March 2010 Energy Research Partnership report

# Energy innovation milestones to 2050

Energy Research Partnership

# Foreword

Managing the transition to a low carbon economy while continuing to ensure energy security and affordability is one of the greatest challenges of our age.

Moving to a secure, sustainable energy system will require the deployment of new technologies, many of which are still at the development stage.

We are faced with critical technological questions. There is uncertainty about both the future cost and effectiveness of some technologies. Resolving these uncertainties requires years or even decades of work. Moving a technology from the demonstration stage to deployment at material scale can also take decades. Since our target date of 2050 is just four of these decades away, we must take action even though we are uncertain about the technologies that will ultimately prove to be the most effective.

The aim of this report is to shed light both on the current consensus regarding the broad direction of travel of the energy system and on the areas of uncertainty about technology choices. By so doing, it will highlight the timescales at which the key pieces of technological learning may be expected to bear fruit.

One of the themes of this work is the pressing need for investment in well-chosen, innovative demonstration experiments to help this learning process.

This is vital work which will help to safeguard our environment for future generations. We believe that industry, government and communities will find this analysis helpful.

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Co-chairs of the Energy Research Partnership

March 2010

## Contents

# Executive Summary

This study of innovation milestones to 2050 sets out how and when selected new energy technologies are expected to develop and what the implications of their deployment could be on the UK energy system. Our objective has been to provide a high-level view to help ensure that policy and investment decisions are taken with a better understanding of the risks and opportunities involved in the transition to a low carbon energy system. We have drawn on scenarios and analyses from across the energy community, and our conclusions represent views that are broadly shared across the public and private sectors. The Energy Research Partnership is in a unique position to offer authoritative and strategic advice to inform decision makers on these matters.

## Key messages

Achieving the goal for 2050 of a secure, affordable and low carbon energy system, means deploying technologies that are currently, or soon to be, available, as well as developing new technologies which may have an impact in the future. To chart the progress that is required by 2020, we have adapted ERP's 'innovation funnel' diagram in Figure 1. This 'pipeline' of technologies balances our analyses of what is needed to meet emission reduction targets and deliver a secure energy supply against that which can be achieved with technology developments. Progress towards these milestones should be monitored and used to guide policy or further investments.

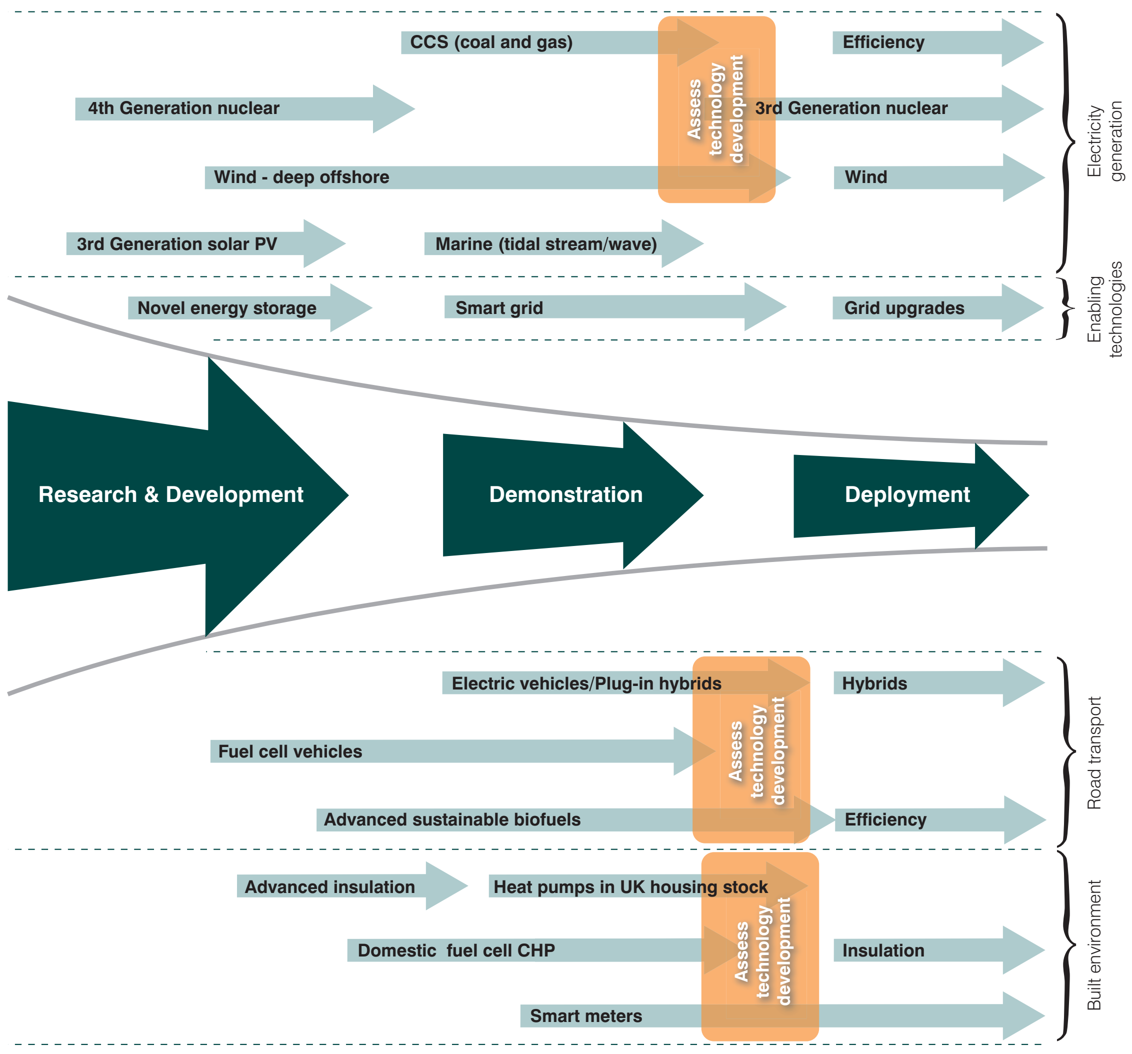



*Figure 1. Pipeline of selected energy technologies showing progress required by 2020*

Some potentially competing technologies (indicated by orange boxes on the chart) will have very different impacts on the energy system. Given the implications for building expensive new infrastructure and on power generation and management, assessments across these areas (particularly for electricity generation, domestic heating and road transport) will need to consider whether there is a case for more specific policy intervention. Although a simplification of the process, this 'pipeline' can offer an overview of some fundamental issues that may arise. When making choices in the next decade, considering the longer term is essential otherwise we risk locking both the energy system and society in an undesirable future.

Technologies will require either funding or policy interventions according to their current status:

**Deploy**
Most of the technologies that will form part of the energy system in 2020 are either available now or at the later stages of the innovation chain. ERP's remit does not extend to advising on mechanisms to ensure technologies are deployed. However, it is clear that their rapid deployment will be essential to meet emission reduction targets and allow new technologies to make a further impact.

**Demonstrate**
Our most important conclusion is that large scale, strategic, demonstration activities are needed over the next decade, which need to be commissioned now. This applies across the energy spectrum and includes electricity generation, transport and the built environment. In some cases, such programmes are already underway. However, the scale needs to be increased over the coming years so that decisions which may affect the long term future of the energy system can be taken with the best available information.

**Research and develop**
More basic research and development (R&D) is needed to develop technologies that will maintain the trajectory of decarbonisation beyond 2030 as well as R&D to support improvements in deployed technologies. A wide range of physical and biological sciences underpin applied energy technology and engineering disciplines and need to be maintained.

The focus of this work is on providing a deeper understanding of a set of new technologies which has the potential to deliver significant carbon reductions in the UK. We have not sought to cover all areas in which innovation will play a part in putting the UK on a low carbon pathway to 2050, nor provide the ideal mix of technologies for the future energy system. Clearly, improvements in efficiency of industrial processes and currently deployed technologies will have a beneficial impact and are vital components of a low carbon energy system. Such improvements are often taken into account by scenarios through 'learning curves' and are implicit in our analysis of an evolving sector. Other technologies exist which have already been deployed commercially in the UK, such as heat networks. They may have a role to play, but their further uptake will be subject to policies outside of ERP's remit.

## The Energy Research Partnership

The Energy Research Partnership is a high-level forum bringing together key stakeholders and funders of energy research, development, demonstration and deployment (RDD&D) in Government, industry and academia, plus other interested bodies, to identify and work together towards shared goals.

The Partnership has been designed to give strategic direction to UK energy innovation, seeking to influence the development of new technologies and enabling timely, focussed RDD&D investments to be made. It does this by (i) influencing members in their respective individual roles and capacities and (ii) communicating views more widely to other key stakeholders and decision makers as appropriate.

ERP is co-chaired by Professor David MacKay (Chief Scientific Advisor at the Department of Energy and Climate Change) and Nick Winser (Executive Director at National Grid). Members come from Government departments, funders of energy RD&D and the private sector. ERP is supported through members' contributions.

This report has been prepared and written by the ERP Analysis Team: Richard Heap, Jonathan Radcliffe and Charlotte Ramsay. More information on the work and role of ERP is available at **www.energyresearchpartnership.org.uk.**

## Box 1: Review of scenarios

We undertook a review of over 20 scenarios from government, academia, industry and NGOs which described the UK's energy system. Our primary aim was to identify some of the main areas of commonality and of divergence in their outputs and to focus our work on the innovation requirements of technologies expected to have significant impact on the transition to a low carbon energy system. The main findings were:

**Electricity generation mix**

- There was consensus on the need for rapid decarbonisation of power generation. Subsequently, heat and transport were potentially decarbonised through electrification thus leading to an increase in demand for electricity. There was less agreement on the increase in the scale of demand which ranged from 50% to more than 100%.
- The main components of the mix came from centralised power generation using nuclear, wind and fossil fuel (mostly coal) with CCS but with variations in the proportions. The degree of dependence on other technologies (such as tidal, wave, waste, bioenergy, solar) was also varied.
- It was not clear how intermittency and load balancing was tackled; some scenarios using unabated fossil fuels with less emphasis on storage and active management of demand and the grid.
- There was consensus that intelligent system operation would be required but divergence on functionality of smart grid operation and how system flexibility and control would be achieved. Some cited a role for energy storage in provision of flexibility but were divergent on whether this would come from distributed (e.g. demand response, low grade heat storage etc.) or centralised (e.g. pumped hydro, compressed air storage etc.) resources.

**Transport**

- The scenarios agreed that efficiency gains in conventional and hybrid vehicles, with greater use of biofuels, would drive the bulk of emissions reductions in road transport up to 2020 / 2025.
- There was a diversity of fuels in scenarios post 2020 according to vehicle type but with a growing role for electric drive-train light duty vehicles between 2020 and 2050. Biofuels, fuel cell vehicles and battery powered vehicles could all have niches if not more widespread application.
- There was uncertainty in technology limitations (between batteries, fuel cells and producing sustainable biofuels); the role of bioenergy (including its availability and conflicting demands between modes of transport, other energy services and non-energy sectors); and delivery of infrastructure change.

**Demand reduction, energy efficiency and heat**

- With energy savings and improved efficiency crucial, there was consensus that final energy demand from end users must stabilise and, preferably, reduce.
- The provision of decarbonised heat is generally met through a shift to electrification between 2020 and 2050.
- However, there were some concerns about the responsiveness of technologies and the capacity of the power system to accommodate additional electricity demand (from heat and also from transport).

A workshop was held in September 2009 to validate this analysis and to bring together those involved in energy scenarios to discuss our preliminary findings. It also allowed us to identify a set of technologies which would require more detailed study; to understand their impact on the wider energy system and to present the options where there was uncertainty.

# Technology innovation timelines

Further study was focused on technologies that are expected to deliver significant carbon emission reductions, and whose development would have wider implications for the energy system. We were guided by the conclusions of the scenarios meta-analysis and an appreciation of current thinking which emerged at the workshop. Areas where 'competing' technologies could have profoundly different impacts and where there may be a case for favouring one or another technology at some time in the future were of particular interest.

This analysis took into account output from the scenarios (see Box 1) as well as other technology-specific roadmaps and analyses. The main findings are presented in the figures below which illustrate the innovation timelines for selected energy technologies by sector. The orange boxes indicate where there are potentially competing technologies which, if developed further, could have differing impacts on the energy system. Given the implications for building new infrastructure and on power generation and management, assessments across these areas will need to consider whether there is a case for more specific policy intervention.

The orange arrows at the top and bottom highlight how the four energy technology areas interact. Feedback from one set of technologies may require interventions to promote one technology over another or to accelerate development of a group of technologies. For example, advances in electric vehicles could lead to greater uptake which could require grid enhancements and an increased demand for decarbonised electricity.

The main conclusions from the timelines were:

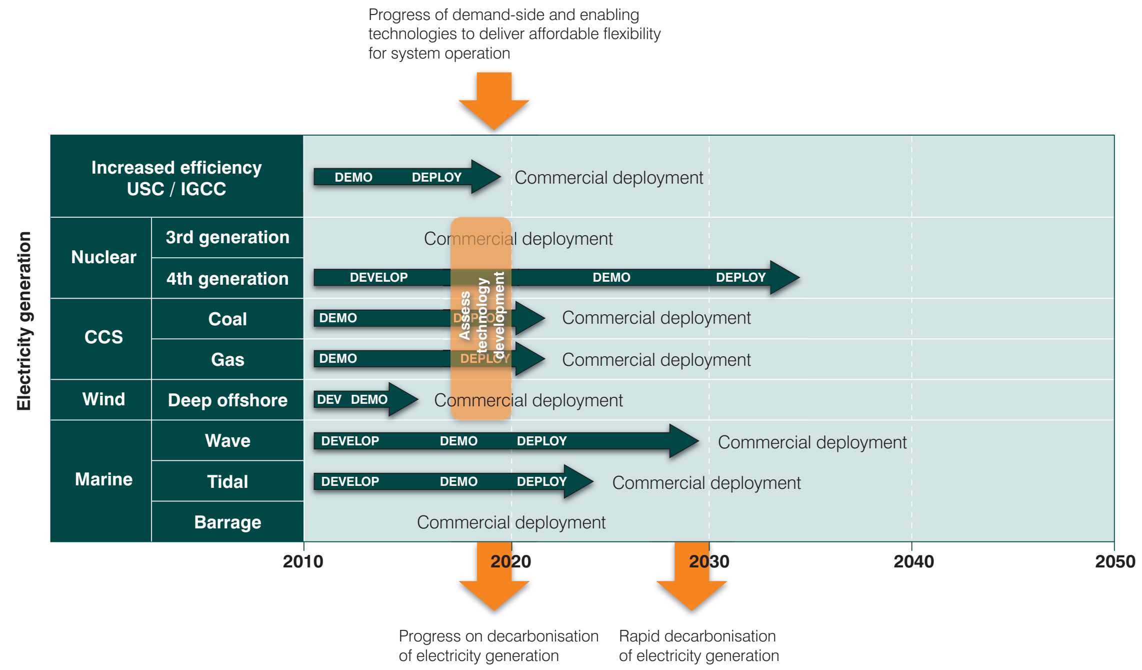
**Electricity generation**

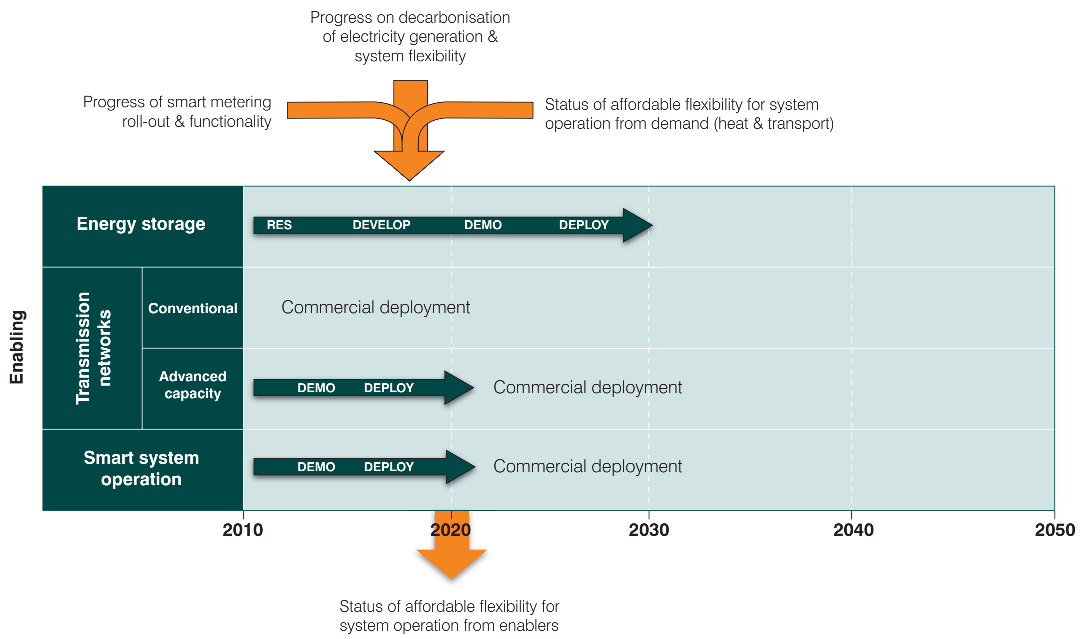
The early demonstration of carbon capture and storage technologies (CCS) on coal and gas fired power stations is critical in determining what generation technologies will be deployed for electricity generation out to 2050. Should CCS prove too expensive or unable to deliver on the scale required, both wind and nuclear power will have to be deployed on a much larger scale. However, both wind and nuclear face challenges that are not all technical and which might restrict the scale and rate of their deployment. This could lead to an increase in gas-fired power stations being built in the short term to meet the electricity demand, emphasising how gas CCS could be an important technology.

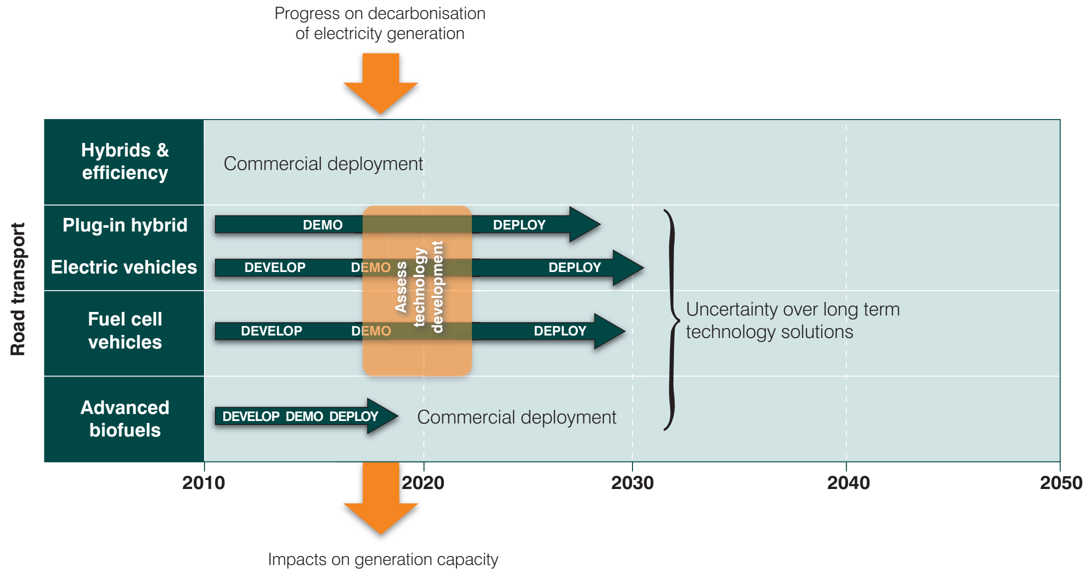
Once the real capability of CCS to reduce emissions is established, an assessment can be made about progress towards decarbonisation of electricity generation on which other parts of the energy system are dependent – in particular, heat and transport. By 2020, a clearer picture will be available of the scale of deployment of other technologies and what impact they will have on the development of the generation system, including grid reinforcement, demand reduction and decentralised generating technologies.

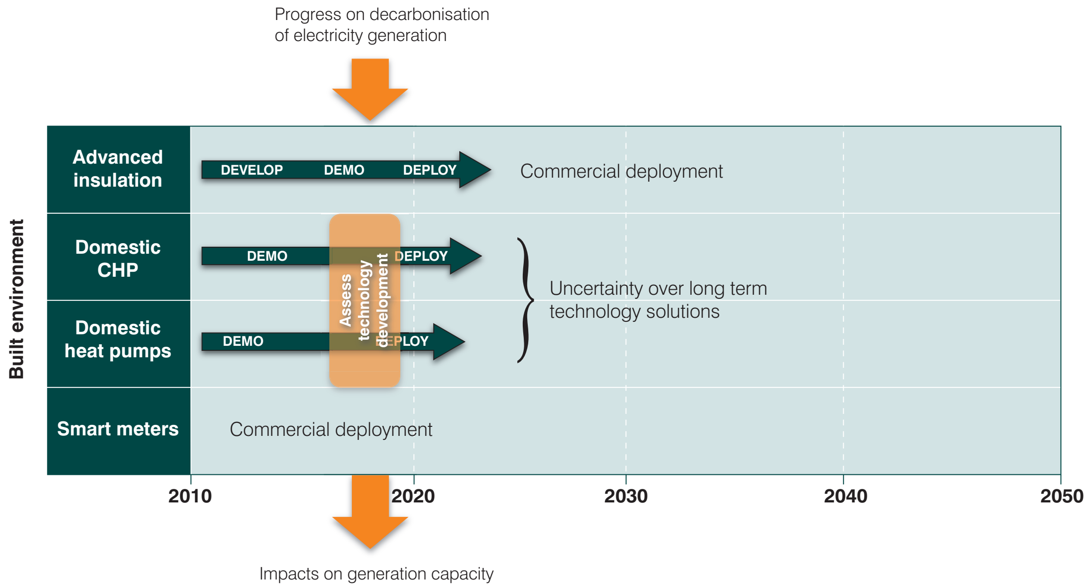
**Enabling technologies**

Enabling technologies have an important role in facilitating efficient integration of decarbonised power generation and various demand side resources. Development and






demonstration of the smart grid, in parallel with novel network technologies to increase network capacity, are essential foundations for the future system. Ongoing development of large scale energy storage technologies could also assist in provision of flexibility for power system operation.

Consumer behaviour and full participation in the smart grid operation is essential for success of this concept. Therefore, large scale demonstrations are needed in the short term to demonstrate not only technologies at scale but the way in which end-user behaviour will modify technology performance and smart grid functionality. Open architecture for all smart grid technology developments is important to avoid lock-in to a particular energy future and to provide flexibility in the face of uncertainty. Furthermore, developments in this area will be heavily influenced by the functionality of smart meters and the rate of nationwide roll-out of this technology together with an associated IT infrastructure.

### Road transport

A range of technologies is likely to be used in the transition to 2050, but vehicles with electric drive trains appear to offer the most promising technology option providing electricity generation is decarbonised. An evolution from the current range of hybrids to full hybrids reaching the mass market, transition to plug-in hybrids and eventually electric vehicles can be expected during the 2020s. However, a failure to improve battery technology, offset by breakthroughs in low-carbon hydrogen production and storage, may make fuel-cells a viable low-carbon option. The role of biomass and biofuels in the energy system is very sensitive to competing demands from energy and other sectors and sustainable alternatives to current biofuels have yet to be fully demonstrated.

Given the uncertainties, a period over the first half of this decade should be used to assess technology development of electric (including plug-in) and fuel-cell vehicles. These pilot studies need to be of sufficient scale to demonstrate what outcomes could be achieved with wider uptake. With some projects already underway, there should be strategic coordination both nationally and internationally. This will also give time to further our understanding of the issues around the sustainability of biofuels.

### Built environment

For heating technologies, heat pumps are favoured by scenarios and other analysis into how to meet the heat demand of domestic buildings. However, the performance of heat pumps in the UK's climate and housing stock, and by real consumers, has not been fully tested. Similarly, the performance of domestic Combined Heat and Power (dCHP) for single households has yet to be proven on a large scale, and new dCHP models are expected to be marketed widely in coming years. An assessment of 'real world' performance is required before wide ranging intervention policies on technology choices are taken. Over this time, a better understanding of future electricity and gas carbon intensity will be formed and will provide a better indication of the relative emission reduction potentials.

There is very little available data that characterises how users interact with the new technologies or on behavioural elements of technology uptake and usage. This means that there is a high degree of uncertainty around whether the demand side will participate in the energy system to the extent required. For example, the roll out of smart metering and intelligent control systems is an enabler of a number of different aspects of the 2050 energy system future. However, a common theme that emerges from scenario analysis of the use of smart meters is a high degree of uncertainty over how end users will use and respond to smart meters and therefore what contribution this technology will make to reducing energy demand. Although the technology itself is well developed, large scale demonstration of the technology in the whole house / whole system context is needed to gather data on actual usage of smart meters and smart appliances in the home.

To understand the extent to which the demand side can become the resource that many scenarios describe, further analysis and consideration is required supported by significant demonstration of these new technologies and concepts.

# Implications for the energy system

It is clear from the timelines that the next decade is crucial for technology innovation, if we are to have the technologies needed to meet the 2050 targets. As highlighted above, there is a pipeline of technologies at various stages of development that need to be deployed, demonstrated and researched by 2020. However, from our analysis of the innovation required across whole energy system, a number of issues are raised which need to be considered when making decisions based on the timelines for the technologies.

**Investment in innovation**

The costs of innovation (from public and private sectors) escalate as technologies move towards commercial deployment. To establish which technologies will be viable and most cost effective over the longer term, costly demonstration activities will be required. In the case of CCS, this nettle is being grasped. But for demand side technologies, such as in transport and for retrofitting buildings, the investment will equally be required for large-scale demonstration projects.

**Costs**

The cost of a technology is a key determinant of its deployment. Cost can be influenced by a range of factors, of which innovation has a major role. Deployment may also be accelerated by policy intervention including through target setting, fiscal incentives and carbon pricing. While not reducing costs of a technology directly, these interventions create market opportunities by reducing the risks, and therefore the cost, of investment. The effectiveness of the policy signals is dependent on them being appropriately long term so as to provide certainty of returns on investments, particularly where they are in early stage R&D.

Understanding the barriers to market and introducing the appropriate incentives could accelerate technology deployment and development. However, while stimulating the market towards particular technologies may be useful in delivering particular energy options, these interventions need to be set in the context of the wider energy system. For many options a significant cost could be the development of new infrastructure (for hydrogen fuel cell vehicles or $CO_2$ transportation) or strengthening of existing infrastructure (to deliver more electricity to households for heating).

**The new 'decarbonised electricity' orthodoxy**

Breakthroughs in particular technologies or the stimulation of a particular market can lead to the creation of orthodoxies on which the future energy system will be based. If this report had been prepared 10 years ago, the focus may have been more on the role of hydrogen as a low carbon storage vector with little on CCS as an enabler of low carbon fossil generation. Four years ago, bioenergy was seen as playing a significant role, particularly in the provision of biofuels for transport. Now, most of the scenarios studied for this analysis conclude that decarbonisation of our electricity supply is the key to providing a low-carbon energy system in 2050 with much of transport (and heating) energy demand being met by a decarbonised electricity supply.

