Research Councils UK Energy Programme Strategy Fellowship

Summary of Workshop on

Energy Infrastructure

Working Document

August 2013

This is a report of a workshop held to support the development of the Research Councils UK Energy Research and Training Prospectus at IET, Austin Court, Birmingham on 17-18 April 2013

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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 Research Councils UK 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 Research Councils UK 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 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 will contribute to the evidence base upon which the RCUK Energy Programme can plan its forward activities alongside Government, RD&D funding bodies, the private sector and other stakeholders. The tool will highlight links along the innovation chain from basic science through to commercialisation. The tool will be flexible and adaptable and will take 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 is a series of four high-level strategic workshops and six in-depth expert workshops taking place October 2012 - July 2013. Following peer-review, the first version of the Prospectus will be published in November 2013 and will then be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This document reports views expressed at a strategic workshop held in April 2013. These views do not necessarily represent a consensus of workshop participants nor will they necessarily be endorsed in the final version of the Energy Research and Training Prospectus.

Contents

List of Acronyms

ABM	Agent Based Model
AC	Alternating Current
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CHP	Combined Heat & Power
DC	Direct Current
DECC	Department of Energy and Climate Change
DG	Distributed Generation
DNO	District Network Operators
DSM	Demand Side Management
EPSRC	Engineering and Physical Sciences Research Council
ESCO	Energy Service Company
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
EU	European Union
EV2G	Electric Vehicle-to-Grid
FACTS	Flexible Alternating Current Transmission System
FP7	The EU's Seventh Framework Programme (2007-2013)
HV	High Voltage
HVDC	High Voltage Direct Current
ICMS	International Centre for Mathematical Sciences
ICT	Information and Communications Technology
IEA	International Energy Agency
IP	Intellectual Property
KTN	Knowledge Transfer Network
LCA	Life Cycle Assessment
LCNF	Low Carbon Network Fund
LNG	Liquefied Natural Gas
LV	Low Voltage
MARKAL	Market Allocation (Model)
NAO	National Audit Office
OEM	Original Equipment Manufacturer
Ofgem	Office of Gas and Electricity Markets
OFTO	Offshore Transmission Operator
PLC	Power Line Communications
R&D	Research and Development
RD&D	Research, development and demonstration

RCs	Research Councils
RCUK	Research Councils UK
SME	Small to Medium Sized Enterprise
STS	Science & Technology Studies
TNO	Transmission Network Operator
TRL	Technology Readiness Level
TSB	Technology Strategy Board
UKERC	UK Energy Research Centre

1. Overview

This document summarises the outcomes of a workshop held on 17-18 April 2013 in order to identify research and training needs relating to energy infrastructure. In terms of scope, the workshop covered the follow areas, defined under the EU/International Energy Agency (IEA) energy R&D nomenclature:

- Electricity transmission and distribution
- Integration of distributed and intermittent generating sources into networks
- Transport and storage of oil and gas
- District heating
- Energy storage (network aspects)
- CO_2 transport
- Storage, transport and distribution of hydrogen
- Aspects of energy system analysis (e.g. energy system modelling).

The workshop was organised with input from the Office of Gas and Electricity Markets (Ofgem), John Scott of Chiltern Power and Chris Dent of the University of Durham.

There were 23 participants at the workshop (excluding the Fellowship and facilitation teams), most of whom were academics and researchers falling within the communities supported by the Engineering and Physical Sciences Research Council (EPSRC) and Economic and Social Research Council (ESRC). In addition, a number of participants were from private sector and government organisations.

The meeting was professionally facilitated by the Centre for Facilitation Services Ltd in association with the RCUK Energy Strategy Fellowship team. This record of the meeting constitutes a working document, intended to capture the outcomes of the workshop. It represents an intermediate step in the production of a full Energy Strategy Fellowship report, which will set out the prospectus for energy research and training needs relating to energy infrastructure. It has two purposes; a) to provide a resource which can be 'mined' in order to produce the prospectus document; and b) to provide an account of the workshop for comment by the participants and for archival purposes.

One of the main inputs to the Prospectus is a series of four high-level strategic workshops and six in-depth expert workshops taking place October 2012- July 2013. Following peer-review, the first version of the Prospectus will be published in November 2013 and will then be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This document reports views expressed at an expert workshop held in April 2013. These views do not necessarily represent a consensus of workshop participants nor will they necessarily be endorsed in the final version of the Energy Research and Training Prospectus.

2. Introductory Presentations

To familiarise the workshop participants with the scope of the workshop, two introductory presentations were made. The first of these was from Jim Skea (Energy Strategy Fellow) who outlined the rationale behind the RCUK Energy Strategy Fellowship and key activities, noting the role of the Prospectus in informing the future design of the RCUK's Energy Programme. He explained how the Energy Infrastructure workshop formed part of a wider programme of work being undertaken through the Fellowship, including five other expert workshops, three strategic workshops and three light touch reviews.

The second of the presentations was from Aidan Rhodes who provided a summary of the three strategic, cross-cutting workshops that preceded the Energy Infrastructure workshop.

2.1 Strategic Workshop 1: Energy strategies and energy research needs

A key message from the first workshop on "Energy strategies and energy research needs" was that people's expectations about progress towards a low carbon economy lagged behind what they thought was desirable. Focusing on heat supply technologies, people had expected the deployment of district heating, solar thermal, heat pumps and fuel cells to fall below desirable levels by 2050 while the use of conventional gas boilers would be correspondingly greater.

The participants of this workshop had concluded that research on energy use in residential and commercial buildings was very relevant to UK energy futures; that scientific capabilities were high; and that the UK was modestly well placed in terms of industrial capability. However, scientific and industrial capabilities in relation to heat pumps and district heating were seen to be low. Under the International Energy Agency (IEA) classification scheme, social and economic research was allocated to the heading "energy systems analysis". This was also seen to be highly relevant for UK energy futures, with strengths in terms of both science and commercial capabilities.

2.2 Strategic Workshop 2: The Role of Environmental Science, Social Science and Economics

It was difficult to present high-level conclusions from the second strategy workshop on the role of environmental science, social science and economics, but some "nuggets" were presented:

- Promoting energy demand research was like Sisyphus pushing his stone up the hill;
- A disproportionate effort has been put into kit as opposed to behaviour;
- There is an over-reliance on economics in the design of energy policy;
- Instrumental social science that helps answer policy questions is popular with funders but it rests on a foundation of fundamental, critical work;
- Language matters, but natural scientists often form the view that a social scientist's first question when approaching a subject is to question terminology and meaning;
- Research Councils can and have forced better interdisciplinary working.

2.3 Strategy Workshop 3: The Research Councils and the Energy Funding Landscape

This workshop explored the relationship between the Research Councils and the rest of the innovation landscape. Two representative case studies were undertaken; marine renewables, an example of use-inspired research, where policy and end-user goals drove the research effort, and molecular photovoltaic research, which was inspired more by basic science. Some key findings were:

- **Basic Research:** There needs to be stronger mechanisms for feeding findings from later in the innovation process back to basic research projects.

- **Scope of the Research Councils:** At which point should the handover between the RCs and the later innovation bodies (ETI, TSB) occur?

- **Applied R&D:** There is a need for adaptable and flexible testing facilities, and for ensuring spin-out companies can understand and access their potential markets.

- **Pre-commercial Deployment:** Clear policy signals and market regulations are needed so that investors feel secure.

A key finding from the workshop was that it is important to have a clear long-term vision alongside a research programme, signalled by market, government and regulatory policies.

2.4 Participants Reactions to Strategic Workshop Results

Participants were then asked to record their reactions to the outcomes of the strategy workshops under three headings: what surprised, delighted and disappointed them. These were discussed in table groups. The outputs are recorded in Table 1.

Table 1: Participants' reaction to the results of strategic workshops.

Surprise	Delight	Disappointment
Inter/multi-disciplinarity		
Very good approach to promoting multi-disciplinary research themes around use cases.	Recognition of role of interdisciplinary work	No actual measure that interdisciplinary research is doing more than in silos.
	Focus on importance of interdisciplinarity	RCUK Energy Programme/academic standing is seen as barrier to interdisciplinarity.
Technology & Infrastructure		
High ranges for many techs – especially CCS	The consideration of a wide range of infrastructures.	Usual suspects of technologies
That ocean energy has no clear lead internationally	District heating is wanted more than expected	That social scientists think 'kit' is less important.
Low UK prominence in some fields such as CCS/fusion		Not much emphasis on the role of SMEs & new entrants in energy sector. 'Disruptive techs'
High range for district heat		Lack of consensus on supply technologies
Innovation System/Chain		
Default R&D spend for DNOs is only 0.5% of allowed revenue. Isn't this where major innovation is needed?	Bringing coherence to a fragmented innovation system.	
	Recognition of the need of linking university research to the wider innovation chain	
	Highlighted path from the Research Councils to TSB, but concern about beyond TSB and in use feedback.	
Structure of Academia & Research		
That we're still complaining about	That I'm not the only one	Do not agree with the criticism

lack of demand-side research.	questioning academic incentive structures!	of academic incentives
	Joining up of science/engineering issues with social outcomes/concerns	
	Importance of reservoir of fundamental/critical social science	
General		
Scope of the project – a lot of work for the team.	High recognition of significance of energy systems analysis	How to focus on the short term wins and long term gains
Some of the data on the UK technology/importance/capability graph.	That the work challenges ways of measuring academic s' performance.	Does not review international research (reinventing the wheel) and how to tap synergies.
Little but not in a bad way!	Output provided a good overview of current and future scenarios	Diversity is double-edged sword , can be good or bad
That there were no surprises.	Little – sorry!	Lack of career paths
Nothing much		Tension with UK market liberal paradigm
		Evidence of groupthink and lack of specificity
		Lack of specificity.
		Lack of considerations around markets/market-driven changes at all levels.

Following this, groups were asked to highlight some key points which they thought were important highlights of the discussion. These included:

- To ensure that district heating and CHP are adequately captured in the upcoming discussions at this workshop, as the quantity predicted at the first strategic workshop surprised many delegates;
- That not everything can be done at once – we need to find examples of what works, then work to scale that up;
- We do not always treat the energy system very systematically, even though we acknowledge it is a system;
- To ensure we understand the impacts of infrastructure (social, climate, visual, health, economic). This is the role of social science.

3 Helicopter View of the Research Terrain 'as-is'

Aidan Rhodes from the Fellowship Team began this section by presenting a diagram setting out basic concepts of the energy infrastructure sector along with a straw-man list of 'big issues' designed to frame some of the research and policy challenges facing the sector.

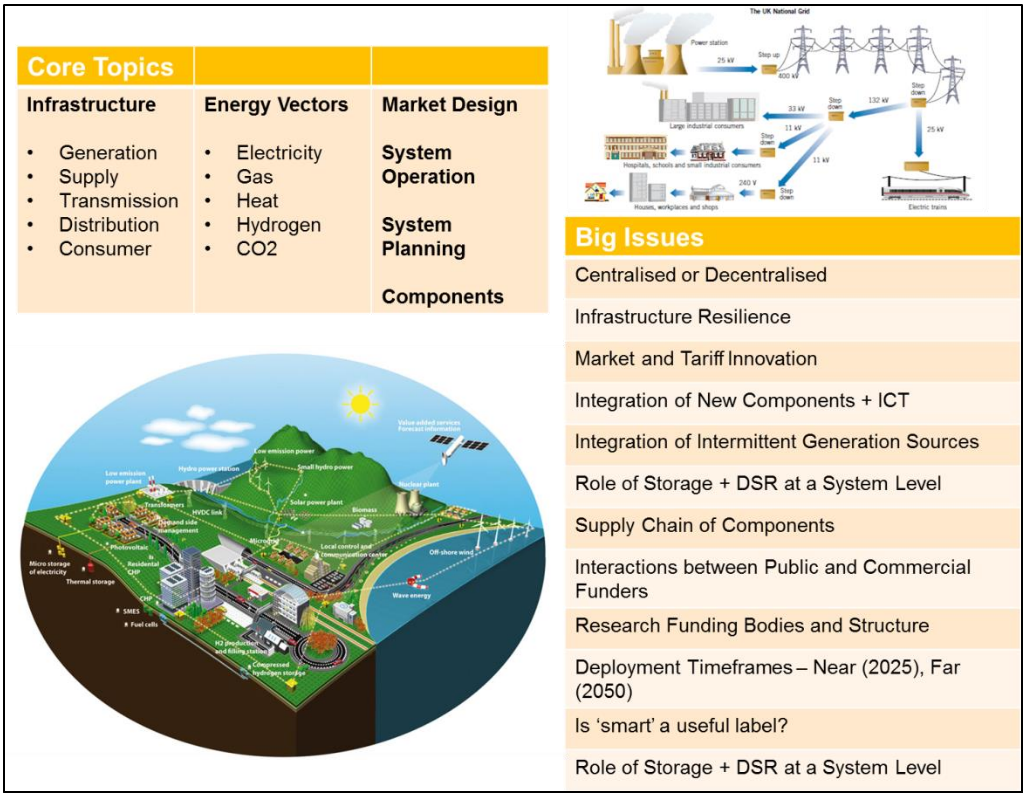

Figure 1 Energy Infrastructure Diagram prepared by the Fellowship Team

The participants were then divided into four table groups, and asked to prepare a briefing on the energy infrastructure research terrain as it is now. The participants were allowed a short period of time for individual reflection before feeding their insights into a group discussion. The group then distilled what they considered to be the 'key themes' onto post-it notes, which they arranged on a wall chart according to the x-y axes displayed in Table 2.

Each group was then given two minutes during the plenary to present the key themes from their discussions. The following is a distillation of the table discussions and the plenary presentations, focusing on the main emerging themes of the discussions. A more detailed account of the key research questions identified can be found in Annex A.

- Incentives are very important and a key point for consideration in the sector. Incentives need to be well targeted and structured. In the UK, there are a lot of 'silos', where businesses operate semi-independently of each other. Self-interest is therefore very high in the UK, and industry finds it very difficult to act when there is no direct and immediate impact on the bottom line. For the greater good there are lots of things that need doing (e.g. open up smart meter data) but no incentives to encourage them. How can we incentivize innovation in a system that is conservative and works adequately in terms of current needs. However, it needs to change with the introduction of new energy technologies.
- If you can achieve coordination and maximize collective benefit in the system, how do these distribute between individual actors and how easy is it for private companies to operate in this structure?

- What is the future of gas networks and how do these systems relate to and interact with electricity networks?

- Risk and uncertainty are intrinsic to investment decisions, how can these be best evaluated with regard to future fuel prices, future plans and policy decisions and the role of current infrastructure in future plans? The UK needs to be careful not to invest in infrastructure that may become useless in a decade.

- There appears to be a move away from electrification as the dominant solution for building and transport energy supply, which differs from the dominant view a few years ago. This is to do partly with the challenges of electrification of heat and transport on local networks. Is this a desirable path to take and how does this affect the generation mix?

- The UK is attempting to deliver a long-term vision, which will not be fully realised until 2030-50. This needs to be done in a dynamic environment – it is a continuous transition, not a single step, e.g. which technologies depend on others to be installed before they can be and what do we need to be doing now? What we install over the next few years may lock us into a specific transition pathway.

- There is a related challenge: how do we and how important is it to accelerate the development and deployment of specific technologies; demand-side management, energy storage and hydrogen technology? These technologies depend on specific pathways to be economic but in many cases need to be developed before we know which pathway the UK is following.

- Data collection may not be considered 'sexy' but it is very important, both in terms of quantity and quality. What are the barriers to researchers being able to access data from energy infrastructure as the quantities collected increase in the future, and what research possibilities open up as a result?

Table 2: Helicopter view of UK's current research terrain

	Market Design	System Planning	System Operation	Components
Consumer	Consumer acceptance: public understanding / political will How to incentivise innovation in a conservative sector (e.g. DNOs, consumers, policymakers)		Coordination of actors to: maximise collective benefits / comply with physical limits / sharing of benefits	
Distribution	New Designs: both incremented & transformative (e.g. elec. Distribution)	Future of the gas system & its interaction with the electricity system Transition: delivering long-term visions in a rapidly changing system		How to accelerate technology development and deployment of e.g. energy storage, DSM, new vectors (liquid air etc.)
Transmission	Tension between liberalised/privatised model and desire to create public goods	Move away from electrification as the only solution Realisation of value. Invent, or just buy what's out there? Scope for an energy company to expand its business (by justifying investment)?	Reliability of supply / robustness of the energy system / what do these mean?	
Supply	Industry engagement: incentives? Ability to deliver? Short-term pressure on cost-cutting. Competition vs. Collaboration. (Market Structure).			
Underpinning Issues	What are the drivers? Decarbonisation / equity / affordability / security Data: quality & availability for planning, operations & research.	Systems of systems: integration / complexity Uncertainty / risk / optionality		

4 How well placed are we to tackle existing research challenges in energy infrastructure?

Working individually, people were asked to identify how well placed the UK is currently in terms of possessing the necessary research capabilities to tackle key existing research challenges relating to energy infrastructure. They were invited to score these capabilities on a scale of 0-10 (0 = no chance, 10 = well setup) and explain their score on a post-it note. The following graph (Figure 2) shows the distribution of the 33 post-it comments.

