutions and industry to facilitate R&D relating to energy infrastructure. This may be achieved for example by the establishment of exchange or secondment schemes to provide a two-way exchange of knowledge and experience. Industry should be dissuaded from participating on a 'token' basis, making sure organisations are full and active partners in research programmes.

The role of Ofgem. Ofgem has taken a substantial role in UK energy infrastructure development with the adoption of RIIO and the LCNF. While focusing on DNO-led consortia, academics play a significant part in many LCNF projects. The research councils and Ofgem should work together to ensure that research council funded programmes complement and provide basic underpinning research for LCNF and NIC projects, and that there is sufficient academic resource available to participate in these programmes.

8.3 International working

Aligning energy infrastructure research internationally. A number of questions should be addressed in considering international linkages: to what extent should the UK adopt a 'go it alone' policy in terms of our own research agenda? where do international overlaps in research exist and how might strategic partnerships best be exploited? are there areas which are too big or risky for the UK to take on alone? Programmes such as the EERA should be engaged with fully to ensure UK research is not duplicating work done elsewhere in the EU, to take advantage of upcoming Horizon 2020 bids and to more fully feed UK research efforts into EU policymaking.

International students. Very high quality international students should be given some form of public funding, in order to attract top talent to the UK. This should be limited and targeted.

8.4 Public engagement

Community engagement. There is a need to experiment with customers and communities in general in order to understand what they think and how they make decisions in relation to energy. Consequently, it is important to evaluate the applicability and viability of different initiatives (new energy tariffs, policies, smart solutions etc.) on customers' and communities' behaviours, and to feed these findings back to policymakers and industry.

8.5 Other issues

Policy Clarity. As in most areas of energy research, clarity about the direction of energy policy and a consistent vision of the future are important to attract and retain skilled researchers, as well as planning and developing long-term research programmes and test facilities. The roles, scale and capabilities of energy infrastructure depend very much on the energy generation mix and demand patterns. Clarity on these issues is important to ensure research is in a position to support the energy infrastructure of the future.

9 Conclusions and recommendations

Energy infrastructure is critical to any future UK energy scenario, with significant asset replacement and upgrading required even in the event of no significant decarbonisation of the system. The increasing quantities of intermittent low-carbon generation and distributed generation found in many decarbonisation scenarios will require a substantial reworking of the UK's infrastructure to handle differing energy flows, with most resource required for the electricity networks.

R&D in this sector, especially on power networks, is well-funded via a combination of RCUK, other public bodies, industry and Ofgem's LCNF. There are potential saturation issues arising from a lack of academic capacity in relation to the volume of work available. Efforts to retain mid-career staff in academia and promote more movement of industrial staff to the academic sector could help prevent further capacity issues.

The LCNF has expanded very significantly the funding available in this sector since its introduction. The research councils, especially EPSRC, should consider how academics split time and resource between RCUK- and LCNF-funded projects, and we would recommend that RCUK, Ofgem and other innovation bodies active in this area work closely together to harmonise research directions and programme, as well as to outline clear splits of research areas and responsibilities along the innovation chain.

There are substantial global opportunities for UK academics in this sector in providing technology, expertise and consultancy services to other nations. Academics and RCUK should be open to international collaboration on a best-with-best basis, and ensure that UK research helps inform and define EU and global standardisation and interoperability efforts. Market and business models, as well as regulation efforts, are crucial for the success of new technologies in this sector and research in these areas should be considered important.

There is a need to systematically collect and curate data arising from smart meter trials, as this provides a powerful research opportunity. Attention should be given to collecting and curating this data, giving careful attention to issues such as data confidentiality and protection of intellectual property (IP).

Greater industry/academia collaboration efforts as well as shared demonstration and testing facilities would allow greater sharing of expertise and working methods between industrial and academic researchers. Secondments of PhD students and early-career postdocs into industry and government should be supported as this provides an opportunity for younger researchers to understand non-academic culture and conventions, helping to foster collaborative efforts.

Annex A: Research needs

These research needs come from detailed discussion sessions held during the Expert Workshop, and represent 'hotspots' of research that were seen to be necessary in the short- to medium- term to answer the research challenges in Section 5.