Understanding the rise and fall of these technology trends is important in our evaluation of the current thinking around the energy system of 2050. Ultimately, analysis of any projected future system requires a planned, coordinated approach. One that understands and responds to the challenges of decarbonisation using the array of technologies already available, is flexible enough to include breakthrough technologies and maintains a whole system perspective that characterises the implications (positive and negative) of technologies in context.

**Taking early action**

Taking early action to reduce $CO_2$ emissions, either by 'leap-frogging' directly to zero carbon technologies or implementing shorter term stringent targets, could have implications for innovation. Some analysis argues for the immediate implementation of zero carbon technologies rather than investment of effort and resources into incremental energy efficiency changes to existing technologies. This could have the dual effect of decarbonising the system faster and ensuring that total emissions are minimised.

However, this is countered with the argument that efficiency gains are often 'low-hanging fruit' in the form of quick and cheap changes that could have immediate effect and get us on the right trajectory to 2050. The alternative of 'leap-frogging' to novel zero carbon technologies could take time to implement, ultimately be far more costly and require greater levels of investment in immature, unproven technologies.

**Bioenergy**

Biomass for heating, electricity generation and transport fuel has issues that are well known with global demand and supply uncertain and the true carbon costs sometimes hidden. Aside from competition between energy sectors, there may be wider environmental concerns, even from non-food crop biofuels. As yet, however, there is no consensus on the best course of action and addressing these concerns must be a priority.

**Life cycle impacts of energy technologies**

The choice of energy technology has wider implications than just its greenhouse gas emissions and includes availability of land and mineral resources and impact on water resources. Some of the impacts will be in the UK; others will be global. The need to understand these impacts was highlighted by the recent debate over land use and food crops for biofuels.

# Next steps

**Technology development**

Action is needed to put in place the policies and investment to ensure that the innovation needs highlighted in the technology pipeline diagram above are delivered. An ongoing role for ERP will be to keep track of progress against the innovation milestones set out in this report.

How the UK chooses to deliver this and encourage domestic innovation is particularly salient. One country cannot expect to lead development across the board. According to our domestic strengths and requirements there must be some prioritisation of technologies. Firstly, to decide which technologies to take a lead on developing in the UK; secondly, which to collaborate in the development of (and with whom) and, thirdly, those which we should take an active interest in so that we are ready for deployment but do not necessarily have the expertise to play a role in developing.

ERP's ongoing work on International Engagement will help the UK take a more strategic approach both to prioritisation, and to taking advantage of collaborative energy innovation activities.

**Supporting analysis**

This study describes the innovation challenges at a high level in order to provide guidance for policy makers and funders/investors. That the analysis comes from a broad spectrum of stakeholders should give confidence that the conclusions have support from across the sector. But further analysis is required to address the issues that we have highlighted and to review our progress towards achieving the 2050 goals. We therefore propose some next steps:

- ERP's future work will look at many of these technology areas in more detail to consider whether there are any funding gaps, and the potential role for the UK in driving forward RD&D.
- Further modelling and scenario work is essential. A diversity of approaches will improve our understanding of how the energy system could develop. The Energy Technologies Institute's new Energy Systems Model will bring a fresh perspective, including the ability to balance energy security and cost considerations. Also, the development of the global TIMES model as a successor to MARKAL will study the UK's position with respect to worldwide resource flows and global technology innovation.
- Energy system modellers would benefit from continued interaction to exchange information, outputs and ideas. The academic community, with input from ERP, has been organising workshops and events to bring researchers together, and to feed messages in to policy makers.
- The development of detailed technology requirements, or specific activities to assist them, such as from the Carbon Trust's 'deep dives', should be undertaken as a matter of urgency.
- Communicating messages effectively from scenarios to those who will use the information is critical. ERP will have a role to look periodically across scenarios and new analyses to assess whether any of our conclusions need revising.

The whole energy community has a responsibility to take forward these conclusions. ERP is well placed to coordinate these activities and ensure that decisions affecting energy innovation are informed by the best available information.

**This report has been prepared by the ERP Analysis Team, with the support of the ERP membership. The views are not the official point of view of any organisation or individual and do not constitute government policy.**

**The full report with supporting analysis is available from ERP. Details of how to obtain a copy are available on our website www.energyresearchpartnership.org.uk.**

# 1 Introduction

Innovation in energy technologies will be a critical factor when considering the transition of the energy system over the coming decades. However, it is a complex, non-linear process with multiple inputs and feedbacks. When this is overlaid with the complexity of scenario modelling and 'forecasting', the uncertainties of the future become even greater.

Scenarios of the UK's future energy system are not predictions but set out possible paths and options. They can be a useful tool for policymakers and investors but the outputs need careful interpretation with an understanding of their limitations. The large number of scenarios which cover the energy system, or aspects of it, can also be confusing when different messages, from different perspectives and with different objectives, are given, Even how they are communicated, with different units and outputs at different points in time, can risk sight of the key points for action being lost.

Furthermore, scenarios often give only a limited insight to the transitions required to achieve them. Roadmaps are needed that set out what we need to know about the technologies, how they need to develop and explore how the different technologies and sectors interact within the energy system. These will help identify investment priorities and opportunities and risks.

The Energy Research Partnership, with a remit covering research, development, demonstration and deployment in fossil fuels, renewables, nuclear, infrastructure, transport and the demand side, is in a unique position to offer authoritative and high-level guidance on how energy technologies may evolve and the resulting implications. By describing some of the common themes from recent scenario work, we set out elements that will make up a 'shared vision' of innovation in the sector.

## 1.1 UK energy innovation

In ERP's 2006 report, the innovation process was defined as a 'funnel' (Figure 1.1). The study reviewed the innovation chain for 12 key energy technology areas that are expected to transform the UK's energy landscape, make dramatic reductions in greenhouse gas emissions while, at the same time, maintaining secure access to competitive sources of energy.

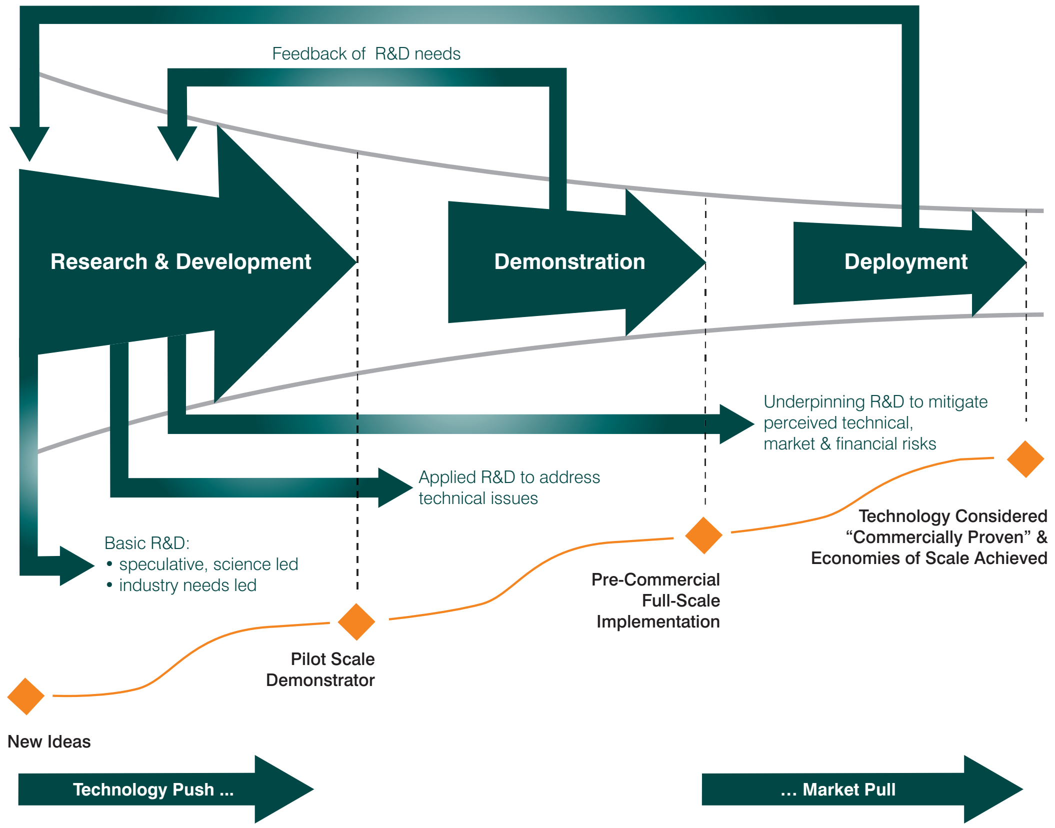



*Figure 1.1: The ERP 'innovation funnel' diagram*

In our work on innovation we use the following concepts:

- The research, development, demonstration and deployment (RDD&D) phases are defined to correspond with government and EU funding definitions.
- R&D comprises basic 'blue-skies' research, applied research, generic development and product development.
- Demonstration takes a product from pilot scale to full scale.
- Deployment is early commercialisation when economies of scale are realised and the technology becomes 'commercially proven'.
- R&D has important roles to play throughout the innovation chain in driving technologies up the 'learning curve'.
- Feedback at all stages defines further needs for R&D.
- Technology push is where ideas emerge from scientific research and are pushed forward towards the market.
- Market pull is where R&D is initiated in response to market need.

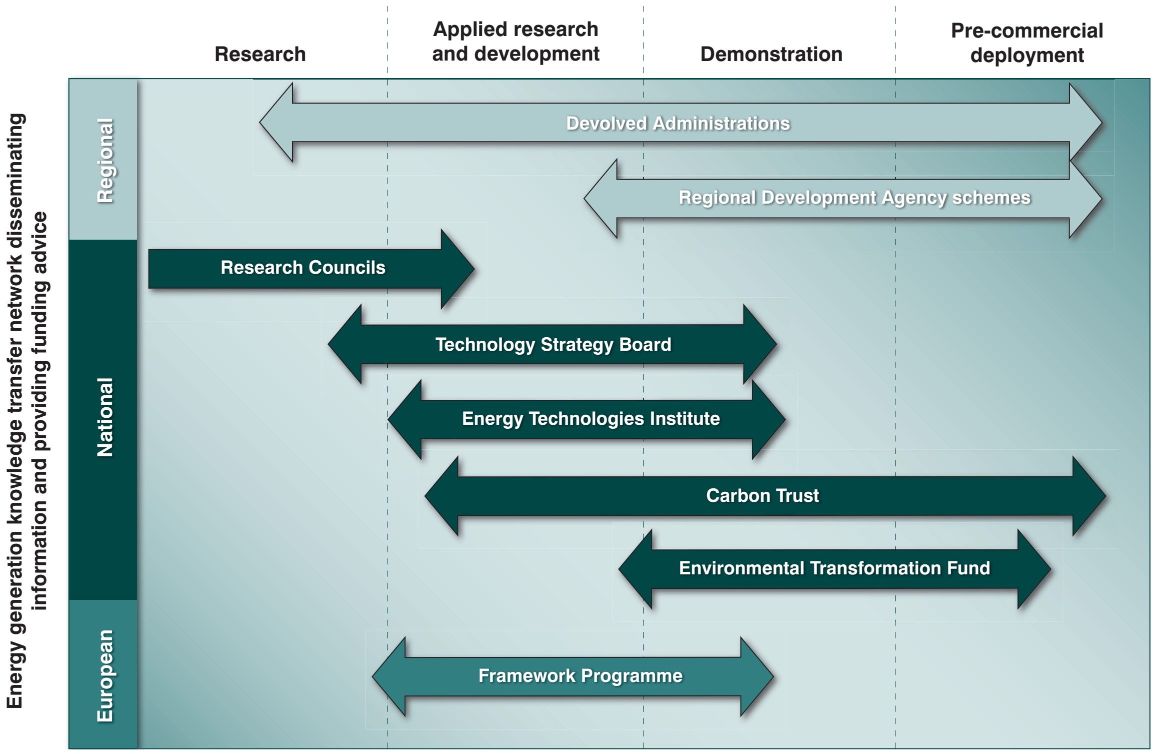
Support for energy technologies across the innovation chain is depicted in Figure 1.2. Many of these organisations are members of the Energy Research Partnership. While in this report we do not draw any conclusions on the suitability of the current landscape, it is clear that effective working between the organisations is essential. Our on-going work looks at how this institutional framework manages the innovation process for energy technologies, both in general strategic terms and by specific technologies.

In summary, the report 'UK Energy Innovation' recommended a need for:

- Development of a strategic vision for each technology area
- Better co-ordination, with some consolidation, of support along the innovation chain
- R&D to be strengthened and more strongly focussed on market need
- Much stronger joint public/private support for demonstration and early deployment

The report with a full set of recommendations by technology area is available from the ERP website.[1]

Recent work by ERP recognises that the development of energy technologies will require a global effort. The UK must engage in international activities on energy innovation or risk losing out on business opportunities and potential to reduce emissions in the UK. A more strategic approach is required in order to focus engagement in areas where there will be an economic or environmental impact. The Energy Research Partnership is working with the Energy Generation and Supply Knowledge Transfer Network to assess which technologies should be priorities for the UK to engage in internationally and how effective national and international mechanisms are for supporting technology development.




Source: Department of Energy and Climate Change

*Figure 1.2: The UK's energy innovation organisational landscape*

[1] Available from **www.energyresearchpartnership.org.uk/tiki-index.php?page=page12**.

## 1.2 Project outline

### Aims

Against this high-level perspective of both energy innovation and the organisational landscape that supports innovation in the UK, this project aims to:

- Develop a shared understanding of what current analysis tells us about the technology development milestones and critical decision points for the likely key components of the energy system in 2050.
- Set out a vision that is shared by Government and industry to give a better common understanding of technology pathways, timeframes and risks and their contribution to the targets.
- Provide a context for future work of ERP on technology assessments of RD&D challenges, gaps and opportunities. Combined with an oversight of the innovation landscape, this can be used to identify and address gaps in provision and priorities for support.

The project is focused on innovation required for the UK energy system. We recognise that important research is taking place in the UK that may lead to technologies that have greater utility in other countries but which also lead to domestic economic benefit. However, we do not seek to assess these technologies in this report.

In parallel with ERP's 'Innovation Milestones' project, the Department for Energy and Climate Change (DECC) has been building a '2050 Roadmap' as described in the Low Carbon Transition Plan[2]. The aim is to build consensus between the Government, industry and the public on the scale and nature of the changes we need to see and the issues that need to be addressed, thus enabling major infrastructure and capacity-building investments to be made. Our analysis of innovation in energy technologies presented in this report has fed into this wider DECC project.

Throughout this project, we have sought to be inclusive by working with all sectors of the energy community both within and outside the ERP membership.

### Scenario analysis

To identify the technologies which were believed to be most important to the future energy system, we undertook a review of scenarios of the UK's energy system to highlight the commonalities, divergences and uncertainties that exist. In Chapter 2, we have drawn on academic and public and private sector work and have been privileged to gain insights from a number of scenario developers whose results are not publicly available for commercial reasons.

To review our findings, a workshop bringing together many of those involved in developing the various energy scenarios was held in September 2009. The results of our analysis were presented and discussed with feedback incorporated into this report. The meeting also launched the second phase of our work to study the specific innovation pathways and challenges of key technologies.

### Technology-specific analysis

Further analysis focused on a select number of energy technologies that scenarios indicated would deliver the most significant impact for emissions reductions. The aim was to describe their possible development paths in the context of the whole energy system. An important component of this work was to set out the critical points along these paths when progress, or lack of, may impact other parts of the energy system.

Analysis, in Chapter 3, includes technology specific roadmaps from sources not considered in the meta-analysis in Chapter 2 as a way of validating (or otherwise) the trajectories described by the broader scenarios. A number of individual meetings and discussions were held to examine and review these findings.

### Conclusions

Chapters 4 and 5 bring together the technologies and explore what RDD&D needs to be undertaken now to deliver these technologies. They also consider the wider implications of our findings for the whole energy system and the UK's energy RDD&D strategy, with recommendations for how to take this forward in Chapter 6.

Supporting documents to this report will be published with details of the scenario and technology analyses.

## 1.3 The Energy Research Partnership

The Energy Research Partnership is a high-level forum bringing together key stakeholders and funders of energy research, development, demonstration and deployment (RDD&D) in Government, industry and academia, plus other interested bodies, to identify and work together towards shared goals.

The Partnership has been designed to give strategic direction to UK energy innovation, seeking to influence the development of new technologies and enabling timely, focussed RDD&D investments to be made. It does this by (i) influencing members in their respective individual roles and capacities and (ii) communicating views more widely to other key stakeholders and decision makers as appropriate.

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## 1.4 Acknowledgements

We wish to thank all those whom we have contacted in the course of the project in the wider energy community including attendees of the workshop held on 28 September 2009. A list of those with whom we have had discussions is provided in Appendix 1.

**This report has been prepared by the ERP Analysis Team with the support of the ERP membership. The views are not the official point of view of any organisation or individual and do not constitute government policy.**

[2] See **www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/lc_uk.aspx**.

# 2 Scenario meta-analysis

The increasing significance of the legally binding 80% $CO_2$ emissions reduction has led most major organisations in the public and private sectors to take a view on how the energy system will evolve to 2050. Scenarios have been developed using a range of techniques; some forecasting likely developments given the current technological, geopolitical, commercial and social environment. Others are 'backcasting' from an idealised low carbon system to devise trajectories that achieve an optimal outcome. Some are built from quantitative modelling techniques using optimisation or macroeconomic approaches to building feasible scenarios; others have a descriptive or consultative approach to building a qualitative perspective on the future possibilities.

Our study of scenarios brings together the different perspectives that exist. We analyse their conclusions on the components of the energy system between now and 2050 and identify the areas of consensus, divergence and uncertainty. It is an opportunity to set out an understanding of the system in 2050 which is broadly shared by the public and private sector and to explore assumptions and perspectives that make up energy system scenarios.

## 2.1 Aim

Our aim was to develop a shared understanding of how the energy system could evolve between now and 2050. Existing scenario and modelling work would be drawn on to identify:

- Areas of consensus for the development of the energy system to 2050 and the RD&D roadmaps for priority technology families required to meet those demands.
- Divergences, uncertainties and risks in scenario outputs and their technology pathways.
- Interdependencies between technologies and key decision points indicating implications of these choices and where large-scale transformations in the technologies and infrastructure will be required.
- Differences in assumptions and modelling techniques.

## 2.2 Method

The meta-analysis was based on a study of a population of scenarios or modelling activities that describe the UK energy system between now and 2050. Reflecting the diverse nature of scenario and modelling activities, the selection criteria set out below are high level and were designed to include as many perspectives as possible:

- Timescale: Looking to 2050 or exploring trajectories consistent with 80% emissions reductions in 2050.
- Emissions targets: Based on (or, in the case of scenarios that do not reach 2050, working towards) substantial $CO_2$ reductions by 2050.
- Coverage: Relevant to the UK whole energy system.

The selected studies were then characterised according to a number of criteria elaborated in Table 2.1. A full list of the scenarios studied is provided in Table 2.2. An overview of each of these scenarios, including the objectives of the study and the type of model used and scenarios produced, is included in Appendix 2.

Bilateral discussions with the authors and researchers responsible for these reports provided additional input to the analysis of each scenario beyond published outputs. Many of the private sector organisations provided us with reports and insights that are not publicly available because of commercial sensitivities. In these cases, their input is described in Table 2.2 as 'ongoing commercial studies'. Where possible the views and perspective of individual organisations are expressed in our analysis. Otherwise, these unpublished perspectives are included as part of the aggregated meta-analysis.

Two significant scenario studies were being conducted at the same time as our meta-analysis. The Energy Technologies Institute (ETI) has been developing a UK system model using probabilistic sampling method and backcasting from 2050, to explore the likely configuration of the UK energy system and the pathways to 2050. The Royal Academy of Engineering has also been carrying out work to explore the engineering challenges of 80% $CO_2$ reduction by 2050, updating the Royal Commission for Environmental Pollution's scenarios from 2000.[3]

These ongoing studies provided insight on scenario and modelling methods and contributed to the ERP workshop held in September 2009. Although the final outputs from these studies are not yet available, they have been important contributors into our analysis and meeting the overarching aim of developing a shared vision of the innovation milestones to 2050.

[3] The report recommended a 60% reduction in $CO_2$ emissions and explored implications for energy use. See **www.rcep.org.uk/reports/theme-energy.htm**.

| Header | Content |
|---|---|
| Purpose of the activity | Description of the purpose of the study and the perspective of the study authors. |
| Model / scenario philosophy | Description of the modelling philosophy, whether it is forecasting or backcasting. What the modelling approach has been designed to achieve. |
| Model type | Where a quantitative model has been used, description of modelling method / type e.g. least cost optimisation, feasible boundaries, Sankey diagram, MARKAL etc. Including detail of objective function if appropriate. |
| Key Assumptions | Description of dominant assumptions driving scenario output. Including quantitative description of generic inputs e.g. carbon price, final energy demand, background economic conditions, population growth. |
| Outputs | Quantitative details on: Final energy demand and breakdown of end-uses (heat, transport, buildings etc), power generation and breakdown of supply sources, end use technologies etc. |
| Strengths and weaknesses | Assessment of the strengths and weaknesses of the approach in the context of how the scenario / model can make a contribution to the ERP 2050 project. |
| Key messages | Key conclusions or messages from the scenario / model, grouped into themes: Power generation and balancing, Demand reduction and efficiency, Heat, Transport, Key risks and other 'non-generic' key messages |
| References | Model / scenario references and web links. |

*Table 2.1: Meta-analysis headings*

In addition, a number of other studies were identified that met the criteria in part and contributed to our background understanding of the population of scenarios. These were: Ernst & Young (2008), '*Costing the Earth*'; Ernst & Young (2009), '*Securing the UK's energy future*'; Greenpeace (2006), '*Decentralising UK Energy: Cleaner, cheaper, more secure energy for the 21st century*'; Pöyry (2009), '*Impact of variability, how wind energy could change the UK and Irish Energy Markets'*; Tyndall Centre (2005) '*Decarbonising the UK*'; Carbon Trust (2008) '*Climate change a business revolution*'; WWF (2007), '*Climate Solution: WWF's vision for 2050*'; and WWF & Greenpeace (2008), '*Implications of the UK meeting its 2020 renewables target*'.

Findings from the meta-analysis were discussed with stakeholders from across the energy sector at a workshop on the 28th September 2009. A report from the workshop with list of the attendees is in Appendix 3.

## 2.3 Scenario descriptions

Mander *et al* at the Tyndall Centre characterised scenarios through five factors:[4]

- **Is the scenario backcasting or forecasting?** Forecasting, or prospective, scenarios look forward and outline possible futures based on the extension of a number of key drivers; they tell us 'where we will be'. Backcasting scenarios, by contrast, tell us 'how to get to where we want to be', taking into account the pathways to achieving a defined and desirable future. A backcasting approach takes a desired end-point as a starting point and the analysis steps back in time to explore how it may be achieved.
- **Is the scenario qualitative or quantitative?** Broadly speaking, quantitative scenarios are based on models, whereas qualitative scenarios are narrative based, often because the relevant information cannot be adequately quantified. In practise, scenarios may have both qualitative and quantitative elements though the synthesis of the two types of data is challenging from a methodological perspective
- **Is the scenario normative or descriptive?** A normative scenario is defined as one that explores probable or preferable futures whereas a descriptive scenario outlines possible futures.
- **Is the scenario approach expert or participatory?** Expert scenarios are developed by a small academic team and participatory scenarios are developed with elements of stakeholder input. In practice, very few scenarios are solely developed through a participatory process but most include an element of stakeholder contribution and input in addition to the expertise of the project team.
- **Is the scenario of the whole energy system or sector specific?** The former explores the UK energy system as a whole taking into account both the energy supply system and the full range of demand sectors.

To give a sense of the different methods used by the scenarios we reviewed, we have categorised them according to the first two of these factors. A full list can be found in Appendix 2.

The final factor was a criterion for inclusion in this meta-analysis though we consider sector specific scenarios and roadmaps in the following chapter.

Recent papers from Hughes give a historical overview of scenario planning and grouped studies within three categories:[5]

- *Trend driven studies:* Developed around high level trends
- *Technical feasibility studies*: Demonstrate technical feasibility of end points, sometimes 'backcasting' from them
- *Modelling studies*: Complex quantitative models are used to generate results, often operating within exogenous emission constraints

All the scenarios considered in this document tend to fall within the last two categories. A full characterisation and analysis of the scenarios will be published in a supporting technical document.

| Organisation | Pub. Year | Scenario Project Name |
|---|---|---|
| BP | Ongoing | Ongoing commercial studies |
| CBI | 2007 & 09 | 'Climate Change, Everyone's Business' & 'Decision Time' |
| Centre for Alternative Technology | 2007 | 'Zero Carbon Britain' |
| Ceres Power | Ongoing | Ongoing commercial studies |
| Centrica | Ongoing | Ongoing commercial studies |
| Committee on Climate Change | 2008 | 'Building a low carbon economy: the UK's contribution to tackling climate change' |
| David MacKay | 2009 | 'Sustainable Energy - without the Hot Air' |
| DECC | 2009 | 'UK Transition to a Low Carbon Economy' |
| E.ON | Ongoing | Ongoing commercial studies |
| EDF | Ongoing | Ongoing commercial studies |
| Energy Savings Trust | 2008 | 'Emission Impossible' |
| Foresight | 2008 | 'Sustainable Energy Management and the Built Environment' |
| IEA | 2008 | 'Energy Technologies Perspectives, Scenarios and Strategies for 2050' |
| Institute of Mechanical Engineers | 2009 | 'UK 2050 Energy Plan: Making our commitment a reality' |
| IPPR, WWF & RSPB | 2007 | 'Delivering the 80% challenge' and 'Policies for a low carbon energy system' |
| McKinsey | 2009 | 'Pathways to a Low-Carbon Economy' |
| National Grid | 2009 | 2050 Network capacity modelling and 'Gone Green Scenario' |
| Ofgem | 2008 & 09 | 'Long-term Electricity Network Scenarios (LENS)' & 'Project Discovery' |
| Shell | 2008 | Shell 'Global Energy Scenarios' and UK specific modelling work |
| Scottish and Southern Energy | Ongoing | Ongoing commercial studies |
| UKERC | 2009 | 'Energy 2050' |

*Table 2.2: Scenarios studied for meta-analysis*

[4] Mander SL, Bows A, Anderson KL, Shackley S, Agnolucci P, Ekins P (2008) '*The Tyndall decarbonisation scenarios - Part 1: Development of a backcasting methodology with stakeholder participation*', Energy Policy, 36, 3754-3763. Available from **http://dx.doi.org/10.1016/j.enpol.2008.06.003**

[5] Hughes N (2009), '*A Historical Overview of Strategic Scenario Planning, and Lessons for Undertaking Low Carbon Energy Policy*', A joint working paper of the E.ON/EPSRC Transition Pathways Project (Working Paper 1) and UKERC; and Hughes N, Mers J, Strachan N (2009) '*Review and Analysis of UK and International Low Carbon Energy Scenarios*'. A joint working paper of the E.ON/EPSRC Transition Pathways Project (Working Paper 2) and UKERC. Available from **www.lowcarbonpathways.org.uk**

## 2.4 Themes and findings from the scenario meta-analysis

This section presents the high level meta-analysis of this scenario review, identifying the areas of consensus and diversity across scenarios and models. It also highlights some of the critical decision or divergence points in the timeline to 2050 and exposes key risks and dependencies with a particular emphasis on technology innovation milestones. The meta-analysis provides conclusions against demand reduction and efficiency, power generation, flexibility and control, heat supply and transport.