The average score given by the group was 4.5 +/- 2.3. Figure 2 demonstrates that workshop participants were generally of the view that the UK did not possess *excellent* research capabilities in the field of energy infrastructure, indicated by the lack of scores above 8. In general, the group believed that the UK possessed poor capabilities particularly in the areas of system-wide infrastructure ("system of systems"), gas infrastructure and infrastructure-related business-model research. However, the group also believed that the UK did possess a wide range of strong capabilities in energy infrastructure research, specifically in relation to electricity system infrastructure, smart metering and network modelling.

In light of these observations the group identified that the energy infrastructure research area in the UK would benefit from the following:

- additional interdisciplinary doctoral training;
- the better availability of datasets & test beds;
- the provision of non-arbitrary funding (i.e. a carefully considered funding programme);
- a stronger ability to capture and accumulate knowledge within research groups;
- additional facilities for testing & trialling energy infrastructure;
- additional incentives to undertake research in this area;
- a more integrated and coherent approach to energy infrastructure research;
- a better understanding of the relationship between research and its impact.

In contrast, the group identified that UK energy infrastructure research was benefitting at present from the following factors:

- a strong base of infrastructure researchers and research groups in the UK;
- the availability of financial resources;
- a relatively strong integration of different research disciplines related to energy infrastructure;
- a strong background in Science & Technology Studies (STS), which has provided insight into the more socio-economic aspects of energy infrastructure.

Table 3 divides the results into three classes: low capability (0-3); medium capability (4-6); and high capability (7-10), set out into detailed results.

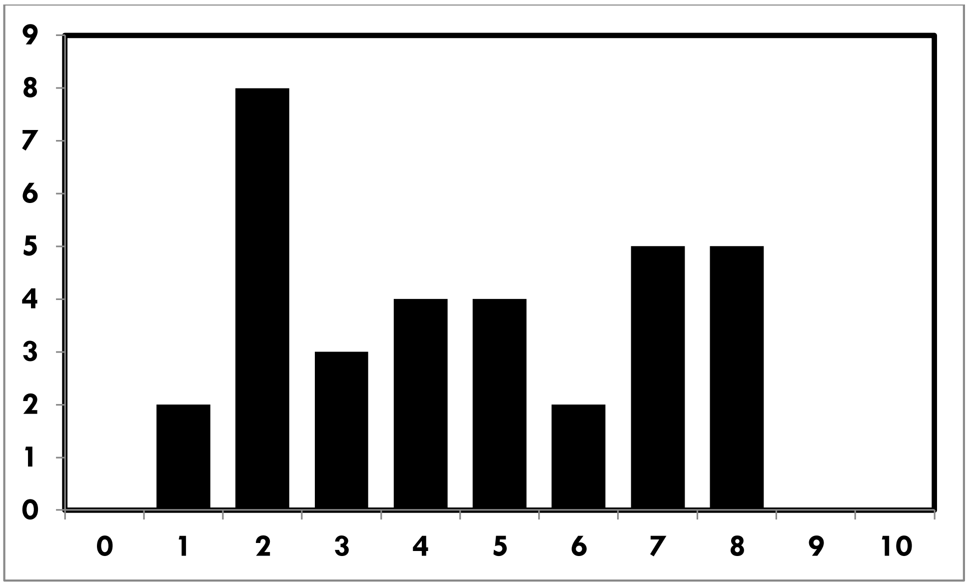

Figure 2 Distribution of perceived UK capability levels to address existing energy research challenges

Table 4: UK's perceived capability levels to address existing energy research challenges

High capability levels	
7	**8**
Strengths: Knowledge and capabilities (breadth and depth) but a need to develop further the facilities for testing & trialling, as well as further incentives	Electrical transmission: Technical perspective good capacity
Only partly joined up	Smart metering: deployment, operations
Lots of resource availability (Ofgem, LCN fund etc). Competent people but do we have the capacity to absorb funds?	Generally very good research groups but the main problem here is implementation.
A good people base, a number of interesting research projects but a need for a more integrated approach	Good capability in network modelling
Electricity infrastructure: there's relatively strong integration of different research areas	The research capabilities are good, however to achieve our objectives there is the need of more incentives

Medium capability levels		
4	**5**	**6**
Strong STS traditions in the UK, but a continuing lack of interaction between social science and engineering	Opaque funding approach	(+) Funding available, (+) This fellowship, (~) Lack of clarity of intended outcomes and objectives?
Energy infrastructure as a whole. There's limited integration of areas	Much activity, limited chain linking research to impact, more focus on top quality outputs rather than activity required	Storage research: Recent increase and possibly a leadership position
System integration: Good capability, but need to better integrate demand side	Good understanding of current infrastructure, but poor integration	
Lack of integrated thinking, fragmented sector structures, lots of independent silos	Infrastructure for flexibility; storage; DSM; etc. Low base, but growing, with a need for greater coherence	

Low capability levels			
1	**1/2**	**2**	**3**
Doctoral training for multidisciplinary energy research	Very little gas research	Availability of datasets and test beds for all academics to test their algorithms/hardware	Funding for collaboration between industry and multidisciplinary research teams
	Poor systems research on infrastructure	Business models: still have to bring about ESCos despite years of policy with the promise of enabling them	Cyber security
	No work on systems integration (e.g. gas+electricity)	Lack of enough good researchers	Floating LNG/receiving terminals?
	Sole focus on decarbonisation as a goal	Inability to capture and accumulate knowledge within research groups	
		Arbitrary funding (EPSRC especially)	
		Uninformed industry engagement	

5 Research 'Hotspots' and Broader Themes for Future Energy Research

5.1 Introduction to the Exercise

This exercise was designed to identify a range of topics that participants believed should be subject to additional UK-led research in the future, and which should therefore constitute an important part of the RCUK Energy Strategy Fellowship's *Research Prospectus*.

5.2 Methodology

5.2.1 Overview

In order to identify future energy research opportunities for the UK in the field of energy infrastructure, the participants were first invited to identify 'research hotspots' that could provide valuable insights, should (further) research be conducted into them. A 'research hotspot' was defined as follows:

> 'A ***Research Hotspot*** is a potentially valuable area of future research, which has been identified by the Expert Workshop participants. It is an area in which the experts believe research challenges will emerge in the future. It may be a broad and overarching question or problem'

To help guide the participants, a couple of good-practice examples of hot spots were presented from the previous Fossil Fuel and CCS workshop.

5.2.2 How were the research hotspots generated?

The first part of the process involved the participants working individually to generate some initial ideas about potential hotspots. The second part required the participants to form pairs to discuss and record these hotspots with a partner. These were recorded on post-it-notes

Once the pairs had discussed and recorded the hotspots they were then asked to place these on a wall chart, which incorporated similar axes to those used in Helicopter View of Research Terrain 'As-Is' exercise (see Table 2) with one amendment. The Y axis still broadly represented the energy supply chain running from supply>transmission>distribution>consumer. However, 'whole systems' was added at the top of the scale. This category reflected research themes that cut across the energy supply chain. The purpose of these axes was to act as a guide for participants to place their hotspots, with a view to clustering related hotspots.

The participants first browsed the wall chart in order to develop a feel for the types of research hotspot that other participants had generated. Participants were then prompted by random image cards in order to identify any further research hotspots that might have been omitted. At the same time, participants were encouraged to comment on existing hotspots. This resulted in a noticeable increase in the numbers of hotspots and comments.

5.2.3 Clustering Hot Spots at Different Scales

During the clustering exercise, participants grouped together similar hot spots in order to create research clusters representing potentially important energy infrastructure research themes. The clustering was performed by three groups corresponding to three broad, thematic categories that had emerged from the hotspots exercise. These were:

- Systems Level;
- Systems Planning & Operation;

- Policy Design & Market Design.

Once the groups had clustered the hotspots, they then named them clearly and concisely in a way that would be meaningful to non-experts. Each group was assisted by a facilitator who ensured that each member of the group had the opportunity to provide input and that the groups had clustered all their hotspots within the time available.

5.2.4 Grouping the Clusters Together

Participants then worked together to aggregate the research clusters into 'super-clusters'. Each group shared one of their clusters with the other groups, who were encouraged to identify any related clusters. Using a system of green, red and yellow cards, participants could confirm their support for a super-cluster, veto it or provoke further discussion. While a number of potential super-cluster arrangements were suggested by the participants, more often than not these were rejected by one or more of the group because they were uncomfortable with further aggregation.

Prior to the 'super-clustering' exercise, a handful of hotspots had not been assigned. During the 'super-clustering' exercise, participants moved certain hotspots from their original clusters and transferred them to others.

5.3 Results

In their three groups, the participants had grouped the large number of research hotspots into 19 different clusters. These clusters were aggregated into 17 'super-clusters', as described above. These 17 super-clusters are outlined in the tables below, along with the associated clusters and hot spots, which illustrate the research foci that make-up these broader research areas. .

Cluster 1 – Natural Capital

Cluster Name(s)	Hotspots
1 – Natural Capital	- Environmentally benign/adaptive infrastructure
	- Understand the resource requirements needed to build future energy infrastructure: ○ Impact on supply chains ○ Impact on price

Cluster 2 – Asset Management

Cluster Name(s)	Hotspots
2 – Asset Management	- Replacing or coping with aged infrastructure
	- Intelligent maintenance of infrastructure systems

Cluster 3 - Appropriate and sustainable business models throughout energy supply chain

Cluster Name(s)	Hotspots
3 – Identifying appropriate and sustainable business models throughout the energy supply chain	- Better business models for infrastructure renewal and maintenance
	- What are the possible new business models across energy, ICT/apps and connectivity? ○ Would they work under current policies and regimes?

Cluster 4 - Market, governance and regulatory frameworks for energy infrastructure

Cluster Name(s)	Hotspots

Cluster Name(s)	Hotspots
4a – What are the opportunities, drivers & barriers for Local Authorities to reshape energy infrastructure and governance?	- Local actors', especially local authorities' role in shaping change in the energy system. ○ Focus on potential challenges & impacts
4b - Understanding the market, policy and regulatory framework required to deliver secure, affordable and sustainable energy	- What market, policy and regulatory framework will be needed to realise the future infrastructure requirements for a low carbon energy system?
	- High level governance of energy and other infrastructure: ○ Risks and transaction costs of the UK's liberalised paradigm for achieving coordinated change and producing public goods
	- Understanding the integrated transitions pathway in terms of the technical, behavioural and institutional changes/connections that might be required to achieve it
	- Energy market reform: ○ Genuine market reform, as opposed to the electricity market reform (EMR) 'tinkering' ○ Fundamental rethink to address issues around: ▪ Relative lack of storage ▪ Splitting of costs and benefits between parties ▪ Overcoming a lack of competition ▪ Incentives to promote energy efficiency and low carbon energy
	- Value of central planning?
	- Understanding the possibility of network effects, gaming and learning

Cluster 5 - Integration of time of use tariffs, smart meters & smart appliances to provide demand response

Cluster Name(s)	Hotspots
5 – How can domestic time of use tariffs, smart meters and smart appliances work together to improve demand response?	- Role of consumers in energy efficiency and demand response
	- Smart meters – development of smart appliances for autonomous demand side management
	- Domestic 'time of use' tariffs ○ How can they be made to get demand patterns to follow supply? ○ Integrating of technologies, tariff structure, role of the consumer etc

Cluster 6 - Electricity Balancing

Cluster Name(s)	Hotspots
6 – Electricity Balancing	*Balancing a more integrated energy system* - Trade-offs between and integration of: ○ Interconnection ○ Transmission ○ Storage ○ Smart demand management - Determining the balance between *demand flexibility* and *grid storage* in balancing supply and demand - Electric vehicles to grid (EV2G) ○ Using parking spaces to provide connection to grid ○ Using EV batteries as energy storage to support the network ○ Demonstration and market design of these infrastructural innovations - Enabling integration of different storage facilities

Cluster Name(s)	Hotspots
	- Role of robust meteorological analysis for system planning and balancing

Cluster 7 - Control

Cluster Name(s)	Hotspots
7 - Control	- ICT interconnection across actors in the system
	- Control of supergrids & smartgrids ○ With more complex systems, whole centralised control is intractable
	- Different coordination mechanisms for energy system control
	- Development of the DSO role for local system balancing and interaction with national system balancing

Cluster 8 - Gas

Cluster Name(s)	Hotspots
8 - Gas	- Could we use the gas distribution networks for something other than the transportation of natural gas for heat generation?
	- How might we make best use of existing gas infrastructure in the future low-carbon energy system (e.g. looking at bio-gas, hydrogen, CO_2)?

Cluster 9 – Principles of energy system & networks modelling

Cluster Name(s)	Hotspots
9 – Principles of modelling: • Necessary but sufficient accuracy/detail • Transparency • Users' knowledge & ability to use models	- What do different classes of model tell us about the real world, as opposed to about the model?
	- Methodology to understand & quantify the interdependency of critical energy infrastructures (e.g. electricity, gas, heating, cooling, CO_2, H_2), as based on detailed physical system modelling
	- We need to be better at using, developing, understand and integrating our models ○ E.g. power systems stability with ubiquitous power electronics

Cluster 10 - Impact of future infrastructure costs and subsidies on tariffs, affordability, energy justice and equity

Cluster Name(s)	Hotspots

10 – Impact of future infrastructure costs and subsidies on tariffs, affordability, energy justice and equity	*Impact of energy infrastructure changes on consumers*
	
	- Consumers perspective on risks of different network infrastructure
	  ○ Justice and equity implications relating to these risks
	- Tariff structures – Public acceptance & social impacts of:
	  ○ Real-time tariffs
	  ○ Subsidies
	- How do different infrastructure scenarios impact upon disadvantaged groups?
	  ○ E.g. remote areas, fuel poor etc

	- Managing the transition to allow appropriate compatibility with older systems or technologies to ensure socially equitable solutions

Cluster 11 - Improving the evidence base for policy evaluation and review

Cluster Name(s)	Hotspots
11 – Improving the evidence base for policy evaluation and review	- Analysis of previous energy policy and its effects on energy infrastructure ○ Review of government modelling of impacts of policy interventions and compare with outcomes to have a better evidence base to inform different kinds of intervention
	- Robust assessment of true lifecycle emissions for policymaking and investment decisions
	- Design of policy evaluation ○ Develop research designs and monitoring technologies for robust demand-side management (DSM) measurement
	- Life cycle assessment of policy programme impacts

Cluster 12 – Data ownership, protection and use

Cluster Name(s)	Hotspots
12 – Data ownership, protection and use	- Household-level data privacy vs. usefulness
	- Regulatory access to data on assets in regulated monopolies
	- Secrecy – what is really commercially confidential? ○ Means of making data available

Cluster 13 - Decision making and investment under uncertainty

Cluster Name(s)	Hotspots
13a – Investment under uncertainty	- Successful generation investment under uncertainty
	- Value/risk of anticipatory investment in networks: ○ Heat networks ○ CCS ○ Grids ○ DNO network upgrade
Cluster 13b - Decision making under uncertainty:	- Characterisation of uncertainty ○ How to use this characterisation to inform decision making (e.g. decision metrics)
	- Decision making under uncertainty: Energy system planning, operation and investment:

Cluster 14 – System of systems

Cluster Name(s)	Hotspots

Cluster Name(s)	Hotspots

14 – System of systems	*Integration of different energy related infrastructures*
	
	- System of systems – Integration of heating and electricity systems:
	  o Feasibility analysis
	  o Carbon intensity
	  o Quantification of potential total reduction of primary energy demand
	- Improve our understanding of how different energy systems complement each other
	  o E.g. variability of wind and demand can lead to a gap that needs to be rapidly (1 – 2 hours) filled by CCGT generation – can the gas system cope?
	- Interdependence of infrastructures
	- Barriers between energy infrastructures – examination of interactions and mutual understanding
	- Transport infrastructure vs energy infrastructure as an example
	  o Electric charging points
	  o Electric-vehicles-to-grid (EV2G)
	  o Hydrogen fuelling stations

	- How might we cope with a series of different technologies that work on different temporal and spatial scales? o e.g. Intermittent supply, storage, daily & seasonal demands etc
	- Research into the range of possible energy system futures to enable design of future energy infrastructure