A.1 Systems planning and operation

A.1.1 System balancing and control

- Understanding issues of balancing with large renewable inputs;
- Understanding to what extent existing distribution networks can cope with low-carbon technologies;
- Control strategies to increase network flexibility;
- Needs of local distribution networks with the electrification of heat and transport;
- The importance of peak flows in electricity supply;
- The observability and controllability of distribution networks, considering large penetrations of distributed energy resources;
- Role of robust metrological analysis for system planning and balancing, including understanding the limits of forecasting for wind power and other intermittent technologies;
- Inter-temporal relationships and rates of change; and
- Improving frequency control in distribution networks via decentralisation or islanding.

A.1.2 Energy system security and resilience

- Understanding the differences between a reliable system and a robust system;
- Energy system security in the case of rare but severe events;
- Cyber-security needs for future networks;
- Intelligent maintenance of infrastructure systems;
- Replacing or coping with aged infrastructure;
- Resilience of energy infrastructure to changing UK climate;
- Understanding the potential consequences of large-scale ICT failures on future networks; and
- Understanding key failure points on the network during potential shocks.

A.1.3 Energy system analysis and modelling

- Challenges in analysing very large systems in sufficient spatial and temporal detail, taking sufficient uncertainties into account;
- Integrating models of different energy systems into a systemic whole;
- Models and frameworks to enable more flexible infrastructure;
- Data quality and availability for modelling: ensuring sufficient data is available to inform complete models and to take account of uncertainties;
- Utilising complexity science to support modelling and analysis;
- Challenges in ensuring that models consider a wide spectrum of robust operational criteria;
- Challenges of linking physical engineering models and investment appraisal models; and
- A need for EU-wide infrastructure models, which we currently lack.

A.1.4 System integration

- Understanding strongly integrated energy infrastructures, electricity, gas and heat together;
- System of systems – considering energy, transport, food waste and other systems as an integrated whole;
- Developing fuller integration between the electricity and gas networks;
- ICT components to monitor and control multiple networks simultaneously; and
- Modelling distribution system investment savings from the introduction of storage/DSM.

A.1.5 Infrastructure planning

- Identifying possible disruptive technologies through the scientific evidence base;
- Understanding the risks of lock-in for different infrastructure options;
- Robust pathways to deliver long-term visions in a dynamic system;
- Mechanical pathways to 2050: is there an order that new components are deployed, and are bridging technologies required?
- The extent of CCS power plants and CO_2 transport networks in future infrastructure planning; and
- Regulatory frameworks to incorporate the consequences of investment risk.

A.2 Policy design and market design

A.2.1 Gas networks

- The changing role of gas in the future and the effect on the networks;
- Heat as a key driver for gas - new heating technologies and the knock-on effects of these;
- Innovative methods for using gas networks to move and store hydrogen;
- Impacts of reduced gas use on consumer gas prices; and
- Reducing the heat of gas in the networks, ways to reduce the loss of gas in the system.

A.2.2 District heating

- The role and extent of district heating and CHP in the future energy mix;
- Coordination challenges to develop a viable heat network in the context of market liberalisation;
- Energy system benefits of heat networks;
- Technologies and policies required to develop heat networks UK-wide; and
- Regulatory framework and business models to support district heating.

A.2.3 Market structure and economics

- Understanding the effect of possible technical gains on business models;
- Challenges of introducing disruptive technologies into the system under current paradigms;
- Systems for collective energy purchasing;
- Cultural challenges with traditionally conservative utility organisations in a rapidly changing paradigm;
- Energy Market Reform (EMR) options to incentivise new business models and technologies; and
- Investment under uncertainty - the value/risk balance of anticipatory investment in networks.

A.2.4 Governance

- Market, policy and regulatory frameworks required to implement future network paradigms;
- Incentivising DNOs to implement new technologies;
- Integrating offshore networks into regulation;
- Institutional frameworks for better cooperation;
- Challenges in balancing industrial collaboration and competition incentives; and
- Hierarchy of energy security, affordability and carbon reduction, how do these priorities compete with and challenge on another?