### 2.4.1 Energy demand reduction and energy efficiency

Across all scenarios there was agreement that energy conservation was a key enabler in meeting the 80% target. Final energy demand from end users must stabilise, and preferably reduce, with the majority of scenarios suggesting a reduction of between 30% and 50% on current levels. Table 2.3 gives an indication of the range seen from the sample scenarios. Many of the scenarios made strong assumptions about the capacity for behavioural change to bring about the necessary demand reductions. Shell's Blueprint scenario saw public engagement with developing the energy system as vital to delivering the behavioural change and new technologies needed to reduce demand. However, there was a paucity of data to support these assumptions and demonstrate how consumer behaviour will change and how they may respond to, and use, new technologies.

There was also a general presumption that demand would be reduced without a corresponding reduction in energy service delivered. The role of energy efficiency across the board was essential, the range of efficiency assumptions varied with each scenario but the reliance on incremental improvements to deliver the same standard of energy service for less was consistent.

However, there was divergence and uncertainty around whether these levels of demand reduction are actually achievable. Although all scenarios recognised that it was necessary, some models, particularly those with a forecasting approach, concluded that this level of demand reduction was not a feasible outcome, either because there are not suitable demand side technologies to make the reduction, or, because the behavioural element of technology use would lower the performance efficiency of end-use technologies.

Achieving the required demand reduction may also be constrained by the rebound effect whereby financial savings from using less energy are used to increase the demand for the service. For example, more insulated housing may reduce heating costs leading to the consumer having the heating on for longer. Alternatively the user may choose to spend the savings on activities in another energy sector, which could be more energy intensive, potentially countering any reduction in demand completely. Work by UKERC suggested that these impacts may be only about 10-30% depending on the sector.[6] The models made some compensation for these effects. However, a lack of data makes modelling these effects difficult, particularly across energy sectors.

### 2.4.2 Power generation and power system control

There was consensus on the need for rapid decarbonisation of power generation and some increase in electricity demand (Table 2.4). However, there was a divergence on the extent of this increase (Table 2.5) with the range varying from 10% to well above 100% increase in demand.

| | |
|---|---|
| **UKERC** Carbon Ambition | Final energy demand reduced 30% by 2050; transport: Energy service demands stays constant though significant fall in actual energy demand. |
| **Committee on Climate Change** | Demand reduction: 40% by 2050. |
| **MacKay** Plan C | Energy consumption down 30-50%. |
| **National Grid** Gone Green | Reduces (non transport related) electricity use by 30% and heat by 20%. |
| **Shell** Blueprint | US and EU using average 33% less energy per capita in 2055. |
| **CAT** Zero Carbon Britain | Total energy reduction >50% by 2027. |

*Table 2.3: Scenario examples on energy demand reduction levels*

| | |
|---|---|
| **Committee on Climate Change** | Carbon emissions from power to drop to <70 $gCO_2$/kWh by 2030 (from current ~430 $gCO_2$/kWh). |
| **UKERC** Carbon Ambition | $CO_2$ emissions from power sector reduced by 93% (to 22 $MtCO_2$) in 2050 compared to Base Case scenario (240 $MtCO_2$, 2000 emissions 181 $MtCO_2$), largely achieved by 2035. |
| **IPPR** | Both the MARKAL-MACRO and Anderson models decarbonise electricity to less than 10% of 2000 levels by 2030. |
| **Ofgem** | Carbon intensity in 2025 reached about 200 $gCO_2$/kWh (between 60 and 80 $MtCO_2$ emitted from generation) in both scenarios from the current 475 $gCO_2$/kWh. |
| **Shell** Blueprint | 60% of power to come from zero carbon renewables, 90% of remaining fossil fuel generation to be fitted with CCS in the developed world by 2050. |

*Table 2.4: Scenario examples on decarbonisation of power generation*

| | |
|---|---|
| **UKERC** Carbon Ambition | Little change by 2035, then >50% increase on current levels by 2050. |
| **Ofgem** | Increases to 372 TWh and 355 TWh by 2025 under *Green Transitions and Green Stimulus scenarios* respectively, from the current 342 TWh. |
| **IPPR** | No increase in demand until 2030, then reaches 530 TWh by 2050. |
| **MacKay** Plan C | Near doubling of demand for electricity with almost all energy for heat and transport supplied by electricity. |
| **Shell** Blueprint | Worldwide electricity consumption increases four-fold. |

*Table 2.5: Scenario examples on increase in electricity demand*

| | |
|---|---|
| **MARKAL-MED** based scenarios | <6% renewables (other than wind) deployed in 2050. Limited role for distributed generation (too expensive). |
| **IMechE** Roadmap & MacKay Plan C | Role for concentrated solar power imports (from North Africa) and energy from waste. |
| **National Grid** Gone green scenario | 15 GW of embedded generation on the system by 2020, 7 GW combine heat and power, 8 GW renewables (wind, tidal, biomass and solar). |
| **CAT** Zero Carbon Britain | Electricity generation from: ~50% wind + 30% marine. Heat: 38% from biomass and combined heat and power from hydrogen. |

*Table 2.6: Scenario examples on other generation technologies*

Scenarios were in agreement on the main components of the power system in 2050, with centralised provision from nuclear, wind, fossil (mostly coal) with CCS taking a lead role, but there were variations in proportion of each major technology.[7] The focus on centralised provision of low-carbon generation could in some part reflect an unintended bias in the scenarios towards large-scale centralised technologies.

There was no consensus on the role for other low carbon generation technologies such as tidal, wave, energy from waste, bioenergy, solar photo-voltaic (PV) and concentrated solar power (CSP) (Table 2.6). Most studies picked out a small role for a wide range of other technologies but there were no obvious patterns in these conclusions.

[6] UKERC (2007) '*The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*'. Available from **www.ukerc.ac.uk/support/tiki-index.php?page=ReboundEffect**.

[7] With the exception of those scenarios that excluded certain technologies on the grounds of political or sociological feasibility.

The future system was found to be more susceptible to intermittency in generation than at present through high penetration of on- and offshore wind. There was also some concern that the flexibility of the system may be curtailed by high penetration of nuclear generation and fossil generation fitted with CCS. Scenarios did not agree on how system control would evolve to resolve these issues (see Table 2.7). A range of solutions were deployed by the models, from flexible conventional generation (e.g. gas turbines, both abated and unabated), to flexible demand (driven by smart metering, electrification of heating and transport and smart grid technologies), interconnection to mainland Europe and large-scale storage solutions (pumped storage, large-scale battery technology etc.).

Forecasting studies cited gas as primary source of system flexibility, particularly in the short to medium term (out to 2030), although this was often coupled with failing to achieve the full 80% $CO_2$ reductions by 2050.

Backcasting studies showed more of a role for interconnection and storage (e.g. pumped storage). The involvement of the demand side in treating flexibility was dependent on the electrification of heat and transport and assumptions around behaviour change and end-use technology capabilities (e.g. to enable vehicle to grid interaction).

There was general consensus that intelligent system operation was required to deliver future system operation. This was highlighted by many as beginning with the roll-out of smart meters to domestic customers by 2020 (or earlier). Beyond this, there was divergence on the extent of functionality of smart grid operation which depended in part on decarbonisation of the power supply and uptake of interactive end use technologies.

### 2.4.3 Road transport[8]

In the studies analysed, efficiency gains in conventional vehicles and hybrids drove the bulk of emissions reductions in road transport up to 2020/2025.[9] Post-2025 there was a diversity of fuels playing a role in both passenger and freight transport (Table 2.8). Nevertheless, the table also shows there was a significant role for electric drivetrain vehicles with some scenarios seeing electric vehicles dominating after 2025.

| | |
|---|---|
| **CBI** Balanced Scenario | Flexible conventional generation provides the bulk of system flexibility along with responsive demand (enabled through smart metering). |
| **MacKay** Plan C | 10 GW new pumped hydro storage (five 2 GW units with 40 GWh) and 19 GW interconnection with Europe, Scandinavia and Iceland. |
| **National Grid** 2050 Model | Decentralised fuel switching (gas and electric) at domestic level to allow use of gas to service electricity peak periods. |

*Table 2.7: Scenario examples on system control solutions*

| | |
|---|---|
| **UKERC** Carbon Ambition | Decarbonisation by plug-in hybrid electric vehicles then biofuels, with some use of hydrogen in heavy goods vehicles.[10] |
| **CAT** Zero Carbon Britain | 100% electric vehicles by 2027. |
| **IMechE** Roadmap | Majority of the vehicle fleet high efficiency electric by 2030, with the residual serviced by biofuels. |
| **MacKay** Plan C | 1.5 million new electric vehicles per year (initially plug-in hybrids, then all electric), each drawing an average power of 8kWh per day. |
| **Shell** Blueprint | >1/3rd passenger kilometres worldwide using electric transport. |
| **IPPR** 2050 Vision | '2nd generation' synthetic biodiesel provides 70% of energy requirement in small vehicle transport. Heavy goods vehicle fleet converts to hydrogen (from electrolysis with zero carbon electricity) by 2030. Rail switches from diesel to electricity. |
| **Energy Savings Trust** Emission Impossible | By 2050, vehicles are powered by various carbon free sources such as electric batteries and hydrogen fuel cells reducing emissions in domestic vehicle by up to 90% (depending on the availability of low-carbon electricity). |

*Table 2.8: Scenario examples on diversity in transport fuel scenarios*

[8] Development in the aviation and marine sectors were not included because these sectors were, in general, not considered in the scenarios that were selected for this meta-analysis.
[9] Findings from a study by AEA for the Department for Transport, which considered whole energy system and other transport specific scenarios to 2050, have also been incorporated into our analysis. A report is due to be published on the DfT website in the first half of 2010.



There was a high level of uncertainty on the development of the transport system driven by a number of factors:

- Technology limitations: Assumptions around the efficiency improvements (or lack of them) for electric, biofuel and fuel cell vehicles drove scenarios down various alternative paths. For example, some cited a technology ceiling on battery technology that would favour a biofuel future. Conversely, others highlighted concerns that co-called 2nd and 3rd generation biofuels would not emerge as a viable fuel for electric vehicles.[11]
- Role of bioenergy: This was still quite unclear across the energy system with some scenarios seeing a strong role for biofuels in the post 2025 system. But again, this was highly dependent on assumptions around availability of biofuels and conflicting demands between modes of transport, from other energy services and from non-energy sectors.
- Delivery of infrastructure change: Assumptions around the feasibility and cost of infrastructure evolution also drove the interplay between biofuel, hydrogen and electric transport futures. With the former being better aligned to the existing infrastructure for liquid hydrocarbon and the latter involving more fundamental changes and technology developments (e.g. in battery fast charging, or battery exchange infrastructure etc).

In overview, there was a general shift toward the large-scale electrification of transport (particularly domestic transport) after 2025. Though this may represent a positive shift driven by technology maturity, there is a case to be mildly cautious about this enthusiasm which has been seen for both biofuels and hydrogen in recent decades but which has now waned. There is a limited role for hydrogen in transport but this is not seen to any great extent in the whole system models that we have explored.

A limitation of many of the scenarios studied is that the modelling approaches used are not well adapted for representation or costing of infrastructure developments. So comparison of alternative transport options is limited to end-use technology.

### 2.4.4 Heat supply

Across scenarios there is some diversity in the energy sources used for provision of heat but with a slight shift towards electrification away from gas-based heating. There is a general theme of heat supply being provided by multiple technologies (electric heat pumps, gas domestic-scale CHP, biomethane, district heating), so moving away from a single dominant technology (gas central heating) that we see today (see Table 2.9)

The role of responsive demand (particularly use of low-grade heat as a storage device through heat pumps and domestic heat storage) in providing power system balancing services was a recurring feature of the scenarios. However, there was variation in assumptions regarding responsiveness of end-users (caused by both technical and/or behavioural limitations). Some scenarios, with pessimistic views on technology flexibility and consumer uptake and behaviour, questioned the capacity of power system to accommodate additional electricity demand which may end up adding to control problems rather than assisting with them. In these studies, uptake of electric heating technologies was limited and a future of mixed heating supply solutions was favoured.

There was considerable uncertainty around deployment and acceptability of new (or alternative) heating technologies. Many of the solutions suggested would require a change in the way that domestic dwellings receive heat services, others require a completely different approach to installation that may not be compatible with retrofit into existing homes and many are susceptible to less than optimal running efficiencies through user behaviour..

| | |
|---|---|
| **UKERC** Carbon Ambition | Replaces gas boilers with heat pumps from 2035, which account for >20% electricity demand by 2050. |
| **MacKay** Plan C | 1 million heat pumps installed per year for 33 years. |
| **Commercial studies** | 2 – 3 million microgen units installed by 2020 is achievable with plausible technologies in place (this is from the Element Energy report but also reflected in Ceres power). |
| **National Grid** 2050 Model | Maintain importance of keeping an electric/gas hybrid heating system capable of using gas to supply peak demand. Assume that electric heating will contribute to increasing system peak beyond feasible limits. |

*Table 2.9: Scenario examples on diversity in domestic heating technologies*

[10] By cost-optimizing, MARKAL tends to over-estimate the deployment of nominally cost-effective energy efficiency technologies. For transport this can fail to illustrate the gradual turnover of vehicles.
[11] A variety of definitions are used for the generations of biofuel technologies. Here it refers to 1st generation biofuels based on food crops; 2nd generation use non-food crop feedstocks and 3rd generation uses advanced processes, such as a single reactor or micro-organism to convert the feedstock directly to fuel or hydrocarbon product.

## 2.5 Technologies for further study

The meta-analysis of scenarios raises a number of system milestones and decision points that will be impacted by technology innovation. We have separated these issues into four technology families; electricity generation, enabling technologies, road transport and the built environment. These are explored briefly below and key technologies highlighted for further treatment in the technology analysis chapter where the technology status on the innovation chain is established along with likely developments and capabilities out to 2050.

### 2.5.1 Electricity generation

The meta-analysis showed a consensus on the significant role for wind (on- and offshore), fossil generation fitted with CCS and nuclear generation. However, there is some uncertainty on the capacity required of each of these components, driven in part by uncertainty over the level of power demand but also by the readiness of technologies for full scale deployment. The uncertainty in the size and composition of the power system impacts investment decisions on supporting infrastructure and on system control tools. According to inputs from the scenarios studied, the capacity of the power system could vary by a factor of two or more. Further analysis on the likely contribution of innovation to bringing technologies on line will assist in pin-pointing critical decision points that will direct the system down alternative paths.

Innovation is important in driving the proportions of each generating technology and total capacity of the system. It is focused primarily on CCS (and the success of technology development and full-scale demonstration), offshore wind (and the success of large-scale demonstration and deployment) as well as the scope and capabilities of enabling technologies (addressed in Section 2.5.2). Applied R&D to improve the efficiency of the existing conventional power generation is a significant factor in meeting short term goals but developing high-efficiency power plants (such as ultra-supercritical boilers which operate at temperatures >700°C) will be important to the success of CCS. The role of early stage innovation in marine technologies and fourth generation nuclear fission technology is noted by some and expected to have impact beyond medium term.

*Section 3.1 provides further analysis on each of these electricity generation technologies: CCS, nuclear fission, on and offshore wind, wave and tidal generation and improved efficiency for conventional generation.*

### 2.5.2 Enabling technologies

As outlined in the previous section, the capacity and composition of the power system in 2050 will be dependent in part on the nature and capabilities of various enabling technologies. The extent to which smart system operation and demand response can be integrated into the energy system will dictate how much additional flexible generation capacity is needed to balance out large amounts of inflexible (and/or intermittent) generation.

From the meta-analysis, the scenarios studied show that the size of the power system in 2050 is highly dependent on the role that demand will be able to take in helping to manage fluctuations in supply. The ability of network operators to adopt more active management approaches to system operation and call on all system users (both generation and demand) in a 'smart grid' approach is also important. However, for those scenarios that place less emphasis on distributed users providing system flexibility, the availability of affordable large-scale energy storage is essential.

The role of innovation in delivering these technologies ranges across the innovation chain. For smart grid operation there may be some development challenges taking existing technologies used in other sectors to apply to power system control and coordination. Whereas for large-scale energy storage, beyond the established options of pumped hydro and compressed air energy storage, the challenge of finding a cheaper alternative is currently at the fundamental R&D stage. All of this is also dependent on innovation in the built environment sector, with the roll-out and effective use of smart meters an essential component of any smart grid operation strategy (smart meters are covered in Section 2.5.4 Built environment).

*Section 3.2 provides further analysis on both of these power system operation enabling technologies: large-scale energy storage, and smart grid operation.*

### 2.5.3 Road transport

Many of the scenarios covered a wide range of road transport technologies, with the period 2020 - 2025 appearing as a critical time for advancement down various pathways (all electric, biofuels, hybrid, hydrogen). With such uncertainty in the medium term, the role of innovation in the short term across a range of technologies will be critical in providing clarity on the implications of following one path over another and on the 'no regrets' infrastructure decisions that can be taken in the short term.

*Section 3.3 provides further analysis on a range of road transport technologies: Plug-in hybrid electric vehicles (PHEV)/electric vehicles (EV), fuel cell vehicles, and biofuels.*

### 2.5.4 Built environment

The built environment covers end-user technologies; the primary technologies of interest are those providing heat services and insulation to the domestic sector. As highlighted earlier, there is some uncertainty around the dominant technology in the provision of heat. Scenarios are split on the role of electrical or gas-based heating, with innovation being one of the major drivers in directing the split. Both technologies are at a similar stage in the innovation chain with commercially available and proven technologies. However, questions remain over how each will perform in a whole system context with assumptions on what innovation will deliver being the primary driver for this decision point. There is very little data cited in the scenarios analysed on the performance of these technologies in large-scale demonstrations; in particular how consumers will interact with their devices and the wider system – a vitally important factor if the demand side is to be able to provide a system balancing resource through, for example, storage of low grade heat.

The widespread deployment of smart meters to allow consumers to participate in system operation in real time is widely cited as a key enabling factor that will influence the role of heating technologies at a domestic scale. For smart metering the initial challenge lies in large-scale demonstration to explore how end-users will operate with this new technology. Further development is also needed to ensure interactivity with household appliances and the network operator. In the short to medium term, large-scale deployment is also vital with many scenarios citing full roll-out of smart meters by 2020 as an essential component of the pathway to 2050.

The need for dramatic demand reduction is a common theme across all scenarios. Detail on delivery of the demand reduction is limited but there is a heavy reliance on the efficacy of energy efficiency through retrofit of measures such as insulation. The challenge here is both in deployment and also in R&D for next generation insulation materials that will facilitate achievement of the more stringent emissions reductions.

*Section 3.4 provides further analysis on each of these technologies used in the built environment: domestic scale CHP, heat pumps, insulation and smart meters.*

# 3 Technology analysis

Our aim was to focus on technologies which could be newly deployed in the UK to deliver significant carbon emission reductions (as set out in Appendix 4) and which would have wider implications for the energy system. We were guided by the conclusions of our meta-analysis of scenarios and an appreciation of current thinking which emerged at the workshop. Table 3.1 lists the technologies studied in more detail.

Areas where 'competing' technologies could have profoundly different impacts, and where there *may* be a case for favouring one or another technology at some time in the future, have been of particular interest. 'Critical decision points' are unlikely to be as easily placed as the phrase suggests, now or even at the time, and will, undoubtedly, be *periods* in time. However, thinking in these terms can help kick-start some activities that will improve our understanding of the consequences of deploying a technology when decisions are taken.

Each section of this chapter begins with a set of high-level innovation timelines to give an indication of how technologies will develop towards deployment (using the definitions we set out in Section 1.1). The critical decision points are marked and arrows show potential impact on, or from, other technology areas. The summary analysis sets out the scale of deployment required for each key technology, the status of innovation and technology road-mapping, and any likely dependencies that will influence the rate of innovation.

Our information has come from the assumptions, techniques and outputs of the scenarios considered in Chapter 2 and more technology-specific roadmaps or analyses (which are referenced in each section). As with the scenarios analysis we describe commonalities, differences and uncertainties, and try to reach conclusions that we hope will be shared by the energy community. The sections below are summaries of the more detailed 'Technology Innovation Analyses' which will be published separately.

| |
|---|
| **Electricity generation** |
| • Carbon Capture and Storage (CCS) |
| • Nuclear |
| • Wind |
| • Marine |
| **Enabling technologies** |
| • Energy storage |
| • Smart grid operation |
| • Next generation networks |
| **Road transport** |
| • Electric/plug-in hybrid vehicles |
| • Fuel cell vehicles |
| • Biofuels |
| **Built environment** |
| • Heating technologies, heat pumps and domestic CHP |
| • Insulation |
| • Smart meters |

*Table 3.1: Areas and key technologies studied in the analysis*

## 3.1 Electricity generation

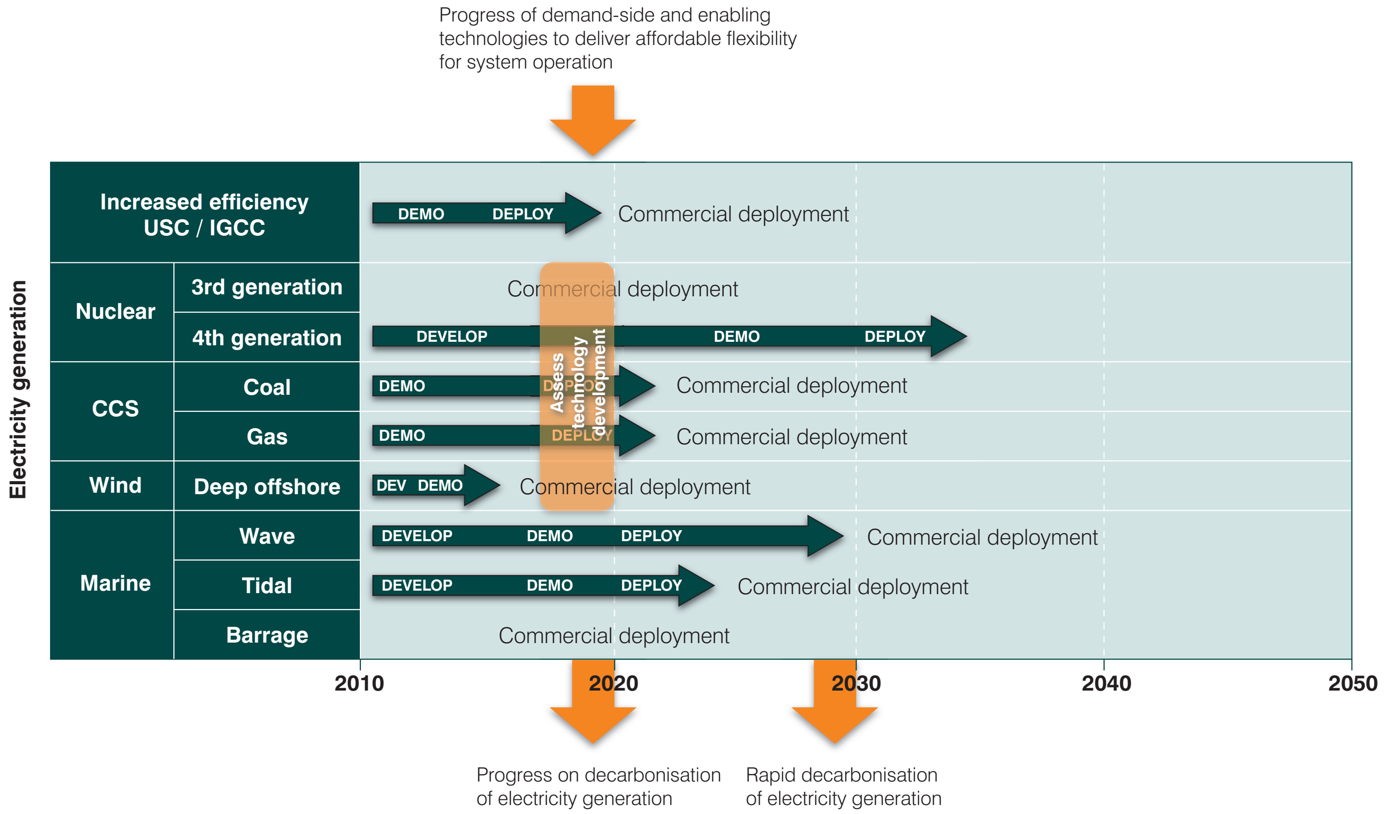


*Figure 3.1: Innovation timeline for electricity generation technologies*

### 3.1.1 Scale of deployment

Decarbonisation of electricity generation is regarded as one of the key milestones in achieving the 2050 emission reduction targets. This will enable other energy sectors to switch to electricity to reduce their emissions. It is unlikely that one technology will dominate the final generation mix. However, the main technologies that are expected to contribute to electricity generation to 2050 face significant challenges to bring down their costs and realise their potential.

Of all the various generation technologies available, three technologies are regarded as the most significant: CCS on fossil fuels, nuclear and wind, primarily offshore. They are all likely to be able to supply significant quantities of power so are generally treated as interchangeable. However, only fossil fuels with CCS and nuclear can reliably provide base load power. A greater proportion of wind on the system will require a more flexible energy system to respond to the intermittency and variability in supply.

A number of other low or zero carbon technologies, such as marine, solar photovoltaic, anaerobic digestion and various micro-generation technologies, are likely to contribute to the energy supply. Apart from a couple of studies that indicate solar playing a significant role in the UK[12] , the scenarios tend to see these technologies as only making a limited contribution, mainly because they regard them as too expensive or with limits to how much can be deployed. For example, the UK has some of the most significant potential marine power resources in the world, yet most scenarios regard tidal stream, barrage and wave as too expensive and only able to exploit a fraction of the potential. Similarly, the returns on investment for distributed generation, e.g. solar PV, micro wind, are regarded as too low for them to make much impact on supply. Their deployment could be much greater if breakthroughs in these technologies reduce their costs or allow them to exploit more opportunities. However, these may not be captured by the models as the technology, such as 3rd generation PV, are often still in the R&D stage.