Cluster 15 - The role of the user, including communication with industry and experts

Cluster Name(s)	Hotspots
15 – The role of the user, including communication with industry and experts	*Public attitudes and levels of acceptance* - Consumer acceptance with regards to blackout, rising bills, transmission lines etc - Public attitudes to CO_2 pipeline safety
	Energy consumers communication and engagement - Communication – Don't keep consumers in the dark. Show them the bright near-future - Who is responsible for public engagement and rebuttal of pseudoscience? - Make it fun to engage with energy issues
	- Understanding how users will react and change their behaviour when faced with new systems

*Link made between this cluster and cluster 17 - *Supply quality and standards*

Cluster 16 – Resilience of energy infrastructure to external events

Cluster Name(s)	Hotspots
Cluster 16 – Resilience of energy infrastructure to external events	- Resilience of energy infrastructure following threats/incidents
	- Resilience of energy infrastructure to changing UK climate
	- Energy system resilience and disaster recovery
	- Design of safety-critical systems

Cluster 17 – Supply quality and standards

Cluster Name(s)	Hotspots
Cluster 17 – Supply quality	- Redundancy – balancing of resilience and optimality

Cluster Name(s)	Hotspots
and standards	- Consumer valuation of supply reliability and equality
	- What are the minimum security requirements (both physical & cyber) in the medium to long-term? Where are the gaps currently?
	- Relaxation of some (technical (both planning & operational) network constraints to allow higher penetrations of low carbon technologies

*Link made between this cluster and cluster 15 - *The role of the user, including communication with industry and experts*

6 Reflections on Day 1

At the beginning of Day 2, the participants were asked to reflect in small groups about the work of the previous day. They were then asked to share any significant insights with the wider group. The following key points were raised:

- **Robustness and resilience -** The challenge of designing an energy infrastructure system that is sufficiently robust against large external shocks, such as the discovery of shale gas, has forced us to reconsider how the energy system might develop. Questions should be raised around the issues of openness and transparency in relation to how robust and resilient our energy infrastructure systems are. For instance, to what extent should we communicate how resilient the UK energy system is to the UK public? Doing so may raise concerns about national security but would also ensure the public are better educated.
- **Technical aspects of infrastructure –** Concern was raised that a lack of attention had been paid during Day 1of the workshop to technical components of the UK's energy infrastructure. Much of the 'technological nitty gritty' had been ignored during the group's discussion around broader research themes relating to energy infrastructure. Specifically, it was suggested that greater attention should be paid to the technical aspects of upgrading the UK's transmission network (e.g. roll-out of better, cheaper cables), as well as the roll-out of HVDC and new network control technologies. A more comprehensive consideration of these technical components could inform our understanding of the costs associated with developing the UK's energy infrastructure system in the future components
- **Network sensing –** We could benefit from additional research into network sensing technologies and how these might provide more detailed information into when, why and how we use energy networks. In particular, research might be conducted into valuable connections between sensing, control and ICT technologies
- **Integration of Europe-wide research funding programmes –** The extent to which EPSRC's energy funding programme complements other research funding programmes, particularly EU-level research calls (e.g. FP7), was questioned. Should the duplication of similar research should be cast in a positive or negative light? For instance, whilst funding two projects with the same objectives may mean that more public money is being spent than necessary to deliver a certain set of research outputs, funding lower quality or more obscure research simply to achieve a broader research portfolio may also constitute a poor distribution of public funds. It could also prove detrimental to the UK's energy research base in the longer term.
- **Consideration of EU policy –** One attendee emphasised the need to be sensitive to EU policy with respect to energy infrastructure research because 'a lot of what we're trying to do in the UK energy system isn't solely up to the UK government' but is reliant on the EU regulatory framework
- **The process of developing new energy infrastructure –** It was suggested that the group may have failed to fully consider the *processes* by which new energy infrastructure is developed and constructed. One example given was with respect to the processes involved in building a new nuclear power station, in light of plans to install its new nuclear generation capacity the

UK. Research could be conducted into how the processes of infrastructure planning and development might change in the relation to very capital-intensive energy infrastructure development, compared to less capital-intensive infrastructure. For example, should the UK government consider 'picking winners' in order to minimise the costs of its most capital-intensive energy infrastructure?

- **The process of moving away from our existing energy infrastructure –** Research in this area should cover the processes that the UK will have to undergo in order to shift away from its existing high-carbon infrastructure. These include decommissioning infrastructure and retraining personnel. This will be important as we will need to consider how to manage the UK's ageing energy infrastructure in the future. For example, what plans will need to be made in order to effectively manage the problems arising from the CCGT plants that are being built now, becoming obsolete in 10 years' time?
- **Implications of a low-carbon energy infrastructure system –**We should pay close attention to the potential implications for the electricity network of moving towards a low-carbon energy system. Such a transition may affect the resilience of the UK energy system.
- **Poor modelling of infrastructure change –** One attendee observed that whole systems models have to date not proved particularly effective in accurately representing important changes in energy infrastructure. Consequently, the research community should ensure these models are refined so that they can be successfully applied to simulate infrastructural change.

7 Research Cluster 'Deep-Dive': Communities

7.1 Introduction to the Exercise

In this exercise, participants were asked to identify: key research questions relating to the research clusters and super-clusters identified on Day 1; any potential challenges that might be encountered when examining these questions; and what might needed to be done in order to address these challenges.

7.2 Methodology

Participants self –selected themselves into three "communities of practice":

a) System Modellers (4 people)
b) Energy System Transitions (8 people)
c) Energy System Balancing And Control (6 people)

The Energy System Transitions group was split into two smaller groups, each containing 4 people, to ensure that every member of each group had the opportunity to provide input into the discussions. Each group was allowed to select whichever research clusters/super clusters they wanted to examine in greater detail, which are outlined in 4.

Table 4 Community groups and their selected clusters for Deep-Dive 1

Group	Community of Practice	Selected Clusters/Super-Clusters	
		No.	**Description**
A	Energy System Transitions (A)	10	Impact of future infrastructure costs and subsidies on tariffs, affordability, energy justice and equity
		15	The role of the user, including communication with industry and experts

B	Energy System Transitions (B)	3	Identifying appropriate and sustainable business models throughout the energy supply chain
		4	Transitions, governance and policy
C	Energy System Balancing & Control	6	Electricity Balancing
		7	Control
D	System Modellers	9	Principles of energy system & networks modelling
		14	System of systems

To assist the deep-dive process, each team was provided with an activity sheet with a set of questions and suggestions as how each question could be approached. The questions were as follows:

1. What are the key research questions relating to this field?
2. What capabilities / capacities do we need in place for the UK to address these questions?
3. What challenges are we likely to face?
4. What do we need to do to ensure we are ready to address these research challenges (e.g. PhD training, data collection/curation, research Infrastructure, funding philosophy etc.)?

Outputs were recorded on flipcharts, after which the groups reported back key outputs in plenary.

7.3 Summary of Results

This exercise generated a large volume of data. Key themes are presented in the main text. The detailed outputs are documented in Annex B.

7.3.1 Important Areas for Future Research

- **Technical aspects of network control –** What are the limitations to energy network control and the opportunities to improve this (e.g. via energy storage)?
- **Technical aspects of energy storage –** What is the role of energy storage in network control & balancing? How might storage technologies best be integrated into existing energy infrastructure? How should storage and DSM be implemented alongside one another?
- **Forecasting levels of energy consumption and generation –** To what extent can we accurately predict consumption and generation (primarily renewable) in order to provide effective network balancing?
- **Energy consumption and network management –** How can we best manage people's energy consumption profiles so that they are in synergy with energy generation & supply? How might this improve network balancing and system resilience?
- **Resilience of energy infrastructure –** How resilient is our energy infrastructure? To what extent can this be realistically improved? What risks do we face if the system is insufficiently robust against external shocks?
- **'System of Systems' –** What are the key interfaces between different energy infrastructures (e.g. regionally, internationally etc) and between energy infrastructure and other infrastructures (e.g. water, waste, transport etc)? To what extent are these integrated?
- **Contribution of modelling to energy infrastructure -** What is the purpose of modelling in the context of energy infrastructure? What can it help us achieve?
- **Modelling methodology -** What types of models can effectively manage/represent the inherent uncertainty of energy infrastructures? How can we improve the spatial and temporal detail in models without losing tractability?

- **Steps to realising system change –** What are the technical steps we will need to take to move from our existing energy infrastructure to a radically new and different one? What arrangements will need to be in place (e.g. regulation, market etc)?
- **Relationship between people and energy infrastructure –** How energy infrastructure impacts upon people (e.g. affordability/equity of energy)? How do these impacts differ for different segments of society?
- **Consumers' attitudes towards energy infrastructure -** What are consumers' attitudes towards key infrastructural developments? How can we effectively communicate and engage with consumers to better facilitate these infrastructure developments?
- **Regulation, business models and market structures –** What are the most appropriate regulatory frameworks and market based mechanisms (e.g. incentives, business models) to encourage investment in energy infrastructure?
- **Actors & power dynamics across energy system –** What are the key actor relationships and power dynamics across the energy system? What are their relevance to energy infrastructure?
- **Governance arrangements and priorities –** What are the different governance arrangements that could be put in place to manage the UK's energy infrastructure? What are the potential implications? What should these arrangements prioritise (e.g. security, affordability, low-carbon)?

7.3.2 Key Requirements to Undertake this Research

- **Input from multiple disciplines –**High quality energy infrastructure research will rely upon input from various disciplines including engineers, mathematicians, social scientists, psychologists, economists etc
- **Truly interdisciplinary research –** Not multi but inter-disciplinary research. 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
- **Design of 'immersive methodologies' –** We could generate significant amounts of valuable data by observing how people interact with technologies in specific controlled situations.
- **Integrate the innovation chain –** There is a need to improve integration of key processes along the energy infrastructure innovation chain. For example, it is not only important 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 flow of evidence between RCUK funded research and ETI funded research
- **Academia-industry collaboration –** 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.
- **Incentives for industry to engage in energy infrastructure R&D –** New incentives (e.g. market competitions) to foster significant industrial engagement with energy infrastructure R&D, specifically for start-up companies and the energy utilities
- **Combination of regulator & RCUK funding –** It is important that RCUK funding is available to drive forward theoretical research into energy infrastructure, whilst regulator managed funding is available to support more applied/practical research to undertake large-scale infrastructure experiments and technological development

- **Test facilities to test energy infrastructure –** Energy infrastructure need to be tested in 'real environments' with 'real consumers'. The necessary test facilities and regulatory frameworks should be in place to enable this to happen
- **Engineers –** Need energy infrastructure engineers with advanced knowledge of the field to develop and integrate new energy infrastructure technologies (e.g. balancing and control technologies)
- **National research centres to concentrate research expertise** - National research labs like the Fraunhofer Institutes in Germany could prove useful in facilitating the development and retention of key energy infrastructure skills in order to drive forward energy infrastructure R&D. This may be particularly relevant for infrastructure modelling, which would provide the modelling community with a strategic lead and help centralise and consolidated their expertise in this field
- **Better integrate research landscape –** A need to not only to bring the various energy infrastructure projects, centres and consortia closer together to share their key findings but also to bring closer together the various disciplinary communities that are expected to make an important contribution to the field.
- **Role of modelling –** Important to consider what role modelling will play in helping to address these key research questions. If its role is considered important then efforts should be made to improve existing models, such as by integrating different types of models (e.g. agent-based, dynamic system etc) and models operating with varying degrees of granularity. Efforts should be made to learn lessons from climate modelling community and ensure that industry is engaged in the process of refining these models.

8 Research Cluster 'Deep-Dive' 2: Community Cross-Cutting

8.1 Methodology

Participants were allocated to four groups, , in which the communities identified in Section 7 were mixed. The groups were asked to cover as many of the remaining clusters/super-clusters as possible but were invited to prioritise the clusters shown in Table 5. Group 1 was asked to perform a 'sweep-up' and focus on technical aspects that had not been covered in the first deep-dive session.

Table 5 Cross-community groups and their selected clusters for Deep-Dive 2

Group	Selected Clusters/Super-Clusters	
	No.	Description of Clusters
1	Technical aspects of energy infrastructure	
2	1	Natural Capital
	2	Asset Management
	8	Gas
3	11	Improving the evidence base for policy evaluation and review
	12	Data ownership, protection and use
	13a	Investment under uncertainty
	13b	Decision making under uncertainty
4	16	Resilience of energy infrastructure to external events
	17	Supply quality and standards

	5	How can domestic time of use tariffs, smart meters and smart appliances work together to improve demand response?

Participants were asked to answer the following questions for each cluster:

1. *What are the key research questions relating to this area?*
2. *Whose job should it be/who is best placed to undertake this research?*
3. *How might the different organisations & research communities collaborate with one another in order to address these key research questions?*
4. *What capabilities/capacities do we need in place for the UK to address these questions?*
5. *What do we need to do to ensure we are ready to address these research challenges (e.g.PhD training, data collection/curation, research Infrastructure, funding philosophy etc)*

8.2 Summary of Results

This exercise generated a large volume of data. The key themes are presented here in the main text. The detailed outputs from each of the groups are documented in Annex C.

8.2.1 Important Areas for Future Research

- **Technical aspects of electricity networks –** examining the 'nuts and bolts' of the electricity network and how technical adjustments might be made to the existing networks (e.g. different cables, change in voltage,
- **Optimising infrastructure maintenance regimes –** Importance of data collection and the design of efficient delivery mechanisms
- **Smart technology –** What is the role of the consumer in a 'smart system'? What level of active consumer engagement do you need? How should/can we use the data generated by smart technology to manage the system?
- **Repurposing of gas networks –** exploring the ways in which the gas networks could be used for other energy vectors (e.g. heat, hydrogen, biomethane etc). What are the issues with retiring the gas network?
- **Improving granularity of gas consumption -** How can we disaggregate gas usage, like with electricity, in order to understand consumption patterns and needs?
- **Resolve uncertainties around heat** - Huge uncertainty over the necessary action and research timelines associated with meeting our targets for heat provision
- **Strategies for developing heat-supplying infrastructures –** How do we effectively manage the shift of hundreds/thousands of consumers from existing heat system to future heat systems (e.g. electrified, district CHP etc)? Could a spatially coordinated shift be a solution? What are the inherent benefits and pitfalls of moving from one system to another, e.g. in terms of equity and affordability?
- **Energy infrastructure resilience –** What constitutes a resilient energy system? How/when do systems fail and what external events do energy infrastructures need resilience against (e.g. cyber-attacks)? How do you achieve the best levels of resilience? In which different ways can resilience be achieved?
- **Minimising the 'pollution' of energy infrastructure –** e.g. CO_2, visual, noise etc
- **Decision making under uncertainty -** Understanding scientifically how decision making (e.g. investment) around energy infrastructure plays out in the context of uncertainty. Is there a typology of uncertainty and can these different types of uncertainty be quantified? How can we manage this uncertainty and its associated risks, e.g. in terms of energy investment?