A.2.5 Interface between consumers and infrastructure

- To what extent can demand response be applied without active consumer involvement;
- Design of incentives in order to change a system when consumers are passive into one where they are more active;
- Consumer acceptance of new, more active technologies such as smart meters and heat pumps;
- Overarching objectives for demand side management – conflict between economic tariff incentives and supply/demand balancing; and
- Public attitudes to environmental and economic impacts of infrastructure.

A.3 Component technologies

A.3.1 Components in energy infrastructure

- Research into Flexible AC Transmission Systems (FACTS) for distribution networks;
- Standard designs for offshore transmission substation platforms;
- DC network protection technologies;
- Research into 'tapping off' power midway on HVDC lines to provide more flexible transmission networks; and
- Reducing the size and local impacts of high-voltage substations.

A.3.2 Smart technology

- Customer acceptance of compulsory smart meters and appliance control;
- Relevance of smart meters and technology in a 'dash for gas' scenario; and
- ICT structure, a large centralised system vs. many smaller decentralised ICT networks.

A.3.3 Data acquisition and use

- Analysing smart meter data to help develop market structures and mechanisms;
- Data quality versus quantity: good quality data is essential;
- Understanding and defining which data is essential to remain commercially confidential;
- The balance of user privacy against value of data;
- Convincing customers to share data – trust issues, incentives, data protection laws; and
- Collecting data – does people's behaviour change if they know they are being observed?

A.3.4 Other

- Liquid nitrogen's feasibility as a possible energy vector;
- Developing countries and decentralised grid structures;
- Vehicle to grid storage systems for grid balancing;
- Identifying collaborations between mathematics and social sciences for modelling and analysis;
- Material requirements for infrastructure changes and effects on supply chains; and
- Radical change instead of incremental change – possibility and advantages/drawbacks.

Annex B: Process for developing the prospectus

This Energy Research and Training Prospectus Report has been developed under the auspices of the RCUK Energy Strategy Fellowship which was established in April 2013. Fellowship activities leading the production of the Prospectus have gone through three phases.

Phase I (Spring –Summer 2012), **the scoping phase,** involved a comprehensive review of relevant energy roadmaps, pathways and scenario exercises in order to provide a framework for possible UK energy futures. Extensive consultation with stakeholders across the energy landscape was carried out in order to encourage buy-in and establish clearly the boundaries and links between the RCUK Prospectus and other products related more to deployment. One conclusion arising from the consultations was that linkage should be sought across the energy research domain and that consequently related topics linked by underlying research skills should be covered in single workshops during Phase II.

Phase II (Autumn 2012 – Summer 2013)**, the evidence-gathering phase,** relied heavily on workshops bringing the research community and stakeholders together round specific topics. Three 'strategic'" workshops on **Energy Strategies and Energy Research Needs, The Role of Social Science, Environmental Science and Economics,** and **The Research Councils and the Energy Innovation Landscape** were held October 2012 – February 2013. Six expert residential workshops on **Fossil Fuels and CCS, Energy in the Home and Workplace, Energy Infrastructure, Bioenergy, Transport Energy** and **Electrochemical Energy Technologies** were held January- June 2013. In addition, "light-touch" activities were conducted in respect of: **Industrial Energy; Wind, Wave and Tide;** and **Nuclear Fission**. A final strategic level 'synthesis' workshop was held in July 2013. During Phase II, reports on each of these workshops were prepared and web-published following comments from participants.

During Phase III, (summer-autumn 2013)**, the synthesis stage,** the workshops reports were 'mined' and combined with contextual information to produce the Prospects Reports which were put out for peer review. The Prospectus, including a hard-copy Synthesis Report, was launched in November 2013.

Annex C: List of prospectus reports

No 1	Investing in a brighter energy future: energy research and training prospectus
No 2	Industrial energy demand
No 3	Energy in the home and workplace
No 4	Transport energy
No 5	Fossil fuels and carbon capture and storage
No 6	Electrochemical energy technologies and storage
No 7	Wind, wave and tidal energy
No 8	Bioenergy
No 9	Nuclear fission
No 10	Energy infrastructure