The proportion of the three main technologies, CCS, nuclear and wind, in the scenarios is determined by inherent and external factors. Inherent elements include the cost of each technology and its ability to compete with the other technologies, the emission reduction potential and the rate of development. External factors are mainly cost of primary fuel, particularly gas,

[12] Solar PV in ongoing analysis by McKinsey, KEMA and European Climate Foundation, and CSP in MacKay's Plan C.

the long term emission targets and government support and policy intervention.

With little previous international experience of deploying 3rd generation nuclear, deep offshore wind and CCS, the greatest uncertainty comes from the cost of their deployment. With almost all the current nuclear and coal fired power stations closing by 2030, the three main technology areas will all require a new build programme. This uncertainty about the scale of deployment is increased further by assumptions about future fuel prices, primarily gas, with additional concerns over security of their supply. Uncertainty around the global availability of gas and where it comes from has led to a range of future prices being used. Indeed, technological advances may make new sources available including in the UK. One scenario by the IPPR sees less of a risk to gas supplies and therefore does not see prices rising significantly. As a result its scenario relies very little on coal, preferring to use gas with CCS.

Short-term and long-term targets have a significant impact on the mix of technologies going out to 2050. Of greatest concern are the residual emissions from CCS. From UKERC's modelling, emission reductions of 32% in 2020 and 80% in 2050 are achieved by 30-38 GW coal CCS in 2035 and 31-43 GW by 2050. In this instance, there is little gas CCS but about 26 GW of unabated gas is installed to provide system balancing although the total supply is low. Higher reduction targets see gas CCS, with its lower emissions, replacing coal CCS although recent proposals suggest that co-firing coal with biomass would reduce the emissions or even deliver negative emissions.

Some scenarios consider the implications of limits on the deployment of either nuclear or CCS, either through political intervention or, in the case of CCS, the technology not being able to deliver as expected. AEA considered the absence of CCS[13] , which leads to nuclear providing a substantial part of the electricity supply, but with wind delivering more, earlier as it is able to deploy quicker. Although the electricity sector is fully decarbonised in 2050, it also sees changes in the wider energy system, seeing more gas use particularly in the residential sector and less demand for electricity.

How the electricity system is managed will change as more inflexible, base load power plant is added alongside more intermittent generation. This presents challenges not only as to how to match the short term changes in demand but also how to fill the longer periods of low supply from wind. A range of options is proposed to deliver this, including greater demand management, where demand can be controlled to match supply, rather than supply match demand. Storage technologies may also play a role either to fill the gaps or to absorb the surpluses. Developments could make CCS and nuclear more flexible but some scenarios keep a large capacity of unabated flexible gas power on the system as back up although its emissions are kept low as it is used for only short periods.

In nearly all the scenarios a significant amount of demand reduction is included. Few consider the implications of not achieving this scale of demand reduction but those that do raise concerns about achieving the scale of deployment, nuclear, wind and CCS, in terms of skills and manufacturing requirement and sites to deploy them. In addition, such a system would have little flexibility and would require either unabated gas or significant grid storage with consequences for cost and emissions.

### 3.1.2 Technology options

**Carbon Capture and Storage**

The primary RD&D issue for CCS is early demonstration. This is essential to understand the technology and to bring down the costs if it is to play a role alongside nuclear and wind. Various options have been proposed for the scale of the demonstration phase but all agree that, by 2020, the technology should be proven at a commercial scale and should be economically competitive or requiring only small further subsidy. Whether this can be done sufficiently early for CCS to be deployed at the scale indicated by some scenarios is uncertain. Recent work by Pöyry[14] suggested that achieving 20 GW of CCS by 2030 would be ambitious and would require a build rate of 2.5 GW per year between 2020 and 2030. This would make achieving the 30–38 GW by 2035, indicated by the UKERC early action scenario, difficult. The Advanced Power Generation Technology Forum (APGTF) advise that 5 GW of capacity needs to be demonstrated by 2020 although the current UK demonstration programme would see only one third of that being available.

In addition to the development of the power plant and capture technology, a number of other activities need to take place in parallel in order to avoid delaying deployment. Research is already underway to assess the UK's potential storage capacity. Detailed characterisation of suitable sites is needed in time to support the demonstration projects. An on- and offshore transport network will need to be implemented with R&D required to support the development of regulations to enable its deployment. During the development of these technologies, the public will need to be engaged so as to understand and address their concerns about this new technology.

Demonstration of gas with CCS is seen as important to enable early abatement of emissions from new gas fired power stations, and most roadmaps put it in the same timeframe as coal demonstration. Similarly, demonstration projects are required for industrial emissions and their integration into the transport network. Efficiency improvements and fuel switching can reduce industrial combustion emissions but CCS is likely to play an important role.

Research and development into technologies for capturing $CO_2$, such as chemical looping and new solvents, could significantly improve the efficiency of the capture process and therefore reduce the cost of CCS. Some of these could be deployed in CCS plant in the 2020s.

Using biomass to reduce the emissions will also require RD&D to integrate it into the combustion or gasification processes and to understand its impact on the furnaces and the capture processes.

The potential for decoupling the carbon capture and transport/storage processes could also improve flexibility of CCS. For example, amine storage could provide a demand response resource to help even out peaks and reduce the impact of CCS on requirements for system flexibility.

**Conventional efficiency**

Efficiency improvements on their own will deliver some reductions in emissions and are also driven by commercial benefits in the power sector with similar improvements occurring in the industrial sector. The development of CCS, which will reduce the overall efficiency of the plant, adds an additional demand to improve performance. Improvements in efficiency therefore need to be in parallel to CCS and designs need to be optimized for capture.

At present the best super-critical coal fired power station delivers about 45% efficiency. The next major advance is ultra-supercritical boilers, working at 700°C with >50% efficiency. These require developments in materials that can withstand the higher pressures and reduce corrosion. Adding CCS plant will reduce the overall efficiency to >45% but will need to be designed for use with CCS so as to optimize the whole system. The APGTF recommend that an ultra-supercritical coal powered plant be operational by 2016.[15]

An alternative process that will improve efficiency is the development of the integrated gasification combined cycle plant (IGCC). Using coal, gas or even biomass, the fuel is gasified into hydrogen and carbon monoxide. The hydrogen is then used to drive the turbine and the carbon monoxide converted to $CO_2$ for capture. It currently provides efficiencies of about 40% but is expected to be able to deliver 50%. However, it faces challenges in reducing its costs as well as its reliability.

**Nuclear**

The immediate need for nuclear is the deployment of a new fleet of third generation technology to replace the existing capacity. While a relatively new technology, it is expected that the problems being faced by the first of its kind that are currently being built in Finland and France will have been resolved. The first new plant could be operational by 2018 with the potential for 2 GW of new plant being built per year up to 2024. Delivering at this rate will require investment in manufacturing capacity along with the continued development of the necessary skills.

Few scenarios distinguish between Generation III and IV reactor technologies. However, the role of nuclear could be significant, particularly in the high emission reduction scenarios. Deployment of nuclear in these scenarios continues after 2030 when Generation IV could be available. Investment in RD&D will be required to bring forward the possible deployment of the technology in the UK.

**Wind**

Scenarios suggest that wind deployment, both on- and offshore, could range from 18–100 GW by 2050; the broad spectrum reflecting a certain level of uncertainty in the proportions of the major generation technologies to be deployed. Onshore wind technology is deemed to be broadly competitive with conventional generation; further deployment is limited, primarily by planning issues and, secondly, by availability of areas with sufficient wind resource to allow reasonable load factors.

Offshore wind faces more uncertainty with much of the deployment using modified onshore technology. Contracts to build up to 32 GW of offshore generation were agreed as part of the 'round three' allocations announced in January 2010. However technology challenges still remain, particularly for turbines going out into deep water, to improve reliability and for the high voltage DC (HVDC) networks that will connect these resources back to shore. Industry innovation programmes (primarily by equipment manufacturers and some energy utilities) are dealing with many of these challenges, particularly those dealing with R&D requirements that feedback from demonstration and deployment challenges. Investment from other sources such as the Energy Technologies Institute (in collaboration with the Carbon Trust), is also expected to have some impact, providing funding support for development and pilot project demonstration of new platform technologies and novel turbine design.

Beyond technical innovation challenges, the Committee on Climate Change have commented on potentially low learning rates in offshore wind development out to 2050; citing the possibility of global supply bottlenecks as many countries implement ambitious offshore build programmes. This has the knock on effect of causing supply shortages and pushing up offshore wind generation technology costs.

**Marine**

A wide range of wave and tidal stream technologies has been developed in the UK. Several are being deployed in increasing size and numbers but very few are proven commercially, particularly wave technologies. The main challenges are designing technologies and developing materials that can survive in the harsh environment as well as developing technologies to install them. Access to distribution and transmission network is also an issue as these are likely to need upgrading if the best marine resources are to be exploited. This is particularly significant off north-west Scotland, where most of the wave resource is, but it currently has limited grid capacity. Significant investment is required to develop and demonstrate the technologies in the harsh environment. Current programmes run by the TSB and the Marine Renewables Deployment Fund are focussed on deploying 2–3 GW of devices by 2020 with the aim of the technology being commercially competitive by 2020. Some wave technologies are predicting to be commercially deployable between 2015 and 2020. Research into new materials and designs and development in dedicated test facilities are likely to reduce costs. Collaboration with other

[13] AEA Energy & Environment (2008), '*MARKAL-MED model runs of long term carbon reduction targets*'.
[14] Pöyry (2009) Report for Committee on Climate Change: '*CCS, Milestones to deliver large-scale deployment by 2030 in the UK*'.
[15] APGTF (2009) '*Cleaner Fossil Power Generation in the 21st Century*'. Available from **www.apgtf-uk.com**

marine sectors, such as offshore oil and gas, could also reduce the risk to investments and prove beneficial to a wider range of marine technologies.

There is a wide range of views on the potential scale of deployment for marine technologies. The Carbon Trust estimates that practical marine energy (excluding barrage) could deliver over 20% of UK's current electricity (about 350 TWh/yr), with offshore wave delivering more than 50 TWh/year. The scenario modelling the National Grid estimate that 2.4 GW of tidal stream and wave could be installed by 2025. Ofgem put a low figure on deployment quoting high costs as a barrier for wave, tidal stream and barrage. Modelling for UKERC (Winskel, 2009) suggests that early investment to develop the technologies will bring forward commercial deployment of marine technologies by 15-20 years and increase capacity in 2050 from about 5 GW to 20 GW.

Black and Veatch (2005) estimated that there was about 12 TWh/yr (about 3 GW installed) of economic tidal stream in the UK with a rough maximum of 18 TWh/yr technically extractable. The opportunities for deploying wave are less clear, although it is possible that the technically available resource may be much larger than tidal stream, potentially supplying 15% of UK electricity from about 19 GW installed (ECI, 2006). However, whether it is feasible for wave power to achieve these figures is doubted and its contribution may be similar to that of tidal stream.

Tidal barrage technologies have already been successfully deployed globally. Various projects have been proposed in the UK; the largest being the Severn Barrage which could supply 5% of the UK's electricity needs. Following a decision to give the project the go-ahead, building could commence in the next 10 years with it coming into operation in the early 2020s.

**Breakthrough technologies**
Investment is still required in R&D into a wide range of potential future energy technologies as these may yield breakthroughs that could have significant impact on the energy system. Modelling may not capture these developments as it can be difficult to put timelines on their development and to forecast costs. Two examples are 3rd generation photovoltaic and fusion.

Two different approaches are being used in 3rd generation PV. The first is dye-sensitized cells which have a lower efficiency but can be produced at very low cost. Their flexibility means they could be applied to a range of applications and some are already emerging on the market. Much further from market is the second group which uses advanced technologies to produce ultra-high efficiency cells. These could lead to a step change in efficiency but, as yet, it is unclear what level they could achieve and how much they will cost.

Nuclear fusion once proven commercially viable could lead to significant changes to the energy supply although as yet it is unclear when this might happen and its deployment is expected to be after 2050.

### 3.1.3 Dependencies

**Flexibility of supply**
At present, the main generation technologies are primarily for base load and provide little in terms of flexibility. Developments may improve their performance but it is not clear if they will be able to fulfil the role that unabated gas and coal currently do. Known flows from tidal technologies could be used to provide some flexibility but this will be limited by coincidence with peak times. Flexibility could be delivered through enabling technologies, such as storage and demand side management controls, which are explored in more detail in the next section. However, several scenarios see unabated gas as remaining on the network to provide the short-term peak supply response. Despite only being drawn on for short periods of the day, conventional gas is still regarded by some as much cheaper than relying wholly on storage or demand management technologies.

**Fuel prices and security of supply**
Uncertainty surrounds future fossil fuel prices and the scale of reserves and what impact this will have on the relative cost of the technologies. On a national scale, consideration is needed on how to deliver a secure supply of energy and what mix of technologies will be necessary, and at what cost.

### 3.1.4 Conclusions

The early demonstration of carbon capture and storage technologies on coal and gas-fired power stations is critical in determining what technologies will be deployed for electricity generation out to 2050. Should CCS prove too expensive, or not able to deliver on the scale required, both wind and nuclear will have to be deployed on a much larger scale, with wind able to be deployed more rapidly at first. However, both wind and nuclear face challenges that are not all technical and which might restrict the scale and rate of their deployment. This may lead to gas-fired power stations being built to meet the electricity demand as it emits less carbon dioxide per unit of electricity produced than unabated coal. This may help keep emissions down in the short to medium term but, in the long term, these power stations will either have to be closed early or be retrofitted with CCS.

Once the real capability of CCS to reduce emissions is established, an assessment can be made about progress towards decarbonisation of electricity generation on which other parts of the energy system are dependent. It should also be noted that by 2020 a clearer picture may be available of the scale of deployment of decentralised generating technologies and progress towards reducing demand, around which there is currently considerable uncertainty.

## 3.2 Enabling technologies

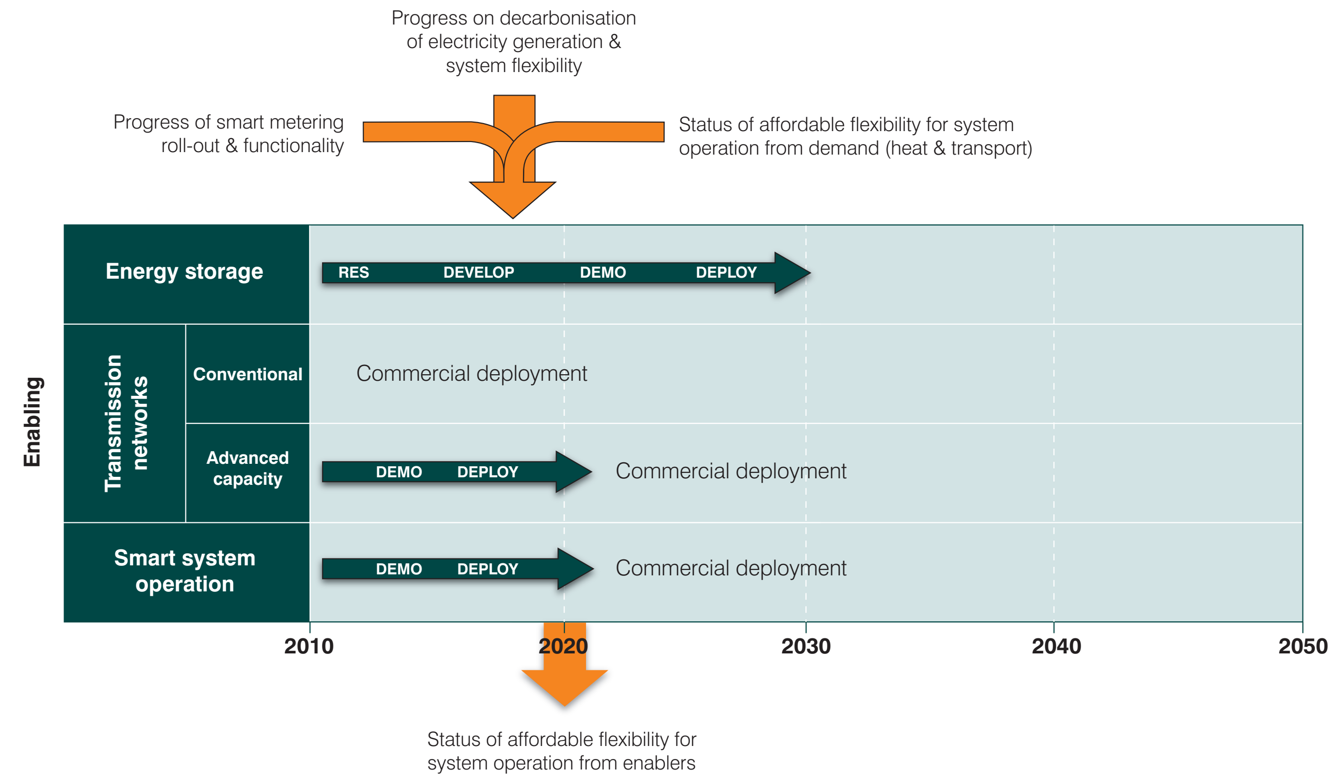


*Figure 3.2: Innovation timeline for enabling technologies*

### 3.2.1 Scale of deployment

The role of enabling technologies[16] in facilitating the low carbon energy system in 2050 was cited in many of the scenarios studied. The primary function of enabling technologies in this context is to facilitate the efficient operation of the power system (and the wider energy system as the energy sector becomes more integrated across power, heat and transport). The value of these technologies comes primarily from provision of reserve to the system operator rather than from the energy markets. Enabling technologies in the case of networks will connect low carbon generation to remote demand and innovation in network materials and components is helping to improve network carrying capacity and optimise operational efficiencies. In the case of energy storage and smart system operation, they will ensure maximum efficiency in balancing intermittent generation and providing access to a range of previously inaccessible resources (primarily demand side) for system operation. If successful, while still maintaining a high penetration of intermittent and inflexible low carbon generation, the net result of this would be a reduced requirement for a large capacity margin (and low load factor flexible generation plant) and optimised network infrastructure investments.

Efficient management of intermittency is the primary challenge for these enabling technologies. The bulk of this is in enabling effective back-up of wind generation, where the most pressing concern lies in covering long periods (several days) of calm weather that extend across large geographic areas. Scenarios show great variation in installed wind capacity from 16 GW (UKERC) to 48 GW (IPPR) and up to 100 GW (MacKay). With an assumed load factor of around 30–35%, this range of installed wind capacity would need between 5–30 GW of back-up cover to be capable of operating to support an outage of several days.

If all this back-up is provided by flexible conventional generation (as explored in the CBI 'Decision Time', business-as-usual scenario), this locks in carbon emitting generation to the medium term future. It also creates a capacity margin of up to 80%, with load factors for some generators dropping well below 20% (National Grid, 2050 modelling analysis), which becomes economically unsustainable. Both storage technologies and smart grid operation have the potential to reduce this capacity margin, either by providing an alternative source of system flexibility (e.g. large-scale energy storage) or by opening up alternative resources that provide an efficient alternative to conventional generation (e.g. smart grids enabling access to demand response and distributed storage options).

[16] In the context of this analysis we have defined 'enabling technologies' as those that facilitate the efficient operation of the future energy system, but that are neither generation nor end-user / demand side technologies. It includes smart grid, transmission network (split into conventional network and new technologies/innovation to improve network capacity) and large-scale, bulk energy storage technologies. Although linked, it does not include distributed, demand side storage technology (e.g. low-grade heat in domestic dwellings), smart metering or smart house technology. These are all addressed in the built environment section of this analysis (Section 3.4).

### 3.2.2 Technology options

**Energy storage**

Energy storage to address intermittency and system balancing can be distributed, i.e. at household scale, or medium to large-scale dedicated bulk storage technologies. Distributed storage is handled in other technology sections through analysis of potential for plug-in electric vehicles and hybrids and the role of heat pumps and low grade heat storage. Scenarios that have cited the use of large-scale bulk storage in the 2050 system tended to base analysis on existing and well proven technologies, such as pumped hydro storage; although most do not cite a role for large-scale storage at all. This partly reflects the high cost of most commercially available storage solutions that exclude it from selection by optimisation type models such as MARKAL. Recent IEA roadmapping analysis in Table 3.2 and Figure 3.3 summarises the capital costs for a range of storage technologies and highlights their potential to contribute to the 2050 system. This provides insight into the commercial availability of technology of sufficient scale and capability to perform the task outlined above.

Beyond the existing proven technologies (pumped hydro and compressed air energy storage (CAES)), further R&D effort is needed in this area to bring on new technologies that are capable of delivering an appropriate service. This is reflected in the technology summary in Figure 3.2 that illustrates large-scale energy storage is unable to play a significant role in the short term but further development could facilitate its contribution in the medium term, 2025–2030.

| Technology | Capital costs ($/kW) | Timescale | Potential |
|---|---|---|---|
| **Pumped Hydro** | 2700–3300 | Minutes to several hours | Technology is close to maturity, costs are unlikely to fall significantly. Output can be maintained for several hours and systems can be GW scale. Potential for sea water pumped hydro technology (~15% cost uplift) could offer new sites. |
| **Compressed Air Energy Storage (CAES)** | 600–1800 (estimate based on small number of sites) | Minutes to several hours | Technology is well established. Costs are very site specific. Most facilities to date around 100s MW scale. Largest (at pilot stage) in USA is 2.7 GW. Output possible over several hours. Technology innovation primarily on efficiency of gas turbine. Primary limitation on deployment is finding suitable sites. |
| **Large-scale heat storage** | variable | Minutes to several hours | Thermal storage losses are favourable (~7% per unit of energy stored). Scale of thermal storage varies with application. Typically CSP plants with storage capability will size to allow a short period of additional operational time after sunset. Aquifer heat storage has also been proposed, using e.g. saline aquifers as large-scale heat storage sites for providing system services. |
| **Vanadium redox** | 7000–8000 | Minutes, potentially hours | Has lower energy density than other battery options, but operates at room temperature and atmospheric pressure. Currently 100s kW to 10s MW scale, larger MW scale presents issues with efficiency of conversion. Output maintained for a few hours if necessary. Commercially available and used in few instances to manage peaking. Expertise in Japan. |
| **Sodium Sulphur (NaS) battery** | 1850–2150 (projected | Minutes, potentially hours | Operating at MW scale in operational networks. Expertise in Japan. |
| **Lithium ion battery** | 4000–5000 | Seconds to minutes and potentially hours | High energy density but larger scale batteries become unstable and less reliable. Ongoing improvements in composition of +ve and –ve electrodes are improving efficiencies. This technology works best at small scale providing kWh scale output. Relies on scarce resources e.g. cobalt. Expertise in Japan and USA. |
| **Flywheel** | 800–2700 | 10s of minutes | Commercially available technology serving the UPS (Uninterruptible Power Supply) market with small-scale (kW) units. Capable of large-scale output, 20MW system (multiple flywheel 'matrix') commercially available in USA. Short discharge time (typically 10's of minutes) limits service it can provide. |
| **Superconducting Magnetic Energy Storage (SMES)** | 380–1970 (depending on size) | Seconds to minutes | Developing technology, small scale units commercially available (100's kW – 10's MW), larger scale in pilot project phase. Has range of applications from frequency regulator to daily load levelling, output from seconds to minutes. Expertise is centred in Japan and USA. |

*Table 3.2: Capital costs and potential for energy storage technologies* [17]

[17] Compiled from IEA working paper, 2009, Prospects for Large Scale Energy Storage for Decarbonised Power Grids.



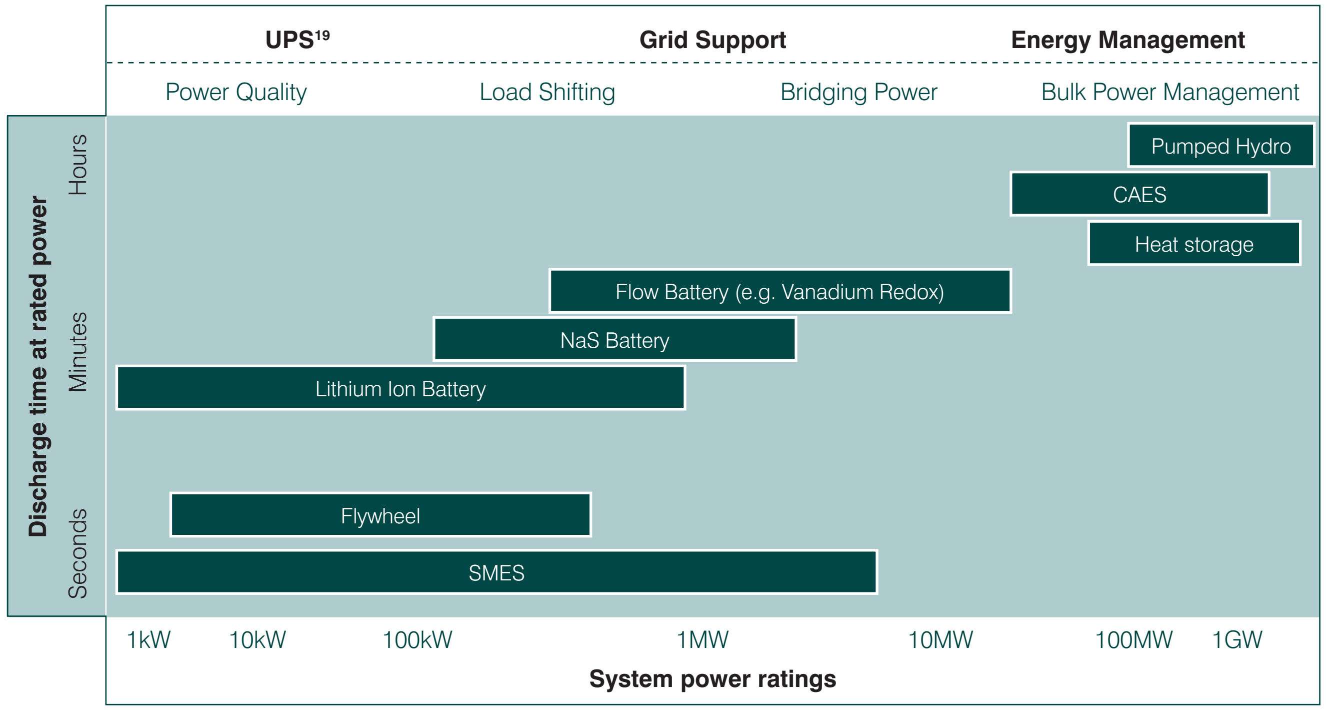


*Figure 3.3: Comparison of storage technologies by typical discharge time, power rating and service type* [18]

**Smart grid operation**

Beyond the requirement for comprehensive national roll-out of smart meters, the technology specifics of smart grid operation are not addressed in the scenarios studied. The concept of smart operation is, however, widely promoted and recognised as a key enabler of efficient integration of electric vehicles and electrified heat demand as well as large proportions of intermittent renewable generation. The recent publication of a smart grid vision for the UK[20] also stated that, while technology is part of delivering smart system operation, other aspects such as market reform and regulation, development of commercial arrangements and legal frameworks and, crucially, consumer behaviour change were also significant contributors. This vision defines smart grids as the following:

*A Smart Grid as part of an electricity power system can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to deliver sustainable, economic and secure electricity supplies efficiently. A Smart Grid employs communications, innovative products and services together with intelligent monitoring and control technologies to:*

*1) Facilitate connection and operation of generators of all sizes and technologies 2) Enable the demand side to play a part in optimising the operation of the system 3) Extend system balancing into distribution and the home 4) Provide consumers with greater information and choice of supply 5) Significantly reduce the environmental impact of the total electricity supply system 6) Deliver required levels of reliability, flexibility, quality and security of supply.*

Much of the technology required for smart grid operation is already commercially available. The challenge here is large-scale demonstration on a geographic and functional level. To illustrate that concepts can be realised, to evaluate how consumers will interact with smart grid functionality and to show that this is possible at scale. Smart grid demonstrations are underway across Europe and the US on varying scales. Through the IFI and RPZ schemes[21], the UK already has a number of localised pilot projects that are demonstrating aspects of smart operation primarily focused on active network management. A capital grant scheme administered by DECC will provide a further £6 million to support smart grid development in 2010/11. In addition, the forthcoming Low Carbon Network Fund, agreed as part of the latest Distribution Network Price Control Review (DPCR5), will open up £500 million of funds to expand on these projects and make the move to larger smart grid demonstrations. Subject to dependencies outlined below, this could precipitate large capital spend in 2020 and beyond that would see large-scale roll-out of the smart grid concept.