- **Innovative governance arrangements for electricity networks –** e.g. greater role for DNOs; changes to the energy supply chain; and the potential for offshore transmission operations. Examine the political economy of energy infrastructure and specifically, how actors interact with these systems and vice versa.
- **Institutions and organisations** – What governance arrangements and business models are require to facilitate the transition to a low-carbon energy infrastructure? How will these be linked as part of a supply chain?
- **Energy policy evaluation –** How should we evaluate policy? What methodologies are required? Explore opportunities for ex-post policy assessments that take into account unexpected outcomes and unintended impacts

8.2.2 Actors Responsible for Undertaking this Research

- Academia
  - Statisticians, mathematicians & modellers
  - Engineers
  - Business studies experts (energy business models)
  - Social Scientists
  - Historians
  - Economists
  - Meteorologists (climate change implications for infrastructure)
  - ICT (smart aspects of infrastructure)
- Regulators
- Standards institute
- R&D institutes
- Government & policy makers (e.g. DECC)
- Professional bodies
- Arm's length organisations (e.g. National Audit Office, CCC)
- Market data companies
- Consultancies
- Energy utilities
- OEMs
- DNOs

8.2.3 Key Requirements to Undertake this Research

- **Data requirements for energy infrastructure research –** What data is required to undertake insightful research and how might this data be attained? Might new methods be necessary (e.g. randomized field trials of new technologies/governance arrangements etc)? What is the acceptability of these methods?
- **Large publicly available data sets of UK energy consumer behaviour** where competition could be established to encourage the innovative design of technologies or software (e.g. apps). It would be particularly useful if these were anonymised & live so that researchers could track and understand demand variations 'in the moment', instead of after the fact.
- **Understanding of the ethical and legal aspects** of data collection, ownership, protection and use
- **Test facilities** that involve people or demonstrations.
- **A management system to assess the resilience of the UK energy system and identify what is required to improve this**
- **Acknowledge the long-term nature of energy infrastructure development,** which should be built into policy, industry and academic plans

- Examine where IP 'goes' if it is generated by foreign companies in the UK. Identify solutions to this to **help UK retain ownership of IP**.
- **Lack of capacity** as international students return home. Need to either 'grow our own' or encourage overseas students to remain in UK.
- **More creative engineers**
- **Longer term research contracts** to retain knowledge in universities due to short-term projects/contracts.
- **Secondments & internships** between academia, industry and government
- **Knowledge Transfer Networks** important for translating key issues between communities
- **Hideaway research boot camps –** Facilities such as the Los Alamos national lab could be useful to get seconded researchers together to intensively think about key energy infrastructure issues.
- **Joint industry/academic funding**
- **Industrially sponsored/funded research centres** (e.g. Tata steel in Cardiff, BAE systems in Southampton) to promote strategic partnerships between academia & industry
- **Using industry bodies to help identify the right people for the right job**
- **Flagship umbrella institutes/centres** (e.g. UKERC) capable of drawing together leading researchers to focus on important energy infrastructure issues (e.g. uncertainty)
- **Research funding calls tailored to 'fill the gaps'** in the energy infrastructure research landscape, e.g. energy policy evaluation
- **Conferences designed to promote cross-organisational and inter-disciplinary learning** around energy infrastructure
- **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. Similar issue between energy infrastructure & ICT communities which operate on different timescales
- **The structures in place to establish a dialogue between policy makers and researchers**
- **Learn lessons from other industries**

9 Reflective Writing

9.1 Process

The purpose of this exercise was to ensure that the finer detail generated during the workshop was not lost. It provided participants with the opportunity to build upon ideas they had formulated during the clustering and deep-dive exercises and allowed them to flag any broader issues they wanted to raise. Participants were provided with three options for the reflective review session:

Option One: *Independent Reflection*

A room was set aside for individuals to work on their own to record their thoughts and ideas.

Option Two: *Chat Room*

A room was provided for participants who wanted to talk through their reactions to the themes and research ideas. A note taker was present to record the discussions.

Option Three: *Reflect and Chat*

Participants in this room first reflected individually and subsequently joined together in groups of three to discuss their individual reflections. This enabled participants to develop their ideas by 'bouncing' them off other members in their group.

Participants were encouraged to post any written output from this session into a reflections post box or email their thoughts to the organisers.

9.2 Outputs

9.2.1 Future Research

- **Influence of energy demand on energy infrastructure -** Urban socio-economic processes likely to take a leading role in shaping energy infrastructure, i.e. acting as a constraint on energy infrastructures, not just vice versa.
- **Resilience of energy infrastructure to shocks in urban contexts –** How will such shocks impact upon 'uniquely urban contexts' such as underground transport, dense urban environments (e.g. sporting events) and the provision of major public services (e.g. education, government, healthcare etc)
- **Routes for laying pipes and wires -** How can we most effectively use our existing infrastructure routes for pipelines and cables (e.g. motorways, rail routes, sewers, water mains)
- **City level shaping of energy policy** - Are cities leading or following in energy infrastructure policy? Contrast between UK & Scandinavia
- **Active or passive cities** - To what extent are cities active or passive nodes in energy systems?
- **Cities as investors -** What is the role of cities as investors in energy infrastructure, alone or in partnerships?
- **Understanding consumer behaviour –** We still don't understand consumers very well, even in relation to some very fundamental questions that define the appropriate type and level of energy infrastructure
- **Changing patterns of supply and demand -** We don't have a good understanding of how spatial and temporal patterns of energy supply and demand might change in the future. This understanding is however vital for infrastructure planning
- **Align research agenda with policy agenda –** 2013 DECC Heat Strategy includes a long chapter on infrastructure and is much less confident about the future than previous heat reports have been. They highlight the need to address:
    - Whole systems modelling
    - Hydrogen in the gas networks
    - Heat storage
    - Decide what to do with the gas networks
- **Identifying strategic priorities –** Are there particular technology fields in which the UK community has capacity, which have the potential to fundamentally transform our energy infrastructure. This may relate to disruptive technological innovations (e.g. transmission or battery technology – grid scale storage, vehicle-2-grid etc)?
    - On what basis are these strategic priorities identified?
- **Aligning energy infrastructure research internationally -** Setting research priorities in relation to Europe and other countries. To what extent should the UK adopt a 'go it alone' policy in terms of its own research agenda?
    - Where do international overlaps in research exist and how might strategic partnerships best exploited e.g. are there areas which are too big or risky for the UK to take on alone? On the other hand, bespoke solutions may be required.

- **Focus on 'real' systems –** We need to identify solutions that work in real energy systems, which may require a fundamental rethink of organising the research effort so that it is focused on less 'blue sky' ideas to more tractable and immediately applicable innovations
- **Distributed generation –** Topics about distributed generation (DG) are commonly related to technical issues (e.g. use of smart grids) however in order to get cheap and quick DG connections we also need innovative commercial arrangements (e.g. market mechanisms, business models etc).
    - This is a new area of research that particularly reflects the value of interdisciplinary work
- **Compatibility of technology/infrastructure and wider systems** - Are future energy infrastructure and key technologies compatible with established systems?
    - Remember that abstract concepts like energy efficiency or smart meters will actually mean making a tangible change in someone's home or office
- **Links between cities & energy infrastructure –** Why is this relationship important? Cities are the places where infrastructure meets consumers. Also, cities provide ready markets for the testing of new products/services and are centres of innovation, which are home to:
    - SMEs
    - Capital markets
    - Homes
    - Decision makers
    -
- **New mathematical models required -** There are no models available that compare transmission, storage and demand management in a comprehensive manner but such models are needed
- How to model the links between development and operation of energy infrastructures and other urban processes, such as land-use planning, transport, gentrification etc. These processes have similar spatial and temporal scales
- **Lower loss HVDC conversion**
- **Superconductors -** Superconductors for transmission upgrades e.g. into city centres
- **Offshore grid** - Relief of on-shore grid by creating off-shore DC networks.
    -

9.2.2 Needs to Undertake Research

- **Respond to importance of career paths –** The group discussed the importance of distinctive career paths for work in energy infrastructure and the availability of opportunities to follow these paths.
    - e.g. National Grid - there is no established path as such to develop expertise. Recruitment procedures have grown organically over time. However, the system in which the company operates is changing dramatically. A new approach to staff recruitment and development may be required to address emerging challenges
- **Approach to creating and retaining expertise in grid operators -** There are several problems with this:
    - Older people tend to have a lot of expertise but in a lot of cases they are no longer working or they walk out after 10 or 20 years to become consultants. Companies support this by preferring to 'contract in' expertise when needed but when they then realize they need somebody it may be too late
    - Consultants don't have the same type of long-term experience operating a particular system (e.g. transmission) as they would if they were full-time employees of grid operators

- **Technical vs. management expertise –** A conflict between: a) moving the best and brightest staff across different parts of the business in order for them to appreciate the breadth of its activities, with a view to them becoming management; and b) ensuring that the smartest technical people continue to work on the technical side of the company. If you do not do the latter this can undermine the company's technical expertise.
- **Reconsidering the UK's innovation system -** It is not just about getting technologies through the TRLs and out to market but also about getting the overarching framework right.
- **Building industrial capacity and human capital –** Doing this takes time and requires a consistent and coherent policy framework. These priorities should be reflected by the Research Councils' strategy and should constitute an important output of the innovation system.
- **Relationship between research funding and energy infrastructure –** A sense that so long as we get the research right, great energy infrastructure will follow. Is this assumption correct?
- **Transition technologies** - There has been no discussion of energy system transition technologies, i.e. if we need to reinforce the distribution networks, can we come up with new technologies for digging up and replacing cables that are less disruptive to end users?
- **Concentrating research efforts in centres –** An argument to concentrate research efforts into energy infrastructure into a smaller number of research centres, still with their basic research remit but also a route through TRLs/innovation stages, which have traditionally been the territory of business and government. At present we have the expertise in universities/research centres to do this but not the necessary mechanisms to enable us to do it
    - Local 'innovation centres' could be established e.g. for flywheels on synchronous compensation at DNO level (rather than transmission level)
- **New/different incentives for academics –** We need to reward outputs from academia that are not necessarily journal papers (e.g. reports, consultancy, providing evidence to committee reports etc)
- **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 decision in relation to energy. Consequently, it is important to evaluate the applicability and viability of different initiatives (e.g. new energy tariffs, policies, smart solutions etc)
- **Industry engagement –** The participation of energy industry is important. The implementation of trials and new policies (e.g. regulation, subsidies, incentives etc) could help to support the expansion and settlement of new practices and smart technologies that could allow us to provide more flexible energy networks and ultimately save customers money on their bills (e.g. by avoiding or delaying network reinforcement).
- **Secondment schemes -** EPSRC needs to find a retreat for academics to allow them to bid for secondments, e.g. for a month. This will allow them to reflect upon knowledge 'already in their brains' but they haven't yet had time to join up.
- **Innovative interdisciplinary research methodology** - We need a research programme on innovating in interdisciplinary research methodology. Specifically, the fusion of quantitative social science, sensing technology, engineering and psychology
    - Interdisciplinarity was a common theme throughout the workshop, often mentioned in tandem with UKERC
- **National demand emulator –** We need to develop a national demand emulator. This will receive high temporal resolution of energy/power data from a spatially and demographically diverse range of housing, as well as commercial and industrial loads. It would be fully anonymised but be available in real time. It would serve as a national reference dataset for the development of DSM technologies and models.

9.2.3 Broader Feedback and Reflections

- **Too much focus on electricity –** The workshop has been very electricity focused, meaning that not enough attention was paid to some other subjects such as:
    - **State vs. market –** Some fundamental discussion around state vs. market in relation to investment in energy infrastructure was missing
    - **Energy transitions**
    - **Heat networks**
    - **Energy storage**
    - **CO_2 networks**
    - **Ports infrastructure**
    - **H_2 infrastructure**
- **Things can slip through the gaps –** Must be careful not to ignore important research themes/topics that do not have a specific advocate/community either at the workshop or operating in the UK research landscape (e.g. distributed generation, energy storage etc).
- **Rigid vs. flexible research programme -** There is a dilemma between whether we should develop a rigid, standardized research agenda to meet new research challenges or a less structured research programme that can flexibly adapt to these challenges as they arise.
- **Danger of focusing research agenda on its 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 a particular technology/solutions could be marketed abroad should be secondary.
- Capabilities of social science to provide answers - Social science often used as a catch all to address the unanswered, difficult questions.

10 How well placed are we to tackle energy infrastructure research challenges of the future?

Working individually, people were asked to identify how well placed the UK currently is terms of possessing the necessary research capabilities to tackle key emerging energy infrastructure research challenges of the future. They were invited to score these on a scale of 0-10 (0 = no chance, 10 = well setup) and explain their score on a post-it note. Figure 3 shows the distribution of the 15 post-it comments.

The average score given by the group was 4.9 +/- 1.7. Figure 3 illustrates how the workshop participants were generally of the view that the UK was only moderately well placed to address the emerging research challenges associated with UK energy infrastructure. This is indicated by the indicated by the absence of scores below 2 and above 8. 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 (e.g. gas) and the integration of different infrastructures. The group also highlighted the need for further inter-disciplinary research to be conducted into energy infrastructure; for more energy infrastructure focused engineers to be trained; and for improved levels of integration across the energy infrastructure research landscape.

Table 6 divides the results into three classes: low capability (0-3); medium capability (4-6); and high capability (7-10.

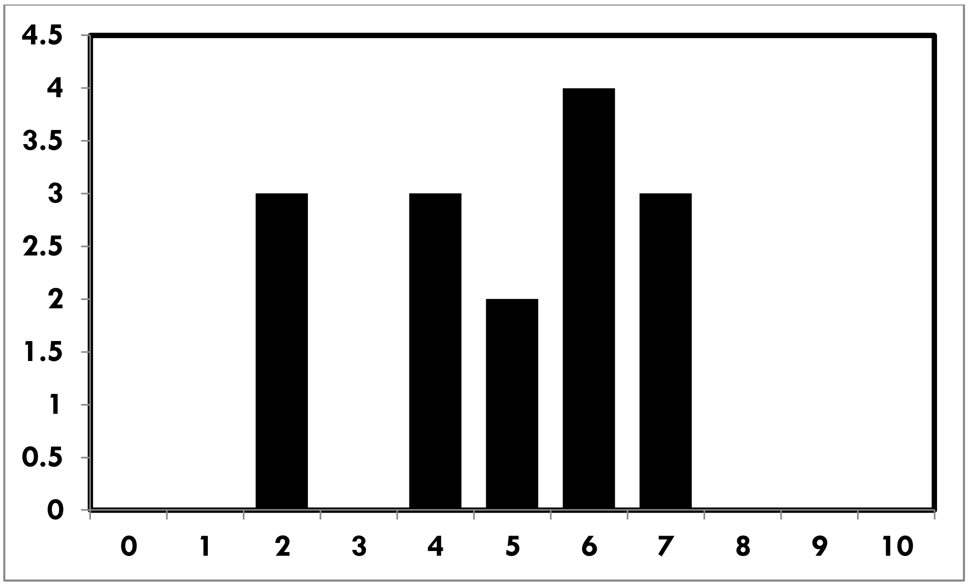

Figure 3 Distribution of perceived UK capability levels to address future energy research challenges

Table 6: UK's perceived capability levels to address future energy research challenges

<table>
<tr><th colspan="3">High capability levels</th></tr>
<tr><th colspan="3">7</th></tr>
<tr><td colspan="3">Electricity infrastructure</td></tr>
<tr><td colspan="3">Good research base. Need to continue bringing individual research efforts together.</td></tr>
<tr><td colspan="3">Electricity infrastructure</td></tr>
<tr><th colspan="3">Medium capability levels</th></tr>
<tr><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Other infrastructure (i.e. not gas & electricity)</td><td>Looking at whole energy infrastructure</td><td>Lots of capability, but questions over coordination</td></tr>
<tr><td>Research organised according to all paradigms: need to think about delivering solutions</td><td>We are far away from what we have discussed, main reasons are lack of engineering within utilities and manufacturing</td><td>Good past experience but future likely to be very different and challenging</td></tr>
<tr><td>Systems Integration</td><td></td><td>New challenges need some reconfiguration</td></tr>
<tr><td></td><td></td><td>Multidisciplinary research: interactivity across different disciplines (cross collaboration)</td></tr>
<tr><th colspan="3">Low capability levels</th></tr>
<tr><th colspan="3">2</th></tr>
<tr><td colspan="3">Insufficient supply of good, creative engineers; fragmentation; little competition in EPSRC.</td></tr>
<tr><td colspan="3">Power engineers</td></tr>
<tr><td colspan="3">Gas networks</td></tr>
</table>

11 Key pointers for the Research Councils – start/stop/continue

Working in groups of four, participants were asked to identify things the Research Councils could:

- Start doing/do more of;
- Continue to do;
- Stop doing/do less

The responses were recorded on flipcharts and each group reported back verbally on one of the issues they had identified. Table 7 below presents the outputs of this exercise.

There were far more suggestions for things that the Research Councils could start or do more of the recommendations for either continuing or scaling back.

Table 7: Suggested Actions for the Research Councils

Start doing/do more of	Continue to do	Stop doing/do less
Research Focus		
Ambitious, evidence-based social science integration	Energy Systems analysis	Less modelling – more measuring!
More 'meta' critiques of modelling	Modelling of system interactions	Stop trying to do everything – focus on what is needed and what we have capability in.
Balance large and small projects – support ECRs and emerging research groups.	Provision of sufficient funding on energy infrastructure.	Be less sensitive to short-term whims of politicians
Engage with industry		
Research Process		
Sandpits	Value training of PhD students (but avoid too much concentration)	Fragmented Grants
Time buy-out for senior academics to provide time to reflect.	Continue to fund research.	Commissioning reviews from insufficiently qualified reviewers.
Responsive mode		
Fund high quality international students.		
Encourage wider participation coverage (some funding was based on invitation only).		
Assess outcomes of funding.		
DTC in Energy Infrastructure.		
Panels should justify project ranking, including the fit to calls and reviews.		
Give genuine opportunities to newer researchers.		
Flexibility to design projects around 'good ideas' instead of specific calls.		
Be transparent with review process and give more than 5 days to respond...		
Avoid industry participating on only token basis.		
Assess outcomes of funding		

Interdisciplinarity		
EPSRC National Centres in Research Methods – specifically pioneering interdisciplinary research methods	Continue to fund large interdisciplinary stuff E.G UKERC.	Less defaulting to big consortia.
Have a capacity to respond to rapid needs for evidence to inform policy.		Stop 'shoe-horning' social science to very technical projects.
Co-funding cross-disciplinary projects on energy infrastructure.		
Encourage more multidisciplinary collaboration.		
More cross disciplinary research in energy infrastructure.		
Support UKERCs and networking efforts.		
Support for interdisciplinary coordination bodies such as UKERC.		