**Next generation network technologies**

Although not explored by the scenarios studied in our meta-analysis, network technology innovation is another potential means of efficiently increasing capacity in the system. High Voltage DC networks (HVDC) will connect the significant offshore wind resources back to the UK onshore grid. While HVDC connections are well used for point-to-point interconnection between neighbouring countries, the sub-sea engineering issues and potential for multi terminal DC networks offshore present new challenges for network innovation. Commercial solutions to tackle these problems are under

[18] Source as per Table 3.2.
[19] Uninterruptible Power Supply
[20] Electricity Networks Strategy Group (2009), 'Smart Grid Vision' , available at: **www.ensg.gov.uk/assets/ensg_smart_grid_wg_smart_grid_vision_final_issue_1.pdf**
[21] Innovation Funding Initiative and Registered Power Zones. See **www.ofgem.gov.uk** for further information.

development. However, further effort and investment is needed to complete this R&D and demonstrate these technologies at scale in live (offshore) systems.

Innovations in material science are also contributing to the contribution of networks to the capacity of the system. The development of high-temperature superconductor materials for use in power transmission and distribution has the potential to dramatically reduce losses and contribute to a considerable increase in the capacity of network lines. This technology has greatest application for heavily loaded lines (e.g. in urban settings) where practical considerations make network reinforcement very costly or complex. Demonstration systems showing superconductor materials in niche network applications are already underway in the United States.

### 3.2.3 Dependencies

Network infrastructure investment is highly dependent on the capacity of generation and level of demand that it is designed to support. The addition of energy storage options and smart system operation changes this network capacity calculation. With the addition of smart grid operation to integrate these technologies into system operation, it increases the network capacity available to maintain system security. A commitment to these enabling technologies and associated smart operation can optimise infrastructure spend on both network and flexible generation capacity.

The scope and success of smart grid technology is highly dependent on the engagement of consumers in demand response activities. This will require considerable behavioural change as well as a significant switch to electricity for provision of transport and heating services. Such a switch would provide a significant and controllable resource which smart grid operation could utilise but, as the scenarios have shown, the scale of this transition is not certain.

The roll-out of smart metering has also been highlighted as a significant dependency for the realisation of smart grid operation. Without smart metering, the smart grid is significantly limited in its scope as it cannot provide access to the bulk of demand (or bring demand visibility to the wider system). In addition, the functionality of the smart meters themselves is a significant influence on the ultimate scope of functionality for the smart grid. In general, the more open the architecture of both the smart meter and the smart grid communication system, the more flexible and responsive to technology evolution uncertainties the system can be. Technology choices for smart grids and smart metering that lock-in a certain type of functionality, communication method or user/participant will be far less future proof than those that are as flexible and open as possible. This could come with an increase in costs but it would limit the risk of asset stranding in the future. This also comes with some complications as it implies that both smart grids and smart metering should be an open and shared resource which, in turn, raises issues of ownership and sources of funding for these enablers.

The development of large-scale storage technologies is highly dependent on electricity prices and carbon price. Higher (and more volatile) electricity prices increase the value of arbitrage and improve the business case for all forms of storage.

Although not a technology that requires significant innovation prior to deployment, the role of interconnection to mainland Europe and elsewhere could also play a role in the costs and requirement for other enabling technologies. Further interconnection, like the forthcoming BritNed interconnector with the Netherlands, could ease some of the problems caused by intermittency by allowing flexibility to be imported from elsewhere in Europe. Investment in interconnectors from the UK is currently only done on a merchant basis (i.e. it is not part of the regulated asset base of the transmission system operator). So, at present, interconnection is only considered on a case-by-case commercial basis rather than as part of a system operation solution for the whole GB system. A change to this approach could see investment in more interconnection projects with a knock-on impact for improving system flexibility.

### 3.2.4 Conclusions

Numerous smart grid demonstrations and activities are underway globally but, with the advent of the £500 million Low Carbon Network Fund, the UK could be in a strong position to take innovation in smart grid operation forward. To realise this opportunity, the comprehensive roll-out of smart meters nationwide is essential as is careful planning of the functionality of the meters to ensure that smart grid has maximum flexibility and functionality.

Consumer behaviour and full participation in the smart grid operation is essential for success of this concept. Therefore, large-scale demonstrations are needed in the short-term to demonstrate not only technologies at scale but the way in which end-user behaviour will modify technology performance and smart grid functionality and potential. With data from large-scale demonstrations we should be in a favourable position to evaluate the potential for large-scale roll-out of smart grid operation in 2020. Open architecture for all smart grid technology developments is important to avoid lock-in to a particular energy future and to provide flexibility in the face of uncertainty.

Large-scale storage solutions are likely to have more impact post-2020. R&D advances should be monitored closely, in parallel with evaluation of decarbonisation of the power system and the need for system flexibility, as the value of services from storage technologies will be driven by the corresponding value of system flexibility and reserve services.

## 3.3 Road transport

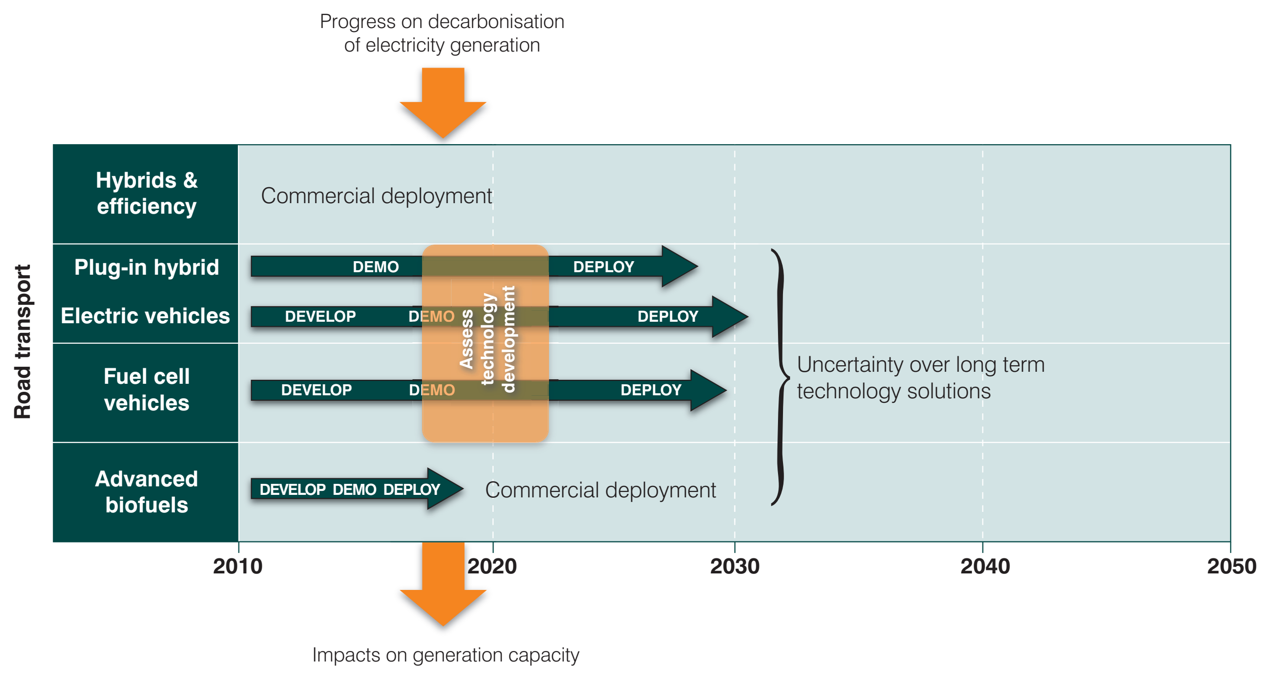


*Figure 3.4: Innovation timeline for road transport technologies*

### 3.3.1 Scale of deployment

Scenarios decarbonise transport to about 20% of current emissions by 2050 to meet the overall 80% target but with some variation on the exact amount and when the decarbonisation takes place. IPPR's MARKAL-MACRO model drops the carbon intensity substantially between 2020 and 2030 to under 20% while their Anderson model is more of an even decline from 2015 to just over 20%. UKERC CAM decarbonises transport by 78%, compared to the base case, but mostly after the power sector is decarbonised – i.e. from 2035.

Many whole energy system scenarios have aggressively adopted new low carbon technologies for road transport at an early stage with large-scale deployment beginning in the early 2020s and improvements to, and increased uptake of, currently available technologies before then. CCC's Extended Ambition scenario sees EV and PHEV combining to make up 12% of medium-sized cars in 2018 and 30% in 2022. IEA's BLUE Map Scenario looks to have PHEV with 5% of market share by 2020. IPPR's MARKAL-MACRO model scenario replaces conventional petrol and diesel with biofuels from 2020 and by 2030 biofuels dominate the fuel mix in cars.

Technology specific roadmaps are much more cautious with large-scale uptake coming after 2020. AEA's analysis[22] for the CCC puts EVs and PHEVs at just 7% of the new car market in 2022. Though it is not an area we consider in detail here, it is important not to overlook how increased efficiency will bring improvements. The CCC estimates that the carbon efficiency of 'conventional' vehicles can be increased 30–40 % on current levels though this will not be sufficient to reduce emissions to the extent needed by climate change targets.

### 3.3.2 Technology options

The challenges that remain for batteries, hydrogen fuel cells and so-called 2nd generation biofuels production, in terms of the technologies themselves, other enabling technologies and the supporting infrastructures, lead to some uncertainty as to which could win-out without further interventions. How consumers may respond to the new technologies is also largely unknown.

AEA's analysis of transport scenarios and roadmaps for DfT concludes that 'There is already reasonable consensus about the mix of surface transport technologies that might be important in 2050 but much uncertainty on their relative significance, and on the pathway to get to 2050. For example, there is a general consensus that vehicles with electric drivetrains will be very significant by 2050, though not on which of battery EVs, hydrogen fuel cell EVs or biofuel powered plug-in hybrid EVs will be dominant.'

[22] AEA (2009), '*Market outlook to 2022 for battery electric vehicles and plug-in hybrid vehicles*'. Available from **www.theccc.org.uk/reports/progress-reports/supporting-research-**.

Further: 'Vehicles with electric drivetrains (be they PHEVs, EVs or fuel cell vehicles) are consistently a major part of the transport technology mix by 2050 but much less significant in the 2020 timeframe. However, whilst PHEVs seem to play a major role in almost all analysis where they are included, the inclusion and/or relative importance of pure EVs versus hydrogen fuel cell vehicles is variable between different studies. This is partly because there is too much uncertainty in the development of energy storage, be it battery or fuel cell + hydrogen storage, to be able to say with any certainty which could win out in the long term. However, it probably also reflects the time at which different studies were carried out; recently there has been a significant shift of emphasis away from hydrogen and towards battery electric vehicles. This has been partly due to the failure of hydrogen technology development to live up to very high expectations.'

**Electric vehicles**

A transition from the current generation of hybrid vehicles to plug-in hybrids and eventually full electric vehicles will depend on improvements in battery technology. The NAIGT (New Automotive Innovation and Growth Team) roadmap expects mass-market PHEV from 2020 as battery weight and cost come down.[23] With further improvements in the 2020s there is a move to range-extended EVs with an auxiliary power unit.

Immediate priorities highlighted by the IEA for RD&D in storage are to resolve technical issues on lifespan and deep cycling with significant cost reductions for batteries by 2015 ($300/kWh); plug-in trials to cover 10,000 vehicles globally.

**Fuel cell vehicles**

International studies show the challenges facing fuel cell vehicles. The IEA's BLUE Map scenario finds that even with redoubled RD&D efforts over the next ten years, with supporting policies, fuel cell vehicles would achieve just a 5% market share by 2030 in OECD countries but rising to 33% by 2050. The European Hydrogen and Fuel Cell Technology Platform has indicated in its Strategic Research Agenda that 'major technological breakthroughs are required with respect to robust operation, sufficient lifetime and competitive cost by research and development before this new and promising technology can enter broad markets.'[24]

The NAIGT report, which represents a UK industry consensus technology roadmap, is more optimistic about the prospects of fuel cell vehicles.

The main RD&D challenges identified by the IEA are to reduce hydrogen storage costs 50% by 2020, to reduce costs of the fuel cell stack to $300/kW (compared with $500+/kW now) with 8000 hour lifespan and to reduce the need for catalysts. The report calls for 10,000 vehicle trials worldwide now, a doubling of RD&D effort and a global roadmap for deployment by 2015.

**Biofuels**

UKERC and IPPR's MARKAL models have a stronger role for biofuels than most other scenarios. UKERC's Carbon Ambition scenario decarbonises transport late in the period to 2050, mostly through petrol plug-in hybrids for cars, hydrogen fuel cells for HGV, and biodiesel plug-ins or hybrids for light goods vehicles. An intermediate step is using bio-ethanol for cars around 2035. In a variant UKERC scenario, forced early decarbonisation leads to uptake of hybrids and plug-in cars and HGV conversion to fuel cells by 2035. This may be a result of MARKAL's cost-optimisation approach which leads to step changes in technology rather than a more gradual turnover.

Developments in biofuel production processes will improve the efficiency of conversion and reduce the emissions of greenhouse gases. These advanced processes and fuels, so-called second and third generation biofuels, will be able to use a wider range of feedstocks, such as ligno-cellulose, and processes such as Fischer-Tropsch. The latter can be used to make synthetic fuels that have exactly the same properties as fossil fuels and therefore used directly in existing engines and infrastructure. IPPR's MARKAL-MACRO scenario has a minor role for electricity to 2050 with synthetic 'Fischer-Tropsch' diesel, being the most important fuel powering 70% of cars.

The IEA's ETP identifies the main technical challenges as: bringing cellulosic ethanol and synthetic fuels production to the demonstration stage, though some basic R&D is still needed; and launching synthetic fuels demonstration projects which are expected in next 5 years in Europe; and ligno-cellulosic demonstration in US in the period 2008–2012.

### 3.3.3 Dependencies

Decarbonising transport depends on access to a low carbon fuel or vector, i.e. on how the fuel/vector is produced, and having an infrastructure set up to deliver it.

Issues of increasing demand for electricity have been treated above but it is clear that the large-scale deployment of EVs will require a significant increase in capacity of low carbon electricity generation and the development of systems to manage supply and demand across transmission and distribution networks. Uptake is likely to start gradually and pose few problems before 2020. Beyond that, high penetration of EVs will make development of a 'smart grid' a priority.

For biomass/biofuels the available resource will be very sensitive to the sector in which the technology develops quickest; transport, heating and electricity generation may all make use of it. UKERC's Technology Acceleration study finds that raising the carbon reduction targets from 60% to 80% is associated with significantly less bio-electricity and residential heat from biomass but much higher levels of transport biofuels.[25] The issue of carbon intensity of biofuels (and for biomass use) also has to be addressed which, in a global market, will not be a trivial calculation.

[23] NAIGT (2009), 'An Independent Report on the Future of the Automotive Industry in the UK', with Government response. Available from **www.berr.gov.uk/whatwedo/sectors/automotive/naigt/page45547.html**.
[24] Available from **http://ec.europa.eu/research/fch/index_en.cfm**.
[25] UKERC (2009), *'Decarbonising the UK Energy System: Accelerated Development of Low Carbon Energy Supply Technologies'*. Available from **www.ukerc.ac.uk/support/tiki-index.php?page=AccTechReport**.



If fuel cell vehicles are to succeed, it will also depend on securing a low carbon (and, of course, cost effective) source for hydrogen. MacKay notes that hydrogen vehicles use four times more energy than electric vehicles and argues that power generation will be stretched without diverting any to producing hydrogen.

Road transport is a global market with significant development occurring elsewhere across the range of technology options. The UK, on its own, is not likely to be in a position to influence strongly the development of either. Close engagement in international activities will be essential.

### 3.3.4 Current activity

There are already several pilot projects being undertaken, including:

- The Low Carbon Vehicles Innovation Platform competition which will be run by the TSB in partnership with the cross-government Office for Low Emission Vehicles (OLEV). The £20 million competition to support industry-led collaborative projects will focus on strengthening UK capability and developing the UK's supply networks for low and ultra-low carbon vehicle projects.[26]
- The Mayor of London's Electric Vehicle Delivery Plan for London[27] sets out key targets:
  - › 100,000 electric vehicles on the capital's streets as soon as possible.
  - › 25,000 charging spaces in London's workplaces, retail outlets, streets, public car parks and station car parks by 2015.
  - › At least 1,000 Greater London Authority fleet electric vehicles by 2015.
- The Hydrogen Energy Project in the West Midlands[28] to further research and develop demonstrator projects with public and private sector partners.
- The CABLED project – ultra-low carbon car trials within Coventry and Birmingham.[29] The project will deliver a showcase demonstration of 110 ultra-low carbon vehicles and plug-in charging infrastructure.
- By 1st January 2011 ONE North east, in partnership with Nissan, will install at least 619 publicly available 'future-proof' charging points which will support both 3 kW and 7 kW charges and will also include twelve 50 kW 'rapid-charging' stations.[30]

### 3.3.5 Conclusions

A range of technologies is likely to be used in the transition to 2050, but electric vehicles appear to offer the most promising technology option providing electricity generation is decarbonised. An evolution from the current range of hybrids to full hybrids reaching the mass market, transition to plug-in hybrids and eventually electric vehicles can be expected during the 2020s. However, a failure to improve battery technology, with breakthroughs in hydrogen production and storage, may make fuel-cells a viable low-carbon option. The role of biomass and biofuels in the energy system is very sensitive to competing demands from energy and other sectors, and will have to address a range of criteria if it is to be regarded as sustainable. Many of the more efficient advanced biofuel production processes have yet to be fully demonstrated.

Given the uncertainties, a period over the first half of this decade should be used to assess technology development of electric (including plug-in) and fuel-cell vehicles. These pilot studies need to be of sufficient scale to demonstrate what outcomes could be achieved with wider uptake. With some projects already underway, there should be strategic coordination, nationally and internationally. This will also give time to further our understanding of the issues around the sustainability of 'second generation' biofuels.

Between 2015 and 2020, we should be in a position to take an informed judgement as to longer term, low carbon options for road transport and, therefore, whether further intervention is warranted to accelerate deployment in a particular direction.

[26] See **www.innovateuk.org/ourstrategy/innovationplatforms/lowcarbonvehicles/ultralowcarbonvehicledemonstrator.ashx**.
[27] See **www.london.gov.uk/electricvehicles/**
[28] See **www.birminghamsciencecity.co.uk/projects/projects/hydrogen-project.aspx & www.fuelcells.bham.ac.uk/projects/DBERR.shtml**
[29] Coventry and Birmingham Low Emission Demonstrators - **http://cabled.org.uk/**.
[30] See **www.onenortheast.co.uk/page/news/article.cfm?articleId=4216**.

## 3.4 Built environment

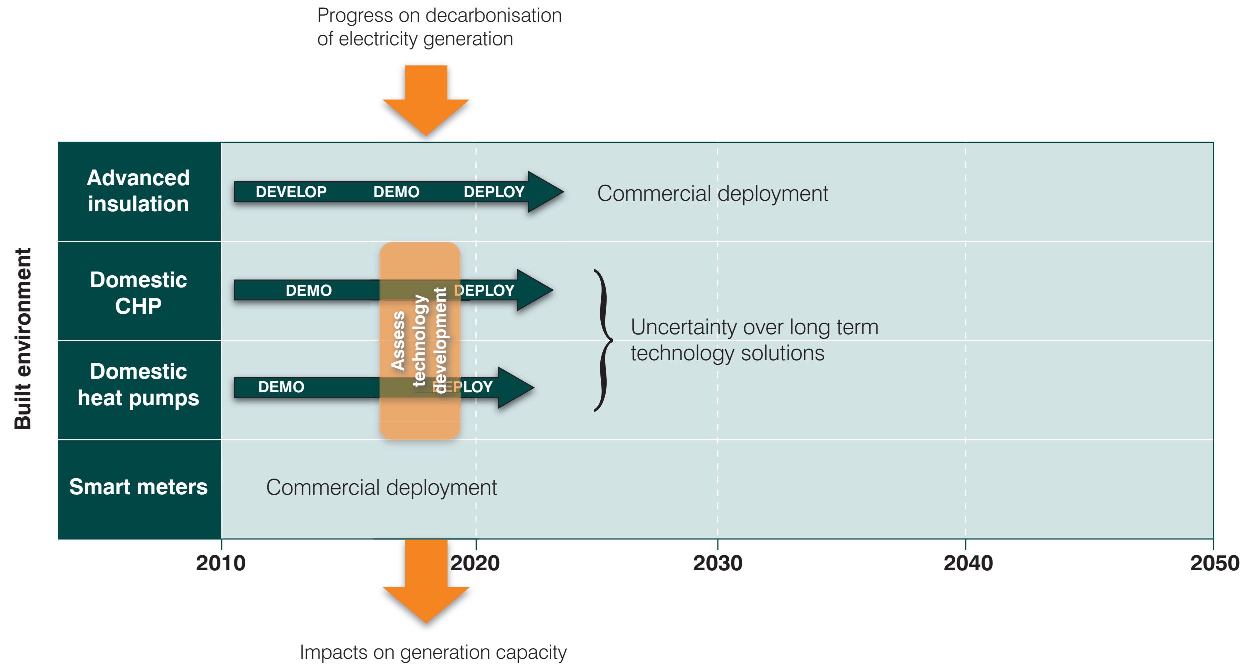


*Figure 3.5: Innovation timeline for technologies in the built environment*

This section is divided into 'heating technologies', insulation and smart meters.

### 3.4.1 Heating technologies

This section focuses on heat pumps and domestic CHP (dCHP), because of their potential impact and level of innovation required to bring them to large-scale deployment in the UK. Heat pumps, though a mature technology in principle, have not been widely deployed in the UK so need to be demonstrated as effective in the UK housing stock and climate.

Other technologies which can provide similar services, such as heat networks (e.g. taking heat from power stations or local dedicated CHP plants), have been tested in the UK[31] and the barriers are generally accepted to be regulatory or economic with less room for technological innovation to develop them further.

**Scale of deployment**

With the decarbonisation of electricity generation, most scenarios have shown air source heat pumps making a very significant potential contribution to domestic heating by 2050. An AEA report for CCC finds the use of low carbon electricity for heating almost exclusively by 2050. The UKERC CAM scenario has the electricity demand rising to meet the requirements of significant levels of heat pumps. Though deployment rates are not specified by UKERC, MacKay's Plan C installs one million 1 kW heat pumps a year which, by 2050, increases electricity demand by 33 GW in winter and 8GW in summer; levels comparable with UKERC. However, there are discrepancies over timing: in the UKERC 2050 CAM scenario MARKAL introduces heat pumps after 2030, whereas Ofgem and MacKay see earlier contributions being important.

Most scenarios (using various techniques) do not have a major role for dCHP in 2050 though some, such as McKinsey, Ofgem and National Grid, see it being a possible intermediate technology under certain conditions. Models run under the Ofgem LENS project found CHP not to be favoured in general: 'At low carbon prices, existing electricity and gas infrastructure are favoured to supply heat and power separately. At high carbon prices, it's not sufficiently low carbon to be selected. It is only when access to transmission grids is severely constrained, in the Microgrids scenario, with high carbon price, that it is used.' However, Element Energy, in a report on the Growth Potential for Microgeneration in the UK[32], highlight limitations of models to capture consumer choices, noting: 'The projection of the potential for microgeneration cannot … be based on an assumption of rational economic behaviour from consumers, as would be used for modelling large-scale energy purchasing decision making. A projection methodology is required which allows a quantification of the range of factors likely to affect consumer uptake.'

[31] A Heat Workshop was organised by ERP, with the ETI and RAEng in January 2009, a report of which sets out many of the issues across all heating technologies and energy efficiency, including the non-technical barriers, see **http://www.energyresearchpartnership.org.uk/heat**.
[32] Element Energy (2008), '*The growth potential for microgeneration in England, Wales and Scotland*'. Available at: **www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/explained/microgen/strategy/strategy.aspx**



Technology roadmaps for stationary fuel cells providing CHP see a role for the technology in a decentralised electricity generation infrastructure in 2050, with a transition from fossil fuels to $CO_2$ neutral fuels powering the fuel cells.

**Technology options**

Heat pumps themselves are a mature technology and most scenarios assume static performance to 2050 with coefficients of performance (COP) from air-source heat-pumps (ASHP) in range 2.18–3.0, which is a reasonable estimate by today's standards (Staffell et al report COP 2.3–2.8 for ASHP producing 55°C hot water in the UK ).[33] However, the IEA sets out some RD&D requirements to reduce wider environmental impacts (from the working fluids used) and targets 60% increase in efficiency by 2030, and 100% by 2050. An 'efficient heating and cooling roadmap' is expected from the IEA in 2010. In August 2009, Japan set up the Next Generation Heat Pump Research Council with a similar goal of doubling efficiency by 2050 and halving installation costs.[34]

Given the small deployment of heat pumps in the UK, and the nature of the housing stock that needs to be retrofitted (which is much less well insulated compared to countries where deployment is widespread), there are uncertainties over the actual performance from ASHP that could be achieved. Gas boilers, which dominate space heating in the UK housing stock, have outputs typically of around 27 kW which can raise water temperatures above 80°C. Currently available ASHPs for domestic buildings, with power of around 7 kW, take water to 55°C/60°C. Such a difference would necessitate substantial modifications to the central heating system and how it is operated.

High efficiency fuel-cell dCHP appliances for residential and small commercial use could reduce the consumption of fossil fuels by up to 50% and hence the emission of carbon dioxide by up to 50%. Though not yet commercially available, such units are entering demonstration projects. The European Hydrogen and Fuel Cell Technology Platform sees the near term priority being to develop low-cost, reliable and robust fuel-cell stacks and fuel-cell systems with lifetimes exceeding 40,000 hours under practical operating conditions. At the domestic level, the technology requires further development to improve cost and reliability to become competitive with conventional boiler systems for heat generation and grid-connected electricity.