12 Outstanding Questions

In the final session, participants were given the opportunity to share any concluding thoughts with the group. This allowed participants to highlight any key insights they had gained. The following summarises the main points:

Opportunities to Improve UK's Research Profile on Energy Infrastructure

- The establishment of **reference data sets or energy demand emulator** where you feed in live data from a representative set of homes and buildings to provide an open and national benchmark for testing.
    - Model could be run in parallel with live data, improving calibration.
- **Promote collaboration between energy researchers and mathematical scientists**
    - This may be achieved in part via the calls that EPSRC has put out as well as organic development between researchers
    - Mathematicians have collaborated with industry and energy engineering (distinct from other countries)
- **Address the fragmentation of current energy infrastructure research agenda**
    - Opportunity to take what we already have and get something bigger and better out of it
- Issue of **undertaking more agile research,** such as professional citizenship or public engagement projects over shorter (e.g. 3 month) timescales
    - Draw on expertise from non-academics to achieve this. Difficult to achieve with smaller research groups with more modest budgets than industry
- **Need to be more entrepreneurial** - putting ideas into practice is ever more urgent due to timescale pressures
- **Infrastructure is becoming more complicated but the UK is at the front of pack to take an international lead**
    - Plenty of opportunities for the UK to lead on research into decarbonisation of heat, smart metering etc
- Consider **how academia could bid into research being funded by the Low Carbon Innovation Coordination Group** (e.g. DECC & Ofgem). Do UK universities have sufficient capacity to fulfil the associated requirements of this funding?

Outstanding Issues

- **Availability of time** - can't really do extra work during term time (especially not with quick turnarounds)
- **Many barriers to energy infrastructure research are often very difficult to identify and disentangle**
- **Unclear how we might encourage industry to sponsor academic research**
- Whilst the value of European-level research collaborations was acknowledged (e.g. learning from international experiences; leading UK institute can collaborate rather than compete for this funding more easily etc) there was concern that it was very **difficult to gain entry into the European consortia**
- The manner in which RCUK structures **its funding calls can make people reluctant to be open with each other** as they are often in competition with one another
    - Because no specific funding call was attached to this workshop, people were more open and honest
- Need to **reconsider the manner in which industrial and perhaps unpublished work is rewarded** compared to published work
- How can we create the **necessary structures to facilitate the development of interdisciplinary collaborations?**
    - Need to create an environment for imaginative projects

General Comments & Observations

- Electricity seems to be where most of the resource is going **with less research effort into gas, heat and hydrogen.** However, there is still plenty of research to be done here, including how these interact with electricity
- Research barriers tend to be related to a **lack of human resource rather than funding**
- Good to see that there has been a **focus on the bigger questions relating to the 'pipes and wires' of the energy system,** e.g. politics, economics, data, interactions of consumers with infrastructure
    - Raises questions as to ESRC's role in supporting energy research as this is the social science council
- Fellowship team believed that the **participants were perhaps the most willing and homogeneous group of people in the workshops so far**

Annex A – Key Questions Being Addressed Around Energy Infrastructure

	Table 1	Table 2	Table 3	Table 4
System Balancing and Control	Perceived conflicts need examining e.g. fossil fuels vs. renewables.		Looking at distributed network and its observability and controllability, considering large penetration of distributed energy resources.	How to connect up new load energy generation?
	Understanding the issues of balancing with big renewable input e.g. solar and wind			What local grids will look like with electrification of heat and transport
	Electricity infrastructure – to what extent can the networks deal with renewable electricity generation.			Importance of peak flows in electricity supply
	To what extent can existing distribution networks cope with low carbon technologies?			Challenges of electrification of heat and transport on the local systems. Is this actually desirable? Do you presume a generation mix in line with this? "a more away from electrification as an answer to everything"
	What are the control strategies to make networks flexible?			
Smart Technology		Smart meters - can you make them compulsory, and get people to accept then controlling their appliances?	Data coming from smart meters, how to implement market mechanisms based on them.	
			If we have a dash for gas, why do we need to invest in smart stuff?	
System Integration	Strongly integrated infrastructure – a 'systems of systems' issue. Studying it as an integrated whole, e.g. energy,			Integrating gas and electricity systems (+ transport and storage integration) + economics system

	transport, food, waste etc			
				How do you get the gas and electricity systems working together?
				How do we get feedback over multiple networks? Social / ICT / Energy
Energy System Security & Robustness	Energy security and rare events			How to make a system robust with a large renewables portfolio?
				What is a reliable system vs. a robust system?
Energy System Analysis & Modelling	Looking at the various different energy sectors as one.		Reconciling very large systems, difficulty of analysing them, spatial and temporal detail, and uncertainty.	Flexible infrastructure (more holistic framework)
	Need to think about infrastructure as a systemic whole			Optimisation models tend to converge and reduce the range of operational criteria, rather than a large spectrum of robust operational criteria for a network. Need to change models to include robustness by building uncertainty into models.
	Looking at uncertainty in energy system modelling. How do the models we build relate to the systems they are modelling Issues of data availability, can constrain modelling			
	Impacts for modelling. Using complexity science to support the modelling of these systems			
	Data – Not just modelling but data to input into the modelling. Issues around quality and availability of data to inform			

	planning, operations and research			
Infrastructure Planning	Trying to understand the scientific evidence base to support future infrastructure planning e.g. disruptive techs	What's the transition pathway, mechanically, to 2050? What components do you need to put in first, and do you need to use bridging tech that you rip and replace later?	Integrative analysis of electricity, gas and heat (engineering) → basis for future operation plan	
	Always a risk of lock-in with infrastructure and the optionality of different infrastructure options	Look at pathways, delivering a long-term vision in a dynamic, rapidly changing system	How do you incorporate implicit knowledge into your analysis, i.e. stuff an experienced engineer knows? E.g. dealing with variability of demand and generation.	
Gas Networks				What to do with gas network
				Future of gas networks: heat is the key driver of infrastructural issues.
				What's the role of gas in the future and how will that change?
District Heating			Challenges of coordinating different heat users to form a viable heat network, in the challenging contexts of liberalized market and relative weakness of local govt which traditionally helped develop such networks.	Role of CHP and district heating in the mix
			What is needed to develop heat networks UK-wide?	
Market Structure & Economics	Trying to understand the technical gains possible and relevant business models	How do you introduce new disruptive energy tech into the current system under current paradigms? E.g. via conservative organisations such as DNOs.	Systems for collective energy purchasing, systems where you have a number of actors that are self-interested, homes, industry.	Promoting infrastructure investment in Market
			Not just security of network but economics of network	

			How to improve utilities way of doing things in the short term? A lot of cultural change issues	
Governance		How can you convince DNOs to implement new techs? Any new element is a risk to them first and foremost.		How to integrate the offshore networks into regulation
		What's the market, policy, reg frameworks needed to bring about the energy infrastructure we need?		Institutional frameworks for better cooperation
Inter-organisational Collaboration		How can you work effectively across the energy sector, including academics, policy makers, industry etc.	Industrial collaboration and competition incentives. Should the company collaborate or kill?	
Interface Between Consumers and Infrastructure	Consumer acceptance issues – might be smart meters and the various technologies e.g. heat pumps, which have implications for how the infrastructure develops	Where is the incentive to change a system consumers are broadly happy with? (You turn on the light and it works)		
	Is there continued political support for low-carbon e.g. offshore			
	To what extent can we apply demand response without customers' involvement			
	Changing fashions, public understanding/acceptance, political will. Striking a balance between a vision and an achievable strategy/plan			
Other	Lot of concerns that CCS won't work and the assumptions need to be tackled	Liquid nitrogen - possible energy vector?	Building grids from the ground up in a decentralized way in developing countries.	What are we trying to do with DSM? Three competing objectives....Why would any consumer choose to opt-in to DSM

	Tackling public ignorance on issues	Electric vehicles have storage. How can you use them as a storage system, ensuring they're manufactured to do that?		Supply chains for materials and manufacturing. What is the material requirement for global infrastructural changes & effects on supply chains
	What are the tipping points?			What do we include in the energy infrastructure? Oil pipelines? Hydrogen? Storage?
	To what extent can decentralised control cope with complexity			Are we trying to fulfil multiple criteria? What are the real energy system drivers? Fuel poverty / carbon / price / security / equity. Will they all do it badly? Link between policy and priorities: who decides? what are the drivers? and do they understand the constraints? Important to get the output of research to align better with the policy agenda.
	Identifying the right collaborations between mathematics and other sciences (e.g. sociology)			
	NEW INFRASTRUCTURE DESIGNS – Need new designs and radical thinking. How can we design a cleverer distribution network – incremental and transformative change e.g. electricity distribution systems			

Annex B – Detailed Outcomes of Research Cluster Community 'Deep-Dive'

B.1 Group A – Energy System Transitions (A)

B.1.1 Key research questions

Consumers' response to security of supply

- What is the evidence for the 'loss-load' assumptions, i.e. the personal cost of disruptions to consumer's power supply?
    - At what price would they be indifferent if they weren't supplied e.g. black out?
    - Not every kW has the same value to people. Power supplied at different times during the day & year (e.g. New Year's/Xmas eve) is likely to have varying degrees of value to different people
- Power rationing as a means of avoiding power cuts. Need to explore the acceptability of this amongst consumers?
- What are the different types of security of supply?
    - e.g. electricity vs. gas shortage – we have rarely/never had a gas 'blackout' in the UK but we continue to be very concerned about it, such as if Russia turns the tap off
- How could practices adapt to long-term changes to supply and availability? Such lifestyle changes may be based upon examples set by island communities (e.g. Shetland Isles)

Affordability & equity

- How do energy infrastructure changes affect disadvantaged groups? (e.g. impacts of price fluctuations and their effect on fuel poverty)
- What are the differential impacts of infrastructure transitions on different consumers groups in relation to issues of equity and affordability?

Consumers' attitude towards infrastructure and engagement with issues

- Public attitudes to human health/safety in relation to the effects posed from energy infrastructure (e.g. do power cables cause cancer?)
- Public attitudes towards the environmental and economic impact of infrastructure (e.g. If we underground things like electricity cables in order to minimize impact, what is trade of in terms of environmental and economic costs?)
- Exploring the capacity of actors at the local level to object to or support national-level energy infrastructure development (e.g. planning system)
- Public attitudes towards pervasive sensing of energy supply & consumption

Typology of Consumers Groups

- How do we segment consumers into different categories in terms of how they interact with the market? (e.g. prosumers, consumers etc)
- How will different groups in society react to certain energy market changes (e.g. middle class taking up PV with the introduction of FiT)
- How do we engage with and subsequently 'draw in' different consumer groups? What strategy/approach should we employ for different consumer groups?

Facilitate the Acceptability of New Policies for Consumers

- 'Public engagement' - Role of disseminating information and promoting understanding in terms of energy infrastructure development
- Whose responsibility is it to undertake public engagement?
    - e.g. what is the role of regulators, DNOs, suppliers in terms of facilitating the acceptability of new energy policies (e.g. FiT, ROCs)
- What approach/strategy should we take to educate consumers via public engagement?

B.1.2 What capabilities and capacities are required to address these questions?

- Need to use both quantitative and qualitative research in this area:
    - *Quantitative* - May need to do some modelling using existing data sets e.g. English Housing Survey (EHS)
        - Quantitative modelling might be useful to understand the differential impacts of infrastructure transitions on different consumers groups in relation to issues of equity and affordability
        - Network modelling to ascertain how frequent/likely power cuts will be in the future?? Maybe enough in the literature around security of supply
    - *Qualitative* - Need qualitative, small/focus group work to understand people's reaction to loss-load
        - To measure people's emotional response to these rare/ high impact events. Data can be fed into the development of scenario and models
    - *Quality of the data* - Is the data we have sufficient in terms of both quantity and quality? Do we have the data e.g. data on how people have reacted to power cuts 'loss-load'
    - *Experiments* - May need to engage in something experimental, such as cutting people's supply off randomly of those who are happy for that to happen (for a fee) or mock radio shows
        - Examining the types of approaches to engage with consumers – you could mock up different environments (e.g. a smart home, to see how people interact with the technology and their energy environment)
- To undertake this kind of work we are likely to require input from the following disciplines:
    - Economists
    - Social Scientists
    - 'Socially minded' statisticians and modellers to build and operate network models
    - Behavioural and environmental psychologists to examine for example how people respond to loss of load
        - Where is the cross over between acceptability and loss of power?
    - If new test environments (e.g. smart homes) are to be developed, designers will need to be brought in

B.1.3 What challenges are we likely to face?

- *Sufficient funds to implement research findings* - We may do some extremely valuable research into infrastructure but we will need sufficient money to implement the research
- *Low response rates & sample sizes* - Getting enough people to respond is a potential issue
    - Big challenge with social surveys relating to energy because of the behaviour of energy utilities and consumers' associated survey fatigue
- *Real-cost of social science research* - EPSRC think that social science is cheap but it isn't. Need the research councils to appreciate the real cost of qualitative data collection & analysis

- *Difficult questions to elicit accurate answer from* – This type of research is likely to include 'double hypothetical' questions which are likely to be difficult to answer (e.g. how someone *might* react in an *uncertain* future). In part this is because it is difficult to communicate what the future might look like and why
- *Lack of truly inter-disciplinary research methods & design* - Still don't do inter-disciplinary research between physical and social sciences very well. Instead we tend to do is multi-disciplinary research rather than inter-disciplinary research.
    - Methodological development has been rare. In the UK we tend to assemble a lot of different methods together rather than integrating them with one another
    - Difficult to get people on both sides of the divide to truly appreciate the value of inter-disciplinary energy research. Pre-conceptions around the value of 'the other disciplines' - e.g. engineering's view of social science and vice versa
- *Availability of data* – There is a lot of empirical data on energy behaviours that we need, such as when and why people open their windows. This might be provided via pervasive sensing e.g. technologies sensors on networks designed to measure their energy behaviours. However, big issues around the ethical barriers issues of doing so even if they some consumers were happy for this to happen

B.1.4 What do we need to do address these research challenges?

- *Design of 'immersive methodologies'* – We could generate significant amounts of valuable data by getting people to become immersed in certain scenarios, in order to observe how they interact with certain technologies in certain situations:
    - We should draw upon the skills and insights of product design e.g. product testing in Loughborough
    - Should balance immersive methodological experiments at different scales, i.e. small scale immersive group work with large-scale scenario/product testing across multiple focus groups? Need to consider how these might work together
    - Can we simulate blackouts? How can we plan these appropriately (ethically) and realistically?
- *Sample size* – Solutions can be found by using professional data collection bodies, such as the National Centre for Social Research (Natcen), who have a wealth of experience in maximizing return rates from surveys and other data collection methods
- *Overhaul the way in which we prepare research proposals* - Change the bad habit of 'bolting on' social research onto energy infrastructure research proposals. Need to bring in this theme of inter-disciplinary research agenda in at the very beginning of research proposals so that the proposal is design in a truly inter-disciplinary manner
- *Development of inter-disciplinary methodologies* - Truly inter-disciplinary research should change the methods you use. Consequently we need to develop innovative methodologies that help operationalize inter-disciplinary research. These may be entirely new methods or methods that integrate multiple existing, 'disciplinary' methodologies.
    - These methodologies should be considered carefully and 'built in' at the research design/proposal stage
    - Need to find a way of training researchers so that they grow up with inter-disciplinary research skills

B.2 Group B - Energy System Transitions (B)

B.2.1 Key research questions?

Incentives

- What market policy and regulatory mechanisms could be put in place to enable an energy transition? What are the potential consequences of these mechanisms?
- Examine the types of appropriate regulatory and market frameworks that would enable long-term investment and innovation in energy infrastructure
- Examine the types of business models required to facilitate such long-term investment
- How can the industry make effective investment decisions for the long-term?
    - How do we move away from the 'short-termist' mind-set of energy infrastructure investment? Is this a problem with the incentives/market mechanisms designed to encourage energy investment or the structure of companies' business models and their associated internal incentives?

Structure of the energy value chain

- The importance and role of business models in this value chain
- What aspects of this chain are regulated vs. non-regulated?
- Where does competition really lie along this chain?