The Technology Platform's Strategic Research Agenda sets out some specific early development priorities for low cost and large-scale manufacturing:[35]

- Reduction of material costs through utilising less or less precious or expensive metals, involving vendors of raw materials and establishing recycling strategies
- Development of more efficient stacks with (i) low electrochemical and IR losses and (ii) high fuel utilisation.
- Enhancement of fuel flexibility.
- Improvement of durability, reliability, robustness and lifetime.

**Dependencies**

The utility of heat pumps to meet emissions targets is dependent on carbon intensity of electricity. The true carbon intensity of the grid, and hence heat pumps, is uncertain and difficult to estimate (even more so when the marginal carbon intensity is to be considered). It may be postulated that, in the medium term, electricity from unabated gas-powered stations would provide extra capacity leading to a significant carbon reduction from heat pumps over conventional gas central heating. However, there is a risk that if heat pumps are deployed, with coal-fired power stations built but CCS not feasible, they become high carbon.

Further, without large-scale storage, meeting peaks in demand that heat pumps could place on the electricity network could require underutilized generation plant that would be expensive to maintain. Options to resolve this issue will require innovation, for example:

- integrating heat pumps with control systems to flatten demand at point of use and bring buildings up to temperature ahead of actual demand
- heat storage to provide a heat 'buffer' during peak demand times
- adapt heat pump technology to incorporate another fuel vector (e.g. gas/biomass) to respond at peak times

Though individual households could run a 7 kW heat pump from the mains supply, if deployment becomes widespread, the electricity distribution network would require reinforcement to meet the additional local demand. As for widespread deployment of electric vehicles, smart system operation of electricity supply and demand will be critical to maintain system integrity.

For dCHP, decarbonisation of network gas could boost its attractiveness. Estimates from National Grid put the potential at 50% of domestic gas supplies from biogas, though this is an upper limit, and figures of less than 10% are more widely accepted.

**Conclusions**

Heat pumps are favoured by scenarios and by many of the specific analyses that have considered how to meet the heat demand of domestic buildings. However, the performance of heat pumps in the UK's climate and housing stock, and by real consumers, has not been tested. Similarly, dCHP has yet to be proven on a large scale, and new dCHP models are expected to be marketed widely in coming years.

An assessment of 'real world' performance of these technologies is required before wide ranging intervention policies on technology choices are taken. Over this time, a better understanding of future electricity and gas carbon intensity will be formed and will provide a better indication of the relative emission reduction potentials.

[33] Staffell I *et al* (in press) '*UK Microgeneration. Part II: Technology Overviews*' (accepted by Proc. ICE: Energy)
[34] **www.ejarn.jp/Type_news_inside1.asp?id=12423&classid=9**
[35] See **http://ec.europa.eu/research/fch/pdf/hfp-sra004_v9-2004_sra-report-final_22jul2005.pdf#view=fit&pagemode=none**.
[36] Ohmic loss: Losses created by the resistance to the flow of ions in the electrolyte and resistance to flow of electrons through the electrode and bipolar plate materials.

### 3.4.2 Insulation

Conventional methods for insulating buildings, such as covering lofts, cavity walls and glazing, are well understood. Increasing uptake is a matter for policy makers though the effect of reducing heating demand has an important impact on how other technologies are deployed, including which ones and on what scale. Cutting heating requirements may make smaller-sized electric heat pumps viable and reduce demand on electricity generation.

Most scenarios assume near saturation of uptake by about 2020 (and the rate of deployment this implies should not be underestimated). In the CCC's progress report from October 2009, the 'extended ambition' scenario sets a target for all lofts and cavity walls (where practical) to be treated by 2015 and 2.3 million solid walls by 2022. The latter is only about 25% of the technical potential owing to the disruption that installation causes. Increasing this uptake therefore represents a significant opportunity if new technologies can be developed.

There appears to be little by the way of research into this area. The UK Energy Research Centre noted that 'new materials could be found to overcome problems with existing solutions (too thick, unsightly). These would require basic research, mainly in the materials sciences.'[37] However, the Energy Saving Trust (EST) is commissioning trials to install and evaluate the performance of new solid wall insulation measures and to assess the suitability for installation of domestic properties throughout the UK.[38] The EST notes 'several new products… have entered the market. They are still developing and their in-situ performance has yet to be established.'

### 3.4.4 Smart meters

**Scale of deployment**

There is widespread consensus across scenarios that some form of smart metering is essential in the 2050 system and that the roll-out of this technology should begin immediately. The CCC and others make specific reference to the use of smart metering as a tool to access demand side response resources to provide system balancing services. The National Grid consultation on network scenarios for 2020, based on their Gone Green Scenario, highlights a possible 8 GW of additional demand side system services resources that could be enabled through smart metering.

Most scenarios also highlight smart metering as instrumental in assisting demand reduction through provision of energy use information to end users. The Energy Saving Trust's Emission Impossible 2050 scenario attributes 5% energy savings in the domestic sector to the roll-out of smart meters on the assumption that 50% of homes have smart meter capabilities and 95% of those with meters are actively using them to help identify and make savings.

**Technology options**

Smart meters are a relatively mature technology. Several countries across Europe already have some form of smart metering in place or are in the process of realising national roll-out programmes. The primary point of differentiation between smart meters lies in the functionality that they enable. This can range from simple energy use information display to full two-way interactions between the home and the wider system, both network operators and suppliers, all functioning under the umbrella of smart home operations.

A recent report from Mott MacDonald[39], commissioned by BERR (now DECC) as part of the smart metering consultation process, provides a summary of the range of metering technologies and associated functionality (primarily from a supplier side perspective). This is outlined in Table 3.3, along with additional input from the Energy Networks Association (ENA)[40] providing detail on a smart meter with network interaction capabilities and smart home functionality.

**Dependencies**

The role of smart metering, and the services that it can help to access, is highly dependent on the system context into which the meter is set; this is well illustrated in the Ofgem LENS studies. In the Energy Service Companies (ESCO) scenario, smart meters are installed by ESCOs, as they are an essential aspect of offering energy service. This scenario requires advanced meters with control functionality for onsite generation, demand and storage as well as services beyond electricity. The Large Distribution scenario sees mandated roll-out of smart meters that are again advanced tools with smart grid capabilities. This scenario requires the integral involvement of the Distribution Network Operator (DNO), who is becoming more of an active distribution system operator. The Microgrid scenario also sees large-scale roll-out of the smart meter; however, because there is less support for accessing its functionality (either through an ESCO or the DNO), a large proportion of meters are not used and the full extent of both energy saving potential and energy balancing services are not realised.

The meter functionality is also a key determinant of the system context that can subsequently evolve. As highlighted in the smart grid analysis, without sufficient interactivity and functionality to allow integration with network services, smart meters could restrict the evolution of the smart grid. Comprehensive functionality, via a smart meter interface, will allow the network access and control of demand side resources (e.g. electric vehicles and heat pumps).

National Grid also highlight that smart metering is vital for optimal integration of electric transport into the power system. To avoid major disruption and cost, electric vehicles should be charged at off-peak times. To facilitate this, smart meters need to be able to communicate real time prices into the home to encourage end users to charge at low-price periods. Without smart meters, charge times will be arbitrary and likely to put more stress on the power system if peak charging coincides with the existing system peak.

The Government's response to the smart metering consultation in 2009 arrived at high-level conclusions regarding the functionality of electricity and gas smart meters.[43] A high number of respondents to the consultation highlighted the need to allow sufficient functionality of the meter to accommodate changes in the system such as electric vehicles. Government conclusions broadly supported integrating more advanced functionality into smart meters in the initial roll-out. However, some respondents also commented that a focus on advanced meters could delay roll-out and reduce the early impact of a smart metering scheme. Balancing these issues is needed, particularly when some of the more advanced functionality is dependent on the arrival of electrical vehicles and large-scale transfer of heat into the power sector; both highly uncertain factors.

**Conclusions**

The roll-out of smart metering is an enabler of a number of different aspects of the 2050 energy system future. However, a common theme that emerges from scenario analysis of the use of smart meters is a high degree of uncertainty over how end users will use and respond to smart meters. Whether smart metering can help to realise a significant level of demand reduction, and whether end users will adopt smart meter functionality to allow smart home or smart grid interactions, is not clear. Although the technology itself is well developed, large-scale demonstration of the technology in the whole house / whole system context is needed to gather data on actual usage of smart meters and smart appliances in the home. This will help to determine whether this technology is capable of delivering on the scale that these scenarios demand and the actions that could be taken to further develop or deploy it.

| Meter Type | Functionality |
|---|---|
| **Clip-on customer display units** | Device clipped on to existing meters. Simple energy use information displayed on meter device, capable of broadcasting to in-house display unit nearby. Communicating to the home owner only. |
| **Standard meter with internal communications** | Retrofitted 'smart' functionality into existing meters. Transmits real time energy use information data to home owners; can also be set up to allow one way communication with suppliers for accurate meter readings. |
| **BEAMA[41] minimum meter specifications** | Complies with the minimum standards for meeting EU Directive on smart metering. New meter. Allows reverse running, two tariff charging, small amount of data storage, local communication to e.g. home PC, TV, mobile phone. Can be adapted to allow one way communication with supplier (i.e. automated meter reading optional function). |
| **ERA[42] minimum meter specifications** | In addition to the features above, this meter allows import/export (electricity), two way communications between meter and supplier (allows automated meter reading as standard, multi-tariff charging, Automated Meter Management as standard (allows interaction with customer meter) e.g. remote connect/disconnect functionality and remote switch for payment options. |
| **'Dumb meter' with smart box** | Metering and communication/control functions, as described above, are separated into two components. This improves communication security and makes updatability and flexibility of the metering solution more straightforward. |
| **'Smart home' enabled meter** | The functionality for the meter is much the same as above, however the meter also has smart appliance / smart home *control* functionality. This can be integrated into the smart meter itself or, as per the 'dumb meter' with smart box configuration, integrated into the smart box.<br><br>Additional control functions allow appliances in the home to be controlled in accordance with user applied parameters (e.g. minimum temperature for the home, time range for washing to be completed etc.). Smart home control allows optimisation of e.g. energy costs, emissions. Data information to convey real time pricing to the smart control functions can also be a part of this metering solution. |
| **Smart grid enabled meter** | As per the smart home enabled meter but with additional communication and control capabilities to allow interaction with network operator, Real time pricing as an increasingly essential part of this metering solution. |

*Table 3.3: Summary of smart meter type and functionality*

[37] See **www.ukerc.ac.uk/Downloads/PDF/06/06Consultations/0604EnergyReview.pdf**.
[38] See **www.energysavingtrust.org.uk/business/Global-Data/Publications/Energy-Saving-Trust-Solid-Wall-Insulation-trials**
[39] Mott MacDonald (2007) '*Appraisal of costs and benefits of smart meter roll out options*'. Available on **www.decc.gov.uk/en/content/cms/what_we_do/consumers/smart_meters/smart_meters.aspx**
[40] Ongoing work by the ENA (Electricity Networks Association) is characterising the additional functionality required in smart metering to ensure compatibility of the meters with smart grid operation. See the ENA response to the 2009 smart meter consultation. Available on the link above.
[41] British Electrotechnical & Allied Manufacturers Association (BEAMA) – representing electricity manufacturers in the UK.
[42] Electricity Retail Association (ERA) put together minimum operational and functional specifications for gas and electricity meters as part of the Supplier Requirements for Smart Metering (SRSM) project.
[43] DECC (2009) '*Towards a smarter future: Government response to the consultation on electricity and gas smart metering*'. Available on link above.

# 4 Conclusions: The technology pipeline

Meeting 2050 emissions targets, and other energy policy aims, will require a significant contribution from new energy technologies. By setting out how the energy system could evolve, and when new technologies may be technically viable, will give decision makers (in public policy and public and private sector investors) a better understanding of the choices that will be faced and therefore how to prepare.

From our analysis of currently available scenarios we consider a ‘pipeline’ of selected technologies that must come on-stream to enable the reduction of carbon emissions through to 2050.

- The technologies that could have an impact by 2020 are generally at or near the commercial **deployment** stage now. For these technologies, policies to support their rapid roll-out are critical.
- Going beyond this first step, we also need large-scale **demonstrations**, or pilots, of technologies which appear to offer further cuts. For these technologies, we do not yet fully understand how they will perform in the context of the whole energy system or in the homes of end-users. This needs to be established in large-scale demonstration projects which will gather data on technology performance efficiencies and end-user behaviour.
- Finally, there are longer term prospects that require more fundamental **research and development**. These technologies may turn out to deliver more effective and efficient solutions but may not be available until after 2030. R&D is also needed to support improvements in deployed technologies.

We represent the anticipated near term technology developments in Figure 4.1, on an adapted version of the ERP innovation ‘funnel’ diagram.

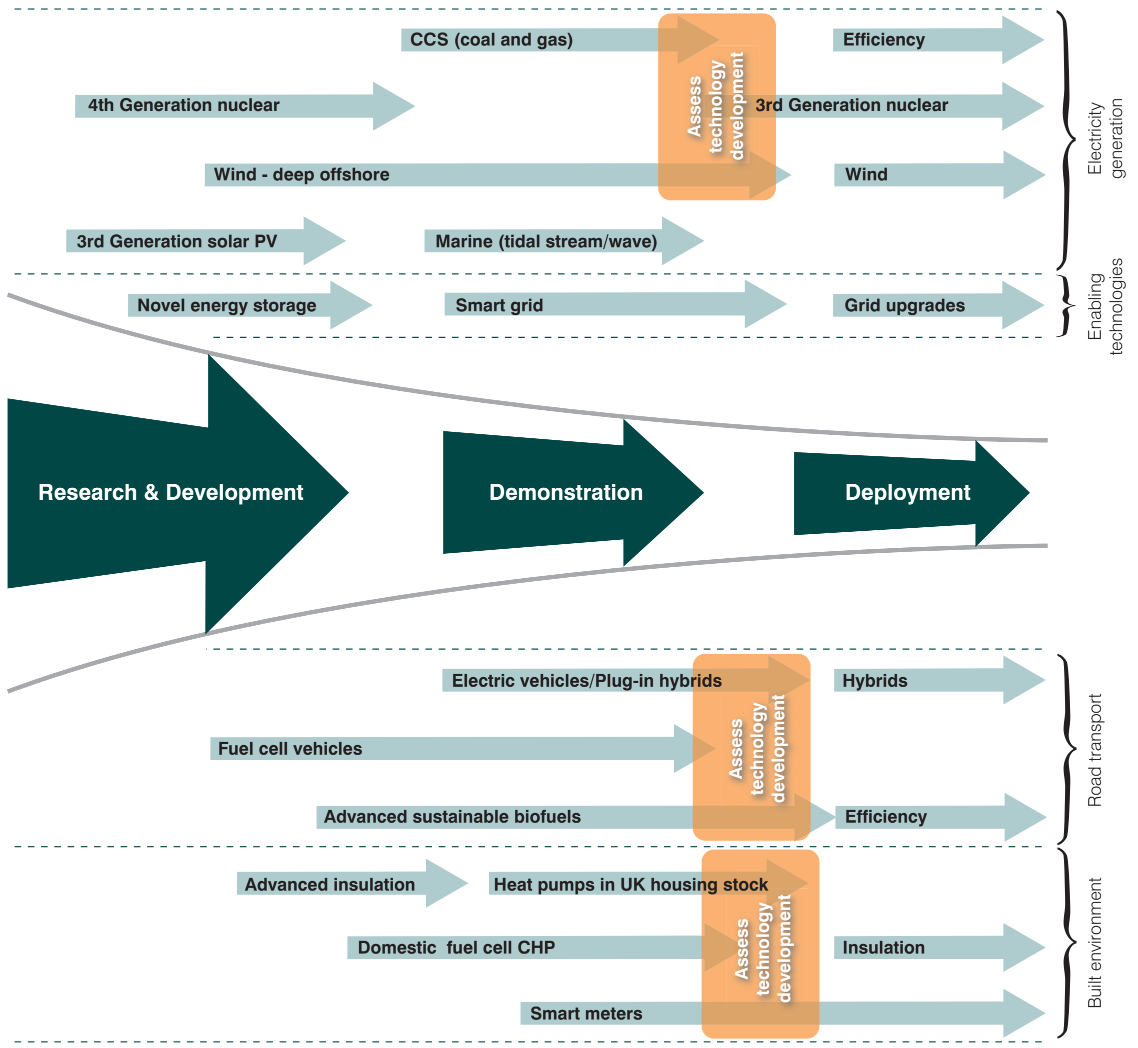


*Figure 4.1: Pipeline of selected energy technologies showing progress required by 2020*

The arrows chart the progress that should be made through the 2010s; balancing our analyses of what is needed to meet emission reduction targets from scenarios with what can be achieved from technology developments. Progress against these milestones should be monitored and used to guide policy or further investments.

The orange boxes indicate where potentially competing technologies could have differing impacts on the energy system. Assessments across these areas, particularly for domestic heating and road transport, will need to consider whether there is a case for more specific policy intervention given the implications for building new infrastructure and on power generation and management. Such a simplification, with discrete technologies occupying specific positions on an innovation ‘chain’ and the appearance of waves of technologies coming to fruition, distorts the reality. But this can offer an overview of some fundamental issues that may arise. Without considering the longer term when making choices in the next decade, we risk locking the energy system and the public into an undesirable future.

An important aspect of innovation is the non-linearity as we describe in Section 1.1. Although a technology may be at the later stages of innovation, deployment will raise new questions that require basic R&D to be answered.

The following sections set out the near-term RDD&D priorities (2010–2020), as illustrated in this diagram.

## 4.1 Deploy

Most of the technologies that will form the energy system in 2020 are either available now or at the later stages of the innovation chain. ERP’s remit does not extend to advising on mechanisms to ensure technologies are deployed but it is clear that their rapid deployment will be essential to meeting emissions reductions targets and allowing new technologies to make a further impact. Deployment is the key task for the following technologies:

### 4.1.1 Generation

- Shallow water offshore wind and onshore wind.
- Third generation nuclear. Although the UK is not building the first of this new generation of nuclear plants, it will need to be supported by an R&D programme along with a robust manufacturing base. A programme is also needed to develop a strategy to deal with the new waste streams. The first round of new build will replace the existing capacity; deployment beyond this level is required to meet many of the scenario projections.
- Improved efficiency of current thermal plant to reduce emissions. This is particularly important on coal to compensate for decreased whole plant efficiency where scrubbing technologies have been fitted to allow them to continue in operation.

### 4.1.2 Built environment

- Conventional insulation – rapid take up, as per CCC targets, is required to reduce heat demand of domestic buildings in particular, lowering $CO_2$ emissions directly. Lower heat demand will also make technologies such as heat pumps, more viable.
- Smart meters – national and comprehensive deployment of smart meters is needed. As CBI analysis demonstrates, UK planned roll-out of smart metering (to be fully implemented by 2020) is behind others in the EU region. Faster deployment of this low carbon technology enabler would be desirable.

### 4.1.3 Road transport

- Increased vehicle efficiencies
- Electric hybrids – to mass market
  Existing regulation should drive emissions from cars down to meet 2020 targets through technologies already available off-the-shelf or near market as described in the King Review of low carbon cars.[44] Similar progress is required for commercial vehicles.

Modal change can also have an impact and may be driven by improvements to information and communications technologies.

[44] See **www.hm-treasury.gov.uk/bud_bud08_king_review.htm**.

## 4.2 Demonstrate

The next ten years are a crucial period for innovation in emerging energy technologies to ensure that they are in a position to be deployed at a large scale in the 2020s. Options for the energy system beyond then have been identified but large-scale demonstrations will be required to prove their viability or otherwise. Pilot projects show how technologies perform in real conditions and, importantly for demand-side technologies, how people perform with them.

There has been good progress in recent years on initiating small scale trials in a number of areas (which were indicated in the previous chapter). As these grow, a strategic approach to demonstration projects is needed to ensure that results from different trials can be assessed together.

Over the course of a demonstration period, innovation in other components of the energy system will provide further information on their suitability.

### 4.2.1 Generation

- Full-scale demonstration of CCS is the highest and most immediate priority, if it is to play a prominent part in the future energy system. Coal with CCS is seen as a priority but gas with CCS should be demonstrated in the same time frame as coal; as should CCS on industrial emissions.
- High efficiency power plant, including ultra-supercritical boilers and IGCC. On their own these will reduce emissions but are also vital to reduce the efficiency losses from adding to CCS.
- Offshore-specific wind technologies are also needed to decarbonise the grid. Current offshore designs are little adapted from those onshore and further activity is needed to develop and demonstrate new turbine technologies better suited to offshore and, particularly, deep-water locations.
- Tidal stream and wave technologies require demonstration to improve their reliability and understanding of their costs. Programmes are focussed on commercial viability in 2020 but it is unclear what the potential scale of deployment will be.

### 4.2.2 Enabling technologies

- Smart grid technology and concepts are being demonstrated at a small scale through initiatives like the Distribution Network Operators IFI and RPZ schemes. The advent of the Low Carbon Network Fund (£500million) should help to accelerate this activity and grow these small scale pilots into larger demonstrations of various aspects of smart grid technology.
- This activity should be supported and built on through the next decade to ensure that the technology and organisations involved are ready for scale up of activities to national roll-out in the early 2020s.
- Subsequent network price control reviews should continue to reflect and incentivise the need for innovation in smarter network operation and integration of renewable resources, as seen in the recent Distribution Price Control Review.
- Demonstration (at scale) of offshore network technologies such as multi-terminal HVDC network should ramp up to facilitate efficient connection of the large amounts of offshore wind generation.

### 4.2.3 Built environment

- Comparison of the options for heating domestic buildings is needed and this requires robust data on technology use in situ (which is not currently available). Heat pumps and dCHP may be alternatives or complementary but neither are well established in the UK to the extent that they can be widely deployed. Heat pump technology, using decarbonised electricity, is favoured by scenario analysis and in most views of the long term energy system. But installing domestic CHP may be less disruptive and offers lower carbon heat and electricity than gas boilers (with the current generation mix).
- Although deployment of smart meters is highlighted as a priority for deployment in the next decade, further data from large-scale demonstrations is desirable to help inform national deployment. There is very little real data available on how end-users will use smart meters to both reduce energy use and provide demand response services. Large-scale trials that look at smart meter usage in context of both the home and the wider system are a priority. These trials should include demonstration of smart home control capabilities as well as simple metering for information provision activity.
- Large-scale, integrated whole-house demonstration projects should be undertaken to assess how the technologies perform; and how people perform with the technologies above. There should be a strategic coordination of trials to ensure consistent monitoring and that information can be collated and compared to feed in to policy and investment decisions.

- The Eco-towns initiative is an opportunity to compare how technologies perform in new buildings but retrofitting is ultimately where biggest gains will be made and where demonstration is most urgent. There is some activity underway already including that funded by the Energy Saving Trust and by the Technology Strategy Board (Retrofit for the Future competition).

- Policy decisions to incentivise large-scale deployment of these technologies should be based not only on information from demonstration projects but also on how other parts of the energy system have and are expected to evolve. The rate of decarbonisation of electricity, smart grid operation, and energy storage will all be factors. There will be implications for strengthening electricity infrastructure, and the amount of generation required.

### 4.2.4 Road transport

- Electric vehicles (including plug-in hybrids), biofuels and hydrogen fuel-cell vehicles are all options which could lead to low carbon road transport from the 2020s. As the technologies develop, the scale of pilot projects should increase. Demonstration projects, including those funded by the Technology Strategy Board and various RDAs, are underway. As with the demonstrations in the built environment, they must be coordinated and strategic.
- The NAIGT recommends going from the current hundreds of low and zero carbon vehicles to thousands between 2011/14 leading to mass scale deployment (normally taken as 100,000 units) by 2020. This is still some way off the targets of the CCC's carbon budgets so should be taken as a minimum level.
- The Office for Low Emission Vehicles has also set out a plan for the shift to low carbon vehicles covering the next decade which is broadly consistent with our timeline.[45]
- Cellulosic ethanol production and production of synthetic fuels using Fisher-Tropsch process are close to demonstration phase. Continued development will show how viable advanced biofuels are to providing fuel for the transport system but issues around the use of biomass will need further study though (explored further in the next Chapter).

## 4.3 Research and Develop

We need R&D in place now to ensure there is a pipeline to deliver technologies that can be on-stream in the medium - long term (post 2030). These technologies are essential for achieving high levels of emissions reductions or as replacements for some interim carbon reduction solutions. Here we flag-up the main technical issues that need to be overcome. Disciplines such as geoscience, biological science, materials science, surface science, catalysis, corrosion, computation and modelling, analytical science, fluid flow and metallurgy will underpin development of energy technologies and need to be maintained.

### 4.3.1 Generation

- Carbon Capture and Storage: Immediate R&D needs are on storage to characterise the geology and understand the potential UK capacity. R&D is also needed on the main combustion technologies to support the demonstration programmes and to prove biomass co-firing with CCS. New technologies and processes that could bring down the costs of capture, such as chemical looping combustion and new sorbents, are being developed. These could be brought to market post-2020.
- Breakthrough technologies: R&D needs to continue on other energy technologies that are far from market but where a breakthrough could make an impact on the electricity generation mix. For example, 3rd generation photovoltaic cells and modules could make solar power much more widespread.

### 4.3.2 Enabling technologies

- Novel large-scale energy storage technologies could provide crucial assistance in managing intermittency and variability, which will result from large-scale penetration of renewables and inflexible generation into the system. Beyond established technologies (e.g. pumped hydro), other options for large-scale storage are usually too expensive to use in anything other than niche applications. Further R&D could help to bring costs down and scale up technologies.
- Development in novel network materials, e.g. high temperature superconductors, could be an important contributor to providing optimal network capacity in the future system. Further R&D and early stage demonstration is needed to test new products in live systems and niche applications.

### 4.3.3 Built Environment

- Advanced insulation, in particular, to treat more than 5million properties with solid wall insulation which is crucially less disruptive than currently available.

### 4.3.4 Transport

The IEA ETP describes the main R&D needs as:

- Electric Vehicles: Storage RD&D to resolve technical issues on lifespan, deep cycling and rapid charging leading to significant cost reductions for batteries by 2015.
- Fuel Cell Vehicles: RD&D on Hydrogen storage to reduce costs 50% by 2020; on fuel cell stack to reduce costs to $300/kW ($500+/kW now) with 8,000 hour lifespan and reduced catalyst needs.
- Biofuels: Some basic R&D still needed to bring cellulosic ethanol and synthetic fuels (from Fischer-Tropsch) to demonstration stage.

[45] See http://www.dft.gov.uk/pgr/sustainable/olev/.

# 5 Conclusions: Implications for the energy system

This report has set out to inform policy makers, funders of RD&D activities and investors when and how new energy technologies are expected to reach technical deployment. The conclusions in the previous chapter have been based on a study of scenarios and analyses from the public and private sectors. We hope, therefore, they will achieve broad support from the energy community.