Institutional Alignment

- How might we encourage joined-up thinking, e.g. via coordination or centralisation?
- Different scales of the energy system - How will they interact in the future?
- Alignment of transport, heat and electricity sectors, particularly their actors and institutions

Governance Priorities

- *Hierarchy of the energy trilemma* - Questions around how the issues of energy security, affordability and environmental sustainability are competing with one another. Focus on how this is playing out in certain key organisations:
    - Is Ofgem concentrating too much on security? Possibly convinced that the boat has been missed for low carbon for the 2016/17 window, therefore just concentrating on building more gas for security reasons. Comes down to a choice between building more gas or relying on demand-side management reductions (including reaching an agreement with industrial gas users to shut down on colder days) and relying on the weather
- What will be the different transaction costs, risks and efficiencies of transition under different industry governance arrangements (e.g. market led, central planning etc)
- Market signals in relation to gas - Ofgem suggests that price signals in the gas market have dulled and that the market needs to increase the cost of gas at peak so people can make an informed decision over how badly people want that gas. Needs to reflect 'true' price of gas. Everyone has a price
    - How does this affect home consumers, e.g. is it a battle between home vs industrial use? Is this a worry? Will industry just pay for it?

Steps to Realise Transitions

- What are the technical steps needed to get to 2050 vision? (Liam)
- What are the current mechanisms (market/policy/regulatory)? How might you design these to achieve the 2050 vision?
- *Management of differential change / decline* - How will we go about managing differential change/decline, e.g. taking down a system, whilst building up a new one, and the impacts of this

Actors & Power Dynamics

- Who are the current actors in the field and their roles?
- Mapping actor dynamics who influence change in the system and why?
- To what extent are these actors institutionally aligned with one another?
- To what extent to non-governmental actors wield their power to try to 'game the system' by actively contravening regulation, designed to provide public wellbeing

International Comparison

- How do other countries or sectors govern their (energy) infrastructure?

District Heating

- What regulatory framework and business models will be needed for the district heating sector in the long-run?

B.2.2 What capabilities and capacities are required to address these questions?

- Consensus amongst the group that these questions will need to be address by researchers from multiple disciplinary backgrounds:
    - Micro-economics
        - Experts capable of drilling down into the causality and chains of decision-making
    - Game theory
    - STS (although effort is currently going to bioscience and cyber issues)
    - Political science (UK quite strong in this but doesn't use it for energy purposes)
    - Systems thinking and systems dynamics:
        - Develop systems of systems approach by working with engineers and modellers, in order to produce a productive dialogue
        - Experts capable of understanding how changes in one network (e.g. electricity) impact upon other networks (such as gas, transport, heat etc) and vice versa

B.2.3 What challenges are we likely to face?

- *Unsure how to encourage interdisciplinary energy research*
- *Integrated research funding strategy?* - Who are RCUK's peers in the funding world? What research is already being funded? Should the strategy be to focus on funding the gaps?
- *Emphasis on TRLs* - Do TRLs allow for these kinds of questions to be asked or do they assume a pre-existing conceptual framework that is at odds with these questions?
- *Relationship between ETI & RCUK* – What is the distinction between ETI and RCUK? ETI currently operating in the structural/institutional space, whilst RCUK takes much more of a lead on the theoretical side, lacking resource on the practical/applied sides?
    - Is the theoretical stuff necessary as a pre-cursor to be able to answer the more detailed, applied questions normally associated with ETI?
    - What is the point at which more theoretical questions feed into the more practical questions? Is there room for additional dialogue between these two sets of research? Important that ETI understands this theoretical research base

- *Gap between economic theory and reality* - Sufficient economists are available and researching in this area, but the question remains as to whether they are engaged in productive dialogue in order to bridge the gap between theory and practice.
- *Mismatch between outputs from consultancy & academia* - problem is that a lot of the bright minds are in technical and economic consultancies that just provide policy-makers with succinct number answers, rather than the true (albeit spectrum of) range that academics provides. Also, academia & consultancy have different ways of working.
    - Also questions over the accuracy of the answers these consultancies provide, as well as the confidence that academics truly have in their own models
    - Academia can provide less than clear outputs but difficulties lie in drawing clear cut answers from these sectors
    - Ofgem would commission a number of consultancy reports in order to inform a decision, but does sometimes 'cut corners' and just ask them for a clear cut answer (essentially outsourcing a decent portion of the decision)

B.2.4 What do we need to do to address these research challenges?

- *Reconsider the purpose of and linkages between TRLs* – Need to ensure that the TRL framework isn't hindering research efforts into innovation systems and innovations that don't necessarily fit the prevailing industry orthodoxy. It is also important to ensure that organisations are responsible for funding and managing research into all aspects of the energy infrastructure innovation chain (i.e. TRL 1-9). Finally, there needs to be some consideration given to the hand-over to the commercialisation stage
- *Increase integration of innovation chain wide research funding landscape* – It is not only important that various themes within the RCUK's research funding programme are fully integrated but that its funding programme is in synergy with that of other key funding organisations across the innovation chain.
    - *Increase dialogue between key stakeholders* - In order to achieve this effectively it might be appropriate to reduce the distance between the parties responsible for setting government priorities and those who set R&D priorities?
    - *Undertake a 'gap analysis' to guide research funding* – Efforts should be made to determine:
        - a) where energy infrastructure research is already being conducted
        - b) what the gaps are in the current energy infrastructure research landscape
        - c) how these might be addressed by research funding programmes
- *Reconsider the role of consultancies in creating value* – Need to question whether key funding bodies (e.g. Ofgem, DECC) should be turning to consultancies or academics to provide them with the necessary evidence base to move on. Argued that consultancies can often provide quick but hurried responses
- *Examine link between theoretical and practical research* – Important that the chain between theoretical to practical energy infrastructure research is well understood and managed, for example the flow of evidence between RCUK funded research and ETI funded research. Worthwhile mapping out the theoretical side so that the applied side knows what evidence base it is working with.
- *Learn from past experience of how to encourage inter-disciplinary energy research* – Look to the wealth of previous (e.g. Transition Pathways project) and current (e.g. End-Use Energy Demand centres) about how to facilitate inter-disciplinary energy research, e.g. between modellers and engineers

B.3 Group C - Energy System Balancing & Control

B.3.1 Key research questions?

Technical Aspects of Network Control

- Designing information systems for TSOs/DSOs that minimises the challenges for human decision makers when dealing with complex balancing & prioritisation decisions
- Extending the scope of coordination for a geographically & electrically larger system than at present, which contains many more elements
- Being able to compute and understand inter-temporal relationships, such as the implications of 'rates of change', as well as issues around whether we should do something now or later?
- How might we improve voltage control?
- How can we improve frequency control in distribution networks, e.g. via decentralisation or islanding?
- What are the limitations of fault current limiters (FCLs)?
- Protection of networks with low inertia
- Fully understanding energy system interactions in order to build, validate and use models
- 'Observability' in terms of EMS/DMS (energy/distribution management systems), which will prove a massive challenge in terms of distribution
- How could we use controlled, distributed energy storage and DSM for balancing?

Technical Aspects of Energy Storage

- Exploring the opportunities for grid/DNO level battery technology storage
- To what extent might we achieve distribution system investment savings from the introduction of local-level energy storage?
- How might we integrate heat storage alongside demand management and system flexibility?
- What is the role of heat storage, district heating and electric heating in ensuring a balanced gas supply?
- What storage and demand-side management characteristics would be most valuable to us?
- How does energy storage and demand-side management actually 'play-out' on the energy system?
- How can storage and balancing technologies be integrated into distribution and transmission networks?

System-wide Development, Management & Maintenance

- How are we able to manage our energy infrastructure in such a way that is sufficiently straightforward that regular engineers are able to understand them?
- What are the costs of supervisory systems, as well as their degree of robustness and maintainability?
- What is the right level of interaction between TSOs & DSOs?
- How centralised does management of the system have to be as control gets more difficult as the system gets more complex?
- What are the business models and market frameworks needed to deploy new balancing technologies?
- How might we increase the capacity but decrease the economic and environmental cost of infrastructure components?

- What is the cost-benefit balance of the various energy network development options, e.g. energy storage, DSM, network upgrading?
    - What is the cost (economic, environmental, cultural etc) of delivering a flexible energy system?

Markets & Consumers

- How can we coordinate large numbers of consumers and embedded producers, who are using a broad range of appliances to keep the system safe (e.g. congestion control using market-based approaches)?
- How do we accurately predict consumption profiles at consumer/neighbourhood/regional level at low cost?
- How can we control electric vehicle users, with respect to both their location & time-of-use characteristics?
    - How can we incentivise EV users to charge their cars in a way that minimises peaks, while meeting their preferences?
- How can we optimise/automate the schedule of appliances/activities of consumers without impacting upon their comfort whilst under a strong degree of uncertainty?
- How can we negotiate contracts between large numbers of producers/consumers to sell/buy electricity?
- Do we really want/need to involve domestic consumers in DSM?

Risks & Limits

- How far can we push our energy system's assets to maximise network control and utilisation?
- What happens to our energy networks when/if ICT falls?
- Understanding the limits to 'smartness' and its associated risks, i.e. in terms of consequences of failures and vulnerability to single disturbances

Forecasting

- What is our current level of ability to be able to forecast wind power in order to provide last minute balancing? How might this be improved?
- How can we accurately predict consumption in smaller areas/greater levels of detail?

B.3.2 What capabilities and capacities are required to address these questions?

- *Test facilities to test network technologies* - If you want to test for problems in a real environment you can't use a simulated environment or test network with no real consumers on it. It's needs to be a 'real life' network, or as close to this as possible
- *Engineers* – Need energy infrastructure engineers with advanced knowledge of the field to develop and integrate new energy balancing and control technologies
- *Regulator Funding* – Funding and associated support programmes from the industry regulator is important in order to deliver such large-scale network experiments and other network related research
- Using game simulations to mix people and software.

B.3.3 What challenges are we likely to face?

- *Regulatory barriers to testing* - Regulatory structures prevent roll-out of infrastructure technology testing. For example, there rules about how customer engagement takes place and there aren't sufficient incentives for companies to engage with and facilitate such testing. Consequently, DNOs have found it really difficult to get meaningful customer engagement.

- *Utilising research experience* - Difficult to capture experience within academic research groups
- *Industrial collaboration* - A lack of commitment from industry with regards to engaging with industry-academia collaborations. Even though there is significant engagement between academia and industry via schemes such as the LCN fund it is often hard to undertake true collaborations because industry doesn't really see the true value of doing so.
- *Lack of suitable test facilities* - Need to test network components first on a test network. However, there is a difficulty in getting real networks and consumers to test on (i.e. test campuses), for instance if there are benefits for consumers the network operator is not interested. Instead there is a need for a test city/region, i.e. a test 'campus' approved by regulator. One of the goals of the LCNF is to achieve this, however this isn't happening, largely because it is too expensive.
- *Lack of engineers* - Need more engineers, especially with advanced knowledge and creativity for PhD/postdoctoral.
- *Poor understanding of technical issues amongst utilities* - Utilities are not doing much R&D anymore and therefore do not possess much capacity in this area. Consequently the utilities don't fully understand the technologies in question (i.e. storage, control, balancing etc).
- *Poor understanding of technical issues amongst regulator* - The regulator knows little about engineering. It is predominantly full of economists, with few technologists/engineers? This poses a potentially important barrier to effective energy infrastructure development.
- *Losing experts from academia to industry* - It's difficult to attract mid-career people back from industry to academia, with pay levels being one big reason. This is damaging as there people possess a lot of experience and skills, which would be valuable to academia.
- UK clients are demanding solutions that are too bespoke

B.3.4 What do we need to do address these research challenges?

- *Exchange/secondment scheme* - An exchange or secondment programme that enables individuals to switch between academic research and industry could help by providing a three-way '*flow of talent*' capable of provide the necessary expertise lacking in government, industry or academia. It was highlighted that university-industry collaboration is far more successful when industry supplies knowledge and people, instead of just funding
- *Incentives for start-up companies* - Better incentives to encourage start-up companies, as these are more able to take risks than big corporations. It has been particularly difficult for these organisations to raise funds since 2008 and to deal with the UK's short-term profits culture
- *Incentives for energy utilities* – Better regulatory incentives for energy utilities to develop and retain knowledge via in-house R&D
- *Incentives for manufacturers* – Make incentives available to manufacturers for collaborating with universities, e.g. tax credits
- *More Catapult centres* - Role for another TSB Catapult centre in this area. Whilst CDTs (Centres for Doctoral Training) are a good thing they are a little too centralised.
- *New competitions* - What about a competition with a defined aim and a prize? Ofgem's Network Innovation Competition was criticised for having no defined aim
- Develop university & industry links
- *Concentrated centres of knowledge* – National research labs like Fraunhofer in Germany could prove useful in facilitating the development and retention of key energy infrastructure skills in the UK but this may inhibit the distribution of knowledge between different sectors,

organisations, countries etc. It is also likely to involve a difficult transition, with various winners and losers – 'there's a value to having dispersed decentralised expertise'.

B.4 Group D - System Modellers

B.4.1 Key research questions?

Time Scales & Spatial Detail of Modelling

- How can we improve the spatial and temporal detail in models without losing tractability
    - When modelling on different time scales for example, how can we decompose them in order to have tractable models?

Objectives of Modelling

- What is the purpose of modelling? - 'What are we doing this for?'

Interfaces & Integration of Systems & Models

- Should we have separate models or huge integrated models? When and where do one or the other make sense?
- When we build giant models how do we assess the relationship between these models and the real world. Can't do conventional validation.
- How can we integrate different infrastructural systems
- Physical engineering models of the electricity system vs investment appraisal models - how do you link the two together? Are there links between spatial and temporal detail and scale?
- How do the linkages between EU nations fit into energy model development?

Modelling Methodology

- How can you model integrated infrastructures? In order to reflect their interdependency, do we require new methods?
- High-level system - are current modelling techniques enough? Do we need fundamental changes? Currently, two big ones:
    - *scenario-based* - we assume some scenarios or extreme conditions and reflect on that
    - *multiple simulation type* - we look at the statistical behaviour of system.
    - We may need a revolution to get new modelling methods. We want models to illustrate a strong understanding of new technologies and their impact on the system, which we can't get very well with current modelling techs.

Uncertainty

- Resolving uncertainty inherent in the real world vs. uncertainty in the modelling methodology (e.g. methods of analysis, quality of the data etc) – 'You often have a great deal of uncertainty in your assessment of uncertainty'
- What are the key differences between operation and planning models? Focus on how a planning model has system background uncertainties, whilst an operation model does not

Other questions

- How do we define a "system of systems"?
- To what extent will the CCS infrastructure become an important question for modellers and energy infrastructure researchers?
- Are different storage systems currently well catered for in current models?

    - Problem is that storage can't be depicted in time-collapsed models, so for many models this represents a fundamental problem where you have to change model architecture…

B.4.2 What capabilities and capacities are required to address these questions?

Group discussed where capabilities currently lay in the modelling community in relation to the energy sector and other related sectors:

- *Elec distribution* – low
- *Elec transmission - high*
- *Gas distribution – very low*
- *Gas transmission* – low (e.g. CGEN)
- *Heat* - proprietary tools, so low
- *CCS – very low*
- *Transport* - very high, in other communities
- *Water networks* - high (e.g. operations of water networks)

In relation to what capabilities and capacities are required to address the questions outlined in the previous section:

- *Mathematical sciences* – There seems to be a good capability of mathematical sciences in the UK and these capabilities and capacities can be brought in from the mathematical sciences particularly to look at the relationship between models and the real world. Their skills can also be used to manage uncertainty within complex models, e.g. Bayesian frameworks. As such, they've produced a software toolkit for assessing uncertainty in large models
- *Statisticians* - Modelling methodology professionals from the statistics community have a big role to play here. They can home in on the key issues about depicting the real world in models
- *Engineering* - important to draw upon the expertise of people that are experts on specific aspects of the energy system (heat, gas…)
- *Focus on skills rather than physical research infrastructure* – In terms of capacities 'it's not like fusion research in that we don't need much physical kit". It's much more about skills capacities than infrastructural capacity

B.4.3 What challenges are we likely to face?

- *Strategic lead in UK energy modelling* - We have people like UKERC & RCUK who can take a strategic lead on UK energy system modelling but we don't have a national energy research lab like most countries have. Consequently, we have large systems modelling groups and economics groups that doesn't really think about the direction the modelling community is taking or the purpose of modelling
- *No clear PhD training programme* - Problem is that there is no clear PhD training programme or a specific set of skills for modellers. Undergrads aren't specifically trained to be modellers. Is this a problem?
- *Not enough focus on system-to-system interactions* - How many people actually look at interactions between systems? Infrastructure Transitions consortium at Oxford (demand) and Cardiff (supply)? Are there groups looking at other interactions other than gas-electricity, such as the Centre for Transport studies at Imperial, which is looking at ICT - Transport links.
- *Lacking capability in systems-of-system modelling* - Interfaces between systems: not enough capabilities there? Not many groups that do these things but maybe capabilities there under surface.

    - DNOs not well placed to do this type of research because it crosses over into other systems e.g. gas system. Also, DNOs tend to only build models up when they have problems
- *Lack of EU-wide energy infrastructure models* – One economic one in the 'Top and Tail' project being led by Richard Green at Imperial but beyond this there are very few
- *Difficult for models to reflect reality* - Building models that actually say something about the real world is incredibly hard. Bad links between people doing economic models and physical models - "We don't know if the systems we model economically would actually work."
- *Fragmented research landscape* - UK has the capacity, but they don't have the capability, because it's so fragmented. We don't link together different capabilities and communities in order to address specific problems.
- *A lot of the research feels amateurish* - This comes across in different ways:
    - Choice of formulation is often bad from the outset, bad model design from the bottom up
    - People often don't write good code as part of the model's design. People still use clunky Excel sheets that don't work
    - Communication and visualization of results is also a challenge. Producing large datasets and having no ways to process them well
- *Mathematical science under-utilised by consortia* - Research consortia work has tended not to drawn on people from mathematical science community. This maybe by coincidence that the big universities with energy systems engineering groups aren't the same ones as the one with good maths researchers.
- *Energy infrastructure underrepresented in economic models* - UCL economic modelling of energy system doesn't really capture energy infrastructure
- *Continuity of research* – Long-term research is always potentially subject to disruption from 'staff turnover', i.e. people leaving & people arriving. This can cause the project to lose focus and/or momentum
    - "You need three people at each point in time, one person arriving, one doing the actual modelling, another leaving and instructing the more recent arrival"
- *Unsure how to integrate different scales in models* - There's a lot of work to find out whether it makes sense to use methods from other fields to better do this
- *Reliance on modelling for policy-making* – There is a culture for policy makers to rely on energy models to provide the evidence upon which they will design their policies, however criticism that many of these policy people don't have the necessary modelling background to properly scrutinize these results

B.4.4 What do we need to do address these research challenges?

- *A national laboratory to take a strategic lead on energy modelling* - We have people like UKERC & RCUK, who can take a strategic lead but we don't have a national energy research lab like most countries have. UKERC is designed to take the role that a national energy lab would normally do but capacities remain fragmented. A national lab may help to address this
    - We don't want to kill our ability to do interesting free thinking but an integrated, focused research community with a set of key objectives is important. A balance can be struck between the two, for instance in the US you have a very clear distinction between national labs and university research.
    - Question about what type of modelling should be centralized, e.g. small models answering specific questions don't need to be, but if you want a large energy systems model that probably has to be centralized.

- *Promote linkages between infrastructure centres & consortiums* – Work at these centres & consortia could be brought together as part of a work package that sought to draw out the key interactions between various different energy related infrastructure system e.g. gas, electricity, transport, ICT etc
- *Need to better integrate research communities* – There is a need to bring communities (e.g. engineering, economics, mathematics etc) closer together in order to better link together existing capabilities and improve people's understanding of what work is already being done. The WholeSEM energy modelling consortium is starting to do this.
  - It is important to draw upon the expertise of people that are experts on specific systems (heat, gas…), e.g. in the engineering community, but which operate outside of the "energy systems modelling community"
  - Discussion around how we link people who use different languages/terminology. Currently we have a number of large, energy infrastructure focused consortium, engaging in multi-disciplinary research but everybody ends up doing their own thing in the end.
  - Linking engineering, with economics, with policy studies etc may require a 'multi-scale approach'. This has been demonstrated by the new project on bio-energy value chains under the Bioenergy Supergen (led by Nilay Shah). This research employs a multi-scale approach to biomass and biomass resources.
    - Concerns that the Supergen model has been good at bringing communities together to talk to one another but not very good at facilitating close collaborative research
    - Emphasis that some areas may still require responsive mode funding and these should be identified. Supergen model doesn't necessarily work for all aspects of energy research landscape
- *Developing and using modelling skills beyond universities* - In terms of modelling skills we predominantly talk about universities but shouldn't we think about other organisations such as DNOs, regulators etc. For instance, National Grid have some serious people and good modelling capacities, but they don't much of it.
- *Explore how models might engage industry* – Energy models might prove a useful mechanism for engaging industry because companies can use these to 'look into the future' and understand whether their business model will thrive or not in the changing energy landscape. Consequently, models could play a key role in not just informing government policy but guiding the business strategies of the private sector
- *Learn lessons from the climate modelling community* - Interesting differences between climate community and energy systems community. Climate modellers have open models, distributed models and lots of collaboration. e.g. the Oxford stuff on distributed climate modelling. Nothing of that scope of ambition in energy systems modelling.
- *Funding for 'high-level' modelling* – Concern that the types of energy modelling projects we fund are at too low a level? Suggestion that we need funding for high-level modelling projects that look at overall energy systems or systems-of-systems
- *Need to make efforts to better integrate different types of models* – There is a need in some instances to synthesise different, existing models, e.g. do you integrate transmission and distribution models because the boundaries are becoming unclear?
  - *Linking models of differing levels of granularity* - Mention that models with greater granularity (e.g. power plant models) have been linked up to larger-scale models that are less granular by Ed Rubin at CMU by reducing the level of detail they contain. One example was that of energy storage or DSM modelling and how these should be integrated into energy network-wide models

    - *Linking technical with socio-economic models* – Efforts need to be made to integrate more physical models, looking at the technical components of infrastructure, with more socio-economic factors relating to energy infrastructure (e.g. capital investment). Specific mention that this might be relevant to understanding the development of CCS networks
- *Project specific PhDs → DTC PhD* - Removing PhDs from normal grant proposals may mean that there is 'less slicing and dicing' and that project leaders actually end up having more resources to drive the project forward. The alternative may be a DTC for energy infrastructure but questions around how supervision is managed without a project framework to marry tutee with tutor.
- *Purpose of modelling must be considered* - Need to differentiate between modelling to answer specific questions and modelling to uncover unknown but potentially important developments

Annex C - Detailed Outcomes of Research Cluster Cross-Community 'Deep-Dive'

C.1 Group 1: Technical Aspects of Energy Infrastructure

This group took no clusters directly but were instead tasked to ensure that the workshop captured the widest range possible of relevant technologies and research questions in this sector.

C.1.1 What are the key research questions relating to this area?

Technical Aspects of Electricity Networks

- FACTS (Flexible AC Transmission System) for distribution networks
- Greater flexibility of cables (which can allow tighter windings)
- Higher rated network cables
- Refusing size and local impacts of HV substations.
- SF_6 long term replacement (SF_6 is used as insulating gas in substations)
- Technology to permit 'tapping off' of low power flows from HVDC lines (useful to take power midway from north-south transmission connections)
- Role of DC networks (What are the possibilities of LV DC connections at home/work?)
- DC network protection.
- Modern LV transformers - cheap with voltage regulation capability.
- Emerging standards for HV networks (or LV)
- Review for potential of relaxation of the grid code (could save cost without impacting on security)
- Standard design of offshore transmission substation platforms
- VSC - high rated cells - less complex operation, higher voltages.
- Electric vehicles used as decentralised energy storage.
- Power Line Communications (PLC).

Governance of Electricity Networks

- Data mining (from smart meters and other ICT technologies) for planning and development of future networks.
- Management/control of low-carbon technologies.
- The OFTO (offshore transmission operators) scheme and risk-sharing.
- Potential for defragmentation of the electricity supply industry, especially metering. (This would allow DNOs greater access to the smart metering infrastructure).

Gas Networks

- Lower heat (and loss) piping
- Innovative methods for repurposing the gas network for other energy vectors.
- Innovative methods for moving and storing hydrogen.
- Innovative tools, technologies and methodologies for installing infrastructure more cost-effectively.

Who defines these needs?

- Buyers of kit
- OEMs seeing an opportunity
- Each utility wants something slightly different
- Role of industry bodies to rationalise requirements

- Competition driving innovation (but when does it not work?)
- Universities - not only answering questions industry can't answer, but also asking the questions industry hasn't thought to ask.

C.1.2 *Whose job should it be / who is best placed to undertake this research?*

- Industry - Manufacturers, Consultancies, Utilities
- Academia
- Regulators
- Standards institute
- R&D institute
- Government

C.1.3 *How might the different organisations and research communities collaborate with one another in order to address these key research questions?*

- *The benefits of collaboration:*
  - Adding value from different organisations/skillsets
  - Demonstration projects – important for commercialisation
  - Sharing of costs
  - Sharing of benefits
  - Sharing of ideas
  - The whole is greater than the parts
  - The bringing together of different skills/capabilities from different sectors.
  - Structural programmes are better than individual projects in order to retain and roll-over knowledge.

- *Barriers preventing collaboration*
  - Issues
  - Different goals
  - IP sharing issues
  - Role of helping competitors (less on longer-term questions)
  - Regulatory worries about cartels
  - Lack of diversity
  - UK academics slow to join EU/US projects. Is it too hard, or do UK academics not need to? Lack of competitive pressure can allow UK academics to be more open with EU partners than they would with other UK universities.

C.1.4 *What capabilities/capacities do we need in place for the UK to address these questions? What do we need to do to ensure we are ready to address these research challenges?*

- *Perceived gaps*
  - Not enough good, creative engineers available to recruit.
  - Effort is fragmented - difficult to retain knowledge in universities due to short-term projects/contracts.
  - Test facilities that involve people or demonstrations.
  - Is it a problem that so much of industry is foreign-owned? Where does IP go? Is there a willingness to invest in UK capacity? How does industrial policy link with public R&D programmes?
  - Problem - too many overseas students and not enough home students? Lack of capacity as international students return home.
- *Opportunities*
  - Are we exploiting areas in which we are (currently) leaders?
  - Engineering expertise not always in same place as manufacturing capability.
  - Learn lessons from other industries.

- At the moment there is a good level of commitment from Ofgem.
- What drives need? Market and market opportunity as well as longer-term vision that markets may not have. How 'long-term' is useful?
- Energy industry/capital/equipment has a long life cycle/time constant. Need to build into plans.

C.2 Group 2

Cluster Name(s)	Hotspots

1 – Natural Capital	- Environmentally benign/adaptive infrastructure
	- Understand the resource requirements needed to build future energy infrastructure:
	  ○ Impact on supply chains
	  ○ Impact on price

2 – Asset Management	- Replacing or coping with aged infrastructure - Intelligent maintenance of infrastructure systems
8 - Gas	- Could we use the gas distribution networks for something other than the transportation of natural gas for heat generation? - How might we make best use of existing gas infrastructure in the future low-carbon energy system (e.g. looking at bio-gas, hydrogen, CO_2)?

C.2.1 What are the key research questions relating to this area?

Heating

- Huge uncertainty over heat - Action/research timelines for heat: meeting targets on time
    - Recognising that the DECC heat strategy has a slightly fluid vision of the future. What should the response to this be? Balancing the need to make investments (which may later prove to be sub-optimal) vs. waiting for the research to be done.
    - Huge uncertainty over heat
- Spatial strategy for heat-supplying infrastructures: Efficiencies and risk
    - -Includes electrification of heat
    - -Fixed cost network with a fixed operating cost, so as number of (gas) customers goes down, the (network) cost per customer goes up.
        - Is the decision down to the customer, or is there room for a spatially coordinated switch from gas to electricity, in order to avoid costs and inefficient infrastructure?
- To what extent should the government direct heat provision? e.g. preventing use of gas.
- Is there a role for micro-CHP in UK? It could work well together with peak heat / peak electricity generation if linked to the gas (hydrogen) network. They would be generating electricity at peak times, thus matching demand with supply (and putting it back onto the electricity grid).

Gas

- How can we disaggregate gas usage in order to understand consumption patterns and needs? This is being done for electricity, but not currently for gas
    - e.g. disaggregating into different appliances (cooking vs. boiler) and understanding the cost and benefits of using electricity vs. gas for these purposes
    - Could be done on a community or on an individual house basis
    - Important for understanding gas distribution on a local distributional level, but on a national level is not so important (as large scale infrastructure is needed anyway).
- What are the issues with retiring the gas network?
- How can we make long-term and better use of ageing infrastructure?

    - Such as alternative gases for the gas network. e.g. Hydrogen, Biomethane, CO_2, Energy Storage & Peak heat use
        - Used for CCS, Heat/CHP and Electricity support etc.
    - Power to gas could be an important technology in the next few years.
- Equity and affordability are important issues for the gas networks
    - Ofgem has a target for gas companies to connect an additional 80000 low income houses in the UK to the gas network in the next 10 years
    - Can we use ABMs (Agent-based models) to understand impacts of different actors?
- What are the issues with retiring the gas network?
    - Do you shut it down slowly? Do you have a long time scale? Do you pay compensation? Who pays for the decommissioning?

Natural Capital

- How do we engineer low carbon manufacturing to build low carbon technologies?
    - Impact of supply chain of building low carbon technologies. LCA and impact minimisation of supply chain. e.g. green/low carbon supply chains (supply chains that don't exist at the moment)
    - How can we develop these supply chains?
- Infrastructure Pollution Minimisation – how can this be managed?
    - CO_2
    - Air Quality
    - Visual
    - Noise
- What are the appropriate institutions and organisations for transitions in and around networks?
    - Business models and economic analysis for integrated infrastructure

Asset Management

- Design on information collection and delivery mechanisms via data collection, to optimise maintenance regimes, including recording of past actions.
- Can you optimise maintenance regimes and influence the various actors in the system in order to better perform this maintenance?
    - Effort to encourage DNOs to take more short-term (rather than long-term) and frequent approaches to maintenance
    - Helps to ensure safe, predictable and stress-resistant system

C.2.2 *Whose job should it be / who is best placed to undertake this research?*

- -Alternative uses of the gas network
    - Are academics best placed to tackle these issues?
        - Need to look at the actual physics of these uses, as well as the optimal usage of these systems
        - Would be a mistake to leave this to industry and not involve people with more of a systems approach (e.g. academia)
- Research needed into business models for infrastructure.
    - To be performed by industry or academia?
    - A coordination of engineering and business would be best
- Separate research needed into governance and network transitions
    - Spatial strategy for network transitions to be developed as well as the impact that these transitions have on customers (e.g. increased cost p.c. with less people on network)
    - Policy makers and academia should work with these issues

- We are looking at designing information systems for networks.
    - Therefore need software engineers and architects, as well as AI and machine learning Social science (+psychology) should also be included at this point.
    - These systems should also look into disaggregation of gas usage.
- Industry plays a major role in deploying the infrastructure, but do they also play a role in the generation of knowledge around this area? Or should that be an academic led area that feeds into industry.
- Should also involve industry in the research level

C.2.3 *How might the different organisations and research communities collaborate with one another in order to address these key research questions?*

- *Conferences*
    - e.g. workshop targeting industry on the future of the gas network
    - network of local authorities interested in district heating (facilitative approach)
    - Considered to be relatively standard practice
- *Secondments / internships*
    - With government or industry
    - Government: spending is an issue here: secondment is a fairly cheap way of getting things done (with budget cuts etc.)
    - Industry: making links can be difficult, finding a useful role and right place within the organisation is also quite tricky. Can be beneficial to increase learning across disciplines (e.g. Toshiba communication department sitting next to engineers)
    - Secondments can help to push ideas into practice, from the inside rather than from the outside

- *Joint industry / academic funding*
    - Onus on industry, not on academia, to identify and define the research direction, and the business case
- *Working through industry bodies and using these bodies as facilitators*
    - Engagement process to be able to access the right people within industry
- *Industrial funded research centres (e.g. RCUK / Industry funded research centres)*
    - Strategic partnerships between academic body and industry body
    - More larger scale undertakings (longer term), but with short-term research focus (this is a drawback)
    - Basically sponsored research centres (e.g. Tata steel in Cardiff, BAE systems in Southampton)
    - Works well when cofounded by both parties

C.2.4 *What capabilities / capacities do we need in the UK to address these questions?*

- Currently no gas distribution research capacity and capabilities
    - Currently no research projects that are looking into this (that the group is aware of)
        - Technical, economic and policy research roles
- Work on the political economy of networks in transition (from a more social science perspective)
    - No models (e.g. ABMs) on how actors and systems (and changes to these systems) interact
    - Capability to run massive simulations of district or neighbourhood models: have the capacity, but not the data
- Low cast sensing capabilities for gas
    - e.g. gas smart meters
    - Do we have enough sensors in the gas network to measure dynamics and capacity?
- Gas transmission: much capacity in national grid but not readily accessible
- Industry is bringing up issues around gas networks, that academia is not involved in

C.3 Group 3

Cluster Name(s)	Hotspots
11 – Improving the evidence base for policy evaluation and review	- Analysis of previous energy policy and its effects on energy infrastructure o Review of government modelling of impacts of policy interventions and compare with outcomes to have a better evidence base to inform different kinds of intervention - Robust assessment of true lifecycle emissions for policymaking and investment decisions - Design of policy evaluation o Develop research designs and monitoring technologies for robust demand-side management (DSM) measurement - Life cycle assessment of policy programme impacts
12 - Data ownership, protection and use	- Household-level data privacy vs. usefulness - Regulatory access to data on assets in regulated monopolies - Secrecy – what is really commercially confidential? o Means of making data available
13a – Investment under uncertainty	- Successful generation investment under uncertainty - Value/risk of anticipatory investment in networks: o Heat networks o CCS o Grids o DNO network upgrade
13b - Decision making under uncertainty	- Characterisation of uncertainty o How to use this characterisation to inform decision making (e.g. decision metrics) - Decision making under uncertainty: Energy system planning, operation and investment:

C.3.1 *What are the key research questions relating to this area?*

Cluster 11 – Improving the evidence base for policy evaluation and review

- What should be a gold standard for energy research? Are there robust methodologies for policies? Is there a way in which we evaluate policy – a common method? How do you make it easier to do policy evaluation research?
    - Minimum requirements for research, like in medical research. In the energy area these standards are employed by the reviewer not the journal.
- Could we conduct randomized control trials on DSM (Demand Side Management?)
- Can we build more longitudinal consistency into our studies? Looking into the same timeframes and granularity? Can you take a sample both before and after the policy?
    - Currently very little ex-post work? What happened? Did it differ from what we thought would happen after the policy? Design to incorporate comparability.
    - Important to address uncertainties correctly

- Is there enough evidence on the policy impacts and unintended impacts. Is this evidence then built into future policymaking? If not, how should it be done?