Our work has raised some important issues that need further consideration which we probe below. Such insight comes from having taken a whole system perspective, seeing interlinking issues between sectors. ERP is well-placed to offer such insight and an objective of this project is to feed back into the work of others.

Through this analysis, a number of linked issues that raise questions for innovation to support the transition to a low carbon future in 2050 have arisen. These range from the impact of bias and 'fashion' in the scenarios analysed to the level of expenditure required for progressing technologies through the innovation chain. They are raised here as items for further discussion rather than specific conclusions. They may have an impact when considering the innovation pipeline conclusions or when making recommendations based on this analysis.

## 5.1 Investment in innovation

In general, the costs of technologies have been an integral part of the scenarios we have studied. We have not sought to undertake new analysis though, where available, this information has been incorporated into earlier parts of this report. However, we can make some general comments on what the wider implications are when looking at the conclusions we draw.

The IEA's ETP report set out costs for the further development of energy technologies according to stage of innovation. Figure 5.1 shows estimates of UK investment required in energy technologies, taken from the IEA report, for both early and late stage investment and for demand side and supply side technologies.

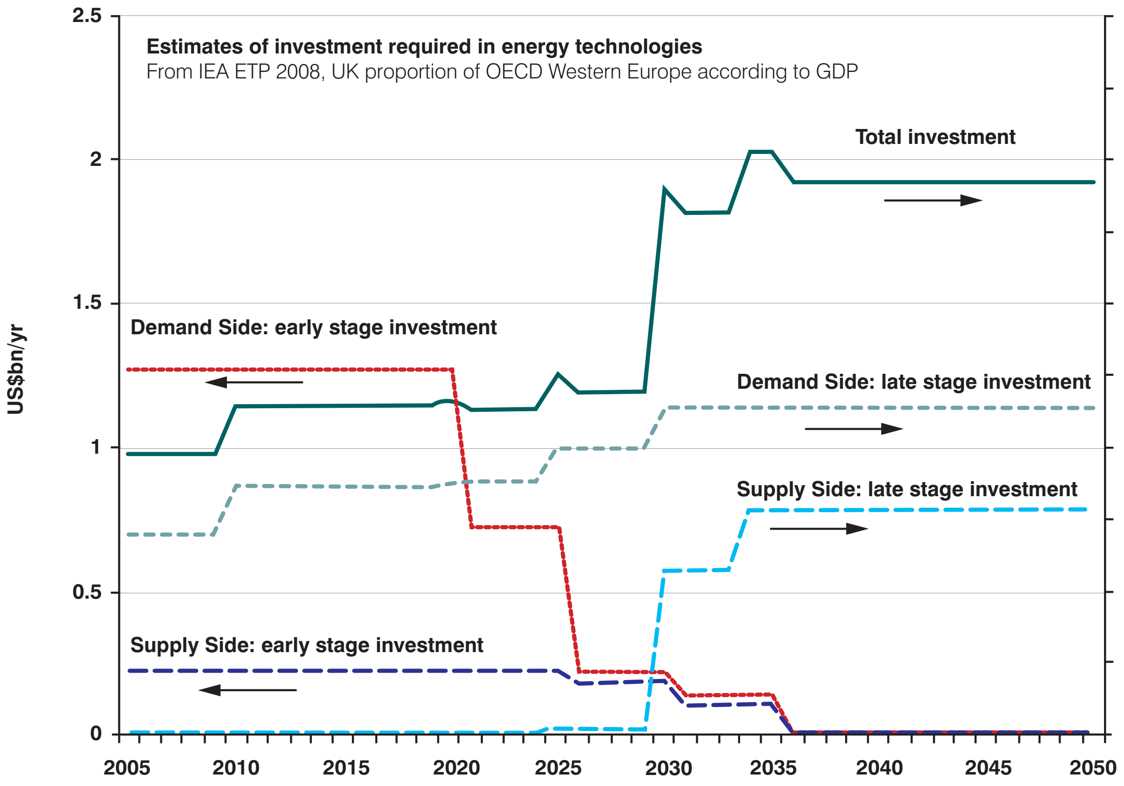


*Figure 5.1 IEA ETP 2008: Estimates of annual investment required in UK energy technologies, for early stage and late stage RD&D*

The costs of innovation (from public and private sectors) can be seen to escalate in the later stages. The implication is that expensive demos will be necessary over the short term to establish which technologies will be viable and most cost effective over the longer term. In the case of CCS, this nettle has been grasped. But on the demand side technologies, such investment will equally be required for large-scale demonstration projects.

There will always be a need for basic R&D also for technologies which we pigeon-hole as being at more advanced stages. A joined-up approach to innovation funding is needed so that such funding is available; otherwise we risk stalling further progress. ERP, through its overview of technologies, can provide this sort of gap analysis.

Additional investment in basic R&D can increase the returns in the long term. Analysis by UKERC (2009) indicates that early funding of new technologies to accelerate their development leads to substantially greater returns in the long term, both in terms of both technology and social costs.[46] However, these returns may not be realised until after 2030.

## 5.2 Costs

The cost of a technology is a key determinant of its deployment. Cost can be influenced by a range of factors, of which innovation has a major role. Deployment may also be accelerated by policy intervention, including through target setting, fiscal incentives and carbon pricing. While not reducing costs of a technology directly, these interventions create market opportunities by reducing the risks, and, therefore, the cost, of investment. For example, targets, set at a European level, have increased the investment in biofuels, leading to targets in some places being met ahead of the deadline. Targets can also accelerate innovation and basic R&D. This has been seen in biofuels where refinements to the targets, to reduce potentially undesirable environmental impacts, were aimed at stimulating new technologies. However, the effectiveness of the policy signals is dependent on them being appropriately long term so as to provide certainty of returns on investments, particularly where they are in early stage R&D.

Non-cost barriers may also restrict deployment, thereby increasing the risk to investment and therefore costs. These include constraints in the supply chain through either insufficient production capacity or a suitably skilled workforce.[47] These are expected to be more likely for demand side technologies; for example, an insufficient number of trained engineers to install the equipment in households. Planning can also create uncertainty and increase costs by delaying deployment, for example in siting wind turbines or external wall insulation, which may change the character of a building. These constraints may have significant impact on the deployment of a technology. Although, in some circumstances, these bottlenecks may stimulate innovation leading to greater cost reduction.

Understanding the barriers to market and introducing the appropriate incentives could accelerate technology deployment and development. However, while stimulating the market towards particular technologies may be useful to deliver particular energy options, these interventions need to be set in the context of the wider energy system.

## 5.3 The new 'decarbonised electricity' orthodoxy

Breakthroughs in particular technologies or the stimulation of a particular market can lead to the creation of orthodoxies on which the future energy system will be based. If this report had been prepared 10 years ago, the focus may have been more on the role of hydrogen as a low carbon storage vector with little on CCS as an enabler of low carbon fossil generation. Four years ago, bioenergy was seen as playing a significant role, particularly in the provision of biofuels for transport. Now, most of the scenarios studied for this analysis support the conclusion that decarbonisation of our electricity supply is key to provision of a low-carbon energy system in 2050, with transport (and heating) energy demand met by a decarbonised electricity supply.

Understanding the rise and fall of these technology trends is important in our evaluation of the current thinking around the energy system of 2050. Ultimately, analysis of any projected future system requires a planned, coordinated approach. One that understands and responds to the challenges of decarbonisation using the array of technologies already available, is flexible enough to include breakthrough technologies and maintains a whole system perspective that characterises the implications (positive and negative) of technologies in context.

**Whole system implications of the all-electric future**

With all these possible energy futures come whole system implications that require consideration to evaluate properly the contribution that technologies can make to the future energy system. The all-electric future presents major challenges for the power system, including accommodating a possible doubling in demand for electricity, while simultaneously introducing new technologies to rapidly decarbonise large-scale generation. It

[46] ibid

[47] ERP's (2007) '*Investigation into high-level skills shortages in the energy sector*' found there was a shortage of technical skills in the energy sector. The report is available at **www.energyresearchpartnership.org.uk/tiki-index.php?page=page12**.

also implies a reversal of the conventional approach of power system planning and operation, namely that flexible power generation follows inflexible demand. The decarbonised electricity system of 2050 features extensive penetration of intermittent wind generation and inflexible nuclear and CCS generation. All of which creates the need for a new paradigm in system operation whereby system flexibility is delivered through demand following the availability of generation. This must be facilitated through various enabling technologies such as energy storage (large and small scale, and a range of energy vectors), demand response technologies, interconnection, smart grids etc. and is highly dependent on the demand side becoming more responsive and interactive with the energy system as a whole.

At present, there are still gaps in understanding as to how this 'all-electric' future will function including the role of distributed generation and the behavioural element of demand side interactions.

**The role of distributed generation**
Most of the scenarios studied present a picture of 2050 that relies heavily on centralised power generation from large-scale units – nuclear, fossil plus CCS and large wind farms. There is limited discussion of the role of distributed generation in most of the models analysed, raising an issue which could warrant further investigation. Network models are not well adapted to the complexities of a highly granular distribution network and optimisation models like MARKAL are highly sensitive to price inputs on technology costs without being able to accurately represent cost savings that come from, for example, reduced transmission cost. Some studies have cited analysis of distributed generation scenarios and, invariably, this is discounted on the basis of high initial costs of small scale renewable generation technologies and/or the sunk costs (and value) of the existing transmission infrastructure.

Given this, further consideration of distributed generation may be needed to ascertain whether the lack of a role for this technology in the scenarios studied is due to an inherent unsuitability of the technology, or to the difficulties around modelling highly granular generation units in a complex distribution network.

**Demand side and behavioural interactions**
As highlighted above, system operation resources to support inflexible and intermittent large-scale power generation are an important challenge for the future system. Most of the low/zero carbon options for providing that flexibility come from granular demand response from tens to hundreds of thousands of individual users. Infrastructure investments to ensure security of supply are happening now. Proposals for network investment (including interconnection with Europe and elsewhere) are in place as are proposals for more traditional sources of generation flexibility (e.g. OCGTs). If the demand side is going to play a significant part in this future system, some certainty is needed soon that that this service will be available. Otherwise, security of supply (ensuring that the lights don't go off) will be met through the traditional and reliable medium of responsive gas generation technologies – locking the system into a carbon future.

There is very little data available that characterises how the demand side may interact with the new technologies (e.g. smart meters and smart home technology) to provide the level of demand response projected. This lack of data on technology performance in context, and on behavioural elements of technology uptake and usage, means that there is a high degree of uncertainty around whether the demand side will participate in the energy system to the extent required. Further analysis and consideration is required, alongside significant demonstration of these new technologies and concepts, to understand the extent to which the demand side can become the resource that many scenarios describe.

## 5.4 Taking early action

Taking early action to reduce $CO_2$ emissions, either by 'leap-frogging' directly to zero carbon technologies or implementing shorter term stringent targets, could have implications for innovation. Some commentators argue for the immediate implementation of zero carbon technologies rather than investment of effort and resources into incremental changes in energy efficiency of existing technologies. This could have the dual effect of decarbonising the system faster and ensuring that total emissions are minimised.

However, this is countered with the argument that efficiency gains are often 'low-hanging fruit' in the form of quick and cheap changes that could have immediate effect and get us on the right trajectory to 2050. The alternative of 'leap-frogging' to novel zero carbon technologies could take time to implement and ultimately be far more costly, requiring greater levels of investment in immature, unproven technologies.

## 5.5 Further increasing emission reduction targets

The scale of the emission reductions for the energy sector has varied between the scenarios. Some have applied the overall national 80% reduction target directly to the energy sector while others have considered the implications for higher reductions, as other sectors will be harder or more costly to reduce their emissions. Targets may also have to be increased in response to the understanding of the climate system.

The cumulative emissions over the 40 year period to 2050 are as important as the final emission rate. Any delays in reducing emissions will require greater effort later on and potentially require a higher than 80% final target for emission reductions.

The implication for the energy system of higher emission reductions could be significant. For example, the remaining 20% of current emissions in 2050 that could have been used for transport, residual emissions from coal CCS or from unabated gas to allow balancing could be halved. Analysis in 2008 by the Committee on Climate Change indicates that 90% reduction sees a shift away from coal with CCS to gas with CCS post 2035 as it has lower residual emissions. Higher targets, above 90%, suggest nuclear will dominate with little CCS remaining in 2050. However, developments in the use of biomass may see CCS playing an important role, potentially providing negative emissions. Furthermore, developments in air capture of $CO_2$ may make it an economic option so $CO_2$ could be removed directly from the atmosphere and fed into what could be a well developed $CO_2$ transport and storage network.

## 5.6 Bioenergy

Biomass for heating, electricity generation and transport fuel has issues that are well known, with global demand and supply uncertain, and the true carbon costs sometimes hidden.[48] Aside from competition between energy sectors, there may be wider environmental concerns, even from advanced, or '2nd generation' biofuels. As yet, however, there is no consensus on the best course of action and addressing these concerns is a priority. For the energy system, the implications of any one sector taking priority for biomass would imply others tackling other technology solutions with greater urgency. Indeed, that all sectors see biomass as a possible solution now (which is unlikely to be the eventual case) may be slowing down progress.

## 5.7 Life cycle impacts of energy technologies

The choice of energy technology has wider implications than just its greenhouse gas emissions, including availability of land, impact on water resources and availability of mineral resources. Some of the impacts will be in the UK; others will be global. The need to understand these impacts was highlighted by the recent debate over land use and food crops for biofuels. Similarly, questions were raised about the amount of carbon emitted from the extraction of uranium and, therefore, how 'low carbon' nuclear power really was, although analysis has clarified these figures.

The cost and availability of mineral resources may also impact on the development of some technologies. For example, fuel cells, catalytic convertors, solar panels and permanent magnets all use specific minerals, which, if substituted, would affect performance. The cost and availability of these elements could impact on how the technology develops. One important group of elements is the lanthanoids. Often referred to as 'rare earth' minerals, they can be abundant but are limited by the number of economically mineable deposits. At present, China is the dominant producer and user but demand is increasing globally and mining is likely to focus on other large deposits.[49] But the feasibility and wider environmental impacts of increasing demand need to be understood at an early stage so as to inform the development of new technologies.

[48] See for example the UKER C report '*Accelerated Development of Low Carbon Energy Supply Technologies*' (Chapter 5 on Bioenergy), available at **www.ukerc.ac.uk/Downloads/PDF/U/UKERCEnergy2050/TAcceleration_Draft.pdf)**
[49] National Academies Press (2008) '*Managing Materials for a Twenty-first Century Military*'. Available from **www.nap.edu/catalog.php?record_id=12028**.

# 6 Next steps

**Technology development**
Action is needed to put in place the policies and investment to ensure that the innovation needs highlighted in the technology pipeline diagram above are delivered. An ongoing role for ERP will be to keep track of progress against the innovation milestones set out in this report.

How the UK chooses to deliver this and encourage domestic innovation is particularly salient. One country cannot expect to lead development across the board. According to our domestic strengths and requirements there must be some prioritisation of technologies. Firstly, to decide which technologies to take a lead on developing in the UK; secondly, which to collaborate in the development of (and with whom) and, thirdly, those which we should take an active interest in so that we are ready for deployment but do not necessarily have the expertise to play a role in developing.

ERP's ongoing work on International Engagement will help the UK take a more strategic approach both to prioritisation, and to taking advantage of collaborative energy innovation activities.

**Supporting analysis**
This study describes the innovation challenges at a high level in order to provide guidance for policy makers and funders/investors. That the analysis comes from a broad spectrum of stakeholders should give confidence that the conclusions have support from across the sector. But further analysis is required to address the issues that we have highlighted and to review our progress towards achieving the 2050 goals. We therefore propose some next steps:

- ERP's future work will look at many of these technology areas in more detail to consider whether there are any funding gaps, and the potential role for the UK in driving forward RD&D.
- Further modelling and scenario work is essential. A diversity of approaches will improve our understanding of how the energy system could develop. The Energy Technologies Institute's new Energy Systems Model will bring a fresh perspective, including the ability to balance energy security and cost considerations. Also, the development of the global TIMES model as a successor to MARKAL will study the UK's position with respect to worldwide resource flows and global technology innovation.
- Energy system modellers would benefit from continued interaction to exchange information, outputs and ideas. The academic community, with input from ERP, has been organising workshops and events to bring researchers together, and to feed messages in to policy makers.
- The development of detailed technology requirements, or specific activities to assist them, such as from the Carbon Trust's 'deep dives', should be undertaken as a matter of urgency.
- Communicating messages effectively from scenarios to those who will use the information is critical. ERP will have a role to look periodically across scenarios and new analyses to assess whether any of our conclusions need revising.

The whole energy community has a responsibility to take forward these conclusions. ERP is well placed to coordinate these activities and ensure that decisions affecting energy innovation are informed by the best available information.

# Glossary

| | |
|---|---|
| **ASHP** | Air Sourced Heat Pump |
| **CAES** | Compressed Air Energy Storage |
| **CAT** | Centre for Alternative Technology |
| **CCC** | Committee on Climate Change |
| **CCS** | Carbon capture and storage |
| **CHP** | Combined Heat and Power |
| **CSP** | Concentrated Solar Power |
| **dCHP** | Domestic Combined Heat and Power |
| **DNO** | Distribution Network Operator |
| **ERP** | Energy Research Partnership |
| **ESCO** | Energy Services Company |
| **EV** | Electric Vehicle |
| **EPSRC** | Engineering and Physical Sciences Research Council |
| **Gen IV** | Generation 4 nuclear fission reactors – advanced reactor systems currently being researched and developed. Includes thermal designs and fast neutron reactors that are characterised by improvements in economics, safety, environmental performance and proliferation resistance. Fast reactors can offer a closed fuel cycle that could reduce fuel demand and dispose of some high level wastes |
| **HGV** | Heavy Goods Vehicle |
| **HVDC** | High Voltage Direct Current |
| **IFI** | Innovation Funding Initiative. See **www.ofgem.gov.uk** for more information. |
| **IGCC** | Integrated Gasification Combined Cycle power plant. Only a few have been built globally and requires further development to improve efficiency on coal and reliability. Uses gasification process to convert fuel to syngas (hydrogen and carbon monoxide) with the hydrogen burnt in a gas turbine at high temperature and pressure. Residual heat is captured to power a conventional steam turbine |
| **LCPD** | Large Combustion Plant Directive |
| **MARKAL** | Market Allocation model – whole energy system model supported by the IEA. It is perfect foresight, partial equilibrium model that minimises system costs |
| **- MED** | MARKAL Elastic demand version – accounts for changes in energy service demand in response to changes in energy price |
| **- MACRO** | MARKAL Macroeconomic version that combines the MARKAL model with a simple economic growth model that accounts for the impact of carbon prices on energy demand |
| **NAIGT** | New Automotive Innovation and Growth Team – industry led initiative launched in April 2008 to develop a collective strategic view of innovation and growth challenges in the automotive industry |
| **OCGT** | Open Cycle Gas Turbine |
| **PHEV** | Plug-In Hybrid Electric Vehicle |
| **PV** | Photovoltaic |
| **RPZ** | Registered Power Zones. See **www.ofgem.gov.uk** for more information. |
| **R&D** | Research and Development |
| **RD&D** | Research, Development and Demonstration |
| **RDD&D** | Research, Development, Demonstration and Deployment |
| **RDA** | Regional Development Agency |
| **Sankey diagram** | Flow diagram where width of arrows is proportional to flow quantity. Used here to show how energy flows through the system, from supply to consumer. |
| **UKERC** | UK Energy Research Centre |
| **USC** | Ultra-Supercritical boilers - operate at temperatures over 580°C, but aim to achieve >700°C and 30 MPa (300 bar, 4,350 psi) with efficiencies of over 50% |

# Appendix 1 – Acknowledgments


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| Organisation | Individuals |
|---|---|
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| **BP** | Rosie Albinson |
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| **Department for Transport** | - |
| **Calor Gas** | Paul Blacklock |

# Appendix 2 – Scenario meta-analysis: Overview

| Organisation | Pub. Year | Reference | Objectives & Background | Timeline | Scenario and Model Type | Website |
|---|---|---|---|---|---|---|
| **BP** | Ongoing commercial studies | | | | | |
| **Centre for Alternative Technology (CAT)** | 2007 | 'Zero Carbon Britain' | Demonstrate that zero carbon Britain is feasible within 20 years using existing technologies and market based instruments including tradeable household energy quotas | 2027 | **Backcasting, quantitative** Backcast to fit energy supply system to match demand, without fossil fuel or nuclear and zero carbon by 2027. | **www.zerocarbonbritain.com/** |
| **Confederation of British Industry (CBI)** | 2007 & 09 | 'Climate Change, Everyone's Business' & 'Decision Time' | To explore the likely outcomes for the UK energy system of meeting the 2020 renewables target under the current set of policy incentives[50] | 2030 | **Forecasting, quantitative** Linear optimisation model. McKinsey proprietary model of pan-European power system. | **www.cbi.org.uk/pdf/20090713-cbi-decision-time.pdf** |
| **Ceres Power** | Ongoing commercial studies | | | | | |
| **Centrica** | Ongoing commercial studies | | | | | |
| **Committee on Climate Change** | 2008 | 'Building a low carbon economy - the UK's contribution to tackling climate change' and 'Meeting Carbon Budgets - the need for a step change' | To underpin recommendations and proposed levels for carbon budgets and path to an 80% reduction in $CO_2$ emissions by 2050. | 2050 | **Backcasting, quantitative** MARKAL-MED modelling, undertaken by AEA Technology, updated by UCL Energy Institute | **www.theccc.org.uk/reports/building-a-low-carbon-economy** and **www.theccc.org.uk/reports/progress-reports** |
| **David MacKay** | 2009 | 'Plan C - A Plan with a time-line', additional material to 'Sustainable Energy - without the hot air' | Aims to decarbonize Britain by 2050 and to keep the lights on along the way. Plan C is a suggested starting point for a single consensus plan. | 2050 | **Backcasting, quantitative** Matching supply and demand, and building a feasible decarbonised energy system within the bounds of technology capabilities. | **www.inference.phy.cam.ac.uk/sustainable/book/tex/PlanC.pdf** and **www.withouthotair.com** |
| **DECC** | 2009 | 'UK Transition to a Low Carbon Economy', Analytical Annex | Scenarios commissioned for a variety of purposes, including meeting the constraint of the UK's renewable energy target. | 2050 | **Backcasting, quantitative** Draws on MARKAL-MED scenarios: includes those commissioned by DECC for the Transition Plan, and for Defra, UKERC and CCC. | **www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx** |
| **E.ON** | Ongoing commercial studies | | | | | |
| **EDF** | Ongoing commercial studies | | | | | |
| **Energy Savings Trust (EST)** | 2008 | 'Emission Impossible' | Focus on identifying the personal emissions reductions necessary to reach the 2050 80% reduction target and the interim steps that can be taken to reach 2050. | 2050 | **Backcasting, qualitative** Evaluation of steps necessary for individuals to achieve 80% emission reduction target. | **www.energysavingtrust.org.uk/Publication-Download/?p=4&pid=1336** |
| **Foresight** | 2008 | 'Sustainable Energy Management and the Built Environment' | Exploration of the future of energy systems in the built environment. Explores how the built environment could evolve to manage the transition to a low carbon society | 2050 | **Forecasting, qualitative** Analysis of a broad evidence base, including academic literature and participation of expert groups. | **www.foresight.gov.uk/Energy/EnergyFinal/final_project_report.pdf** |
| **International Energy Agency (IEA)** | 2008 | 'BLUE Map' from 'Energy Technologies Perspectives 2008, Scenarios and Strategies for 2050' | Responds to the G8 call on the IEA to provide guidance for decision makers on how to bridge the gap between what is happening and what needs to be done in order to build a clean, clever and competitive energy future. | 2050 | **Backcasting, quantitative** IEA MARKAL model. Reduces global $CO_2$ emissions by 50% (from 2008 levels) by 2050. | **www.iea.org/techno/etp/index.asp** |

[50] This work was done in collaboration with McKinsey, but it is not linked to the previous CBI/McKinsey outputs based on the McKinsey Marginal Average Cost of Carbon (MACC) curves ('*Climate Change: Everyone's Business*' ref. **www.cbi.org.uk/pdf/climatereport2007summary.pdf**).

# Appendix 2 – Scenario meta-analysis: Overview

Continued

| Organisation | Pub. Year | Reference | Objectives & Background | Timeline | Scenario and Model Type | Website |
|---|---|---|---|---|---|---|
| **Institute of Mechanical Engineers (IMechE)** | 2009 | 'UK 2050 Energy Plan: Making our commitment a reality' | The UK 2050 Energy Plan was developed as part of an international engineering institution initiative to contribute towards the discussions at COP 15 in December 2009. Engineering institutions from across the world are generating national technology based climate action plans for the period up to 2050. | 2050 | **Backcasting, qualitative** Descriptive routemap to 80% $CO_2$ reductions by 2050 within the mathematical bounds of technology capabilities. | **www.imeche.org/NR/rdonlyres/BB6FF365-FAFD-4B3E-8C8C-6D85084F43E7/0/IMechE_UK_Energy_2050_Report.PDF** |
| **IPPR, WWF & RSPB** | 2007 | '80% challenge: delivering a low-carbon UK' | To investigate whether a target of 80% could be achieved in the UK by domestic efforts alone and what the costs of doing so would be. | 2050 | **Backcasting, quantitative** MARKAL-MACRO and a model developed by Professor Dennis Anderson for estimating the global costs of mitigating climate change for the Stern Review. | **www.ippr.org.uk/publicationsandreports/publication.asp?id=573** |
| **McKinsey** | 2009 | 'Pathways to a Low-Carbon Economy' | The model illustrates potential, not likely outcomes. Forecasting, using expert input to determine likely technology developments, learning rates and associated cost reductions over time, alongside an evaluation of the carbon abatement potential of particular technologies (or approaches). | 2050 | **Forecasting, quantitative** Using the MAC Curve (Marginal Abatement Cost) approach to determine costs of emissions reductions. | For UK MACC see: **www.cbi.org.uk/pdf/climatereport2007summary.pdf** For global MACC go to: **https://solutions.mckinsey.com/climatedesk/default/en-us/contact_us/fullreport.aspx** |
| **National Grid** | 2009 | 'Gone Green Scenario' [51] | Developing an illustrative scenario to show the components of the energy system in 2020, where the UK is meeting its target of 15% of energy coming from renewable sources and reflecting closures of existing generating plant due to legislation (LCPD) and age profile.[52] | 2020 | **Forecasting, quantitative** A descriptive scenario that quantifies the key components of the UK power system and related energy demands in 2020 based on current trends. | Gone Green Scenario Narrative: **www.nationalgrid.com/NR/rdonlyres/554D4B87-75E2-4AC7-B222-6B40836249B5/32656/ScenarioNarrative.pdf** and consultation on operating the Electricity Transmission Networks in 2020: **www.nationalgrid.com/uk/Electricity/Operating+in+2020/2020+Consultation.htm** |
| **Ofgem** | 2008 | 'Long Term Electricity Network Scenarios (LENS)' | To generate a set of credible scenarios that describes the possible extremes of network development. The scenarios could then be used to assist understanding of the implications for regulation of networks of the various possibilities. | 2050 | **Forecasting, qualitative** Qualitative, descriptive scenarios based on alternate extreme visions of future network evolution, not constrained by $CO_2$ reduction. Backed up with MARKAL-MED evaluation of each scenario | **www.ofgem.gov.uk/Pages/MoreInformation.aspx?docid=67&refer=Networks/Trans/ElecTransPolicy/lens** |
| **Ofgem** | 2009 | 'Green Transition' and 'Green Stimulus' scenarios from 'Project Discovery' | The scenario approach is used to identify the scale of the challenge and risks facing the GB and wider European and global energy markets over the next two decades. Under these two scenarios, the 2020 Renewables targets were met. | 2025 | **Forecasting, quantitative** The study developed four descriptive scenarios setting input assumptions for quantitative modelling of the GB energy markets and energy system. | **www.ofgem.gov.uk/MARKETS/WHLMKTS/DISCOVERY/Documents1/Discovery_Scenarios_ConDoc_FINAL.pdf** |
| **Shell** | 2009 | 'Blueprints' from 'Shell energy scenarios to 2050'[53] | 'Blueprints' describes the dynamics behind new coalitions of interests. This leads to the emergence of a critical mass of parallel responses to supply, demand, and climate stresses, and hence the relative promptness of some of those responses. | 2050 | **Forecasting, quantitative** Global with expert input. | **http://www.shell.com/scenarios/** |
| **Scottish and Southern Energy** | Ongoing commercial studies | | | | | |
| **UK Energy Research Centre (UKERC)** | 2009 | 'Carbon ambition' (CAM) from 'UKERC Energy 2050'[54] | Developing a series of model runs to explore system costs and composition based on background scenarios that reflect a need for greater system resilience, carbon reduction or both. | 2050 | **Backcasting, quantitative** MARKAL-MED: quantitative cost optimization, with perfect foresight and elastic demand. CAM targets: 26%$CO_2$ reduction by 2020, 80% by 2050 | **www.ukerc.ac.uk/support/tiki-index.php?page=Energy+2050+Overview** |

[51] National Grid 2050 Network capacity modelling project was an in-house exercise to take a 'broad and shallow' analysis, backcasting from 2050, exploring the implications of the 80% target for the UK electricity and gas networks. The results have not been published, but were made available to the ERP Analysis Team.
[52] The Gone Green scenario has also been used to generate further scenarios for ongoing work on electricity network development, e.g. the Electricity Network Strategy Group (ENSG) derived a number of background generation scenarios from the Gone Green framework to explore network requirements for the system in 2020.