- Assessments and communications of uncertainties in policy? People need to take ownership of their evidence based decisions. How do we draw conclusions from this evidence base?

    - Is there enough dissemination of research to policy makers? Is this done correctly?

- Need to conduct research in the field of monitoring technology and data collection.

- Evaluation of the life-cycle of equipment. If it's new it's difficult to know how it will behave, especially in the long time cycles needed for energy infrastructure.

Cluster 12 – Data ownership, protection & use

- What is the data that would be useful for research? Researcher should qualify what they consider to be useful.

- A rigorous methodology for the collection, storage and mining of data is needed.

- How do you convince consumers to allow use of their data?

    - Do you need guarantees around use and access for the data?

    - Can we understand consumer attitudes around giving and sharing data?

    - Compare with other sectors e.g. social media, banking. How are things done there?

    - Who do people actually trust with their data? Government, businesses?

    - Should consumers be paid for their data, would this increase levels of acceptability? Incentives to share data, for example a reduction in council tax. What do you need to do to get participation?

- Randomized trials – are there issues of selection bias due to relying on people that already have the technology installed – often in properties that are owner occupied.

- Are there significant effects on people's behaviour if they know they're being observed?

- Issues of commercial sensitivity of data. Who will it benefit and why?

- Who would be trusted with the data? The least trusted are possibly most appropriate e.g. energy companies. Data protection laws also apply.

- Supermarket loyalty cards – huge amounts of data and transparency issues. Can we learn from them to understand how we might be able to collect the data? The role of the media is key around this issue.

Cluster 13 – Decision making and investment under uncertainty

- Understanding scientifically how decision making is undertaken – real options theory, network analysis, decision trees. Companies & businesses use them to understand how they should make decisions under uncertainty - need to apply this thinking to energy.
    - There is an idea that uncertainty isn't properly embedded in lots of energy research methodology. Uncertainty is something that can and should be quantified.
    - Uncertainty in system planning. Is this currently incorporated correctly?
    - There are different types of uncertainty - e.g. those that are reducible if you have more information or those that are reducible if you know things will break but not when. There are methodological questions over how these different types of uncertainty are quantified.
    - How can we build in resilience into decision making?
    - How can a reflexive policy learning model help us to deal with uncertainty?
- How favourable must investments be in the energy sector compared to other sectors to happen?
    - How are risks affected by the portfolio composition? Do some options have hedging/de-risking effect on further reinvestment?
    - What regulatory frameworks are required to deal with investment risk?
    - Should we allow some orgs e.g. DNOs to make riskier investments?

C.3.2 Whose job should it be / who is best placed to undertake this research?

Cluster 11 – Improving the evidence base for policy evaluation and review

- Professional bodies
- Statisticians
- Research councils or professional bodies may have a role.
- Arm's length offices such as the National Audit Office – they would have the statistical and data gathering experience and capabilities to do such objective policy evaluation
- DECC does some work in this area.
- There should be a body that has a statutory obligation to do this, which produce work which is accepted by government e.g. NAO, CCC
- Not enough influence of technologically minded individuals on policy design. There needs to be technical input into this area.

Cluster 12 – Data ownership, protection & use

- Market data companies are very powerful, and possibly interested in working closer with universities.

- Statisticians are very important in these projects.
- Want to avoid organisations that have vested interests in the results. Maybe need an energy outsider who has the expertise to manage the data sets e.g. Google.
- Need to have organisations that can provide insight into the ethics of the project and the legalities of the project (e.g. law firms).

Cluster 13 – Decision making and investment under uncertainty

- Business schools have a great deal of expertise in this area.
- Statisticians have a role in the quantification of uncertainty.
- Historians could play a key role in looking back at the long-term processes of change and transition and how actors dealt with it.
- Business management consultancies could provide a more commercial viewpoint.
- Utilities have a very particular investment profile but other organisations e.g. SMEs and technology companies may take a radically different investment approach.

C.3.3 How might the different organisations and research communities collaborate with one another to address these key research questions?

Cluster 11 – Improving the evidence base for policy evaluation and review

- There needs to be significant interaction between the organisation that is commissioning the research and the organisation undertaking the research.
- There are potential issues in this area around the IP of the methodology for the models being used to evaluate the policy.

Cluster 12 – Data ownership, protection & use

- The relationship between universities and the market data companies is potentially difficult because the market data company might not want to disclose all the data.
- The people who are introducing the calls need to know more about this area and what good standards are.
- The Low Carbon Networks fund team (OFGEM) may need to be brought in to understand these projects as part of their review.

Cluster 13 – Decision making and investment under uncertainty

- How do you encourage research proposals to include the necessary collaborations in this area?
- People need to be able to talk to all involved communities to ensure these collaborations take place. For example the investment communities & mathematicians.
- UKERC is currently undertaking a flagship project on uncertainties – All the various research groups have been asked to consider the impact of uncertainties e.g. resources. A special

journal issue will capture the various different thoughts on uncertainty relating to the different aspects of the energy system. It is a systemic/system wide issue.

C.3.4 What capabilities/capacities do we need in place for the UK to address these questions?/ What do we need to do to ensure we are ready to address these research challenges?

Cluster 11 – Improving the evidence base for policy evaluation and review

- RCUK could issue a call to study the impacts of a policy before and after it is implemented. There is a lot less evidence examining the past unfolding based on decisions made.
- There is a conflict between policy based evidence and evidence based policy – policy can shape evidence as well.
    - Policy moves quicker than the research area or the evidence that has been collected. The need to do things is moving more quickly that the pace at which we can undertake the research to support the design & implementation of the policy.
        - There is a significant mismatch between research and policy time frames, therefore, by the time government gets the research evidence it might have already changed its mind.
- Fast track RCUK/DECC call for more responsive funding for specific cases that arise.
    - Universities struggle to respond on a consultancy time basis, however.
    - Is there a need for academic research groups to be established that are capable of responding on these short timescales?
- Responsive communication between policy makers and researchers – we need to have an infrastructure in place to ensure this happens, and ensure the evidence is heard, not just political imperatives.

Cluster 12 – Data ownership, protection & use

- Need to understand the ethics and legal aspects of data collection.
- Social scientists help to engage the consumers and understand matters from their perspective e.g. willingness to engage and valuation of the data.
- Need to learn from engaging and rewarding projects that do good work in this area
- We need to know how frequently this data should be collected and how invasive this data collection can be.

Cluster 13 – Decision making and investment under uncertainty

- Is there a role for someone/an organisation to bring these parties together? UKERC, for example, was the forum in which uncertainty was identified as not only a key issue but a system wide issue that needed addressing.

- Knowledge Transfer Networks can translate issues between communities. KTNs try to synthesise research that has already been done, but don't often commission much of their own research.

- Organisations that can run events, for example the Isaac Newton Foundation and ICMS in Edinburgh/Cambridge to get people together.

C.4 Group 4

Cluster Name(s)	Hotspots
Cluster 16 – Resilience of energy infrastructure to external events	- Resilience of energy infrastructure following threats/incidents
	- Resilience of energy infrastructure to changing UK climate
	- Energy system resilience and disaster recovery
	- Design of safety-critical systems
Cluster 17 – Supply quality and standards	- Redundancy – balancing of resilience and optimality
	- Consumer valuation of supply reliability and equality
	- What are the minimum security requirements (both physical & cyber) in the medium to long-term? Where are the gaps currently?
	- Relaxation of some (technical (both planning & operational) network constraints to allow higher penetrations of low carbon technologies
5 – How can domestic time of use tariffs, smart meters and smart appliances work together to improve demand response?	- Role of consumers in energy efficiency and demand response
	- Smart meters – development of smart appliances for autonomous demand side management
	- Domestic 'time of use' tariffs o How can they be made to get demand patterns to follow supply? o Integrating of technologies, tariff structure, role of the consumer etc

C.4.1 What are the key research questions relating to this area?

Resilience and supply quality

- How do you define resilience? It can be defined as the acceptable losses of service and the acceptable rates of recovery. There needs to be acceptable costs to reduce risks/increase resilience.

- What external events do energy infrastructures need resilience against? What are the best techniques to address these questions? (Models, simulations and war-games were all discussed).

- How do you 'get' the best levels of resilience - spending a lot on kit upfront or by operating your kit in a smart way?

- How do we move away from optimising the energy system for cost to optimizing for resilience? Very specific use of resilience in ecosystems/ecology: the ability of a system to absorb stress and bounce back.

- How do improvements related to resilience affect consumers? They will increase costs, but what about the other impacts?

- How can resilience be better regulated into the system?
- A very important point with the advent of smart grids will be cyber-security. Need to differentiate physical security and risks from cyber-security.
- There are different scenarios/pathways to resilience: reinforcing the existing network or having a massively parallel network. A more decentralized network vs a centralized network. It all comes down to the costs.
- Structuring resilience is important – different types. Technical responses, consumer responses and market responses.
- What are the key failure points during potential shocks and how can we address them?

Smart Metering

- This relates to the 'Internet of things', the kit in the home that responds to outside signals
- Needing to understand how people use energy in the first place → gather data → design tariffs. How do we get and access the data we need? Once we have this data, how do we use it to design tariffs?
- What level of active consumer engagement do you need? Do you automate 'smart' appliances or do you actively engage the consumer in the process?
- What is the role of the consumer? How do you get consumers to opt in? Which consumer would choose to opt in to such tariffs? We know that consumers don't act "rationally" – so cost savings by themselves may not be sufficient incentives.

C.4.2 Whose job should it be / who is best placed to undertake this research?

Resilience and supply quality

- There's a big role for industrial research, as they need to understand and secure their infrastructure. Resilience deals with external shocks so we need people external to the energy community that understand these events better.
    - climate, weather community
    - security, terrorism, network/IT people
    - DNOs
    - ports, natural gas people
    - fuel security, "energy weapon" – international relations
- Government and military – are they already doing this type of research?
- Need a set of future energy systems to understand drivers and shocks – energy system modellers. We need to quantify probabilities and consequences – going beyond just future energy system scenarios.
- Need to work with stakeholders in the key areas – engineering responses, consumer responses and market responses.

Smart Metering

- A great deal of people and organisations are involved – almost everyone!
- Role for social marketing -understanding consumers from psychologists/sociologists point of view → A 'big mother rather than big brother' approach
- ICT issues and interoperability. Different meters need to talk to one another!

- Need to understand business models and the resilience of those models to active or disengaged consumers.

C.4.3 How might the different organisations and research communities collaborate with one another to address these key research questions?

Resilience and supply quality

- The most useful thing to come out of work in this area wouldn't be so much specific research outputs but a management system. This process could be used continually to revise assessments of how resilient the system is and whether something needs to be changed.
- This is a role government should be playing to coordinate such a system, not the research community.
- Pilot studies – need to understand the system ecology. LCNF projects and demonstration projects on actual networks to explore resilience.

Smart Metering

- Big publically available datasets allow the ability to run competitions to design apps or technologies. Imagine an 'X-Prize' for this to get the hacker community engaged.
- Smart metering and ICT is a very fast moving field - having a 3-year research project is challenging, as by the time it's finished it's already outdated. Academia may be too slow moving to keep up with developments here. Need to collaborate with more agile partners.

C.4.4 What capabilities/capacities do we need in place for the UK to address these questions? / What do we need to do to ensure we are ready to address these research challenges?

Resilience and supply quality

- Capabilities we have include understanding consumer behaviour and future scenarios, as well as econometric modelling.
- Capacities include reference data sets (but privacy concerns), and real-time emulation environments.
- We need to move to faster iterations of funding and grants in academia in this area – shorter projects.

Smart Meters

- Once again, a focus on responsive, agile research is needed – not necessarily going through publishing, as greater impact will come from different routes.
- An emphasis on public engagement and professional citizenship over detailed fundamental research is required.
- It would be useful to have anonymous data from homes feeding into labs and test beds in real-time, so researchers could track and understand demand variations 'in the moment', instead of after the fact.

As a final point, participants identified researchers' time as a valuable resource, and stated the example of Los Alamos national lab, which apparently has a desert facility, where you can apply to be seconded to, with no internet connection, no computer, just pencil and paper and communal meals with other intelligent people there. Can we have something like this in the UK so that researchers can step back and see the big picture?

Annex D: Agenda

Wednesday 17th April	
10.15	Arrival and Registration
10.30	**Session One: *Introduction*** Introduction to the purpose and process of this Expert Workshop and the overall development plan to create an Energy Research and Training Prospectus
	Discussions and activities to share current thinking in this key area of the energy domain in order to generate different perspectives and ideas on the challenges we are facing
12.15	Lunch
13.15	**Session Two: *Exploring the Research Themes*** Discussions and activities to identify and develop potential research themes from different perspectives
	Session Three: *Reflection and Summary* Activities to reflect on the various different emerging research themes and their relationships
17.30	Close
19.00	Drinks Reception and Dinner
Thursday 18th April	
9.00	**Session One: *Introduction to Day Two***
	Session Two: *Deeper Analysis of the Emergent Research Themes* Discussions and activities to explore emergent research themes more deeply, with the aim of identifying drivers and barriers to these different future research themes
12.15	Lunch
13.15	**Session Three: *Further Development of Research Themes*** Discussion and activities to further shape the prospectus
	Session Four: *Summary and Next Steps* Plenary session to summarise and discuss the key outputs of the workshop, as well as the next steps in the development of the prospectus
16.00	Event Finishes

Appendix E: Attendance List

Surname	Forename(s)	Organisation
Bell	Keith	University of Strathclyde
Bell	Christine	Centre for Facilitation
Bolton	Ronan	Leeds University
Chapman	Nigel	Centre for Facilitation
Chung	Chris	British Gas
Coffele	Frederico	University of Strathclyde
Dent	Chris	University of Durham
Dodds	Paul	UCL
Gruenewald	Phillipp	University of Oxford
Handysides	Tom	Ofgem
Hannon	Matthew	Fellowship Team
Harrison	Gareth	Edinburgh University
Hawkey	Dave	Edinburgh University
Hemsley	Mike	Notetaker
Hodgson	David	UKTI/PA Consulting
Kammerer	Iris	Fellowship Team
Keirstead	James	Imperial College
Lidstone	Liam	ETI
Ochoa	Luis	University of Manchester
Pfenninger	Stefan	Notetaker
Radcliffe	Jonathan	University of Birmingham
Ramchurn	Gopal	University of Southampton
Rhodes	Aidan	Fellowship Team
Rolls	Mike	Siemens
Salisbury	Gavin	EPSRC
Shipworth	David	University College London
Skea	Jim	Fellowship Team
Speirs	Jamie	Imperial College
Stucchi	Karim	University of Cambridge
Taylor	Gareth	Brunel University
Wu	Jianzhong	Cardiff University