[53] We also received briefing on UK specific output, not publicly available.
[54] Other UKERC scenarios which reached 80% by 2050 were also considered.

# Appendix 3 – Scenarios Workshop report

## 28 September 2009, Institute of Physics, London

## Programme

| | |
|---|---|
| 1.00 | **Welcome and introduction**, Nick Winser (ERP Co-Chair and National Grid) |
| 1.10 | **Overview of scenario meta-analysis**, ERP Analysis Team |
| 1.30 | **Validation of meta-analysis in plenary discussion**<br>Discussion and 'validation' of the main findings of the scenario meta-analysis; areas of commonality around the future energy system and trajectories to 2050 and exploring why there are differences owing to different assumptions, implicit uncertainties or modelling techniques. |
| 2.15 | **Introduction of break-out groups**<br>Discussion of the implications of our findings for technology choices and at what points should decisions be taken that will have longer term impacts on the energy system. Three break-out groups will cover:<br><br>1) Responsive and reliable electricity supply<br>- How the system responds to inclusion of large amounts of intermittent generation<br>- Infrastructure implications and smart grids<br>- Investment signals to renewables, CCS, other generation e.g. distributed generation<br>- Demand response and storage<br><br>2) Transport<br>- Drivers for low carbon transportation – EU policy on emissions reductions, UK policy, others<br>- Evolution of transport services<br>- Electricity vs. biofuels vs. hydrogen vs. hybrid<br>- Technology ceilings and floors<br>- Timing of turnover of vehicle park, technology learning curves<br><br>3) Energy efficiency and heat<br>- Electrification of heat – ceiling on heat uptake in electricity<br>- micro-CHP vs. heat pumps and the role of renewable heat<br>- Technology innovation, uptake and timescales<br>- Decarbonisation of the gas supply<br>- Scale, rate and nature of energy demand reduction<br>- Scope and rate of uptake for demand side participation |
| 2.30 | Coffee |
| 2.45 | **Break-out groups** |
| 3.30 | **Report back from group 1 and 2** |
| 4.10 | Coffee |
| 4.25 | **Report back from group 3** |
| 4.45 | **Discussion of whole system implications** |
| 5.10 | **International Context**, Peter Taylor (IEA) |
| 5.25 | **Concluding remarks**, Nick Winser |
| 5.30 | Close |

## Feedback from plenary session on meta-analysis conclusions

The first presentation set out the initial findings from the meta-analysis (as detailed in the earlier sections of this report). Themes from the plenary discussion following this presentation were:

- Act now, continual improvement in the efficiency in existing technologies is important, leap-frogging straight to low/zero carbon technologies could delay action and cost more.
- Can't extract economics from the decision-making process. This will be a key driver of many of the critical decision points.
- Information on the demand side – how we use energy, how we could use it in the future and how end users will respond to new technologies – is lacking.

**Whole System**

There was some discussion around the $CO_2$ reduction benefits of jumping straight into roll-out of low and zero carbon technologies and not spending time on implementation of incremental efficiency changes to existing technologies. This was countered with the comments that efficiency gains were often 'low-hanging fruit' i.e. quick and cheap changes that could have immediate effect and get us on the right trajectory to 2050. There was also a reminder that 2050 was chosen as a staging point because this allowed a relatively long term look to the future whilst still dealing with known technologies. Looking out to 2050 was intended to encourage us to take action with what we have now, rather than waiting until less proven technologies are ready to come on-stream.

**Transport**

As part of a discussion on transport, it was highlighted that 50% of all journeys taken are long distance, or freight, and not necessarily suited to electrification. Tackling this 50% of journeys is a crucial issue and raises challenges for e.g. intermodal transport to complete particular journeys and consideration of a necessary role for fossil based fuels (e.g. compressed natural gas) in servicing this sector.

**Demand**

The outcome of many scenarios, and their success at meeting the 80% target, is often driven by the level of consumer engagement in the energy system. However, it was highlighted that many of the scenarios included in the meta-analysis present demand as a statistical input, rather than drilling down into the energy services that generate the statistic. This makes it impossible to really identify areas where energy service demand could be fundamentally reduced, as opposed to more straight forward delivery of energy efficiency. This impeded representation of demand means that one of the most critical factors in achieving 80% reductions (large-scale demand reduction) can't be accurately represented.

**Prices**

Several contributors emphasised that prices and price assumptions in modelling will drive most of the outcomes. The issue of carbon pricing was also raised as this will be a significant driver in the development of low carbon technologies over the incumbents. This was highlighted as an extreme uncertainty, particularly beyond 2025. The discussion prompted an emphasis on the affordability question – and the fact that (without alternative intervention) economics is probably the key factor that will ultimately drive all these decisions.

**Skills**

The scale of the challenge in engineering terms was highlighted several times throughout the discussion and the workshop. The fact that this level of construction rivalled that seen after World War 2 – and that a lack of engineers or those with a first-hand experience of delivering these projects – could also be a challenge for timely realisation of the 80% target.

## Feedback from breakout group 1: Responsive generation and infrastructure

From the meta-analysis of 2050 scenarios, we see a clear consensus that rapid decarbonisation of the power sector is necessary and that the power sector will be responsible for meeting at least some new demand from heat and transport. There is less certainty around how system operation will be managed, how much intermittency will affect the system operation and what approaches can be employed to maintain system security whilst also remaining economic and low-carbon. There is some consensus that a new level of 'intelligence' in the networks and connecting infrastructure will be needed to deliver a functional system with these new low carbon components but the extent and functionality of this smart grid is uncertain. The aim of this breakout group discussion was to identify and discuss the critical decision points that will impact development of the power system and infrastructure in response to the 80% $CO_2$ reduction target and to begin to identify technology solutions and innovation milestones to achieve this reduction.

**Question 1**: To achieve the stringent 80% emission reduction target by 2050 means that the entire basket of known low / zero carbon generation technologies will all need to be deployed. The group was asked to consider what technology (and other) factors will influence the relative proportions of the major power generation technologies out to 2050?

The discussion was initiated with the broad statement that decarbonised power generation would need to come from roughly one third each of renewables, fossil with CCS and nuclear. Discussion explored the potential for CCS with a broad consensus that, although the technology was currently unproven, this was not a major blocker to its deployment. Factors such as health and safety risk and business risk were deemed more important in driving forward deployment. A similar conclusion was reached for offshore wind, in that although there were challenges with developing technology, e.g. for deep waters, the risk to managing deployment came more from operational factors like the complexities of maintenance of turbines at sea etc. There was no discussion on nuclear.

There was an emphasis on the international dimension of technology RD&D and discovering where the UK had strengths; not just in technology know-how but also in resource (e.g. offshore wind). Understanding where we can buy-in developed technologies versus areas where the UK can develop technologies that build the UK economy as well as meeting targets was a key point.

It was also noted that whilst proportions of technologies are useful – there are also absolute boundaries within which a technology exists e.g. available land area etc.

**Question 2**: The possibility of electrification of heat and transport would put an onus on the power system to provide additional (decarbonised) capacity. How does electrification compare to the alternative sources to serve heat and transport? And what are the primary drivers and challenges for electrification of heat and transport?

There was consensus that electrification of heat was inevitable to meet the 80% targets. The main driver for this was thought to be a) the unsuitability of any other primary energy source to serve heat demand without resulting in unacceptably high $CO_2$ emissions (e.g. natural gas) and b) the lack of availability of low-carbon energy sources such as biomass or biogas.

However, discussion outside the breakout group raised the issue of the peakiness of gas demand (not just intra-day – but through the year) i.e. that energy demand for heat currently increases almost 4 times from its lowest point to peak over a yearly cycle. This is unlike electricity where the average daily demand remains fairly flat throughout the day. End use technology to drive heat will also impact the way that energy demand is distributed intra-day. Typical heat pumps are designed to provide steady low-level heat throughout the day (a flat output profile). Current gas central heating boilers provide on demand response to meet peaks in heating demand that coincide with occupancy of the building.

It should also be noted that changing heating services to heat pumps that operate as described above will necessitate a significant shift in the way people use heat. Plus, problems may be experienced with retrofit of this type of technology into wet systems.

The group also highlighted the large-scale electrification of transport as a likely factor that the UK system would need to account for. There was some disagreement over the capacity that would be required to service this new demand and how much the demand could be utilised to provide system flexibility – as this ultimately will drive the impact of transport on the power system. It was noted that the total population of vehicles that could be suited to electrification would depend on their function and the distances covered. Discussed in the earlier session – it was highlighted that around half of the journeys made by car may not be suited to electric vehicles (e.g. heavy goods transportation and longer journeys). This should be taken into account when considering the capacity that the power system would have to supply if transport demand is met by power.

**Question 3**: The mix of renewables (wind), fossil+CCS and nuclear is potentially both inflexible and intermittent. Providing economic system flexibility that is also low/zero carbon and maintains system security will be a key challenge. What factors (technical, policy, economic, social) will drive the impact of intermittency and inflexibility and the response to providing system management resources? Which technologies will be capable of providing flexibility requirements in 2020 and 2050? Can technology innovation in generation or demand mitigate these problems? Are other developments (e.g. behaviour change) required to make a major impact?

The size of the power system is bounded by the need to be able to provide power for several hours and potentially several days at a time when weather conditions prevent wind generation. The group noted that anticyclones (affecting the whole of Europe and not just the UK) can cause days of calm weather and that the likelihood of this happening for up to 7 days is not uncommon. Certainly a few days at a time is a yearly occurrence. These weather patterns are often experienced simultaneously on the continent, making importing power as a solution to this issue unlikely.

With a high penetration of wind generation, backing up the system in the event of this kind of weather front is essential; perhaps to the point of being able to supply the entire country's power demand from non-wind resources for several days on end. There was the concern that there are few low-carbon technologies available and proven today that could provide this service. The most obvious provider would be responsive fossil fired units. However this comes with a carbon cost and these units would only be used for a few days per year, making the economics of maintaining a near 100% capacity margin somewhat dubious. The group noted that, at present, gas generation is the default investment for providing flexible plant. Gas is relatively low cost so the economics of providing capacity for the system is highly competitive.

The role of storage in providing days worth of power supply was discussed. There was a divergence of views on whether there could be sufficient power stored in the system to provide coverage over long periods of calm. This could be coupled with demand reduction; but again, as this is spreading over several days, so the options for reducing demand so significantly on concurrent days seems limited.

The contribution that heat and transport could make to mitigation of intermittency was raised. There was a divergence of views as to whether this resource could ever be sufficient to meet power demand over several days. The economics of provision of this service were also questioned.

There was a brief discussion of the role of smart grids in which it was highlighted that the main purpose of this technology is to facilitate the optimal choices being made on system operation. To provide data on energy use, supply and prices to enable the optimal decision to be taken throughout the day. It was also highlighted that because of problems with intermittency being particularly pertinent for an island, the UK would need to respond to these challenges earlier than others on the Continent. Given this, there could also be competitive advantage for the UK in the development of smart grid industries.

## Concluding remarks:

Much of the uncertainty around what role various technologies will have and how they can contribute to system flexibility cannot be resolved without a better understanding of how energy is used in the first instance, and how the power system interacts with its users to supply power and manage system operation. The need for data on how people heat their homes and use their vehicles (both now – and some modelling on the various options for how this could change with e.g. heat pumps and PHEVs) is essential to be able to understand how the system will operate in the future. This is needed in tandem with an understanding of how the power system operates (and will operate in the future) and the demands that it may make on system users.

## Feedback from breakout group 2: Transport

From the scenarios there is a general view that there will be mixed energy sources and technologies for transport going out to 2050. The mix is most influenced by which transport sector they are applied to and where limitations in a particular fuel/technology restrict its application. Differences were also found in when a technology will be available and whether there are external limitations to the extent of its deployment.

Greatest consensus was over the need for increased efficiency, both technical (vehicle design and power train), and operational (logistical and modal shift). However there are mixed views as to what impact this will have owing to uncertainties in what can be achieved. Other factors that affect the development and deployment of technologies are the rate of fleet turnover and infrastructure developments, including supply chain.

This breakout group explored these issues and asked the questions: What is the demand for transport, how will that demand be met and what is the relative significance of technology innovation and behaviour change in achieving this?

Transport is clearly divided between land/road, marine and aviation, with distinctly different approaches for reducing emissions.

**Marine**
Solutions for Marine are also not clear. This is not well covered by the scenarios explored in the meta-analysis.

**Aviation**
Efficiencies in the operation and movement of aircraft could make significant reductions in emissions. On average 25% comes from airport taxiing, 25% from stacking, 25% from climbing and 25% from flying. Other inefficiencies come from practices used by low-cost airlines which aim to reduce refuelling time and refuel at the cheapest locations. This means turnaround time and passenger numbers outweigh the cost of taking off with larger than necessary fuel loads and therefore with greater emissions. The OMEGA[55] programme was highlighted as a good source of information on these issues.

**Road transport**
The group highlighted that it is important to distinguish between passenger and goods vehicles as options are different. A

[55] See **www.omega.mmu.ac.uk**

distinction should also be made between long and short distance travel. The largest proportion of emissions comes from passenger vehicles.

*Freight – road*: There are no clear options for non-passenger transport. Efficiency is a common solution but freight operators pursue this as it has direct cost savings. Further analysis is needed of other options to understand their benefits.

*Passenger – road*: Vehicle 'park' turnover – Total UK fleet is 34 million private cars with 0.75 million new cars per year. Journey length is important. Most journeys are short and inefficient/high emitting. Long journeys are more efficient per mile. Hire schemes/car clubs may offer one quick option for reducing emissions where low emission vehicles may be made available for short journeys. Range extended vehicles could reduce emissions further for long journeys where an on board generator runs at high efficiency to top up the batteries. Social issues are important. Attitudes to car ownership and expectations from a vehicle vary between countries; users may choose to own one or other of the vehicles – in part for convenience. A 'business as usual' scenario would see users driving the same vehicle. This is unlikely to be the best option and therefore intervention is needed to change consumer expectations of vehicles and how they use them. European efficiency policy and vehicle standards will be important. But manufacturers are struggling to meet the increasingly diverse national consumer demands.

Timing is important. Four areas were highlighted:

1. Efficiency in vehicles – New Toyota Prius about 80 $gCO_2$/km. Engineers suggest that limit on hybrids is about 70–80 $gCO_2$/km.
2. Biofuels – wider availability at 50 $gCO_2$/MJ would mean that a new Prius would emit <50 $gCO_2$/km.
3. Decarbonisation of the grid. Would allow widespread introduction of electric vehicles.
4. Cost of electric vehicles. Batteries are too expensive to be included in purchase price. Suggest that the battery could be leased but then who would take the risk for such a scheme?

2020 targets of delivering <80–90 $gCO_2$/km (new fleet average) is likely to be surpassed.

*Batteries*: US are investing heavily in batteries and new chemical combinations. Biggest challenges are reducing size but the increased energy density often leads to an unstable battery. Materials for use in batteries are also constrained, e.g. lithium. Recycling batteries is also a challenge and currently expensive. Range extending vehicles could be a stepping stone technology here as they can reduce the size, and therefore the cost, of the battery.

Other factors to consider include: impacts of congestion and possible saturation; air pollution as a driver of policy

## Concluding remarks:

Most of the technologies that could be used for transport are currently expensive and have limitations. Significant cost reductions are needed, but will take time. Technology change is also dependent on wider energy system conditions, such as a decarbonised grid and greater quantities of biofuels. Technology choice and development in the UK will also be influenced by developments in other countries. Until these become clear, a technology hedging strategy should be adopted to keep options alive and with an R&D focus on reducing technology costs. This would prepare the way for a more focused strategy in about 15 years time when the choices become clearer.

In the meantime, efficiency should be a priority across all transport sectors. Technology will provide some savings but the majority will come initially from operational improvements and behaviour change.

## Feedback from breakout group 3: Heat and Energy Efficiency

Most scenarios require significant increases in efficiency in the end use of energy. Buildings are a key area where demand could be reduced through improved efficiency and demand reduction but it remains a challenging area and there are uncertainties about what can be achieved.

Reducing emissions from buildings is also highly dependent on tackling heat supply. There is divergence in which technologies will be used owing to uncertainties in the technology development and in their deployment. A wide range of technologies is proposed but many are dependent on other factors, such as decarbonised electricity or gas supply. As a consequence some technologies may only be used as intermediary steps and be phased out by 2050.

This break out group explored these factors and identified the dependencies and the technology timeframes.

Demographic change could have significant impact on total domestic energy demand - important aspect for scenarios.

Uncertainty on possible energy service demand changes: average house temperatures are still increasing but potential scope for active behavioural change is unclear. Comes from lack of data on energy use. More sophisticated control systems/smart metering are required as a first step in providing information on energy use and affecting behavioural change in users; likely to be a 'no regrets' policy.

Hot water, heating and 'coolth' (to allow for climate change impacts) will have to be provided to buildings.

Heat input requirement will still be of a scale that could make heat supply networks viable. Sourcing heat from power stations should be borne in mind when locating power stations, industry or housing (ICE report referred to www.ice.org.uk/downloads//heat_report.pdf).

Scepticism that electricity will decarbonise so quickly that natural gas district or micro CHP should not be considered. Churn of short life-time technologies will not lock-in high carbon future. Need to understand what technologies have such short life-times though.

Heating from electricity will require infrastructural upgrades. Danger that decarbonization of electricity will lead to inefficient use.

There are higher level issues over the use of biomass for heating. However, the most thermodynamically efficient use of biomass is as fuel itself and not converted to liquid. Role for biogas in the gas network not expected to be as significant as some reports indicate. Injection of hydrogen into the gas network is also possible ('virtual green gas' referred to).

Need innovative finance mechanisms and methods for large-scale deployment to overcome skills gap.

## Concluding remarks:

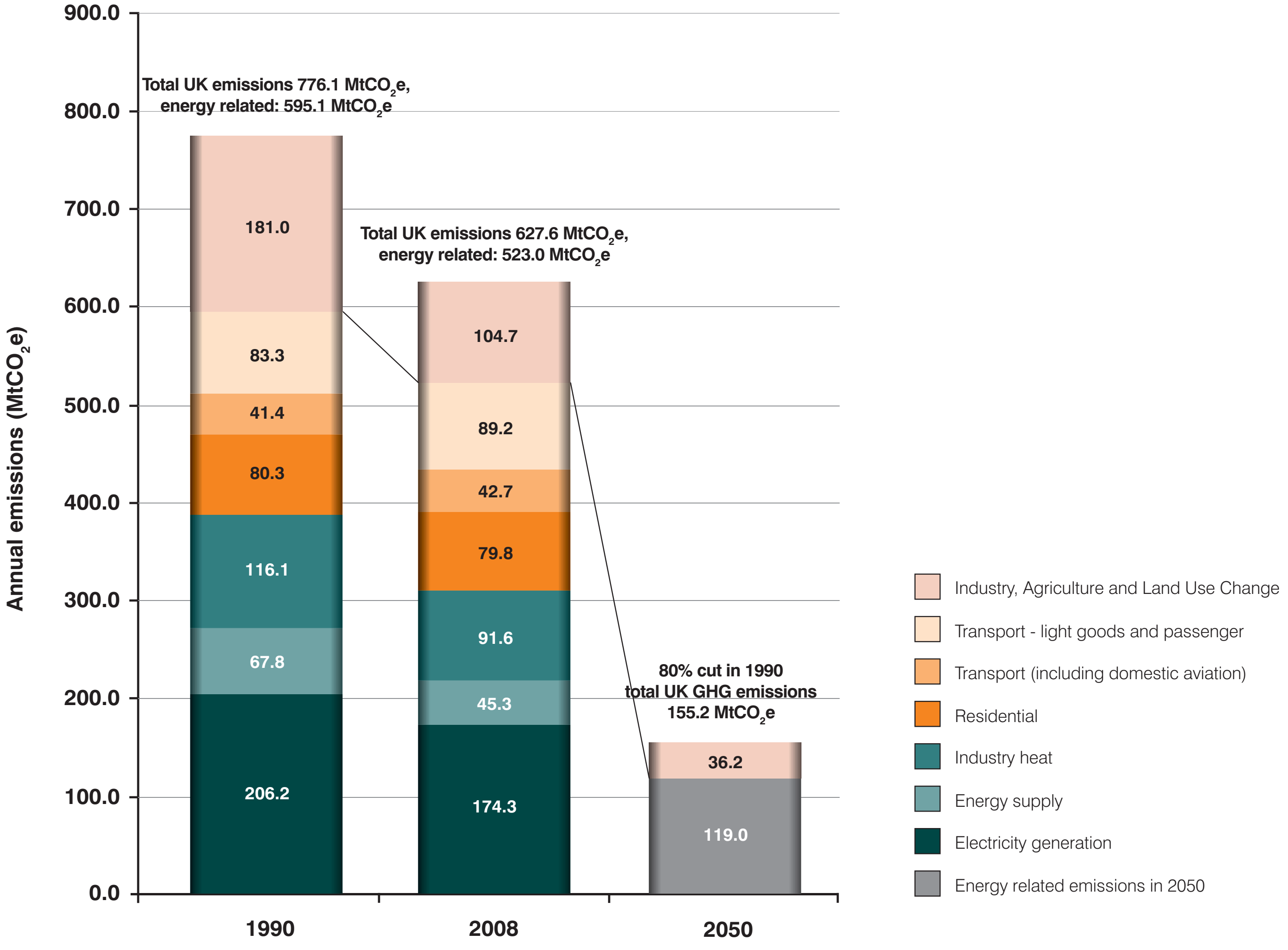
Demand reduction is key to achieving the target and, to optimise this process, we must reduce demand first and then optimise supply.

## Workshop attendees

| Name | Affiliation |
|---|---|
| Tom Palmer | AEA Technology |
| Turlogh O'Brien | Arup |
| Graham Boyd | BIS |
| Rosie Albinson | BP |
| Garry Staunton | Carbon Trust |
| Matthew Farrow | CBI |
| Alex Hart | Ceres Power |
| David Joffe | Committee on Climate Change |
| Steven Daniels | DCLG |
| Vivienne Geard | DECC |
| David Wilson | DECC |
| Graeme Childe | DECC |
| Hunter Danskin | DECC |
| Andy Goodwin | DECC, Energy Security Strategy |
| Matthew White | Department for Transport |
| Brian Collins | DFT / BIS |
| Caroline Cantley | Doosan Babcock |
| Andy Boston | E.ON |
| Matthew Nunn | EDF |
| Henry Jeffrey | Edinburgh University |
| Rod Davies | Energy Technologies Institute |
| Michael Talbot | Foresight, Government Office for Science |
| Jon Parker | HM Treasury |
| Goran Strbac | Imperial College |
| Alison Cooke | Institute of Mechanical Engineers / Cooke Associates |
| Brian Cox | Institute of Mechanical Engineers/ Shelford Business Consultants |
| Peter Taylor | International Energy Agency |
| Ian Welch | National Grid |
| Nick Winser | National Grid |
| Phil Lawton | National Grid |
| Graeme Cuthbert | Office for Climate Change, DECC |
| Stuart Cooke | Ofgem |
| Tim Helweg-Larsen | Public Interest Research Centre |
| Alan Walker | Royal Academy of Engineering |
| Angus MacRae | Scottish and Southern Energy |
| Jim Davis | Scottish Enterprise |
| Frigyes Lestak | Shell |
| Will Usher | UKERC / University College London |
| David MacKay | University of Cambridge / DECC |
| Roland Clift | University of Surrey |
| Ron Loveland | Welsh Assembly Government |

# Appendix 4 – Carbon emissions from the energy sector

Emissions from the energy sector account for over 80% of the UK's total greenhouse gas emissions. The figure below shows energy related emissions from 2008 broken down by the main energy sectors, set against the baseline of 1990. The figure also illustrates the amount of emissions will be allowed from the energy sector if they were to be cut by 80% in line with achieving the overall 80% emission reduction target. Energy supply accounts for a majority (60%), mainly from electricity generation (34%), with the 9% coming from upstream emissions including refineries, mining and gas flaring and leakages. Industrial energy supply accounts for a significant proportion although the technologies to tackle these emissions will be similar to those for electricity generation including CCS. Total transport emissions, including domestic aviation, totals 131.9 $MtCO_2e$, but a clear majority (68%) comes from light goods and passenger vehicles. Residential does not include emissions associated with electricity use.




*UK energy related emissions of greenhouse gases by supply, 2008 (Source DECC/NAEI)*

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